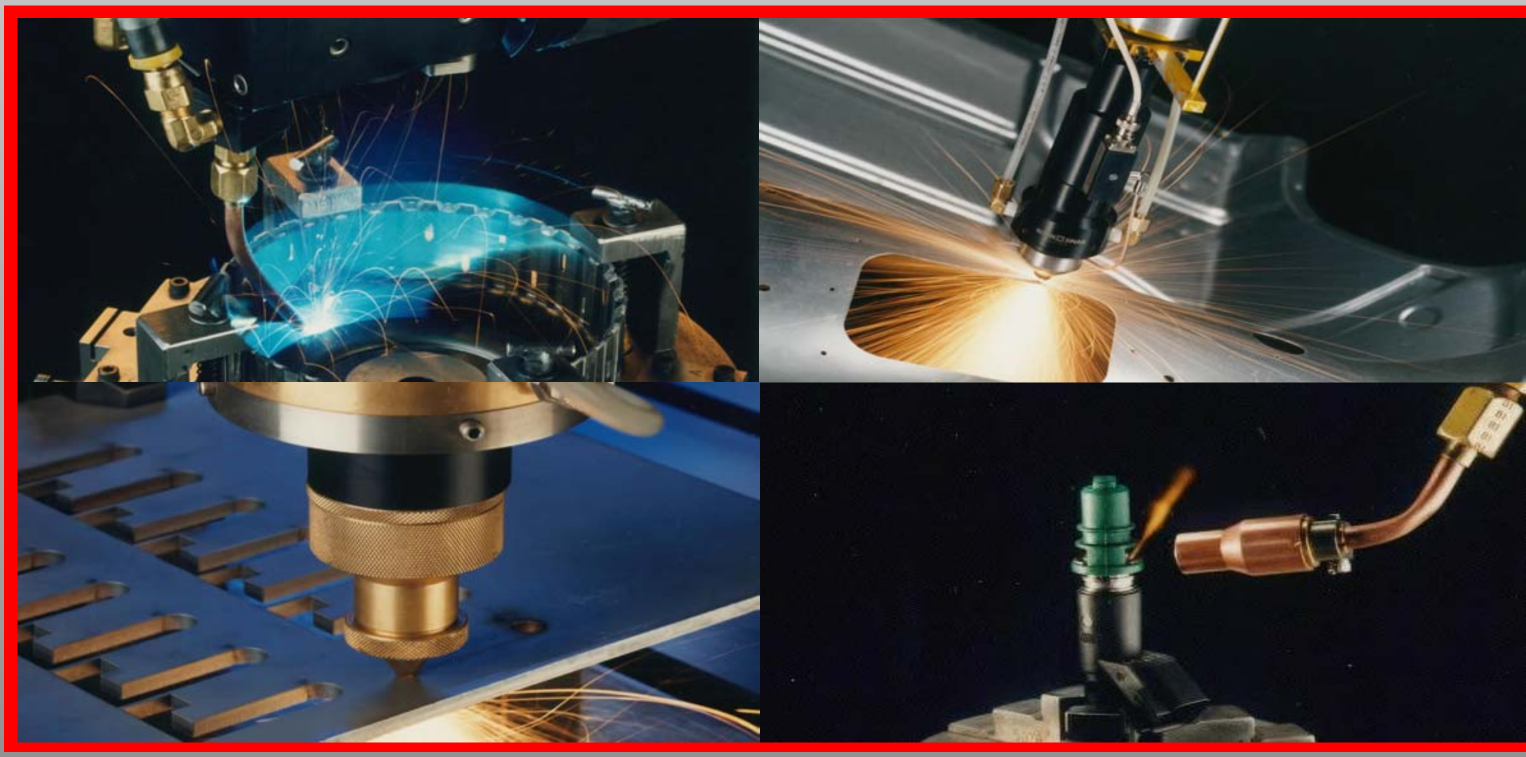
ROFIN-SINAR LASER



Process Fundamentals of Industrial Laser Welding and Cutting

THE POWER OF LIGHT

PROCESS FUNDAMENTALS OF INDUSTRIAL LASER WELDING AND CUTTING

Comprised of the documents:

Part 1
Laser Welding Design and Process Fundamentals and Troubleshooting Guideline

Part 2
Laser Cutting Process Fundamentals and Troubleshooting Guideline

Cover Photos *(clockwise from upper left corner)*
CO_2 laser welding of automotive transmission component / Robotic Nd:YAG laser cutting of automotive floor pan / Nd:YAG welding of automotive fuel injector / CO_2 laser cutting of stainless steel plate with high pressure nitrogen.

PREFACE

We are pleased to make this book available to you in the hope that it will prove beneficial in developing your understanding, acceptance and application of lasers in the manufacturing environment. It is a merging of two previously published guidelines, “Laser Welding Design and Process Fundamentals and Troubleshooting” and “Laser Cutting Process Fundamentals and Troubleshooting”. As stand-alone references both guidelines have been enthusiastically received over the past two years by both the experienced laser user and integrator, as well as those considering lasers as a manufacturing tool for the first time. We feel confident that this book will provide a reference for the two major material processing applications for the industrial laser, namely welding and cutting. “Process Fundamentals of Industrial Laser Welding and Cutting” complements the previously published book entitled “Introduction to Industrial Laser Materials Processing”. The combination of both of these Rofin-Sinar publications will provide the reader with a comprehensive reference for current industrial laser technology and material processing applications.

It is refreshing to find a laser materials processing reference source which does not assume a level of familiarity with the subject, yet meets the needs of a wide range of customers and integrators. This book has been written, as far as possible, in a style which minimizes references to specialized terminology in order to appeal to a broad range of readers. This has resulted in a publication which includes sufficient mathematical treatment to be of interest to the experienced laser user balanced by numerous charts and examples to make it interesting and beneficial to first time laser users. Emphasis has been placed on “real life” case studies and practical discussions to demonstrate the basic principles introduced. The sections on troubleshooting guidelines are applicable equally to both new and established applications and can be readily implemented into process tracking documentation or process troubleshooting procedures. This reference book will prove to be invaluable both on the production floor and in the product design area.

We welcome your comments and questions regarding this publication and any laser material processing application. Our growth and success over the past 20 years has been a reflection of our customer’s willingness to accept the laser for what it is – a versatile, reliable and cost effective machine tool meeting the challenges of an increasingly demanding and competitive production environment.

Richard Walker
General Manager
Rofin-Sinar, Inc.

Plymouth, Michigan
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LASER WELDING

DESIGN AND PROCESS FUNDAMENTALS

AND

TROUBLESHOOTING GUIDELINE

(2nd Printing)

Prepared by:

David Havrilla
Mechanical Engineer, Product Support Group

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1. INTRODUCTION

Industrial lasers have gained acceptance as effective and reliable production tools. As the use of lasers becomes more widespread, designers need to gain familiarity with not only the properties, advantages and applicability of the laser welding process, but also with how to design components and assemblies for successful laser welding. The fundamental properties of laser light, choice of laser (only CO_2 and Nd:YAG are considered), materials, weld joint design, component part preparation and fixturing are all addressed in the text that follows.

Since the advent of the industrial laser, laser welding has been chosen over conventional welding processes (such as resistance spot or arc welding) due to several primary advantages (see ***Table 1.1*** below):

a. Minimum heat input and high aspect ratio, resulting in minimal shrinkage and distortion of the workpiece.
b. Consistent, repeatable welds.
c. Small heat affected zone.
d. Narrow weld bead with generally good appearance.
e. High strength welds (often resulting in an increase in rigidity and a reduction of component size – typically higher static and fatigue strength as compared with the intermittent spots produced via resistance welding).
f. Easily automated with accurately located welds.
g. Ability to weld some dissimilar materials.
h. Generally no flux or filler material required.
i. Flexibility of beam manipulation (including time sharing).
j. Ability to weld in areas difficult to reach with other techniques.
k. Often faster than other techniques.
l. In some cases, post processing operations (such as weld bead clean-up) can be eliminated.

A few of the disadvantages that should be considered are:

a. Hard and often brittle welds may occur in hardenable materials.
b. Vaporization of some alloying elements can result in porous or undercut welds.
c. High capital investment relative to other techniques.
d. Workpiece fit-up and handling, and beam manipulation accuracy requirements are relatively high.

With some of these factors in mind, it is not difficult to understand why the choice, and anticipated success, of welding processes can be somewhat complex. In fact, the success of any laser welding process strongly depends on the careful consideration of three primary areas. These areas are the laser process parameters, the welding process requirements, and the related process considerations. The purpose of this guide is to discuss these considerations and to define the correlation between them. It may be used to build the foundation for sound laser welding design and process troubleshooting.

Each of the areas of consideration are dependent on many factors, some of which are listed below:

i. Laser process considerations:

   a. laser type and wavelength *(e.g. CO_2 or Nd:YAG)*,
   b. laser power and type *(e.g. pulsed or CW)*,
   c. beam quality *(e.g. focusability)*,
   d. raw beam size *(e.g. divergence)*,
   e. focal length,
   f. focused spot size,
   g. depth of focus,
   h. power density, energy density and weld energy,
   i. polarization,
   j. beam delivery considerations, and
   k. system considerations.

ii. Welding process requirements:

   a. material selection,
   b. joint fit,
   c. joint geometry and positioning tolerances,
   d. joint preparation and cleanliness,
   e. part/joint location,
   f. part fixturing,
   g. shielding and plasma suppression,
   h. focus position,
   i. weld spatter protection, and
   j. weld parameters.

iii. Related process considerations:

   a. part functional requirements (design criteria),
   b. process cycle time,
   c. process part handling considerations, and
   d. pre and post process operations.

Laser process parameters refer to the group of parameters which influence what type of laser is used and how its power is delivered to the workpiece and focused on it, thus providing a useful source of energy. The welding process requirements, on the other hand, refer to the factors which influence how successfully the focused energy is coupled with the weld joint. The related process considerations define the overall process and part requirements.

Table 1.1

COMPARISON OF LASER WELDING TO CONVENTIONAL WELDING PROCESSES

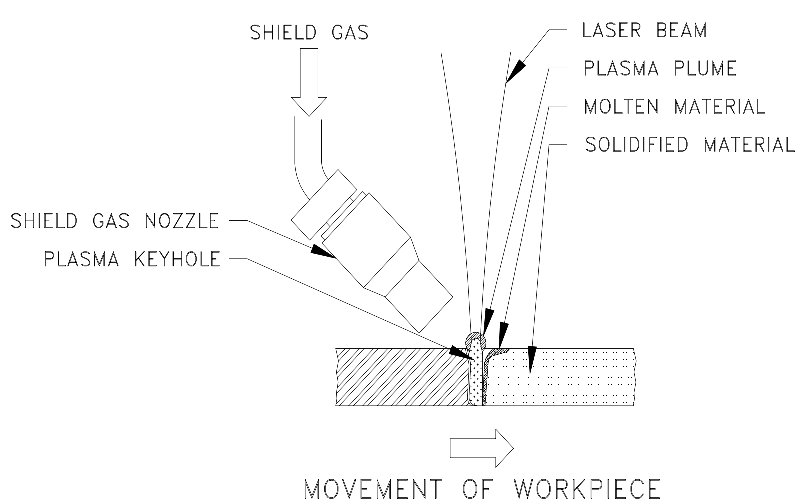
CHARACTERISTICS	LASER	ELECTRON BEAM	RESISTANCE SPOT	GAS TUNGSTEN ARC	FRICTION	CAPACITIVE DISCHARGE
❒ ***Weld quality***	Excellent	Excellent	Fair	Good	Good	Excellent
❒ ***Weld Speed***	High	High	Moderate	Moderate	Moderate	Very High
❒ ***Heat input into welded part***	Low	Low	Moderate	Very High	Moderate	Low
❒ ***Weld joint fit-up requirements***	High	High	Low	Low	Moderate	High
❒ ***Weld penetration***	High	High	Low	Moderate	High	Low
❒ ***Range of dissimilar materials***	Wide	Wide	Narrow	Narrow	Wide	Wide
❒ ***Range of part geometries/sizes***	Wide	Moderate	Wide	Wide	Narrow	Narrow
❒ ***Controllability***	Very good	Good	Fair	Fair	Moderate	Moderate
❒ ***Ease of automation***	Excellent	Moderate	Excellent	Fair	Good	Good
❒ ***Initial costs***	High	High	Low	Low	Moderate	High
❒ ***Operating/ maintenance costs***	Moderate	High	Moderate	Low	Low	Moderate
❒ ***Tooling costs***	High	Very High	Moderate	Moderate	Low	Very High

2. LASER PROCESS PARAMETERS

The laser beam is comprised of electromagnetic radiation which is both highly monochromatic (single wavelength) and coherent (in phase). The ability of a laser to weld is primarily attributed to these two characteristics, which allow the beam to be focused to a very small spot [typically 0.1 mm (0.004 inch) - 0.8 mm (0.035 inch)]. Since the laser power is focused to a relatively small spot, the resultant power density (the ratio of laser power to focused spot area) at the workpiece is typically greater than 10^7 Watts/cm^2 ($6x10^7$ Watts/in^2). At incident power densities of this magnitude or greater a phenomenon referred to as "keyholing" occurs, which makes possible deep penetration continuous laser welding of metal (***Figure 2.1***). With excellent laser beam quality (see *Section 2.2*), keyholing may occur as low as 10^6 W/cm^2 ($6x10^6$ Watts/in^2) for steel, and at about $4x10^6$ W/cm^2 ($2.6x10^7$ Watts/in^2), depending on spot intensity profile (i.e. power distribution). Keyholing occurs when the material at the interaction point melts and vaporizes. The resultant vapor pressure is high enough to overcome the surface tension and forces the molten material out of the way, forming a hole or cavity which captures nearly all of the laser energy via internal reflections. As the workpiece moves relative to the beam, the vaporized material becomes molten and flows back into the cavity and solidifies behind the weld point, forming the weld. Keyholing makes possible weld depths of several centimeters. At incident power densities below that which yields keyhole welding, only melting occurs. This mechanism is referred to as conduction welding. Without the formation of a keyhole (due to insufficient vapor pressure) weld depths are limited to about 1 millimeter (0.04 inch).

Figure 2.1

KEYHOLING



2.1 Laser Considerations

2.1.1 General

Although there are many types of lasers, only the CO_2 (carbon dioxide) and Nd:YAG (neodymium:yttrium-aluminum-garnet) lasers are commonly found in industrial applications. Representative weld speeds for CO_2 and Nd:YAG lasers at various power levels are presented in ***Figure 2.2***.

The choice of laser type (i.e. wavelength) is typically a function of the type of material to be welded (how well it absorbs laser power of a particular wavelength), as well as the weld speed and weld penetration requirements. In general, the Nd:YAG laser wavelength is absorbed better than the CO_2 wavelength by most metals. The use of fiber optics for Nd:YAG beam delivery has taken the important consideration of flexibility into the realm of relatively low cost three-dimensional laser welding. Several of the primary considerations when choosing between CO_2 and Nd:YAG lasers are listed below:

Carbon Dioxide Laser Considerations

a. Higher powers
b. Better focusability (i.e. beam quality)
c. Higher weld speeds on materials non-reflective to CO_2 wavelength
d. Deeper weld penetration on materials non-reflective to CO_2 wavelength
e. Lower capital and operating costs
f. Less expensive safety precautions with CO_2 wavelength

Nd:YAG Laser Considerations (w/ Fiber Optic Beam Delivery)

a. Fiber optic delivery (especially when considering robot applications)
b. Materials reflective to CO_2 wavelength can often be welded
c. Easy beam alignment, beam switching and beam sharing
d. Less extensive and simpler maintenance on laser (solid state device) and beam delivery
e. Less floor space with laser and beam delivery
f. Long and varied fiber lengths with no effect on process
g. High peak powers with high energy per pulse

2.1.2 Pulsed and Continuous Wave Power

Laser power can be produced in either a pulsed fashion or a continuous beam [referred to as continuous wave (CW)]. Pulsing the laser power can be used to overcome material reflectivity (e.g. superpulsed CO_2 welding of copper or aluminum) and to minimize workpiece distortion. In pulsing, the laser power is cycled on and off, between a high power short pulse time and an off time. Due to this cycling, “average power” rather than CW power is used to define the power of the laser. Average power is simply the laser power multiplied by the duty cycle for normal pulsed operation (where duty cycle is the ratio of on time to the total on plus off time). During the high power pulse, the material is melted or vaporized. During the off time, the material is allowed to re-solidify and cool while the material or focus module advances, awaiting the next high power pulse. In addition, pulse repetition can be varied with welding speed. Obviously, the pulse repetition rate is critical and directly dependent on welding speed. If there is too long of a time between pulses (minimum off time is limited by the laser power supply), a continuous weld cannot be obtained. If there is too short a time between pulses, the laser power approaches the CW level. See *Section 4.10.8* for further discussion of pulsing (including superpulsing).

2.1.3 Mode, Power and Pointing Stability

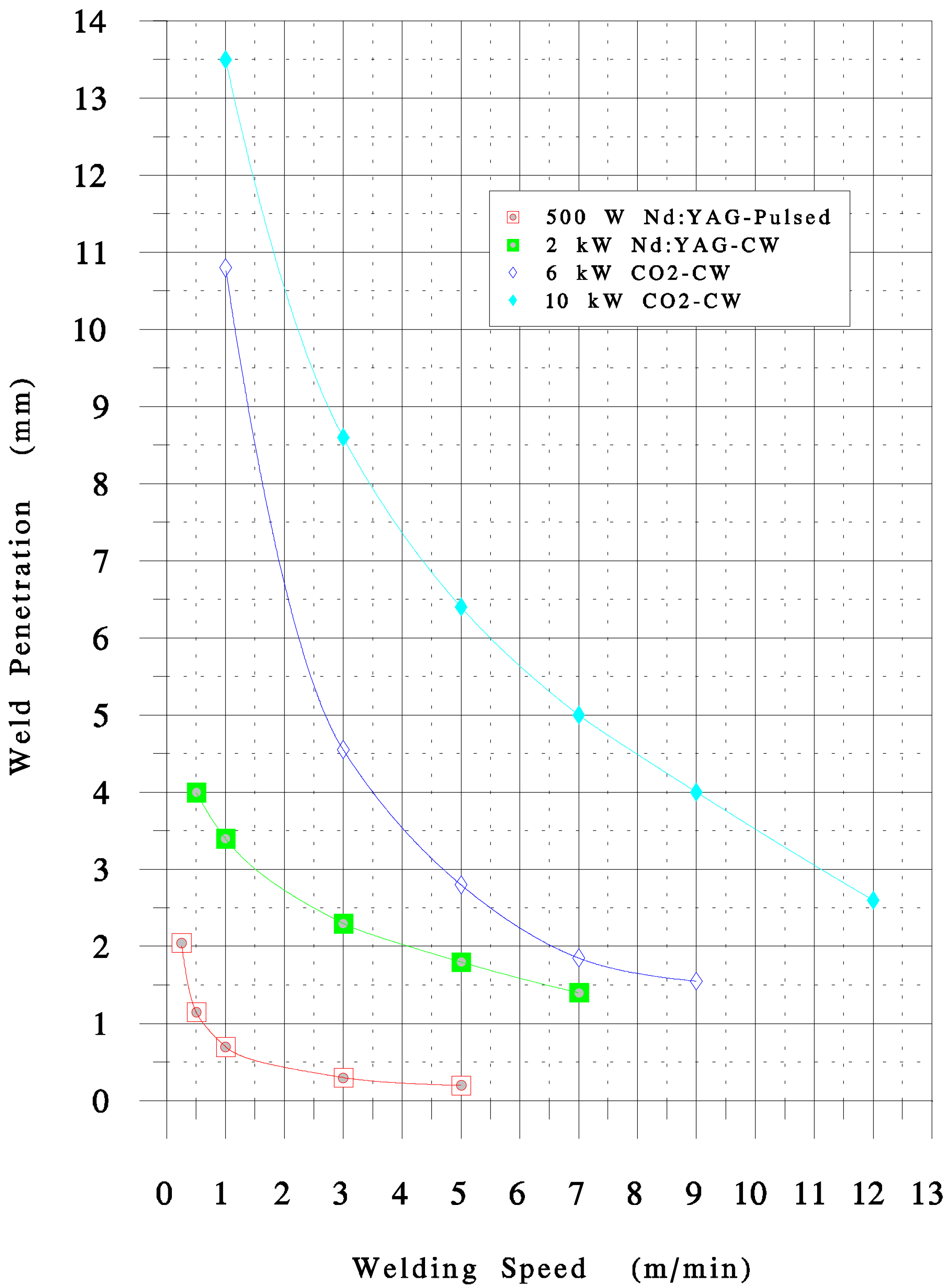
Consistent weld penetration can be obtained only by the application of consistent laser energy. Therefore, the stability of the laser's output is critical in welding. This includes maintaining unwavering output energy (power stability), consistent beam quality (mode stability), and fixed energy concentration (pointing stability). Should the power increase or decrease by more than a few percent over short term operation, the beam quality oscillates between two or more mode profiles (see *Section 2.2*), or the location of the beam's direction shifts more than a few tenths of a milliradian, there will result a change in the available power density for welding, and a resultant change in weld penetration.

2.2 Transverse Electromagnetic Mode

The focusability of the laser beam is a function of the transverse electromagnetic mode (usually referred to as TEM, or simply "mode"). It is basically a means of describing how the power is distributed within the laser beam. A "bell" shaped (or Gaussian) power distribution is the most focusable mode (also referred to as TEM_{00}). Modes which approach this power distribution can be focused down to the theoretical minimum spot size. The TEM_{00} mode provides the most concentrated power density, which yields the fastest welding speeds and narrowest weld widths (with a given raw beam size and focal length). However, because of the concentrated power density, care must be taken to ensure the thermal stability of the internal (resonator) and external (beam delivery) optics. From the standpoint of the design of the optical components, this includes considerations such as; 1) appropriate optical material selection (reflectivity or transmittance), 2) optical component mass (thermal mechanical stability), and 3) efficient cooling of the optical component (typically requiring water cooling above 1500 Watts). From the maintenance side, this includes insuring a high degree of optical cleanliness, both from a preventative aspect (see *Section 3.4.3, Beam Delivery Purging*) and from a maintenance aspect (a more vigorous inspection and cleaning schedule).

Figure 2.2

REPRESENTATIVE WELD SPEEDS FOR CO_2 AND Nd:YAG LASERS ON MILD STEEL



The mode of a laser is characterized by a numerical value referred to as M-squared (M^2), see also *Section 2.3.1*. The full divergence angle (far field) of the raw laser beam (φ) is directly related to the M^2 value and the laser wavelength (λ), and inversely proportional to the waist diameter of the raw laser beam (D_o) as follows:

$$\boxed{\varphi = M^2(4\lambda/\pi D_o)}$$

Therefore, higher order or multi-mode beam profiles (higher M^2 values) are characterized by a tendency to spread out the energy distribution away from the center of the beam. The resultant focused spot is larger with higher order modes yielding a lower power density or concentration. Furthermore, higher order beam profiles may have a different (asymmetric) power distribution in two axes. This is a result of having differing modes in the two axes. The divergence of the beam effects where the focus spot is located relative to the focus optic (note that the focal length "f" of a focusing optic is the location of the focused spot for a perfectly collimated beam, see *Section 3.4.4*). Therefore, beams with asymmetric modes result in a different focus spot location for each axis. This condition is called astigmatism, and yields a weld quality (e.g. penetration and bead width, and weld geometry) which is inconsistent and dependent upon weld direction. Due to this, lasers with asymmetric power distributions are generally not used on moving beam systems where weld consistency is critical. However, if consistent weld width is not absolutely critical, the weld speed can be varied to keep weld penetration consistent.

Lasers with modes from near Gaussian ($M^2 \cong 1$) to multi-mode lasers with M^2 values as high as about 10 are used for CO_2 welding, while much higher order modes are obtained with fiber optic beam delivery systems (M^2 values as high as 300, but Nd:YAG wavelength is one tenth that of CO_2 , see *Section 2.3.1* for how wavelength effects focused spot size).

2.3 Focused Spot Diameter

It is the size of the focused beam, at a given power, which dictates the power density at the workpiece, and therefore controls the weld speed and penetration. It is therefore useful to present the factors which influence the size of the focused beam.

2.3.1 Reflective/Transmissive Beam Delivery

The laser parameters that determine the size of the focused spot diameter (d) when focusing a raw laser beam, are wavelength (λ), mode/focusability of the laser beam (M^2), focal length (f), and raw beam diameter at the focusing optic (D), (see ***Figure 2.3***). The wavelength depends on laser type (i.e. CO_2, Nd:YAG, etc.). The wavelength of a CO_2 laser is 10.6 micrometers (10.6 microns or 0.0106 mm), for a Nd:YAG laser the wavelength is 1.064 microns (0.001064 mm). As stated in *Section 2.2*, the focusability of the laser beam is a function of the transverse electromagnetic mode. For a perfect "bell" shaped power distribution, M^2 =1 (referred to as high beam quality or low order), for other distribution types, M^2 >1 (referred to as lower beam quality or high order). See ***Figure 2.4*** for M^2 values for several radially symmetric modes. The focal length defines the distance from the focusing optic to the focal plane. Note that it is the diameter of the laser beam at the focusing optic, rather than the diameter of the beam as it exits the laser head, that determines focused spot size. This is important because laser beams are not perfectly collimated. The raw beam either converges to a "waist" region and then diverges, or in some lasers, simply diverges from the output of the laser head (referred to as having an intracavity "waist"). Note that the waist may move with output optic(s) temperature (e.g. laser power and optic(s) absorption). A change in waist location affects the size of the raw laser beam at the focusing optic. See *Sections 3.4.4 and 3.5.4* for further discussion of this topic.

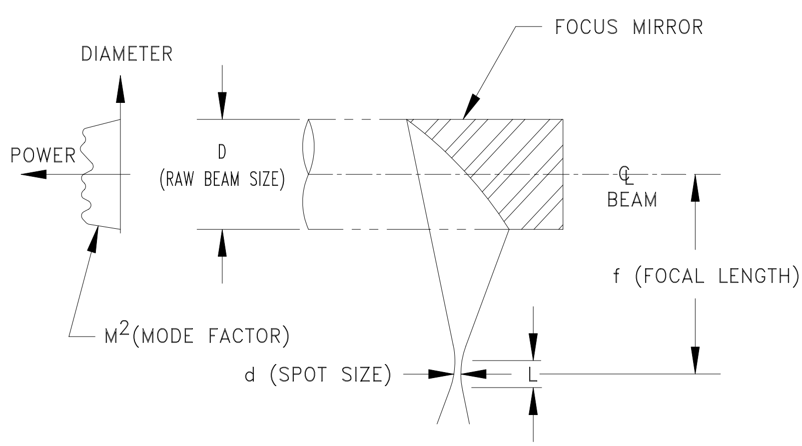
These parameters are related to the focused spot diameter by the following equation:

$$\boxed{\mathbf{D = M^2 (4\lambda f/\pi D)}}$$

Example 2.3.1: Calculate the spot diameter of a CO_2 laser with an M^2 = 5.5, a focal length of 200 mm, and a raw beam diameter at the focus optic of 40 mm (1.6 inch). Substituting for d = [(5.5)(4)(0.0106)(200)/ [(3.14)(40)], and solving yields d = 0.37 mm (0.015 inch). *See also Examples 2.4.1A, 2.5, 4.8A and 4.8B.*

Figure 2.3

FOCUSING PARAMETERS
(Reflective/Transmissive Beam Delivery)



An alternate method of describing focusability is in terms of the "F" number (F#), which is defined as the ratio of the focal length (f) to the raw beam diameter at the focusing optic (D). Therefore, the smaller the "F" number, the smaller the focused spot diameter, as shown by the following equation:

$$\boxed{\mathbf{d = M^2\ (F\#)(4\lambda/\pi)}}$$

For a raw Nd:YAG laser beam the "beam quality" (BQ) factor is most often specified and not the M^2 value. The M^2 value, however, can be calculated from the beam quality value (with BQ expressed in millimeter-milliradians) by the following (see *Section 2.3.2, Fiber Optic Beam Delivery* for further discussion of beam quality):

$M^2 = (\varphi D_o \pi)/(4\lambda)$, (see *Section 2.2*), and

$\varphi D_o = (4BQ)/1000$, (from *Section 2.3.2*, where $\varphi/2 = \Theta$, $D_o = D$ and the factor of 1000 is required to convert from milliradians to radians)

$M^2 = (\pi)(4BQ)/(1000)(4\lambda) = (3.1416)(BQ)/(1000)(0.001064)$

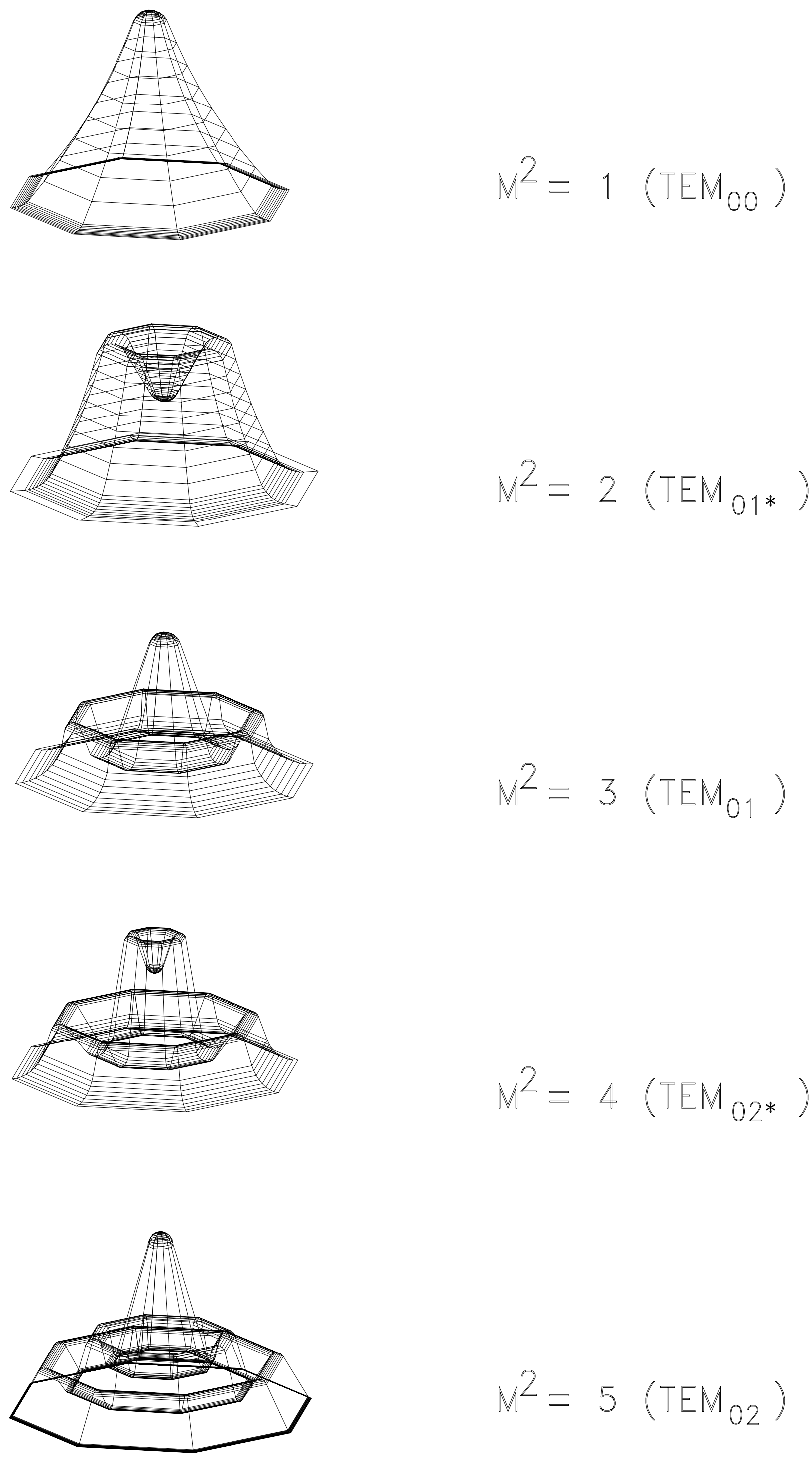
$M^2 = 2.9526\ BQ \cong 3BQ$

Therefore:

$$\boxed{\mathbf{d \cong 3BQ\ (4\lambda f/\pi D)}}$$

Figure 2.4

FOCUSABILITY FACTORS FOR SEVERAL MODES



2.3.2 Fiber Optic Beam Delivery

2.3.2.1 Entering the Fiber

With fiber optic beam delivery systems the M^2 value used to described the laser mode in reflective/transmissive systems is replaced by a "beam quality" (BQ) measure (sometimes referred to as "beam product" (BP)), which is expressed in millimeter-milliradians. The beam quality is the product of the half-angle beam divergence (far field) in milliradians (Θ; note $\Theta = \varphi/2$), and the raw beam radius at the beam waist in millimeters (D/2). It also can be defined in terms of the radius of the raw laser beam (D/2), the focal length of any focus optic in millimeters (f_i), and the radius of the focused beam at the specified focal length in millimeters ($d_i/2$), or in terms of the focused beam cone half-angle in milliradians (θ_i) as follows:

$$\boxed{\mathbf{BQ = (\Theta)(D/2)}}$$

$$BQ = (\theta_i)(d_i/2) = \{1000 \tan^{-1}(D/2f_i)\}(d_i/2)$$

Note that the factor of 1000 is to convert radians into milliradians, and that $\tan^{-1}$ must be in radians.

Example 2.3.2A: Estimate the beam quality of a beam that has a diameter of 22 mm at the exit of the laser and a diameter of 31 mm at a distance of 2 meters from the first beam diameter location. First the divergence (Θ) must be calculated, where $\Theta = \tan^{-1}\{[(31-22)/2]/2000\} = 0.0023$ radians = 2.3 mrad. Therefore, BQ $\cong (2.3)(22/2) = 25$ mm-mrad.

In a fiber optic delivery system the raw beam from the laser is focused into the fiber. The ability of the fiber to transmit the input beam is dependent on the "numerical aperture" of the fiber and the beam quality (i.e. focusability) of the raw laser beam. The numerical aperture (N.A.) defines the angle in which the focused input beam must stay within in order to be efficiently coupled into the fiber, and is defined in terms of half-angle (θ). In other words, the cone angle of the focused laser beam ($2\theta_i$) must be smaller than the "acceptance cone" of the fiber optic (2θ) for efficient fiber optic transmission. Therefore:

$2\theta_i < 2\theta$, or simply $\theta_i < \theta$,

$\theta_i = BQ/[1000(d_i/2)]$ in radians from above, and

$\theta = NA/1000$ (1000 to convert from milliradians to radians)

Therefore, $BQ/[1000(d_i/2)] < NA/1000$, which reduces to
$BQ/(d_i/2) < NA$, or $BQ/NA = (d_i/2)_{minimum}$

If we let $(d_i/2)_{minimum}$ = $(\Phi_c/2)$ *fiber core radius in millimeters*, then

$(\Phi_c/2) \geq BQ/NA$

Furthermore, if the focused spot diameter of the input beam to the fiber optic is set to a predetermined maximum allowable size relative to the core diameter [based on a percent fiber fill (%Fill), typically set at about 70-90% of the fiber core diameter in order to accommodate misalignment and optical distortion (aberration) effects], then the minimum fiber optic core diameter (Φ_c min) can be determined for a given laser beam quality and fiber optic numerical aperture using the following equation:

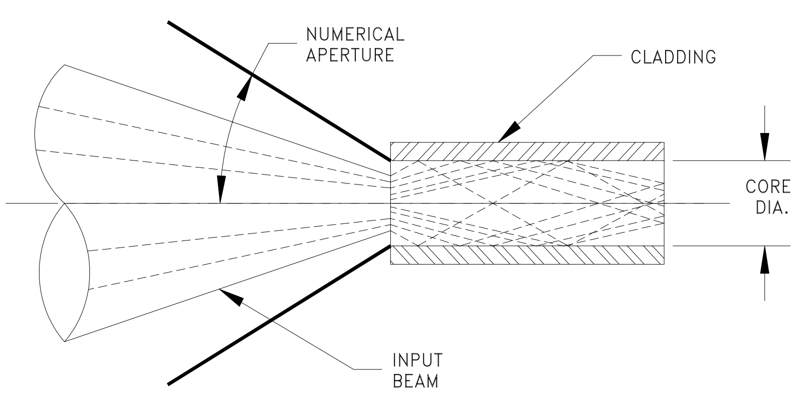
$(\%Fill/100)(\Phi_c/2) \geq BQ/NA$, therefore

$$\boxed{\mathbf{\Phi_c\ min = (200/\%Fill)\ (BQ/N.A.)}}$$

Example 2.3.2B: For 70% fill, a beam quality of 25 mm-mrad, and a N.A. of 220 mrad, yields a minimum fiber core diameter of Φ_c min. = (200/70)*(25/220) = 0.325 mm. Therefore, the smallest standard fiber optic core diameter that can be used in most cases is about 400 micron.

Figure 2.5

FIBER OPTIC TRANSMISSION



2.3.2.2 Exiting the Fiber

Within the fiber the beam is transmitted via internal reflections within the fiber optic core (see ***Figure 2.5***). Typical fiber core diameters range from 0.3-1.0 mm. The beam exits the fiber optic at an angle limited by the N.A. of the fiber optic. The exit beam is then focused by one or more lenses (typically a collimating lens and a focus lens) to a small spot diameter. The parameters that determine the size of the focused spot (d) when focusing a laser beam that has been delivered through a fiber optic, are; i) fiber optic core diameter (Φ_c), ii) collimator focal length (f_c), and iii) focal length (f) of the focusing optic (***Figure 2.6***).

These parameters are related to the focused spot diameter by the following equation:

$$\boxed{\mathbf{d = (f/f_c)\ \Phi_c}}$$

<u>Example 2.3.2C:</u> Utilizing a collimator with a focal length of 120 mm, a focusing optic with a focal length of 80 mm, and a fiber optic with a core diameter of 600 micron (0.6 mm), yields a focused spot diameter of d = (80/120)(0.6) = 0.4 mm (0.016 inch). *See also Examples 2.4.2A and 2.4.2B.*

Notice that the smaller the fiber optic core diameter, the smaller the focused spot diameter. However, reducing the fiber core diameter is limited by the beam quality of the input laser beam. Focal length can also be reduced to decrease spot diameter, but proximity to weld smoke and spatter, as well as a reduction in depth of focus dictates the lower limit on focal length.

2.3.2.3 Exit Beam Quality

At present, there are two basic types of fibers used for high power Nd:YAG transmission, namely, step index and graded index (see *Section 3.5.1* for a further discussion of graded index fibers). The step index fiber is comprised of a core material (typically quartz) and an outer cladding material. In a step index fiber optic, all internal reflections of the transmitted beam occur at the core/cladding interface. The numerical beam quality of an exit beam (BQ_{exit}) that has passed through a step index fiber optic can be significantly greater than the numerical beam quality of the input raw beam (BQ_{input}). The resulting exit beam has a power distribution that is, in general, uniformly distributed (i.e. "top-hat" distribution) and less focusable. The actual exit beam quality is dependent on several factors, including: i) the length of the fiber optic, ii) the number and severity of bends in the fiber optic, iii) the core diameter of the fiber optic (smaller core diameters preserve the input beam quality better than larger core diameters), iv) the input cone angle (larger input cone angles preserve the input beam quality better through the fiber because your closer to the N.A.), and v) the angular alignment of the input beam relative to the centerline of the fiber (i.e. the input beam and the fiber should be coaxial, the quartz block surface should be perpendicular to the fiber, ...).

In general, however, the ***worst case*** exit beam quality can be approximated knowing the fiber core radius ($\Phi_c/2$) and the numerical aperture of the fiber optic (N.A.) by the following (i.e. the input cone angle is not preserved through the fiber, and in the worst case scenario the cone angle at the fiber exit is equal to the fiber numerical aperture):

$$\boxed{\mathbf{BQ_{exit} \cong (\Phi_c/2)(N.A.)}\ ^{[1]}\ \textit{\textbf{worst case}}}$$

[1] Note that the optical aperture of the collimator should be used if it is smaller than the numerical aperture of the fiber. For example, a collimator with a focal length of 120 mm and a clear aperture of 50 mm, yields an optical aperture of 205 mrad {from: $1000 \tan^{-1}$ [(50/2)/120]}.

The ***best case*** exit beam quality can be approximated by assuming the input beam cone angle (θ_i) is preserved through the fiber so that the exit cone angle is the same as the input cone angle (as opposed to the numerical aperture of the fiber optic) by the following:

$$\boxed{\mathbf{BQ_{exit} \cong (\Phi_c/2)(\theta_i)}\quad \textit{\textbf{best case}}}$$

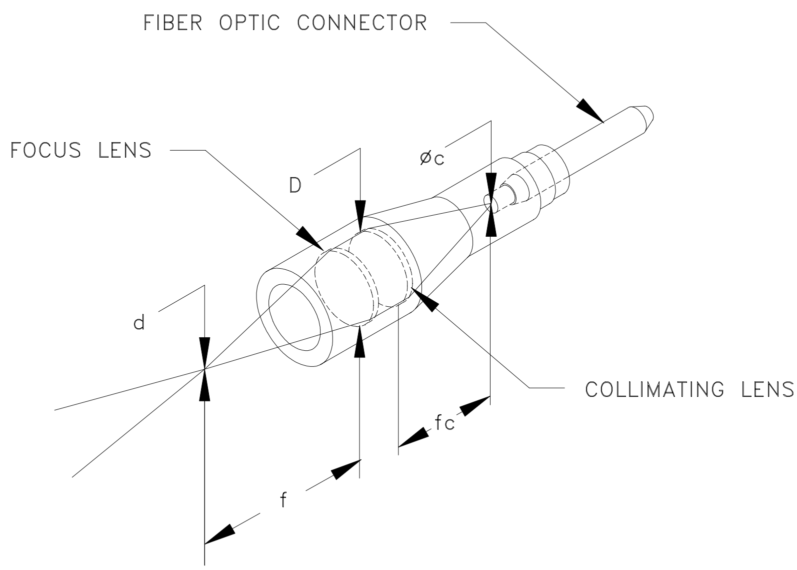
$\theta_i = 1000 \tan^{-1}(((D_i-d_i)/2)/f_i) \cong 1000 \tan^{-1}((D_i/2)/f_i)$ *in milliradians*,

where D_i is the beam diameter at the incoupler with incoupler focal length of f_i and where the 1000 is required to convert radians to milliradians (because the focus spot size at the fiber $d_i << D_i$, d_i has a negligible effect on the incoupling angle and therefore can be ignored in this computation).

Example 2.3.2D: With an input cone angle of 110 mrad, a fiber optic core diameter of 600 microns (0.6 mm), a fiber numerical aperture of 220 milliradians, and an optical aperture of 125 milliradians. The best case and worse case exit beam quality would be approximately $BQ_{exit} \cong (0.6/2)(125) = 38$ mm-mrad (worst case, using the optical aperture since it is smaller than the NA, see Note [1] above) and (0.6/2)(110) = 33 mm-mrad (best case). Note also that $M^2_{exit} \cong 3BQ_{exit}$ yields a range of 99 to 198 (see *Section 2.3.1*).

Figure 2.6

FOCUSING PARAMETERS
(Fiber Optic Beam Delivery)



2.4 Depth of Focus

Another characteristic of the focused spot is the depth of focus (L), which defines the full range at which the focus spot size increases no more than a preset percentage (p), i.e. p=0.05 for 5%. In practice, the depth of focus defines the range in which the weld penetration does not significantly degenerate. As a result, the depth of focus is one of the primary factors which influences part location requirements. See *Section 4.5, Part/Joint Location* for further discussion.

2.4.1 Reflective/Transmissive Beam Delivery

The depth of focus can be approximated by the following relationship:

$$L = [(p+1)^2 - 1)]^{1/2}(\pi d^2)/2\lambda M^2$$

Note: For raw Nd:YAG beams, beam quality values may be substituted by setting M^2 = 3 BQ.

Typically, the value of "p" is set at 5% (0.05), which reduces this equation to:

$$\boxed{\mathbf{L_{5\%} \cong d^2/2\lambda M^2}}$$

Example 2.4.1A: Using the factors from *Example 2.3.1*, $L_{5\%} = (0.37)^2/(2)(.0106)(5.5) =$ 1.17 mm (0.046 inch). *See also Example 2.4.1B.*

With the value of "p" set at 5%, the power density within the depth of focus region decreases no more than about 9.3% (see *Excursus 1* below). This is typically a good approximation of the actual process depth of focus (which is the range over which there is no change in either the weld geometry or weld penetration). However, if the actual depth of focus (L_{actual}) for a certain focal length (f1) is known, and is different than the value of $L_{5\%}$, the actual depth of focus for a different focal length can be easily calculated via the following relationship:

$(L_{actual}/L_{5\%})_{f1} = (L_{actual}/L_{5\%})_{f2}$

Example 2.4.1B: For the depth of focus from *Example 2.4.1A* (which is 1.17 mm and corresponds to a 200 mm focal length, a 0.37 mm spot size and an M^2 of 5.5, see *Example 2.3.1*), consider a process where the actual depth of focus is 0.9 mm (0.035 inch). What would be the actual depth of focus if the focus optic was changed to a 150 mm focal length? The spot size with the 150 mm f.l. is 0.37(150/200) = 0.28 mm. Therefore, the calculated value of $L_{5\%}$ for the 150 mm f.l. is $L_{5\%} = (0.28)^2/(2)(0.0106)(5.5) = 0.67$ mm (0.026 inch). Rearranging $(L_{actual}/L_{5\%})_{f1} = (L_{actual}/L_{5\%})_{f2}$, yields $(L_{actual})_{f2} = (L_{5\%})_{f2}\ (L_{actual}/L_{5\%})_{f1} = (0.67)(0.9/1.17) = 0.52$ mm (0.020 inch).

Excursus 1
Depth of Focus Derivation

One of the fundamental beam propagation relationships that describes the beam diameter at any location along the propagation axis is generally presented as follows:

$$2W_Z = 2W_O\,\{1+ [(Z-Z_O)/Z_R]^2\}^{1/2} \qquad \textbf{(1)}$$

The terms in this equation are defined below, and can be correlated to the terms presented in this paper:

$2W_Z = d_Z$ = beam diameter @ reference location (Z) from waist
$2W_O = d$ = beam diameter @ waist location (Z_O)
$Z_R = \pi d^2/4M^2\lambda$ = Rayleigh range
$Z-Z_O = \Delta Z$ = distance between reference and waist locations

Substituting these terms back into equation (1) yields:

$$d_Z = d\ \{1+ (\Delta Z 4M^2\lambda/\pi d^2)^2\}^{1/2} \qquad \textbf{(2)}$$

Rearranging and solving for ΔZ yields:

$$\Delta Z = \pi d\ (d_Z^2 - d^2)^{1/2}/4M^2\lambda \qquad \textbf{(3)}$$

If we allow the spot size to change 5% (i.e. $d_Z = 1.05d$), then equation (3) becomes:

$$\Delta Z_{5\%} = \pi d\ (1.1025d^2 - d^2)^{1/2}/4M^2\lambda = \pi d^2\ (1.1025 - 1)^{1/2}/4M^2\lambda$$

However, the quantity $\{\pi(1.1025 + 1)^{1/2}\}$ approximately equals unity, therefore:

$$\Delta Z_{5\%} \cong d^2/4M^2\lambda$$

As defined above, ΔZ represents only half of the depth of focus:

$$\Delta Z_{5\%} = L_{5\%}/2 \cong d^2/4M^2\lambda$$

Therefore, multiplying $\Delta Z_{5\%}$ by two is equivalent to the 5% depth of focus as given in *Section 2.4.1*:

$$L_{5\%} = 2\Delta Z_{5\%} \cong 2(d^2/4M^2\lambda) = d^2/2M^2\lambda$$

A corresponding 9.3% loss of power density (i.e. 90.7% of the focused spot power density) is associated with a 5% increase in spot diameter, as shown below:

$$P_{d5\%} = 4P/\pi d_{5\%}^2 = 4P/\pi(1.05d)^2 = 0.907\ (4P/\pi d^2)$$

2.4.2 Fiber Optic Beam Delivery

Recall that the depth of focus can be approximated by the following relationship:

$$L = [(p+1)^2 - 1)]^{1/2}(\pi d^2)/2\lambda M^2$$

As before, if the value of "p" is set at 5% (0.05), and using the mode value associated with the beam exiting the fiber optic $[(M^2)_{exit}]$, this equation reduces to:

$$L_{5\%} = 1.0058\ d^2/2\lambda(M^2)_{exit} \cong d^2/2\lambda(M^2)_{exit}$$

For Nd:YAG lasers, beam quality values may be substituted by setting $M^2 = 2.9526$ BQ. Using this, and by setting λ equal to 0.001064 mm, results in:

$$L_{5\%} = 1.0058\ d^2/(2)(.001064)(2.9526\ BQ)_{exit} = 160.08\ d^2/BQ_{exit}$$

From *Section 2.3.2.3, Exit Beam Quality*, we see that the beam quality of the exit beam is not known exactly, but can be bracketed between "best case" and "worst case" values, as follows [knowing the fiber core radius ($\Phi_c/2$), the numerical aperture of the fiber optic (N.A.), the radius of the beam at the incoupling lens ($\Phi_i/2$) and the focal length of the incoupling lens (f_i)]:

$BQ_{exit} \cong (\Phi_c/2)(N.A.)$ *Worst Case*

$BQ_{exit} \cong (\Phi_c/2)\{\tan^{-1}[(\Phi_i/2)/f_i]*1000(\pi/180)\}$ *Best Case*

Substituting these values back into $L_{5\%} \cong 160.08\ d^2/BQ_{exit}$, the following relationships result:

$\boxed{L_{5\%} \cong 320\ [d^2 / \Phi_c\ N.A.]}$ ***Worst Case***

$L_{5\%} \cong 320.16\ \{d^2 / \Phi_c \{\tan^{-1}[(\Phi_i/2)/f_i]*1000(\pi/180)\}\}$ *Best Case*

$\boxed{L_{5\%} \cong 18.34\ \{d^2 / [\Phi_c \tan^{-1}((\Phi_i/2)/f_i)]\}}$ ***Best Case***

Example 2.4.2A (Worst Case): Using the factors from *Example 2.3.2C* & assuming a NA of 220 mrad, $L_{5\%} = 320\ [(0.4)^2/(0.6)(220)] = 0.39$ mm (0.015 inch).

Example 2.4.2B (Best Case): Using the factors from *Example 2.3.2C*, a beam diameter at the incoupling lens of 22 mm and a incoupling focal length of 60 mm, $L_{5\%} = 18.34\ \{(0.4)^2 / [(0.6) \tan^{-1}((22/2)/60)]\} = 0.47$ mm (0.019 inch).

These values can be significantly different from each other depending on the incoupling beam diameter and focal length. It is important to note that because of the reduced beam quality of a Nd:YAG beam that has been transmitted through a fiber optic (especially a step index fiber, see *Section 3.5.1*), the depth of focus for a given spot diameter is much smaller than that of a reflective/transmissive beam delivery system.

In summary, note that the depth of focus is dependent on the exit beam quality (which is dependent on the fiber N.A., the fiber core diameter and the incoupling configuration, see *Section 3.5.1*) and the spot diameter. Therefore, if the numeric value of the ratio (f/f_C) remains constant, it has no influence on either spot diameter or depth of focus. For example, a fiber optic beam delivery system having f = 60 mm and f_C = 60 mm has the same spot size and depth of focus as a system having f = 120 mm and f_C = 120 mm.

Additionally, since $L_{5\%}$ is directly proportional to (d^2/Φ_c), and since d is directly proportional to $(f\Phi_c)$, the following relationship proves insightful:

$$L_{5\%} \propto d^2/\Phi_c \propto (f\Phi_c)^2/\Phi_c \propto f^2\Phi_c$$

What this relationship indicates is that, under normal circumstances, the fiber core diameter should be minimized for a given laser in order to maximize the focal length (which maximizes the depth of focus and the distance the focus lens is away from smoke and spatter). This also allows for more flexibility when choosing the focal length (in other words, different focal lengths can be used to alter the focused spot size).

Table 2.1

SPOT SIZE AND DEPTH OF FOCUS INTER-RELATIONSHIPS

Process Parameter	**Short Focal Length**	**Long Focal Length**
Spot Size	<u>smaller</u>	<u>larger</u>
	higher weld speed *smaller weld width* *lower heat input* *smaller HAZ*	*lower weld speed* *larger weld width* *higher heat input* *larger HAZ*
Depth of Focus	<u>shorter</u>	<u>longer</u>
	higher part tolerance *higher tooling tolerance* *longer time to find focus*	*lower part tolerance* *lower tooling tolerance* *shorter time to find focus*
Focus Optic Maintenance	<u>higher</u>	<u>lower</u>
	closer to smoke & spatter	*further from smoke & spatter*

2.5 Power Density, Energy Density and Weld Energy

Power Density

Power density is defined as the ratio of laser power to the area of the focused spot and is directly related to weld penetration. It is critical in that it encompasses both the laser power and the area in which that power is concentrated (see *Section 3.6.1* for a summary of factors which effect power density at the weld point). Neither a high power unfocused laser beam nor a low power focused beam is of much use for laser welding. Power density (P_d), is related to laser power (P) and to the area of the focused spot (d) by the following (assuming a focused spot which is circular):

$$\boxed{\mathbf{P_d = 4P/\pi d^2}}$$

Example 2.5: For a raw beam of 6000 Watts, with a diameter of 1.6 inch, the P_d = 2,984 W/in^2. On the other hand, for the focused beam used in *Example 2.3.1*, with a power of 6000 Watts, the P_d = (4)(6,000)/(3.1416)(0.015)^2 = 33,952,975 W/in^2!

Notice that doubling the focused spot diameter (by doubling the focal length for example), results in only one fourth the power density. However, doubling the focal length yields four times the depth of focus. This trade off between spot size and depth of focus is at the center of all focus optic choices when considering weld penetration and speed, part and material tolerance, weld nugget geometry, heat affects and focus optic maintenance.

In some cases the beam is focused onto the workpiece orthogonal (perpendicular) to the surface that comprises the weld joint plane. However, in many cases the focused beam is directed at the weld joint at some included angle relative to the plane of the weld joint. This is often required to prevent the beam from being obstructed by either part of the component to be welded or part of the tooling which clamps the component (see ***Figure 4.19***). The resulting focused spot at the weld joint becomes increasingly elliptical as the incident angle varies from orthogonal. This results in a larger focused spot area, and therefore a reduced power density. Therefore, incident focused beam angles should be kept as close to orthogonal as possible in order to maximize the weld power density.

Energy Density

Energy density is related to the speed at which the power density is imparted into the weld joint. A high speed weld imparts less energy density into the weld joint than does a low speed weld (at a given power density). The available energy density is directly proportional to the power density (P_d) and spot size (d), and inversely proportional to the weld speed (V):

$$\boxed{\mathbf{E_d = d(P_d/V)}}$$

Note that: $E_d = d(P_d/V) = d(4P/\pi d^2V) = 4P/\pi dV \propto \mathbf{P/dV} \propto \mathbf{DP/fV}$

(where "D" is the diameter of the raw laser beam at the focus optic, and "f" is the focal length of the focus optic)

Therefore, if P/dV (or DP/fV) is held constant, the energy density into the part is constant (see *Section 4.10.2* and *Example 4.10.2*)

The energy density along with the coupling efficiency (the ability of the weld joint and material to use the available energy density of the focused beam), establishes the required weld speed for a desired weld penetration. The coupling efficiency is dependent on many things, a few of which are: laser type, power density, material reflectivity and conductivity, weld joint geometry, weld joint cleanliness and surface condition, the amount of volatile constituents in, or coatings on, the material, and for keyhole welding, the efficiency of plasma suppression (e.g. shield gas type, flow rate, shield nozzle geometry, nozzle stand-off, flow direction, etc.).

Weld Energy

While the ***energy density*** is related to the ***power density*** and ***spot size***, the **weld energy** is related to the **power** and **weld length**. The weld energy (E, i.e. how much energy has been utilized for a given length of weld) is directly proportional to the power (P) and weld length (w), and inversely proportional to the weld speed (V):

$$\boxed{\mathbf{E = w(P/V)}}$$

Table 2.2

SUMMARY OF LASER PARAMETER CALCULATIONS

Process Parameter	Reflective/Transmissive Beam Delivery	Fiber Optic Beam Delivery
Spot Size	$d = M^2 (4\lambda f/\pi D) = M^2 (F\#)(4\lambda/\pi)$ $d = 3BQ (4\lambda f/\pi D)$	$d = (f/f_c)\Phi_c$
BQ of Focus Spot	$BQ_{spot} \cong$ BQ of raw beam	$BQ_{exit} \cong (\Phi_c/2)(N.A.)$ *worst case* $BQ_{exit} \cong (\Phi_c/2)(\theta_i)$ *best case*
Depth of Focus	$L_{5\%} \cong d^2 /2\lambda M^2$	$L_{5\%} \cong 320\ (d^2/\Phi_c N.A.)$ *worst case* $L_{5\%} \cong 18.34\ \{d^2/[\Phi_c \tan^{-1}(D_i/2f_i)]\}$ *best case*
Power Density	$P_d = 4P/\pi d^2$	$P_d = 4P/\pi d^2$
Energy Density	$E_d = dP_d/V$	$E_d = dP_d/V$
Weld Energy	$E = wP/V$	$E = wP/V$

3. SYSTEM CONSIDERATIONS

3.1 Basic Components

Recall that the laser is a device that generates a nearly collimated beam of light energy. The laser by itself has extremely limited potential. However, when its beam is directed, manipulated and focused with respect to a workpiece, it has a consistency that makes it ideally suited for automated processing.

3.1.1 Beam Delivery System

The beam delivery system is comprised of components that accept the beam from the laser (and enclose it), direct it to the workpiece, and condition it into a useable form of energy. These generally include: i) beam bending mirrors, interconnecting beam guard tubes, and may include a beam collimator for moving beam or long beam delivery systems in a reflective system, or ii) a coupling module, fiber optic cable and a collimator in a fiber optic delivery system. In addition, both systems require a focus module with a focusing optic, and a shield gas delivery nozzle.

Focus modules provide a housing for the focus optic(s). These assemblies must generally be attached to a rigid, linearly adjustable axis (e.g. dove-tail slide, THK style rails, etc.) which can be used to adjust the focus position relative to the weld joint [usually about $\pm$ 25 mm ($\pm$ 1 inch) is all that is required if only one focal length and one part geometry is to be welded with the system]. This axis may be controlled either manually or via automation (i.e. servo motor, etc.). The adjustable axis may be designed to allow for various focal lengths (such as on a lab or development system), or various part geometries, thus significantly increasing the range of adjustment required. The focus adjustment axis, if manual, should have a lock down provision, as well as an integrated dial indicator (for both tracking and holding the focus position). If multiple part geometries are to be welded on the same system with frequent changeover, a servo controlled axis (with a brake if this axis is parallel to gravity) can be considered.

Focus modules that use a nozzle cone for shield gas delivery often provide the adjustments required to center the focused beam through the nozzle orifice. Nd:YAG focus modules typically use inexpensive, expendable glass cover slides to protect the focus optic from spatter and smoke from the welding process. With CO_2 lasers, glass cover slides cannot be used, and the cover slide materials which can be used cost almost as much as the focus optic and hence are generally not used. Height sensing devices (either mechanical or electronic) can be incorporated to automatically maintain the proper focal point position regardless of undulations in the workpiece surface.

A shield gas nozzle is usually integrated with the focusing assembly. It can be either an auxiliary tube (with or without a nozzle tip) or a nozzle cone attached directly to the focus module. The tube type generally provides a stream of shielding gas at some angle (usually about 45°) relative to the weld joint/surface, while the cone type provides coaxial flow of shield gas through the cone which is normally perpendicular to the weld surface (depending on joint geometry). The coaxial or nozzle cone configuration has the advantage of rigidity and pointing stability, as well as consistent shielding for multi-directional welding (e.g. robot welding applications, etc.). The primary advantage of the auxiliary tube style is that the focus unit can be equipped with an air knife to protect the focus optic from weld spatter (see *Section 4.9*). Nozzle configuration and design plays an extremely important role when high power welding. See *Section 4.7* for further discussion.

3.1.2 Motion System

Generally, lasers must be integrated as part of larger systems. In addition to the laser, each system features beam delivery components (see *Section 3.1.1*), a method of material handling, and a control system to govern its action. Systems range from simple set-ups where material is moved linearly (or rotated) under a fixed beam, to sophisticated multi-axis motion systems used for three-dimensional contour welding.

Two dimensional welding systems come in the following three configurations: 1) fixed beam (where the optical delivery system remains fixed), 2) moving beam (where the workpiece remains fixed), and 3) hybrid system (where one optical axis and one table axis moves). Each have strengths and weaknesses which must be weighed. In general, fixed beam systems are the most cost effective for high volume production welding of the same (or similar) parts. Presented in ***Table 3.1*** below is a summary of a few of the more important considerations for two-dimensional welding systems.

Three dimensional welding systems presently make-up a very small percentage of the installed base. Three dimensional welding systems are in the form of either robot or multi-axis gantry types. Robots have had renewed usage with Nd:YAG lasers because of the fiber optic beam delivery (see ***Figure 3.1***). Robot rigidity and accuracy must be considered, along with the basic laser considerations (e.g. the effect of wavelength on material interaction, and the effect of fiber optics on spot size, depth of focus and weld geometry).

Dynamic positioning accuracy poses the most significant problem in maintaining the welding system's overall precision. This concerns the dynamic response in movement of the positioning system's drives rather than the system's point to point positioning and repeatability capabilities. Inadequate encoder line count and mechanical deficiencies such as low motor torque, excessive backlash, excessive system inertia, and insufficient mechanical rigidity can all contribute to erratic contouring. High precision systems utilize mechanical assemblies compatible with the system's anticipated changes in inertia. They use precision components such as low inertia high torque servos, high resolution encoders, rigid low mass structural parts, and high-efficiency, high accuracy ball screw, rack and pinion or linear motor assemblies.

Table 3.1

SUMMARY OF 2-D MOTION SYSTEM CONSIDERATIONS

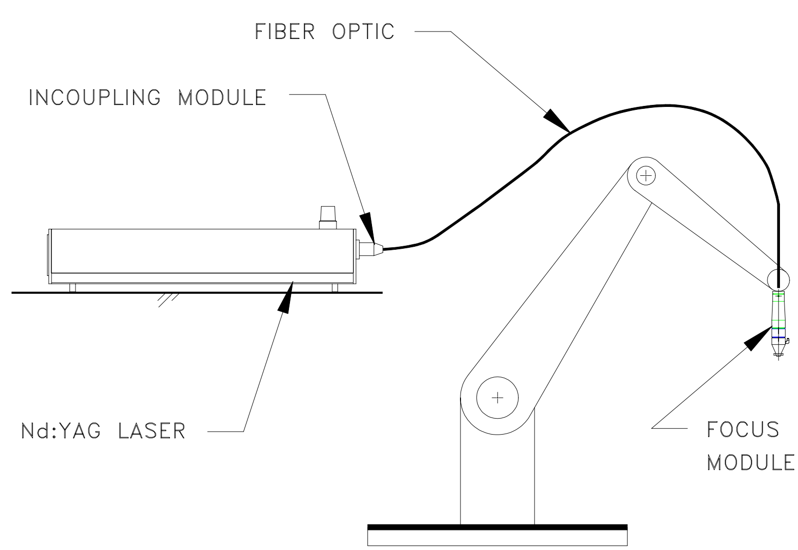
Parameter Considered **In Design of Machine**	**Fixed Beam** (moving x-y table)	**Hybrid** (x table, y optics)	**Moving Beam** [1] (flying x-y optics)
Cost	lowest	medium	highest [2]
Laser Beam Alignment Time	shortest	moderate	longest [3]
Effects of Divergence on Weld	none	some	most [4]
Inertia Effects on Accuracy & Speed *(also vibration)*	highest	medium	lowest
Material Weight Restriction	highest	medium	lowest
Foot Print	largest	medium	smallest
Part Clamping & Handling Requirements	highest	medium	lowest
Optical Power Loss	lowest	medium	highest
Ability to Keep Optics Clean *(Due to particulate migration [5] & number of optics)*	highest	medium	lowest

[1] Including moving laser (e.g. Nd:YAG with reflective/transmissive beam delivery, and “no flow” CO_2 slab laser.
[2] Cost is relatively high due primarily to [3] and [4] below, but also because more optics are required.
[3] Orthoganality of beam delivery and mirror stability become critical, design and cost increase.
[4] Collimating of laser beam may be required, this adds optics and associated maintenance and alignment issues.
[5] Especially in the case of bellows w/o proper venting, or telescoping tubes w/o proper sealing.

The laser is capable of continuously delivering a consistent amount of light energy that is directed at the workpiece. The interaction of the beam with the material occurs at a predictable rate. To achieve consistent weld performance, the focused spot must move smoothly at a constant velocity throughout the desired weld contour. Any dwell, acceleration or deceleration during the weld at constant laser power will result in inconsistent weld penetration. Therefore if a constant welding velocity cannot be maintained by the motion system or the system control, decreased power or pulsing during transition velocities is required (see *Section 3.2, System Control*).

Figure 3.1

ROBOT WITH FIBER OPTIC BEAM DELIVERY



3.1.2.1 Round Part Welding

Rotary Axis

For almost all round part welding systems, the part is rotated under a fixed laser beam. There are many ways to accomplish this, depending on whether or not clamping force or part centering is required. The method of part loading and unloading is also a determining factor. For example, for manual loading of a press fit part, only a stand alone rotary stage may be required. On the other hand, for automatic loading of two (or more) lose components where clamping is required, an upper rotary tooling and lower spindle/slide assembly may be required. For the lower spindle/slide arrangement, the considerations include: a) required clamping force (e.g. cylinder size, hydraulic versus air, and rotary stage torque), b) maximum weld speed (e.g. motor and gear reducer selection), and c) weld rotation and speed control (e.g. ranging from variable DC for time based welding to servo drive with encoder for position based welding).

Cross Part Adjustment

In addition to the rotary stage, a cross part adjustment is required for positioning of the weld onto the weld joint (or at the appropriate diameter for a lap joint configuration). Like the focus adjustment axis, manual adjustment via something like a dove-tail slide or THK style rail is normal. For a system that welds only a single component with a fixed weld diameter, only about ± 25 mm (± 1 inch) adjustment is required, if different components (and therefore different weld diameters) are to be welded on the same system, then the required adjustment should be about 25-50 mm (1-2 inches) greater than the maximum difference in weld radii (note that a change in weld angle, especially if going from a vertical to a horizontal weld orientation, must also be considered for specifying cross part axis adjustment). In this case, a servo controlled axis can be considered.

Servo Rotary Focus Unit

A servo controlled rotary focus unit allows the beam angle (relative to the part) to be changed via servo control. This is useful for systems designed to weld either various part geometries or several welds on the same part (when different beam angles are required). In most cases, a manually adjustable rotary focus unit is all that is required.

Parts Clamping and Loading

Parts can be loaded either manually, or in a semi-automatic or automatic mode. This has a major impact on system cost. Manual loading typically involves a workstation having an enclosure with an interlocked access door which is opened and closed for each part welded. A typical semi-automatic scenario may include a dial or turn table along with a spindle slide assembly. In this situation, a press fit assembly (or component parts) is loaded onto the dial and indexed into a position below the weld enclosure, and then lifted via a spindle/slide assembly into the upper tooling for the welding cycle. Automatic load normally incorporates plant provided conveyor or parts feeding systems.

3.1.3 Weld Enclosure Design

Almost all systems include a cabinet which encloses the weld area and protects the operator from exposure to the laser welding process. For systems where cabinets or weld enclosures are impossible or impractical (e.g. robotic welding systems), protection from the laser beam and the welding process must be accomplished via light curtains or barriers designed for the appropriate wavelength (CO_2, Nd:YAG, etc.). There are many important enclosure design features which require consideration, a few of which are discussed below.

Interlocked Access Doors

All enclosure access doors that are opened on a routine basis (e.g. part load/unload door, or doors/panels required for routine maintenance) must be interlocked with a safety interlock switch. The safety interlock must be fail safe and must prevent access to the laser beam (i.e. by preventing the laser beam shutter from opening when the interlock is open).

Light Tightness

DOORS AND PANELS: Infrequently used service access panels should be bolt on panels which are attached to the main enclosure in a sealed, light tight fashion. This can be easily accomplished by either a foam gasket attached to the perimeter of the panel, or by a labyrinth closure between the panel and the cabinet (which can also be designed to seal against a foam gasket). The interlocked access doors must also be light tight by using similar means.

PART LOADING AND UNLOADING: In systems that incorporate automatic load and unload of component parts, the part access ports must be light tight during welding for Class I systems, and this should be the design intent of all industrial welding systems. For example, for loading of a round part (such as a transmission component, air bag component, fuel filter, etc.), the part can be loaded into the workstation through a hole in the enclosure which seals via a labyrinth closure with the part fixture (see also *Section 3.1.2.1, Parts Clamping and Loading*). In this case, the part itself may actually act as part of the enclosure. The closure of the port must be confirmed via redundant proximity switches (e.g. cylinder up, fixture present, part present) or a safety switch (or switches). When two openings are required in an enclosure (for continuous part flow), there are a couple of options for light tightness. One possibility is to have interlocked pneumatic sliding doors which are closed during welding. Another option is to use a long tunnel with one or more hinged baffle plates, which are designed to prevent direct viewing of the weld point. Another example worth mentioning is continuous welding of roll formed tube, where a rubber gasket can be used to seal around the tube (by using two halves and overlapping them), thereby creating light tight seals at both the inlet and exit of the weld cabinet.

EXHAUST INLET: The exhaust inlet, whether filtered or not (because almost all flat filters have some degree of transparency), must be baffled in such a way as to not allow direct viewing of the weld area. The baffling scheme must also take into account the appropriate inlet cross-sectional flow area needed for the exhaust volumetric flow rate (see also *Section 3.1.4*).

VIEWING WINDOW: Almost all systems incorporate a viewing window so that the welding process can be monitored. For CO_2 laser systems, dark tinted Lexan, or clear Lexan sandwiched with #6 welding glass can be used to filter the UV wavelength (from the welding process), the IR wavelength (from the CO_2 laser) and the bright visible weld plume. For Nd:YAG laser systems, a special viewing window must be used which is designed for the 1.064 μm wavelength.

CO_2 CONDUCTION WELDING APPLICATIONS: Conduction welding is where welding occurs by conduction only, with no keyhole formation, and is typically only used for butt welding of thin materials (typically less than 0.5 mm (0.020 inch)) in order to avoid material ejection. For CO_2 lasers, this results in a significant amount of reflected laser energy off the workpiece. This reflected power should be absorbed by strategically placed water cooled beam absorbers to prevent damage to hoses and wires in the proximity of the welding zone, and to prevent damage or significant heating of the enclosure.

Maintenance Access

Maintenance access is often overlooked in the enclosure design, and this greatly influences the process capability. Items usually within the enclosure that need to be accessed, adjusted, removed, cleaned or otherwise maintained include; a) the mirror focus unit mirrors (for CO_2) and the cover slide (for Nd:YAG), b) weld cone and nozzle tip or shield nozzle tube, c) beam bender mirror, d) inlet air filter, and e) tooling or fixture components. Repeatability of the mounted focus optic after removal and replacement must be carefully considered (especially in a butt weld configuration). Note that for beam delivery optics where cooling lines are attached to the optic mount, either quick disconnect water fittings or a maintenance holder should be provided for the ease of maintenance and beam alignment (for CO_2).

Additionally, for CO_2 systems beam alignment maintenance is routinely required which typically consists of taking mode burns in Plexiglas at each optical component. Therefore, designing holders for the Plexiglas coupons would make the alignment procedure safer and faster (especially if the holder is designed with a mode burn coupon present limit switch and a backing plate equipped with a thermal switch). One easy way to do this is to extend the beam bender support bracket beyond the beam bender housing so that it provides a "shelf" to set a mode burn coupon on. Mode burns should be taken at least 150 mm (6 inches) away from the optics holder to prevent smoke from migrating into the beam delivery system. Often times the weld enclosure is close to the laser and prevents far field mode burns from being taken. In this case, a removable panel should be incorporated into the enclosure which allows for a far field mode burn.

3.1.4 Exhaust System

An exhaust system for removing weld smoke is generally required. When welding materials that can emit toxic vapors (such as those containing beryllium or lead), fumes must be collected and filtered, and the filters must be safely handled and properly disposed of. In general, the type of exhaust system (including volumetric flow rate and filtering capacity) must be considered along with weld cycle time requirements, material(s) to be welded and filter changeover options. In addition, careful attention must be given to the location of the inlet and exhaust ports, to insure smoke and fume removal without disrupting the gas shielding of the molten weld pool. In this regard, flexible exhaust tubing may be used to exhaust closer to the welding process. However, care must be taken to ensure that the shield gas flow is not disrupted.

The cross sectional area of the inlet and exhaust ports should be appropriate for the volumetric flow rate required. The inlet port should incorporate a filter, and be baffled in order to maintain a light tight weld enclosure (see *Section 3.1.3*). The effect of a filter and the baffle on air flow rate must be considered. In addition, it may be useful to electronically monitor filter cleanliness (via flow or pressure drop sensing) so that filter exchange/cleaning occurs at intervals designed to ensure optimum smoke and fume removal. This will help keep the optics and weld enclosure as clean as possible, thereby maximizing process performance and uptime.

The material's Material Safety Data Sheet (MSDS), can be helpful for identifying hazards. Federal, state and local laws should be researched for regulations concerning fume handling. In addition, users must work closely with the welding system manufacturer to design a fume removal system appropriate for the material(s) intended to be laser welded. See also *Section 3.7, Laser Safety*.

3.1.5 Gas Delivery System(s)

Laser gases (if required) and the shielding gas must be delivered to the laser and shield gas nozzle respectively (see ***Figure 3.2*** for example of a shield gas delivery panel). Gas bottles, liquid gas containers or bulk vessels are utilized. A few of the many considerations when specifying a gas delivery system are:

Laser Gas Delivery Considerations

a) pressure regulation,
b) pressure adjustment and setting,
c) pressure sensing (e.g. detect when gases are low), and
d) in process bottle or vessel changeover.

Shield Gas Delivery Considerations

a) pressure regulation,
b) flow adjustment and setting,
c) flow sensing (e.g. detect when shield gas is not flowing),
d) solenoid life cycle specification and cycle rate (e.g. ball valve with pneumatic actuator may be desirable for high cycle requirements), and
e) supply hose materials which can withstand reflected power (e.g. stainless steel braided hose), especially when welding highly reflective materials such as aluminum.

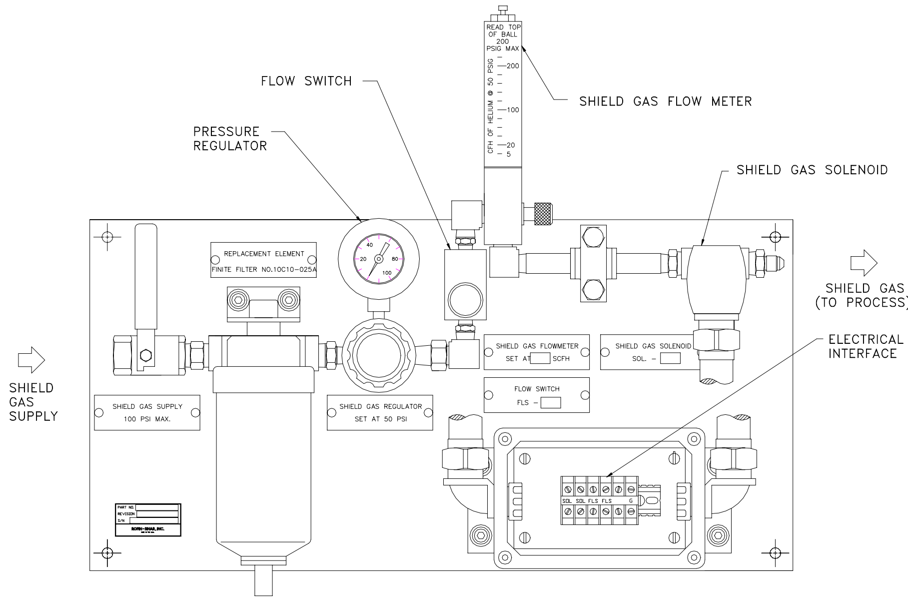
3.1.6 Chiller

Lasers and many beam delivery components require water cooling to maintain consistency and function. Using city water for this purpose is cost prohibitive, therefore an industrial water chiller is typically required. The chiller can be either water cooled (using city water or a cooling tower) or air cooled via integral fans. The laser and beam delivery may require cooling water at two temperatures to avoid condensation on moisture sensitive components, in which case either a dual circuit chiller, or a chiller and an auxiliary cooler may be used. A few of the considerations for proper chiller selection and installation are listed below:

Cooling Water Flow
A flow rate equal to or greater than the specified total minimum flow rate is required for the laser as a stand alone system. If water cooled accessories (e.g. beam benders or focus module) are integrated into the system, a flow rate greater than the specified total minimum flow rate will be required for adequate cooling. Installing a flow meter on the chiller supply line will help identify maintenance requirements (e.g. filter replacement, chiller flushing). Note that water additives can increase viscosity and therefore change chiller pump requirements. In addition, manual water by-pass systems on chillers (to prevent pump from dead heading) will also reduce water flow to the system. Automatic by-pass systems (which open only during a dead head condition) are preferred but are more costly.

Figure 3.2

EXAMPLE OF SHIELD GAS DELIVERY PANEL



Pumping Supply Pressure

A supply pressure (flowing not static) equal to or greater than equivalent to the sum of the maximum total pressure drop across the laser (ΔP_{laser}) plus the pressure drop from the chiller to the laser inlet ($\Delta P_{supply\ line}$) and the pressure drop from the laser outlet to the chiller ($\Delta P_{return\ line}$), must be available at the chiller [P_{supply}, not to exceed the maximum supply pressure allowed at the laser inlet ($P_{laser\ max.}$)]. Consult the chiller manufacturer for the pressure drop in the supply line (including filters and/or strainers) and the pressure drop in the return line, to insure adequate chiller supply pressure. Note that the pressure drop in the supply and return lines is dependent on many factors, a few of which are: i) flow rate, ii) water additive, iii) line material, inner diameter and length, v) quantity and geometry of all fittings (e.g. elbows, reducer bushings), vi) filter quantity and mesh size, and vii) straightness of hose (if used).

$$\mathbf{P}_{\mathbf{supply}} \geq \Delta\mathbf{P}_{\mathbf{laser}} + \Delta\mathbf{P}_{\mathbf{supply\ line}} + \Delta\mathbf{P}_{\mathbf{return\ line}} < \mathbf{P}_{\mathbf{laser\ max.}}$$

Temperature Control
Note that an increase in supply water temperature to the laser results in a decrease in maximum laser power output. Therefore, it is critical to operate at the nominal water temperature, and within the temperature stability, specified for the laser. The temperature set point and stability must be maintained regardless of laser and accessory heat load. This can range from 10-100% of the maximum cooling requirement. An adjustable temperature control on the chiller (and the resonator circuit for models requiring dual circuit cooling) is recommended to avoid operating at conditions below dew point (see *Section 3.4.5*).

Cooling Capacity
Review the cooling requirements with the chiller manufacturer to insure that the chiller will give the desired temperature control when running the laser at low power and will give adequate cooling on hot days. Note that water additives generally reduce heat transfer, and chillers must be sized to accommodate this. Also, consider the increased heat load from the chiller (particularly with an air cooled chiller) on facility air conditioning.

Water Quality
Typically, clean tap water can be used for filling the chiller (providing it meets the water quality specifications required for each laser). Sometimes distilled or deionized water is specified. Note that water additives may also be recommended. Filters should be provided on the chiller supply line to decrease contamination particulate in the water system (filter sizes are typically given for each laser). Filters and/or strainers must be routinely cleaned/replaced to avoid flow restriction. A viewing port for confirming water quality is recommended. The water system should be flushed and refilled regularly.

Plumbing
Non-corrosive materials (e.g. CPVC, PVC, copper, stainless steel, and brass) should be used for all wetted surfaces within the chiller and the field installed plumbing components. Do not use carbon steel, black iron or galvanized pipe due to their high rust and corrosion potential which may result in water system blockage and subsequent heat damage to laser components. Review plumbing requirements between laser and chiller with the chiller manufacturer to insure minimum pressure drop and adequate flow rate. Keep in mind that as the distance between the laser and the chiller increases, and as the flow rate requirements increase, the inner diameter of the plumbing which connects the laser with the chiller must also increase. ***Note:*** for CO_2 systems, if hard plumbing is used (e.g. copper or PVC), a flexible connection to the laser is required to allow the laser to be moved for beam alignment.

Accessories Cooling
In general, water cooled beam delivery accessories are cooled via the industrial chiller used to cool the laser. Accessories should be connected in parallel with the main laser cooling circuit in single circuit cooling systems, and connected in parallel with the resonator cooling circuit in dual circuit cooling systems. For systems with many water cooled accessories, and with accessories requiring different flow rates, several parallel branches may be necessary to achieve the required flow rates. A flow meter and flow

switch should be installed in each parallel water circuit so that the water flow rate can be monitored both visually and via the system controller.

3.2 System Control

The entire welding system should be under the direction of a central controller capable of actuating the laser in coordination with the motion system. It is key that the controller have sufficiently high sampling rates to effectively deal with the encoder signals to maintain accuracy and smoothness of motion. In order to process information at high speeds for smooth continuous motion, the controller should be able to pre-read blocks or program information in advance to determine the accelerations required to maintain constant velocity during a change of direction. Refer to ***Table 3.2*** for a typical laser system interface.

Dynamic Power Control
In the event that a constant velocity cannot be maintained throughout the weld (e.g. during the welding of sharp radii), a system which employs interactive laser power ramping can be used. However, much better results are obtained when direct pulsing is employed by varying the duty cycle of pulsing, on the fly. By utilizing frequency modulation of pulses of predetermined pulse energy (i.e. a given peak power and pulse length, and therefore constant power density), the welding performance of the laser can be matched to the actual feedrate with a linear relationship.

For multi-purpose processing, welding systems normally use computer numerical controllers (CNC). These devices provide flexibility for multi-axis control. Hardware features to assist in programming generally include a CRT display, keyboard, manual axis controls, feedrate overrides, and a variety of input/output devices such as tape readers, disk drives, DNC links and other communication interfaces. While programming features tend to distinguish one controller from another, most offer features including: linear and circular interpolation, axis scaling, inch or metric programming, absolute and incremental dimensioning, axis rotation, sub-routines, calculation blocks, and insert/modify/delete capabilities of stored part programs. Off-line programming allows for maximum laser utilization.

3.3 Polarization

As discussed previously (see *Section 2*), laser light is comprised of electromagnetic waves. This means that laser beams possess electric and magnetic components (i.e. vectors) which are at right angles to one another and are perpendicular to the laser beam's direction of travel. It is the orientation of the electric vector that determines the direction of the beam's polarization.

Table 3.2

TYPICAL LASER SYSTEM INTERFACE

Program Controlled Outputs from System Controller	Status Inputs to System Controller
Laser	
Emergency Stop to Laser	Emergency Stop from Laser
	HV is ON (Ready)
HV Enable	System Safety Interlocks are Open/Closed (e.g. beam delivery components to enable HV)
Shutter Enable	System Safety Interlocks are Open/Closed (e.g. guards and access doors to enable shutter)
Open/Close Shutter	Shutter is Opened/Closed
Laser Discharge On/Off	
Select: a) Power Level (analog or digital) or b) Preprogrammed Power Level	
Select Preprogrammed Pulse or Ramping Program	
Other Associated System Components [1]	
Chiller Start/Stop [2]	Chiller Status (may require several inputs)
Shield Gas On/Off	Shield Gas Pressure/Flow Status
Exhaust System On/Off	Exhaust System is On/Off

[1] Does not include I/O required for material handling.
[2] Laser may have chiller remote start/stop capability.

The significance of the orientation of polarization is related to the role it plays in the relative degree of absorption of the laser's energy into some materials, most notably metals. Welds made parallel to the beam's polarization are narrow and deep. As the direction of travel of a weld angles away from the direction of polarization, the weld penetration is reduced and the weld widths widen. Once the direction of travel becomes perpendicular to the direction of polarization, the weld penetration is reduced even further and the weld widths are widest.

While in theory it is desirable, it most often not feasible to orient the polarization parallel to the direction of travel for even simple beam delivery systems, let alone for complex moving beam systems (examples of exceptions would be roll formed tube welding and one-dimensional tailor welded blanks). Circular polarization of the laser beam has been successfully employed to negate the unfavorable traits of a linearly polarized beam, thereby allowing the user to obtain consistent weld penetration (in round and symmetric laser beams) regardless of weld direction. Lasers which emit linearly polarized light, in some cases must be transformed to circularly polarized light. If the plane of the linear polarized light is set at 45° (to the horizontal), then circular polarization is normally achieved via one external beam bending mirror which has a special coating (referred to as either ¼ wave or 90° phase shift mirror). Once circular polarization is achieved, care must be taken to preserve this condition. This is accomplished by using optical components that induce a minimal change in polarization (0° phase shift) to the reflected or transmitted beam.

For CO_2 lasers, circular polarization is used on linearly polarized, round beams that have symmetric power distributions (i.e. same mode) in both the horizontal and vertical axes: i) when a moving beam system is used (e.g. gantry or robot), or ii) when several of the same type of laser is being used in the same facility and the polarization orientation cannot be maintained (this will yield consistent results between weld stations and enhances quality control). Circular polarization is typically not employed on asymmetric or oblong shaped laser beams because the associated asymmetric or oblong spot will generally yield a weld penetration that varies with weld direction, regardless of polarization. Lasers which emit beams that are randomly polarized (in which the polarization plane rapidly changes in all directions) exhibit an effect similar to that of circular polarization, and generally would not require circular polarization for welding applications. Nd:YAG lasers typically produce higher order modes with random polarization, which in most applications does not require circular polarization, especially in view of the high cost that would be required to produce circular polarization. However, for a Nd:YAG laser integrated to multiple beam share modules, a ½ wave (i.e. 180° phase shift) transmissive element may be required to insure the desired power distribution to the individual fibers. An adjustable energy share module may be able to ensure equal power distribution without the use of a $\lambda/2$ element providing the adjustment range is adequate (e.g. > ±5%).

3.4 Beam Delivery Considerations for Reflective/Transmissive Beam Delivery

3.4.1 Beam Alignment

Beam benders use mirrors at a 45° angle which can redirect an unfocused “raw” beam at right angles to its incident axis. Typically, one to four beam benders are used in a beam delivery system, each additional unit adding more freedom of adjustment at the expense of some power loss and increased alignment time. The final mirror typically projects the beam vertically downward through the focusing assembly. While not required from a welding standpoint, vertical orientation minimizes concerns about laser beam safety and simplifies protection against beam hazards since the beam is directed downward and can be absorbed and/or diffusely reflected by the workpiece. The raw laser beam must be aligned through all of these components (see also *Section 3.1.1*).

Improper beam alignment accounts for many of the instances in which laser welding degradation occurs. There are two primary effects from improper alignment which decrease weld quality (maximum speed, depth of penetration, and uniformity). First, if the beam alignment is such that beam obstruction or "clipping" occurs, the power at the weld joint will be reduced (with a resultant loss of power density) and there is the possibility that the beam delivery components may be damaged by the misaligned laser power. The beam can be obstructed by (or at) the beam benders, focus unit, shield gas nozzle, part positioning/clamping fixture, or the component(s) to be welded.

Secondly, in order to minimize spot size (and thereby maximize processing speed) alignment of the laser beam through the focusing optic requires that the incident beam be parallel with the optical axis. For transmissive focusing optics this, typically requires the incident beam to be parallel with, and generally central to (i.e. coaxial), the optical axis. For reflective focusing optics, this requires the incident beam to be perpendicular to, and centered with, the optical axis. If these conditions are not met the resultant focused spot can be either distorted or elongated, which increases the focused spot area, and therefore reduces the power density at the workpiece. An increased spot size increases the weld width and decreases the weld penetration (at a given weld speed), or reduces the weld speed. For moving beam systems (e.g. robot or gantry type) where the laser beam is not coaxial (or parallel) with the optical axes of the beam delivery system (especially at the focus optic), the focused spot size will vary at different locations in the work envelope of the beam delivery system.

3.4.2 Beam Delivery Stability

Another factor which influences beam alignment is the stability of the supporting structure or foundation for the laser and its beam delivery system. If the laser and beam delivery system are not located on a solid, stable floor, or a robust single superstructure, beam misalignment can occur. Avoid branching across expansion joints (between laser generator and system) and locating systems in areas of significant vibration. When branching across expansion joints, unequal motion of foundation sections, due to settling or thermal shifting, can cause severe misalignment of the beam delivery system. Similarly, when locating systems in close proximity to vibration source (e.g. near a press area), vibration induced misalignment can adversely affect process performance and quality. Failure to comply with either of these requirements can result in either: i) poor alignment at the focusing optic resulting in a larger focus spot size and therefore a lower power density, or ii) poor alignment through the beam delivery system resulting in a "clipping" and therefore a loss of power density at the weld point. Consult the system manufacturer for specified foundation and/or maximum shock specifications. See *Section 3.4.1* for a further discussion.

3.4.3 Beam Delivery Purging

Beam delivery systems must be well sealed. Aluminum tubes (fixed or telescoping), reinforced bellows, and other metal safety enclosures are generally used for this purpose. This limits the amount of contamination which can migrate onto the optical components, as well as provides a safety enclosure for the invisible laser beam. In addition to this, the beam delivery system should be purged with an inert gas (such as nitrogen) or clean, dry air {air quality to be at least (unless otherwise specified): *Water vapor* < 550 ppm @ 35°F; *Solids* < 1,000/ft^3, < 0.2 μm; *Oil aerosols* < 0.0005 ppm by weight; *Oil vapors* < 0.003 ppm by weight}. This maintains a positive pressure inside the sealed system which minimizes the ingress of ambient contamination (oil mist, water vapor, smoke, dust, solvent fumes, etc.) into the beam delivery system.

Purging helps keep the beam delivery components clean and dry prior to and during operation. A build-up of debris and foreign matter on the optical components has two primary detrimental effects. First, any debris (dust or oil for example) that contaminates any of the optical surfaces will absorb laser beam power. Second, as the surfaces absorb power they will distort due to that thermal load. Focusing optics are particularly sensitive to thermal loading because they are generally smaller (less thermal mass) than output optics and beam delivery mirrors, and they are most susceptible to contamination (especially from the welding process). They distort due to the thermal load, which will cause the focus position to drift (referred to as thermal lensing). This results in an increase of the spot size at the weld joint, and an accompanying loss in power density. Insufficient cooling of the beam delivery components can result in a similar phenomena.

Additionally, if contamination or moisture is present in the path of the beam in the beam delivery system, a condition referred to as "thermal blooming" may result. Thermal blooming occurs when foreign matter (i.e. oil mist, or hydrocarbons such as paint thinners, acetone or alcohol fumes, etc.) in the path of the beam absorbs some of the beam energy, thus heating up. The rise in temperature is accompanied by a change in the refractive index, which in-turn can redirect and cause divergence of the laser beam resulting in internal beam clipping (with an accompanying loss of power and power density at the weld joint), and potential damage to beam delivery components. Purging helps prevent thermal blooming from occurring.

3.4.4 Raw Beam Size and Thermal Lensing

The raw beam has differing sizes within the beam delivery system, and therefore will exhibit a different focusability depending on where the focusing optic is located. As discussed in *Section 2.3.1*, the size of the raw beam at the focusing optic is inversely proportional to the focused spot size. Therefore, for moving beam systems, or for systems where the beam is shared (shuttled) between two or more work stations, a difference in weld performance may be evident from one position (or station) to another.

Similarly, as the temperature of the lasers output optic(s) increases, the optic(s) refractive index and/or geometry changes (i.e. behaves more like a lens). This changes the location of the waist, and therefore changes the raw beam size (i.e. propagation characteristics). Generally, beam divergence is greater with a “cold” optic than it is with a “hot” optic. An increase in temperature of the output optic(s) occurs with; i) an increase in laser power, ii) an increase in the optic(s) absorptance (e.g. if the output optic(s) become dirty or damaged), or iii) a decrease in cooling of the optics. For example, a build up of debris (carbon deposits for example), or damage (cracks or pits) on the output optic can cause it to absorb additional energy and increase in temperature, thus resulting in thermal distortion (thermal lensing) and thermal focusing of the output beam. Insufficient cooling (e.g. low flow rate or higher cooling water temperature) of the output optic can result in the same phenomenon. Thermal focusing of the raw beam will yield a beam size at the focusing optic which can be significantly different from that of the raw beam which has not been thermally focused, which in-turn will result in inconsistent weld penetration.

Additionally, not only does thermal focusing effect the spot size of the focused beam, but because the raw beam divergence changes during thermal focusing, the focus plane shifts. A converging raw beam will cause the focus plane to move toward the focusing optic (with respect to the theoretical focal length of the focus optic), while a diverging raw beam will cause the focus plane to move away from the focusing optic. In practice, all raw laser beams go through thermal focus cycles (from when the output optic(s) is new to when it requires replacement). Replacement intervals are determined by the optic quality, exposure to contamination, laser power, and weld/process sensitivity to the increasing spot size. The rate of degradation can be minimized with timely and correct routine maintenance of the output optics (inspection and cleaning) and insuring the integrity of the output optic(s) gas shroud protection and the beam delivery purging (quality and flow, see also *Section 3.4.3*). Since the focused spot size almost always increases as the output optic ages, either the laser power will have to be increased, or the weld speed decreased, in order to keep weld penetration constant. However, both of these result in an increase in weld energy, which results in a larger weld and in general, a greater thermal distortion of (and/or residual stresses in) the welded component. Adjustments in focus position (see *Section 4.8*) to account for the shift in focus plane during the thermal focusing cycle will help maximize the weld penetration. Note that contamination on, or insufficient cooling of, the focus optic can result in the same sort of spot size changes and focus plane shifting.

Similar effects can also occur with Nd:YAG lasers. This is caused by thermal distortion of the Nd:YAG rod(s), as well as thermal lensing of the laser output optics.

Consequently, the raw laser beam generally has differing beam quality with respect to power, and therefore, differing focused spot diameters at the weld point with respect to power. This is especially noticeable on components requiring power ramping at the start and end of the weld (see *Section 4.10.5*), as is the case in most round part welding. As noted above, the same is true of focusing optics.

3.4.5 Dew Point

If moisture is present on optical surfaces, the violent vaporization of the water as the beam impinges them can cause surface damage (similar to a cavitation erosion condition). This situation is typically associated with water cooled components which are cooled to temperatures below the dew point. When operating at this condition, water will condense on the optical surfaces that are exposed to the ambient environment. To avoid this situation: i) insure that the system purge gas (see *Section 3.4.3*) is clean, dry and properly functioning in to order prevent ingress of moisture into the beam delivery, and ii) insure that any water cooled beam delivery components that are exposed to the atmosphere are cooled at temperatures above dew point.

3.5 Beam Delivery Considerations for Fiber Optic Beam Delivery

3.5.1 Fiber Types

As presented in *Section 2.3.2*, there are two basic types of fibers used for high power Nd:YAG transmission, namely, step index and graded index. Graded index fibers are infrequently used at high laser powers because: i) they are expensive to manufacture, ii) they are highly sensitivity to alignment of the input beam into the fiber, and iii) Nd:YAG lasers typically have such a low beam quality that graded index fibers yield only marginal improvements of spot diameter and depth of focus as compared with a step index fiber.

The numerical beam quality of an exit beam (BQ_{exit}) that has passed through a step index fiber optic can be significantly greater than the numerical beam quality of the input raw beam (BQ_{input}). The resulting exit beam has a power distribution that is, in general, uniformly distributed (i.e. "top-hat" distribution) and less focusable.

3.5.2 Alignment

Improper alignment of the focused input beam into the fiber optic reduces the power transmitted through the fiber, and therefore reduces the available weld energy. Additionally, misalignment at the fiber input can severely damage, and in many cases damage beyond repair, the fiber optic. Water cooled fiber connectors can greatly reduce the risk of fiber damage caused by misalignment.

Related to alignment, note also that the focused beam at the workpiece can also be obstructed by (or at) the focus unit, shield gas nozzle, part positioning/clamping fixture, or the component(s) to be welded. See also *Section 3.4.1* for further discussion.

3.5.3 System Stability

As for the transmissive/reflective beam delivery systems, the stability of the supporting structure or foundation for the laser and its work station influences weld quality. If the laser is in a location where intense vibration is present (e.g. near a press area) random misalignment at the fiber optic input can occur. Similarly, vibration induced movement of the welding focus module and the component to be welded can cause a cyclical out of focus condition, which changes the focused spot size at the part, and thereby adversely affects the weld quality. This is especially critical when utilizing a robot to manipulate either the focus module or the component to be welded. The rigidity of the robot (in all orientations, and at all expected velocities, accelerations and decelerations) coupled with the fixture or welding module, must be carefully considered. See *Section 3.4.2* for further discussion.

3.5.4 Raw Beam Effects

As discussed in *Section 3.4.4*, the raw beam at the laser head generally has differing beam quality with respect to power for a Nd:YAG laser. Transmissive/reflective beam delivery systems are significantly affected by this because a change in beam quality results in a change in focused spot diameter, and therefore a loss of power density. With fiber optic beam delivery systems however, especially step index fibers, this effect is normally insignificant. The reason is that the fiber optic delivery system produces a nearly "top hat" power distribution at the exit of the fiber regardless of the input beam quality. While this keeps the weld penetration consistent, the “top hat” mode is not as focusable as the raw beam (see *Section 3.5.1*). Therefore, the weld penetration with a fiber optic beam delivery will be less than that of a reflective/transmissive beam delivery. The flexibility of the fiber optic, however, in many cases outweighs this effect.

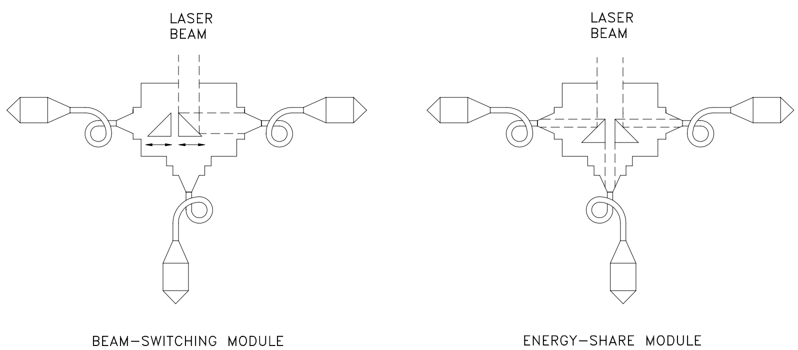
However, if thermal distortion of the Nd:YAG rod(s) or thermal lensing of the output optic(s) results in an input spot size that overfills the fiber optic core diameter (see *Section 2.3.2*), then the welding process would be affected. This is because overfilling the fiber optic means absorption of the beam into the fiber clad material, and therefore a loss of power and power density at the weld point. This can occur if either; a) there is significant thermal affects in situations where the spot size is normally very close to the diameter of the fiber core, or b) there is extreme thermal affects in situations where the spot size is normally much smaller than the fiber core diameter.

3.5.5 Fiber Configurations

One of the many advantages offered by fiber optic beam delivery systems is the ability to switch or share the laser between many modules (see ***Figure 3.3***). With reflective/transmissive beam delivery systems, only switching is practical, and then only between two work cells. Maintaining beam alignment and raw beam divergence (and therefore beam delivery length) are two primary limitations. However, with a fiber optic beam delivery system, fiber length has virtually no affect on power transmitted or on the exit beam quality.

Figure 3.3

EXAMPLES OF FIBER CONFIGURATIONS



3.6 Summary of Beam Delivery Effects on Weld Energy Density

3.6.1 Energy Density

i. Energy density (along with coupling efficiency) determines weld penetration and it is directly proportional to power density (and focused spot size), and inversely proportional to weld speed.

ii. There is always a trade off between the focused spot diameter and depth of focus with focal length.

iii. The power density is decreased when:

   a. Power is decreased via:

      i. beam clipping due to poor alignment or installation site vibration/shifting,
      ii. beam clipping due to thermal blooming *(reflective/transmissive systems)*,
      iii. contamination on beam delivery optics or damaged optics,
      iv. spatter on focus optic or cover slide,
      v. poor plasma suppression, and
      vi. thermal lensing of Nd:YAG rod or optics resulting in an overfill of the fiber optic core *(fiber optic systems)*

Note: Loss of power generally results in a shallow, <u>narrow</u> weld.

b. The focused spot diameter is increased via:

   i. out of focus,
   ii. alignment not coaxial to focus optic *(reflective/transmissive systems)*,
   iii. reduced raw beam size through thermal focusing of output optics or moving beam/beam shuttling because of beam propagation characteristics *(reflective/ transmissive systems)*,
   iv. weld joint location drifts in and out of focus due to part tolerance or fixturing repeatability/stability, or tool wear, and
   v. thermal shifting of focal point due to insufficient cooling or contamination on focus optic or cover slide.

Note: Increase in spot size generally results in a shallow, <u>wide</u> weld.

3.6.2 Coupling Efficiency

i. Coupling efficiency determines how much of the available energy density is transferred to, and absorbed at, the weld joint (and thus becomes weld energy).

ii. Coupling efficiency is affected by:

   a. laser type,
   b. power density,
   c. material reflectivity, conductivity and volatile constituents, and
   d. joint geometry, cleanliness and surface condition.

3.7 Laser Safety

Safety concerns can be grouped into many categories, a few of which are: 1) high voltage and related electrical hazards, 2) laser beam hazards to skin and eye (alignment laser and main beam, direct and reflected), 3) hazards from laser generated fumes, 4) handling of hazardous materials (e.g. filters from exhaust system, laser optics, and vacuum pump oil), 5) fire and explosion hazards, 6) noise hazards, and 7) the hazards associated with compressed gases.

The standard pertaining specifically to the laser that every end user in the United States must comply with is ANSI Z136.1-latest revision. This standard is the American National Standard for *Safe Use of Lasers*, and is approved by the American National Standards Institute. In general, all laser users must appoint a Laser Safety Officer (LSO) that takes responsibility for compliance to this standard (which requires not only the identification and evaluation of hazards, but also criteria for control measures, training and medical surveillance, all of which are outlined in Z136.1). A summary of a ***few*** of the pertinent standards and references are listed below:

1) American National Standards Institute (ANSI), 11 West 42nd Street, New York, New York 10036.
   National Fire Protection Association (NFPA), 1 Batterymarch Park, Quincy, Massachusetts 02269.

   i) ANSI Z136.1, *Safe Use of Lasers*
   ii) ANSI Z49.1, *Safety in Welding and Cutting*
   iii) ANSI Z87.1, *Practice for Occupational and Educational Eye and Face Protection*
   iv) ANSI Z117.1, *Safety Requirements for Confined Spaces*
   v) ANSI/NFPA 70, *National Electric Code*
   vi) ANSI/NFPA 79, *Industrial Machinery*

2) Occupational Safety & Health Administration (OSHA), Department of Labor, Washington, DC 20210.

   i) US Department of Labor, *Code of Federal Regulations*, Title 29-Labor, Part 1910, "Occupational Safety and Health Standards"
   ii) Instruction Publication 8-1.7, *Guidelines for Laser Safety and Hazard Assessment*

3) Center for Devices and Radiological Health (CDRH), FDA, Department of Health and Human Services, 8757 Georgia Avenue, Silver Spring, Maryland 20910.

   i) US Department of Health and Human Services, *Code of Federal Regulations*, Title 21, Subchapter J, Part 1040.10 (latest edition), "Performance Standards for Laser Products"

4) Laser Institute of America (LIA), 12424 Research Parkway, Suite 130, Orlando, Florida 32826.

   i) LIA, *Laser Safety Guide*
   ii) LIA, *Guide for Selection of Laser Eye Protection*

3.8 Operating Costs

Laser welding system operating costs can be estimated if the application data is known. One way to calculate cost is calculating it per hour, while amortizing some of the more significant maintenance costs into an hourly figure. The following examples are given primarily as an aid. They may be altered and enhanced to suit individual laser products and applications.

3.8.1 Conventional CO_2 Welding System

Typical welding systems utilizing carbon dioxide lasers have operating costs generally falling into the categories listed below. However, recent developments in CO_2 laser technology has made available a CO_2 laser which does not use a continuous flow of laser gases, but rather uses a static volume of gas. For this style of laser, the laser gas consumption data and costs would differ from that listed below.

Example 3.8.1: A 6000 Watt transverse flow laser, welding carbon steel with a 200 mm focal length focusing optic, and requiring a 5 mm (0.2 inch) weld penetration, with helium shield gas @ 40 scfh (1,130 Nl/hr):

Welding speed: 2.4 m/min (95 inch/min)

Laser electrical power:	(70 kVA)(0.8 pf)($0.08/kWhr)=	[1] 4.48
Laser gas, Carbon Dioxide:	(0.07 scf/hr)($0.12/scf)=	0.01
Laser gas, Helium:	(1.00 scf/hr)($0.14/scf)=	0.14
Laser gas, Nitrogen:	(0.53 scf/hr)($0.08/scf)=	0.04
Chiller electrical power:	(30 kW)($0.08/kWhr)=	2.40
Chiller additive:	(0.10)(200 gal)($20/gal)/(6000 hr)=	0.07
Laser optics (2000 hr):	($3720)/(2000 hr)=	1.86
Laser optics (4000 hr):	($3120)/(4000 hr)=	0.78
Shield gas, Helium:	(40 scf/hr)($0.14/scf)=	[1] 5.60
Exhaust system power:	(5 kW)($0.08/kWhr)=	0.40
Exhaust system filters:	($5)/(100 hrs)=	0.50
Maintenance labor (with overhead):	(12 hrs/2000 hr)($45/hr)=	0.27

Total approximate operating cost per hour (full power continuous weld): $16.55/hr

[1] Cost per hour (assuming 75% duty cycle of items marked [1]): $14.03/hr

3.8.2 Conventional Nd:YAG Welding System

Typical welding systems utilizing Nd:YAG lasers have operating costs generally falling into the categories listed below. Note that the laser arc lamp life is strongly dependent on laser power and duty cycle (assumed below as 500 hours at 85% power and 100% duty cycle).

Example 3.8.2: A 2500 Watt CW laser, welding carbon steel with a 120 mm focal length focusing optic, and requiring a 3 mm (0.12 inch) weld penetration, with helium shield gas @ 40 scfh (1,130 Nl/hr):

Welding speed:	2.3 m/min (90 inch/min)	
Laser electrical power:	(90 kW)($0.08/kWhr)=	[1] 7.20
Chiller electrical power:	(45 kW)($0.08/kWhr)=	3.60
Chiller additive:	(.35)(75 gal)($10/gal)/(4000 hr)=	0.07
Laser arc lamps:	($250)(8)/(500 hr)=	4.00
Shield gas:	(40 scf/hr)($0.14/scf)=	[1] 5.60
Cover slide:	($50)/(500 hr)=	0.10
Exhaust system power:	(5 kW)($0.08/kWhr)=	0.40
Exhaust system filters:	($5)/(100 hrs)=	0.50
Maintenance labor (with overhead):	(5 hrs/2000 hr)($45/hr)=	0.11

Total approximate operating cost per hour (full power continuous weld): $21.58/hr

[1] Cost per hour (assuming 75% duty cycle of items marked [1]): $18.38/hr

4. WELDING PROCESS REQUIREMENTS

4.1 Material Selection

Many ferrous and non-ferrous materials can be laser welded. Dissimilar materials can often be welded providing they are metallurgically compatible. The alloying elements added to materials to enhance their service or fabrication characteristics (such as strength, wear resistance, formability or machinability) also impact the weldability of the material. From a laser welding perspective, the volatility of the alloying element is important, because highly volatile alloys (such as sulfur and phosphorus) will vaporize out of the molten weld pool resulting in porosity, and possibly undercutting. In addition, because of the relatively high cooling rate associated with laser welding, carbon content (or carbon equivalent) becomes a critical factor in so far as weld embrittlement, microcracks and fatigue strength is concerned.

4.1.1 Carbon Steels

Low carbon, low alloy steels are typically highly weldable. General guidelines on the weldability of steels are:

a) In general, steels with low carbon equivalent (C_{eq}) values have high weldability. If the carbon equivalent exceeds about 0.30 percent, resultant welds have both high weld hardness and a propensity toward cold cracking, both of which increase the potential of brittle failure under fatigue and cryogenic conditions. The carbon equivalent for low alloy steels (alloy content < 5% cumulative total) can be approximated by the following formula which is used by the International Institute of Welding:

$$\boxed{\mathbf{C_{eq} \cong C + Mn/6 + (Cr+Mo+V)/5 + (Ni+Cu)/15}}$$

A weld joint designed to allow for weld shrinkage (and thereby minimize stresses in the weld and heat affected zones) can minimize cracking when welding materials with C_{eq} greater than 0.30%. Also, weld biasing when welding a material of C_{eq} greater than 0.30% to a material of C_{eq} much less than 0.30% can minimize cracking (because it helps ensure sufficient dilution at the weld interface which limits martensitic transformation).

Reducing the quench rate may also be used to minimize cracking in steels where the C_{eq} is greater than 0.30%. Some methods of reducing quench rate are: i) preheating and/or post-heating operations (e.g. via induction heating), ii) dual beam welding (one beam focused, one beam defocused), and iii) welding at a slower speed with a lower power (while maintaining the same weld penetration as the higher power, faster speed weld).

b) It is sometimes possible to successfully weld relatively high carbon steels to relatively low carbon steels by employing one or more of the techniques described in paragraph 4.1.1.a (above).

c) Fully killed or semi-killed steels are preferable (i.e. steels where dissolved oxygen content has been reduced to a low level by the addition of deoxidizing elements, such as aluminum and silicon, before pouring). If steels are not killed (i.e. rimmed steels), they should not be used for laser welding unless the oxygen content is otherwise minimized (because porosity can result due to trapped bubbles caused by out gassing).

d) Steels with high sulfur (greater than 0.04%) or phosphorous (greater than 0.04%) content are subject to hot cracking.

e) Weld porosity or solidification cracking can result when welding free-machining or billet steels containing sulfur, phosphorous, selenium, cadmium or lead (typically a maximum of 0.05 percent cumulative total is acceptable).

f) Pulsing of the laser output can be used to minimize heat input. This may be used to overcome cracking or part distortion.

g) Carburized steels, because of high surface carbon content, result in weld solidification cracking and shrinkage cracking in the carburized layer, and therefore generally cannot be laser welded. Fusion welding of nitrided steels is generally not acceptable because it removes the surface hardness in the vicinity of the weld, and the resultant weld will be porous and may also have cracks.

h) Zinc coated (galvanized) steels are generally difficult to weld in an overlap configuration because of the low vaporization temperature of zinc (903° C (1657° F)), compared with the melting temperature of iron (1535° C (2795° F)). As a result, zinc vaporizes during welding, and due to the high vaporization pressure, violently exhausts out of the molten weld pool, carrying molten material along with it. Resultant welds can be extremely porous with significant undercut. On the other hand, if the total zinc coating thickness in the overlap region is less than 5–10 μm (0.0002-0.0004 inch), acceptable welds are probable. However, a coating thickness of 10-20 μm (0.0004-0.0008 inch) zinc per surface is typically required to obtain adequate corrosion resistance. Therefore, an overlap weld joining a zinc coated component to bare (uncoated) component may yield acceptable welds.

   Electrogalvanized zinc coated steels are generally better for laser welding (compared to hot dipped galvanized steels) because the coating thickness is more consistent over the entire coated surface. Techniques to overcome the problem of zinc vaporization during overlap welding usually involve attempting to control one of the following; 1) the exhaust path, 2) the exhaust time, or 3) the zinc vaporization temperature or pressure. The most common approach is to control the exhaust path. A number of methods have been proposed (many of which are patented) to provide an alternate exhaust path for the zinc vapor by introducing a small, controlled gap at the interface of the overlap weld joint, or via the weld joint design itself. Some of these methods include: a) shimming, b) knurling, c) stamping dimples, d) joint design ("Y" type or "edge" welds), or e) clamp designs which cause the material adjacent to the weld to form a gap. Gaps approximately equivalent to the total zinc thickness at the interface (up to about 0.1 mm (0.004")) seem to provide enough of an exhaust path so as to minimize porosity without introducing significant undercutting. Exhaust time and zinc vaporization temperature/pressure techniques are much more exotic, and much less understood. For example, pulsing techniques to control and stabilize vaporization, or degasification and oxidization techniques which attempt to increase the vaporization temperature. Finally, minimizing the focused spot size, and thereby minimizing the volume of vaporized zinc, may help minimize the porosity and undercutting associated with overlap welding of galvanized steel.

4.1.2 Stainless Steels

Austenitic

Stainless steels are generally laser weldable. However, the austenitic (i.e. 300 series) grades 303, 303 Se, stabilized 321, and 347, because of the addition of sulfur and selenium for machinability, may exhibit a tendency for solidification cracking. Due to a lower thermal conductivity (about one third that of carbon steel) and a slightly higher absorptivity, slightly deeper weld penetration (about 5-10%) can be achieved with austenitic stainless steels compared with plain carbon steels. Due to the relatively low heat input and high welding speeds, 300 series stainless steels are ideally suited for laser welding because high heat input, low speed welding (such as TIG welding) reduces the corrosion resistance of the weld metal. In addition, laser welding of the austenitic grades results in less thermal distortion and residual stresses compared with conventional welding techniques, especially in light of the fact that they have a 50% greater thermal expansion than plain carbon steels.

The austenitic stainless steels are generally weldable when the Cr/Ni equivalent (Welding Research Council) is greater than about 1.6. If the Cr/Ni equivalent is lower than this, the tendency toward hot cracking is higher. The Cr/Ni equivalent can be approximated using the following relationships.

$$\boxed{\textbf{Cr eq} \cong \textbf{Cr + Mo + 0.7Nb + 3Ti}}$$

$$\boxed{\textbf{Ni eq} \cong \textbf{Ni + 35C + 20N}}$$

Ferritic and Martensitic

Laser welding of the 400 series (ferritic stainless steels) generally yields higher malleability and ductility as compared to other welding processes. However, because of martensite formation and the grain coarsening associated with fusion welding, weld joint strength and corrosion resistance is somewhat reduced (albeit much less than conventional welding techniques). Laser welding of ferritic stainless steel generally yields the lowest tendency toward hot and cold cracking as compared with the austenitic and martensitic grades.

The martensitic grades have the poorest weldability of the stainless steels. Resultant welds are very hard and brittle, with a tendency toward cold cracking. Preheat and tempering can be used to reduce cracking and embrittlement in grades where carbon content is greater than 0.1%.

4.1.3 Special Alloys

Titanium and titanium alloys are also welded. However, titanium is highly sensitive to oxidation, as well as interstitial embrittlement (via oxygen, hydrogen, nitrogen and carbon), and therefore special attention must be given to joint cleanliness and gas shielding. Magnesium and its alloys, in general, can suffer from HAZ cracking and porosity when laser welded, although not a great deal data is currently available. Cobalt and cobalt based alloys are readily weldable, but some of the highly alloyed forms may suffer from fusion zone and HAZ cracking.

4.1.4 Heat Resistant and Reactive Materials

Most nickel based alloys are good candidates for laser welding. However, cracking in the HAZ can occur in alloys such as 718, Hastelloy X, and Inconel 600. Refractory metals (such as niobium, tantalum, molybdenum and tungsten) and alloys based on these metals are also laser welded (although tungsten alloys can be susceptible to weld cracking). Like titanium, refractory alloys are sensitive to interstitial embrittlement, and therefore special attention must be given to joint cleanliness and gas shielding.

4.1.5 Brass, Copper and Aluminum

Brass, copper and aluminum are generally not laser welded with carbon dioxide lasers. Brasses weld poorly because of their zinc content regardless of laser type. Zinc has a relatively low melting temperature and vaporizes readily, resulting in a porous weld with many large voids and discontinuities.

The high reflectivity of copper alloys to the carbon dioxide laser wavelength, is greatly reduced with the Nd:YAG wavelength, making laser welding of copper alloys possible. For CO_2 welding, extremely high energy densities from highly focusable beams, high power lasers, and high peak power pulsing techniques show promise for the future of copper laser welding. In addition, surface treatments can be used to enhance absorptivity.

Autogenous laser welding (welding without filler material) of many aluminum alloys, because of the highly volatile alloying constituents (silicon and magnesium for example), results in porous welds with low adhesion regardless of laser type. However, the 2219 series, as well as the 1000 and 3000 series alloys can be successfully welded without filler material. Laser welding of pure aluminum is not beset with this problem. In the case of aluminum or any aluminum alloy, the Nd:YAG wavelength couples into the material much better than does the CO_2 wavelength. Due to the high initial reflectivity of aluminum to the CO_2 wavelength (i.e. 90-98%), very high power densities (typically greater than 4 x 10^6 W/cm^2) are required to sustain a keyhole when welding with a carbon dioxide laser. The molten pool of aluminum welds, because of the low viscosity and therefore low surface tension of the molten aluminum, generally must be held in tension (i.e. insure that the molten pool can not drop out). This can be accomplished either through joint design (a jog in the weld joint), or by designing for incomplete penetration welds.

Even with the power density problem solved, three critical problems remain, induced porosity, hot cracking and severe weld bead irregularity. Pores are induced into the molten pool due to hydrogen solubility, which is proportional to both the volume of the molten pool and the quench time (both of which are relatively small when comparing laser welding to TIG and MIG welding). Further, the natural surface oxide films (e.g. Al_2O3 and $3H_2O$) also combine with the molten pool during welding, resulting in both porosity and embrittlement. These oxide films can be mechanically or chemically removed prior to welding if required. Hot cracks, which form in some alloys during solidification of the weld pool, leads to reduced mechanical properties of the welded joints. The crack formation is a function of quench time (and therefore weld speed), as well as a function of shielding. Insufficient protection leads to exposure to, and the absorption of, both nitrogen and oxygen, which forms pores and inclusions of AL_2O_3 and/or AlN, which act as crack propagation sites for small cracks, as well as results in a weld bead surface which is contaminated with these chemicals (AL_2O_3 is white and AlN is black in color). Weld irregularities include rough and severe weld surface ripples, edge undercuts and irregular root shaping. All this is attributable (at least in part) to low vapor pressure, the high affinity to N_2 and O_2, as well as to low surface tension. Using helium as a shield gas and argon as a protection gas gives a bright and shinny weld bead with uniform, closely spaced ripples. Root shielding (e.g. via a gas filled back up duct) on through weld applications is critical.

Special Welding Processes for Aluminum

Laser welding aluminum alloys with filler material can be used to avoid hot cracking, undercutting and reduce bead discontinuities. In addition, welding with filler material can increase the ability to tolerate some degree of poor fit-up and can provide higher weld strength. Laser welding with plasma transferred arc (PTA) augmentation (Plasma Arc Laser Welding) for either CO2 or Nd:YAG, can increase weld speed (up to 2 times faster), reduce cracks (which are most often associated with rapid cooling) and create smoother weld beads.

4.1.6 Powdered Metals

The successful welding of powdered metals is generally a function of i) composition, ii) density and uniformity, and iii) manufacturing process of the powdered metal (PM). The composition limitations follow the above mentioned criteria. The density and uniformity, if not controlled, can result in weld porosity due to the presence of oil and other trapped contaminants (such as oxides) which vaporize through the molten material when welded. Typically, when the powdered metal density exceeds 97% of the solid material density, laser welding produces acceptable results. If the powdered metal density is between 93% and 97%, achieving acceptable results is extremely difficult. When laser welding powdered metals with densities less than 93%, it is almost impossible to achieve acceptable results. The powdered metal manufacturing process (e.g. nitrogen, water jet, or inert gas atomization) dictates the amount and type of material contaminants present within the powdered metal. The contaminants are typically organic substances such as water, oxides, carbon monoxide, and carbon dioxide. During welding, these contaminants vaporize (or dissociate and vaporize) and exhaust through the molten material, resulting in a porous weld.

Maximizing the weld melt zone has been one means which has been used to control the amount of weld porosity produced when welding powdered metals. Increasing the melt zone allows for a greater area and time for which the vaporized contaminants can exhaust through the molten weld zone. This minimizes the amount of vaporized contaminants that get trapped within the weld zone. The weld melt zone can be increased in several ways: i) use a longer focal length (increased focused spot size), ii) slow down the weld speed along with lower power, iii) create a relative angle between the focused laser beam and the weld joint (increases the relative spot size at the weld joint), and iv) scan the focused beam on the weld joint (increases the melt zone). Joint design also plays a role in exhausting vaporized contaminants. A butt joint configuration allows for a natural exhaust path (both up through and down through the molten weld pool), especially if there is a slight gap present (see *Section 4.3* for the maximum allowable gap for a butt joint configuration). Also, a butt joint configuration where the PM material is welded to weldable steel, either an offset toward the steel or welding at an angle (preference in the steel) may help reduce weld porosity. Overlap configurations, however, are more susceptible to weld porosity, especially if through penetration is not specified or possible. This leaves only one exhaust path (up through the molten weld pool), and therefore reduces the area through which the vaporized contaminants can exhaust.

4.2 Joint Fit

Laser welding is most often an autogenous process (with no filler material added). This is especially true for precision manufactured components for which fit-up is well controlled. Often times interference fits are specified which requires the components to be pressed together. Therefore it is critical that weld joint fit-up be intimate. The degree of fit-up required is dependent on primarily two parameters, the first being the required strength of the weld. The weld strength (either shear or tensile, static or fatigue) is generally a function of the weld cross-sectional area at the weld joint interface. A large gap will result in a reduced weld cross-sectional area, via undercut or voids, which decreases both the static and fatigue strength of the weld. As the joint gap increases, the volume of molten metal generated to bridge it decreases. Similarly, welding at high speeds, or welding with low power, decreases the volume of molten metal generated to bridge the gap.

The second parameter which influences fit-up requirements is the focused spot size (see *Section 2.3* for detailed discussion). A small focused spot cannot bridge a gap as well as a larger one because it produces a narrower fusion zone with less molten material. In addition, for a given laser, a small focused spot size implies a small depth of focus. A small focused spot size and small depth of focus renders joint location (both horizontal and vertical) a critical factor when considering tooling requirements and process sensitivity. A small focused spot size, on the other hand, will yield a faster weld speed for a given weld penetration.

Further, voids that result from reliefs, chamfers and fit-up gaps can only be filled by molten parent material. Therefore, increasing the size of any of these voids, reduces the weld fusion zone, and therefore weld strength. This is especially critical for transmission component welding, such as a hub and shell assemblies, where chamfers, reliefs and gaps must be minimized (see ***Figures 4.1, 4.2 & 4.3***).

Figure 4.1

GOOD FIT-UP VERSUS POOR FIT-UP

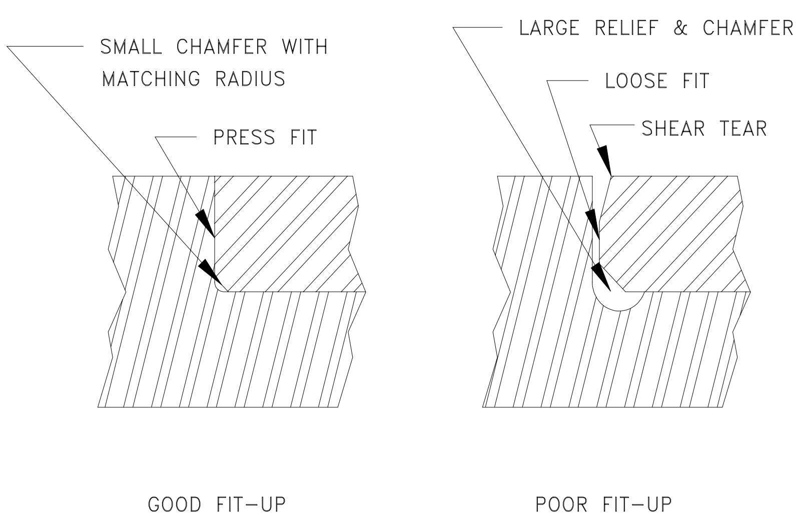


Figure 4.2

RESULTANT WELD WITH POOR FIT-UP

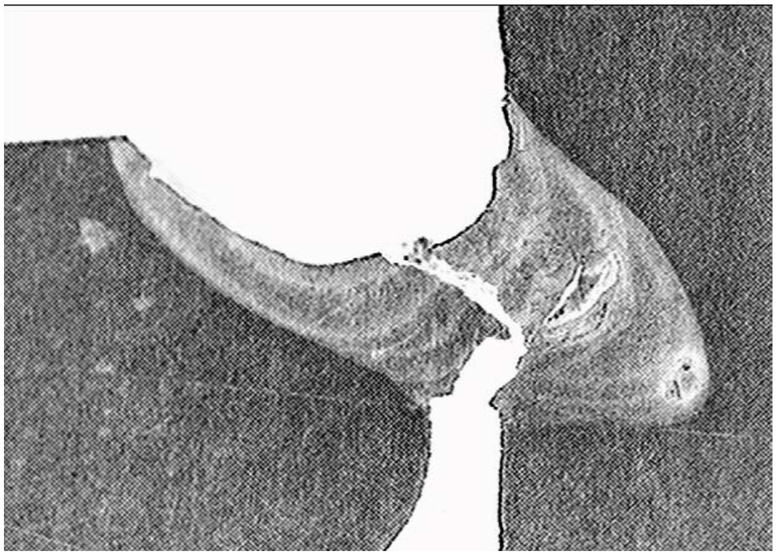
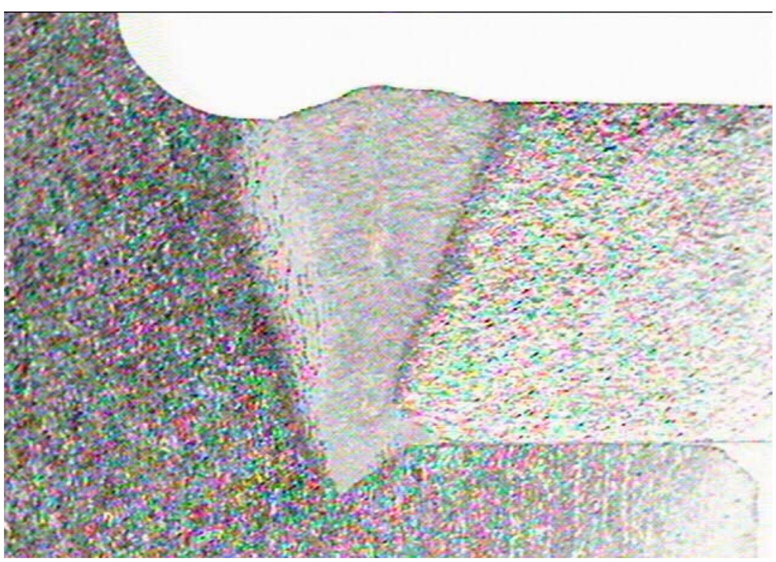


Figure 4.3

RESULTANT WELD WITH GOOD FIT-UP



4.3 Joint Geometry and Positioning Tolerances

It is evident that there are many factors which influence gap tolerances (see *Section 4.2*). However, the following guidelines on several typical joint geometries will help insure a joint design which is laser weldable.

4.3.1 Butt Joint

(***Figure 4.4, 4.7, 4.8, 4.9 & 4.10***)

Maximum gap (general rule: maximum 0.05-0.10 t of thinnest):	0.1 mm (0.004 inch)
Focus position:	± 0.25 mm (0.01 inch)
Vertical mismatch (general rule: maximum 0.01 t of thinnest): [1]	< 0.2 mm (0.008 inch)
Beam centerline to joint (general rule: max. 0.10 t of thinnest):	± 0.05 mm (0.002 inch)

[1]:Values apply for typical sheet metal welding applications (high speed, low power, shallow penetration). Vertical mismatch is dependent on speed and penetration.

4.3.2 Overlap Joint

(***Figure 4.4, 4.11 & 4.12***)

Maximum gap (general rule: maximum 0.10 t of top plate): [2]	0.1 mm (0.004 inch)
Focus position:	± 0.25 mm (0.01 inch)
Vertical mismatch:	Not applicable
Beam centerline to joint:	Not critical

[2]: Maximum gap is dependent on the degree of penetration into the second (lower) layer, weld bead width requirement, material type and welding speed. Full penetration welds can generally accommodate a larger gap, at the expense of undercut on the weld face.

4.3.3 Coach Joint

(***Figure 4.5***)

Maximum gap [3]:	0.125 mm (0.005 inch)
Focus position:	± 0.25 mm (0.01 inch)
Vertical mismatch:	± 0.50 mm (0.02 inch)
Beam centerline to joint:	< 0.15 mm (0.006 inch)

[3]: Assumes contact at a minimum of one point.

4.3.4 Standing Edge Joint

(***Figure 4.5***)

Maximum gap (see note [3] above):	0.125 mm (0.005 inch)
Focus position:	± 0.25 mm (0.01 inch)
Vertical mismatch:	± 0.25 mm (0.01 inch)
Beam centerline to joint:	< 0.10 mm (0.004 inch)

4.3.5 Edge Fillet Joint (Type #1)

(***Figure 4.6***)

(40-60 degree beam incident angle)

Maximum gap:	0.25 mm (0.01 inch)
Focus position:	Not Applicable
Vertical mismatch:	Not Applicable
Beam centerline to joint (lateral):	± 0.125 mm (0.005 inch)
Beam centerline to joint (vertical):	+ 0.0 − 0.25 mm (0.01 inch)

4.3.6 Edge Fillet Joint (Type #2)

(***Figure 4.6***)

(60-80 degree beam incident angle)

Maximum gap:	0.25 mm (0.01 inch)
Focus position:	Not Applicable
Vertical mismatch:	Not Applicable
Beam centerline to joint (lateral):	± 0.25 mm (0.01 inch)
Beam centerline to joint (vertical):	± 0.10 mm (0.004 inch)

Figure 4.4

BUTT JOINT AND OVERLAP JOINT

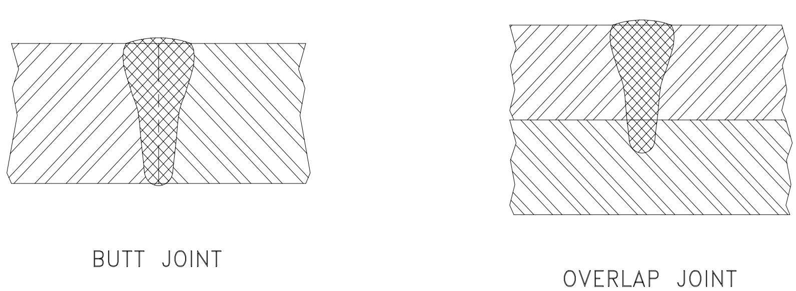
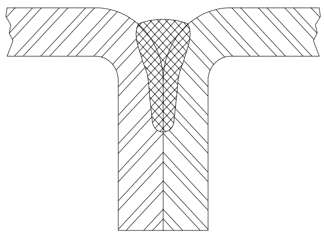
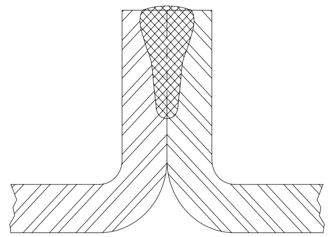


Figure 4.5

COACH JOINT AND STANDING EDGE JOINT



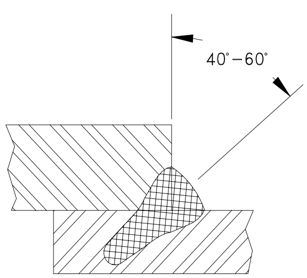
COACH JOINT



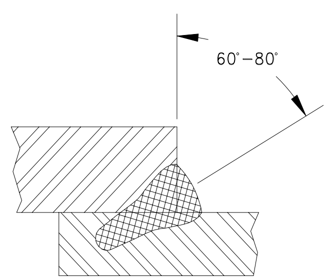
STANDING EDGE JOINT

Figure 4.6

FILLET JOINT (TYPE #1 AND TYPE #2)



EDGE FILLET JOINT (TYPE #1)



EDGE FILLET JOINT (TYPE #2)

Figure 4.7

UNDERCUT DUE TO GAP IN A BUTT JOINT

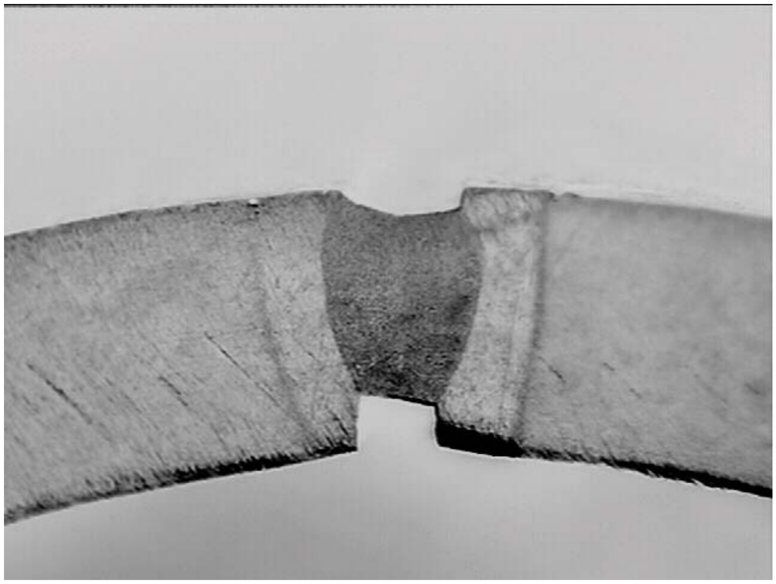


Figure 4.8

TAILOR BLANK BUTT WELD WITH GOOD FIT-UP

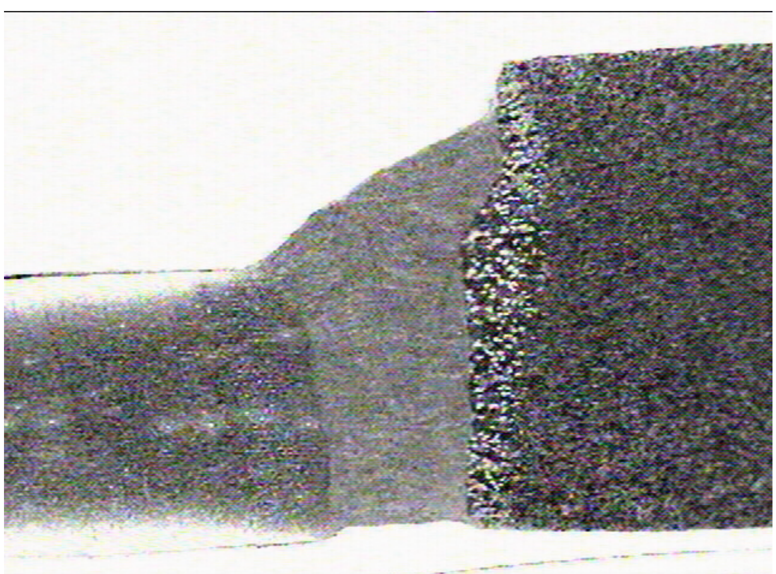


Figure 4.9

MISMATCH IN A BUTT JOINT

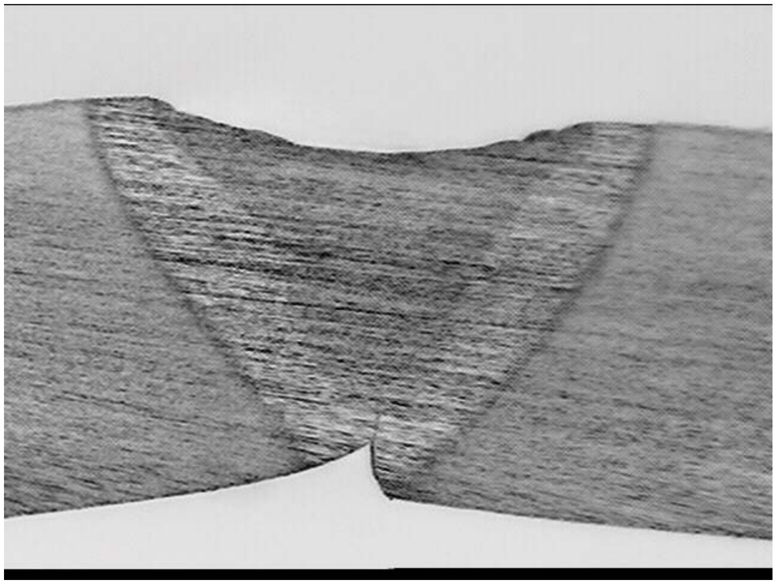


Figure 4.10

BUTT WELD WITH NO MISMATCH

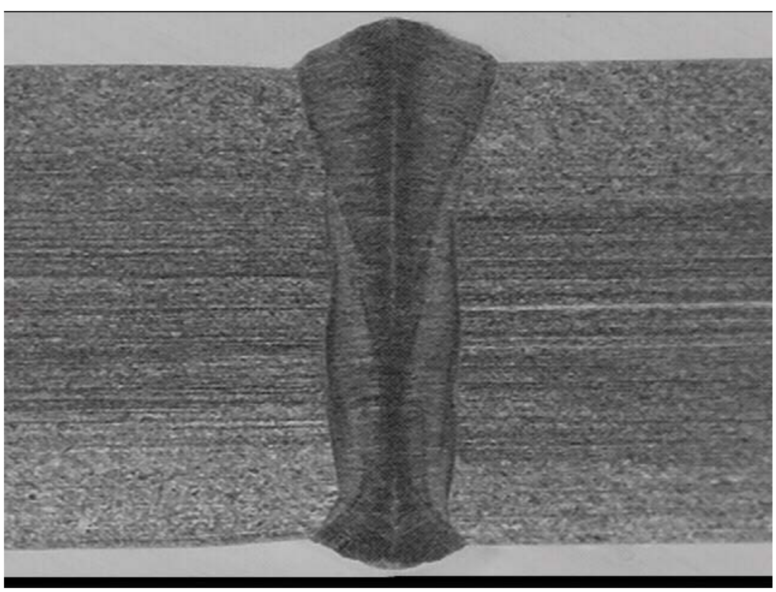


Figure 4.11

UNDERCUT DUE TO GAP IN AN OVERLAP JOINT

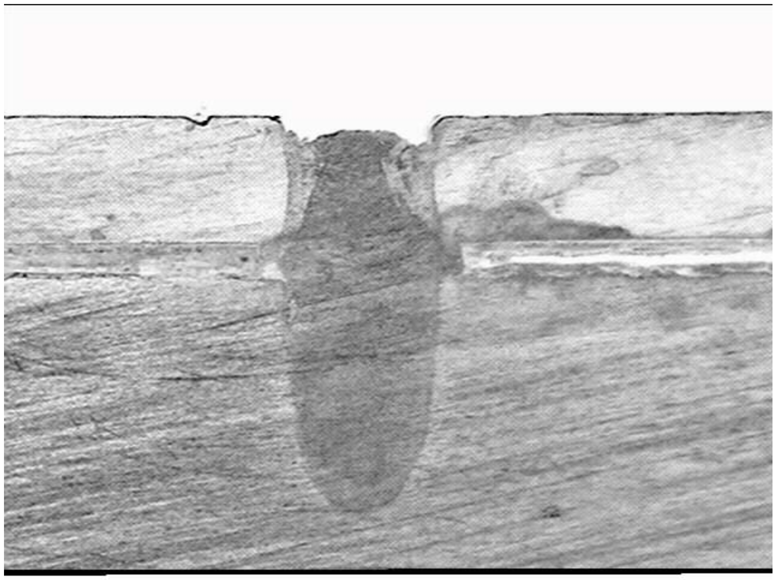
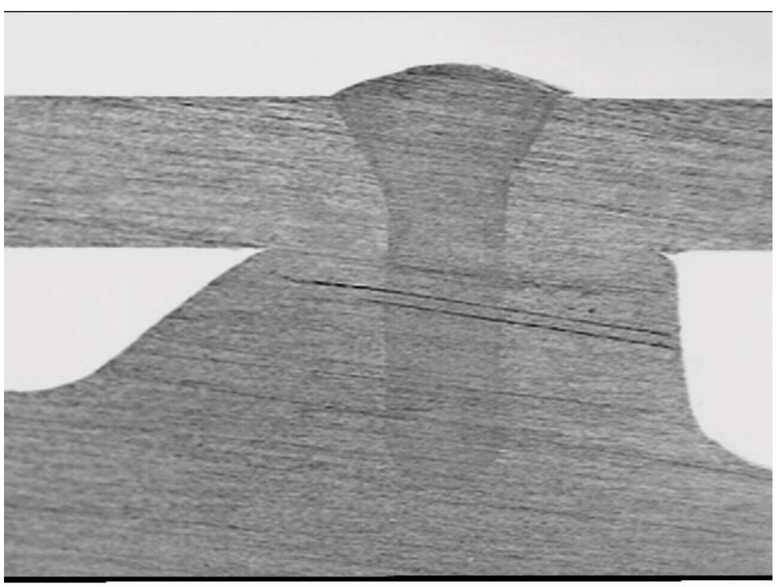


Figure 4.12

OVERLAP WELD WITH GOOD FIT-UP

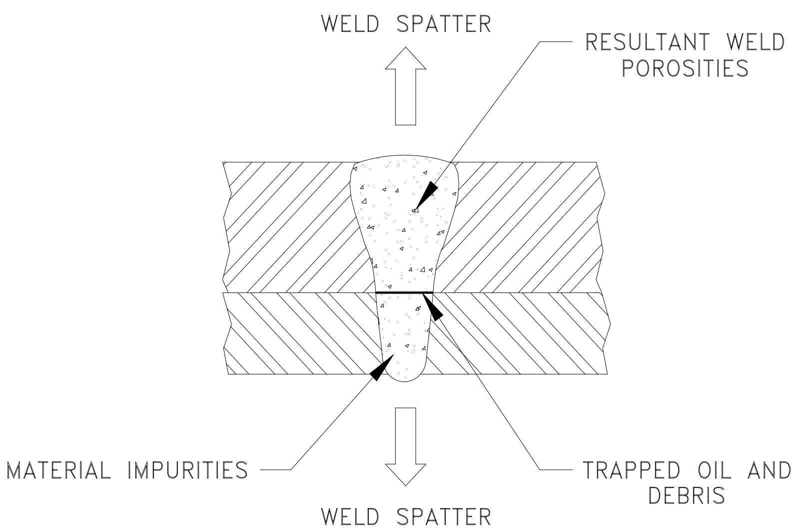


4.4 Joint Preparation and Cleanliness

Oil, grease, moisture, debris, rust and other gross contaminants which are present at the weld joint interface will vaporize when impinged by the focused laser beam and exhaust through the path of least resistance, namely the molten weld pool (***Figure 4.13***). The resultant weld may either be porous (with decreased weld cross-sectional area and an increased number of crack propagation sites) or may have an undercut, both resulting in decreased weld strength.

Figure 4.13

WELD SPATTER MECHANISMS



A further effect of weld joint contamination is weld spatter (molten metal exhausted with oil or debris vapor), which can increase the required focusing optic maintenance and decrease its life. Additionally, weld spatter can build-up on the shield gas nozzle and decrease shielding performance. Adjacent tooling, and spatter sensitive component surfaces, may also be adversely affected by weld spatter build-up. Refer to ***Figure 4.14***, where weld spatter on tooling for diamond saw blade welding causes a misalignment between the segment and the core.

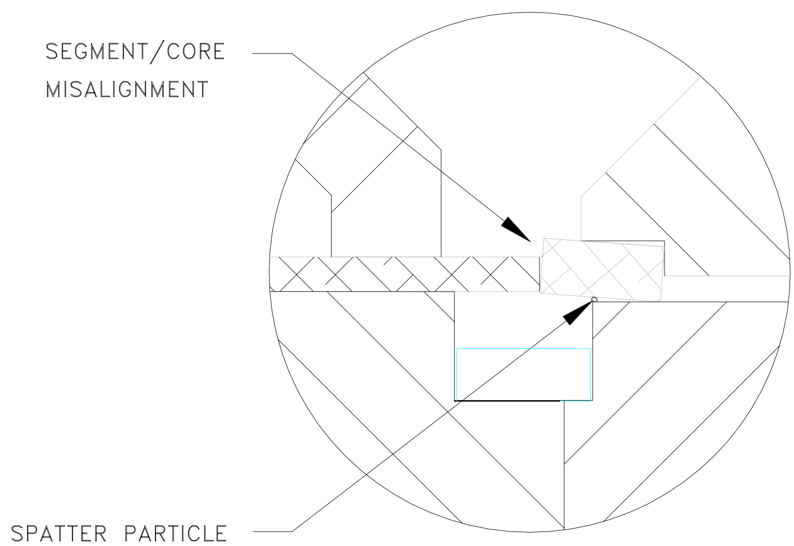
Material Handling
The packaging and handling of the components to be welded is critical. For components which are stored prior to welding, the packaging container should protect the components from ambient contaminants (such as dirt, dust, or oil). In addition, the packaging container should protect the weld joint (or area) from dings, scratches or dents. When loading components into the weld station, they should be handled with clean gloves, or at bare minimum clean and dry hands to reduce the chance of contamination into the weld area. Whether gloves or bare hands are used, the components should be handled away from the weld area whenever possible.

Cleaning Techniques
If oiled (e.g. machining oils or rust inhibitor) or contaminated components cannot be avoided, a cleaning processes may be required. The cleaning process may be as simple and inexpensive as manual cleaning, or as involved as solvent wash stations incorporating a hot water rinse and hot air dryers. Other cleaning techniques include electrolytic and ultrasonic methods. The required cleaning process depends primarily on the amount and type of contaminant. Metal parts cleaning solutions generally fall into the categories of i) aqueous (essentially soap and water), ii) semi-aqueous (solvent and water), and iii) solvent alone (bath or vapor systems). Note that some cleaning solutions (such as those which contain sulfates or phosphates) if not properly rinsed, may actually result in a high degree of weld spatter, and ensuing porosity in the weld. Even if the cleaning solutions are adequately rinsed off, the parts must be air dried before welding, because water in the weld zone will vaporize out through the weld pool, and cause the same problems as does the oil. The water used for rinsing the parts must be clean, with no additives such as a rust inhibitor, because water additives may form a residue on the components to be welded.

In general, non-contact cleaning methods are preferred because contact methods involving the use of wiper pads or brushes invariably leave residue (such as cloth or metallic particulate) in the weld area. However, the non-contact cleaning methods are generally more expensive than the contact methods, and some techniques, such as the electrolytic method, may have metallurgical effects on the material (i.e. embrittlement). If manual cleaning is used, a cleaning material that does not leave material fragments (e.g. cotton fibers) in weld zone must be used. Acetone or methanol may be used for manual cleaning. However (as is the case with any solvent or other fluid used for cleaning purposes), they must be used in light of the Federal, State & local legislation and regulations, the Material Safety Data Sheets, and in accordance with all precautions listed on the container label(s) concerning safe use and disposal of spent and/or soiled product and bi-products.

Figure 4.14

EXAMPLE OF NEGATIVE EFFECT OF SPATTER ON TOOLING FOR DIAMOND SAW BLADE WELDING



4.5 Part/Joint Location

The weld joint location is a function of primarily three factors: i) the manufacturing and assembly tolerances of the component assembly to be welded, ii) the contouring accuracy, repeatability and stability of either the beam and/or part manipulation, and iii) the repeatability, stability and accuracy of the part fixturing. The weld joint location must be held within a tolerance which is dependent upon several factors, a few of which are the depth of focus of the focused beam, laser power, weld speed, and joint geometry. If the weld joint location is not properly maintained, the result is either poor penetration (due to welding with a defocused beam) or poor weld joint cross-sectional area (due to welding off the joint).

Depth of focus, as described in *Section 2.4*, is typically defined as the range in which the focused spot diameter increases no greater than 5% (conversely, the range in which the power density decreases no greater than approximately 9.3%). As the depth of focus decreases, weld quality (maximum weld speed, depth of penetration, and the size of the heat affected zone) becomes more sensitive to part location (See ***Figures 4.15, 4.16 & 4.17***).

Additionally, a larger focused spot size results in a larger weld width, which is typically a more desirable weld nugget geometry for sheet metal lap welding, since weld fusion area increases with increased weld width, and not weld depth.

However, as the depth of focus and focused spot size increase (by increasing focal length for example), the maximum welding speed, at a given power and penetration requirement, decreases. Therefore, it becomes apparent that focused spot size, depth of focus, part location and weld nugget geometry all must be taken into consideration to insure welding results which adhere to the specifications of each application.

While an indicator may be used to track the relative motion of the weld joint, a visual inspection of the welded part will aid in determining whether or not the part location stability is adequate for high quality, consistent welding. Welding with a short focal length and highly focusable beam, at maximum weld speeds, requires joint location tolerances that can be as low as ±0.076 mm (±0.003 inch).

Note: *Although general guidelines can be followed for material selection, joint design and tolerances, and tooling design, the most important aid in determining laser welding feasibility begins in the laboratory. Up front welding of prototype components and assemblies is the best way of identifying feasibility, required material or part design changes, and significant tooling requirements.*

Figure 4.15

EFFECT OF FOCAL LENGTH ON SPOT SIZE & DEPTH OF FOCUS

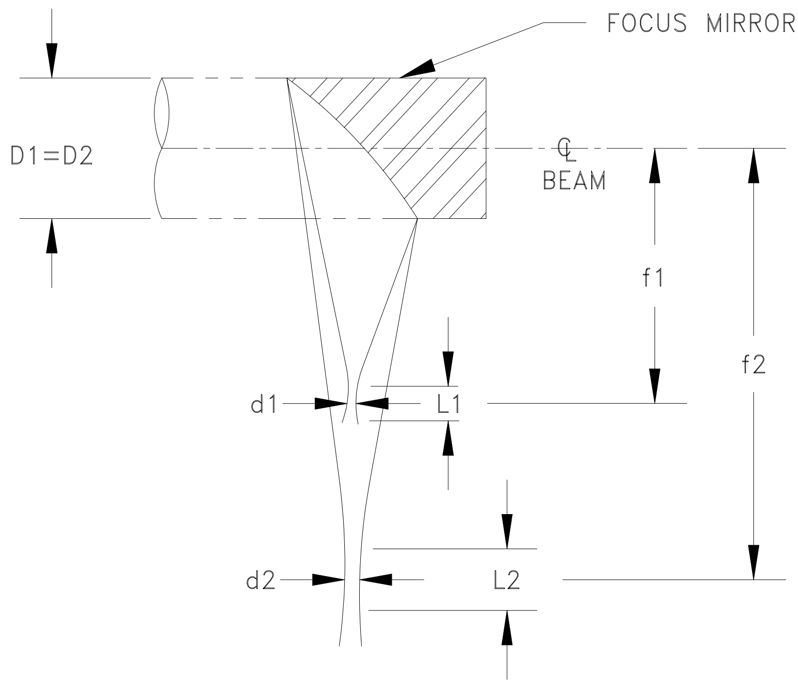


Figure 4.16

EFFECT OF BEAM DIAMETER ON SPOT SIZE & DEPTH OF FOCUS

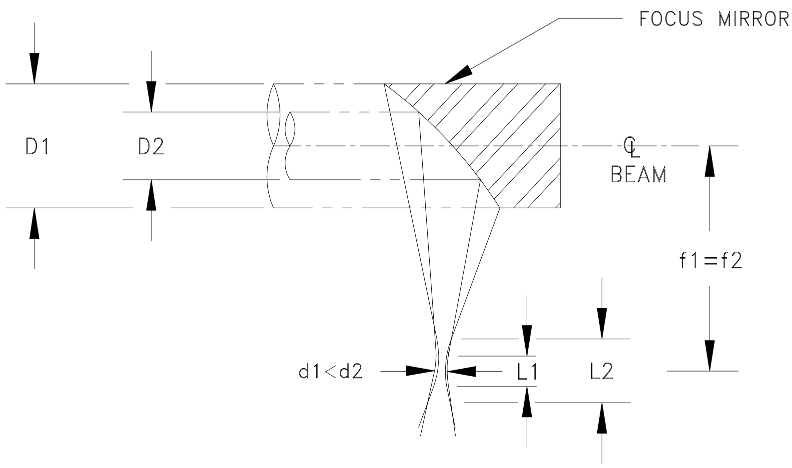
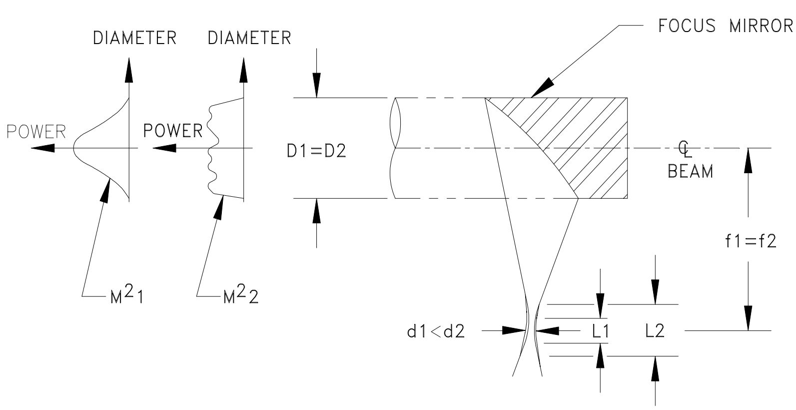


Figure 4.17

EFFECT OF LASER MODE ON SPOT SIZE & DEPTH OF FOCUS



4.6 Part Fixturing

Due to the relatively small focused spot size and depth of focus of the laser beam, accuracy and repeatability of production tooling must be carefully examined prior to implementation. Although laser welding produces less heat than conventional welding processes, it is a thermal welding process, and induces thermal distortion of the welded components which may result in gap formation during welding. A small focused spot diameter (as compared with a larger spot diameter) will reduce the total amount of energy required to produce a given weld penetration, and therefore reduce the associated thermal distortion. However, a small focused spot size requires more precise joint location (see *Section 4.5*). Therefore, a thorough review of potentially unacceptable thermal distortion specific to each application may be required. A careful review of *Section 4.3* will aid in determining tooling accuracy requirements. When considering component clamping, bear in mind the following factors:

a. The wear associated with repeatedly cycled tooling may result in weld joint fit-up gaps. Therefore, a wear resistant steel should be utilized to maximize tool life and insure proper part clamping and locating,

b. When clamping heat sensitive components, such as highly formed transmission components which may distort when residual forming stresses are relieved, design the clamps such that they provide a heat sink for the weld energy. Use the mass, surface area and location of the clamps to best utilize this capability. Water cooling of clamps may also be considered when this effect is critical. Additionally, when welding low mass to higher mass components, thermally induced gaps may result during welding. A high speed, low penetration weld or spot tack welds prior to the full penetration weld can keep these gaps, and the resultant undercut, to a minimum,

c. Avoid off-sets or force moments when designing clamp and fixture tooling. This will minimize unequal loading which may induce gaps at the weld joint,

d. Welding precision manufactured components which contain press fit weld joints simplifies part loading and fixturing requirements,

e. Allow for shielding nozzle access (including underbead shielding on through penetration welds), and for plasma suppression shielding as required, when designing clamping geometry, and

f. Allow for underbead and weld through clearance on fixturing designed for full penetration welding (butt and overlap style weld joints).

4.7 Shielding and Plasma Suppression

Laser welding, like arc welding, usually requires the use of an inert shield gas to provide protection against oxidation and atmospheric contamination. However, there are some cases (i.e. high speed, shallow penetration welding) in which shielding may not be critical. The most frequently used cover gases are helium and argon. Industrial or welding grade quality shield gas is all that is normally required for most welding applications. If industrial grade helium is used, care must be taken to insure that the shield gas is not used for the CO_2 laser gas, which requires high purity helium (the quality requirements for the helium used for Rofin-Sinar standard CO_2 lasers is 99.995% purity and a –90 °F (-68 °C) dew point). When welding titanium, however, higher purity shielding gas may be required, depending on the weld requirements.

Typically, the shield gas is directed centrally at the laser/material interface (refer to *Section 3.1.1* for a further discussion of shield nozzle configurations), and if an auxiliary tube design, directed toward the trailing weld (hot material). This will insure protection of the already solidified weld bead which may have sufficient temperature to oxidize. It also helps prevent oxide inclusions and resultant weld porosity and spatter. For high speed, shallow penetration welding, however, directing the shield gas toward the leading edge (cold material) allows for increased plasma suppression without disturbing the molten pool. Underbead shielding is recommended for full penetration welds. Finally, because of the higher density of argon, its shielding performance is subtly superior to that of helium.

Plasma Suppression

Unlike conventional welding processes, the shielding gas used for CO_2 laser welding has two functions, both protection from oxidation & atmospheric contamination, as well as, plasma suppression. For Nd:YAG laser welding, the shorter laser wavelength results in much less power absorption in the plasma and therefore plasma suppression becomes uncritical. For Nd:YAG welding applications, usually argon is used for shielding because: a) its relatively inexpensive, b) it provides excellent protection against oxidation and atmospheric contamination, and c) it posses no plasma suppression concerns.

Although argon is successfully used in many CO_2 laser production systems, especially in Europe where there is a significant price differential between argon and helium, it can be a very sensitive shielding method in terms of nozzle design and flow geometry. Argon, because of its low ionization potential of about 15.7 eV (i.e. requires less energy to ionize than does helium, which has an ionization potential of about 24.5 eV), has an affinity to enhance plasma formation of the metal vapor above the weld pool. This resultant plasma is much more intense than the plasma formed when utilizing helium as a shield gas and can absorb a vast amount of the laser power. This not only impedes the energy from reaching the workpiece, but also augments the effect by forming more plasma. Helium, however, may also form significant plasma when used with high power lasers or with high focused spot energy densities.

Shield gas nozzle design and flow geometry are critical parameters for the successful implementation of argon for CO_2 welding applications. The basic criterion is to provide a jet of high velocity argon across the molten metal, while simultaneously insuring the argon does not reach a volume and temperature at which plasma formation is imminent. Generally, the greater the power density of the focused beam, the higher the shield velocity required to suppress plasma formation. With laser powers greater than 10 kW, plasma suppression with argon becomes extremely limited in that the high shield velocity required is likely to result in unacceptable displacement of the molten metal. Typically, the flow rate of argon (30-45 l/m (66-100 scfh)) required is almost twice that of helium (20-30 l/m (44-66 scfh)) for adequate plasma suppression.

Further, since it is crucial to minimize the volume and temperature of the argon at the weld zone, any clamping that would impede the flow of argon, such as slotted clamps, may reduce its effectiveness of suppressing plasma formation. Helium, on the other hand is relatively insensitive to nozzle design and flow geometry. Therefore, when shielding with argon or when shielding with helium under high focused spot energy conditions, more critical plasma suppression techniques may be required.

Auxiliary Shielding
In some cases, auxiliary shielding may be required to insure oxide free welds. This usually demands an inert environment while the weld is cooling. The entire weld enclosure can be purged with an inert gas such as helium, or more localized protection devices can be used. Note that argon, because of its low ionization potential, should not be used for enclosure purging for high power density welding. A localized inert shroud (i.e. protecting several inches of the weld during cooling) can be used. This can be installed directly downstream of the weld point, and should be made as long as practical. Depending on the weld power and the duty cycle (i.e. welding of roll formed tubing is 100% duty cycle), water cooling of the inert shroud device may be required.

4.8 Focus Position

Optimum focus position is dependent on weld joint geometry (type, orientation, gap and mismatch) and weld strength requirements (penetration, bead width and material bias). The optimum focus position is typically that which yields the maximum penetration for butt joint configurations or the maximum weld width at interface for lap weld configurations. One technique which can be used to determine the weld focus position is to adjust the focal position until weld coupling ceases in both directions and set the final focal position to the average of that range.

If the weld width for a focus position which yields maximum weld penetration (at a given maximum speed) is not sufficient, using a longer focal length, rather than defocusing, is the preferred method of increasing weld width. Both methods equally reduce weld speed (for a required weld penetration), however a longer focal length provides a longer depth of focus, provides an equal reduction in power density on both sides of the focused spot, and positions the focus optic further away from the weld spatter. If, however, defocusing is utilized, the defocus distance (z) can be calculated by knowing the required defocused spot diameter (d_z), the focused spot diameter (d), the wavelength of the laser (λ), and the beam quality (M^2) by using the following equation (*see also Section 2.3*):

$$\boxed{z = \pi d[(d_z)^2 - d^2]^{1/2}/4M^2\lambda}$$

Example 4.8A: Refer to *Example 2.3.1*. If a 1.5 mm (0.06 inch) spot diameter is required, then $z = (3.14)(0.37)[(1.5)^2-(0.37)^2]^{1/2}/(4)(5.5)(0.0106) = 7.2$ mm (0.29 inch). *See also Example 4.8B.*

Rearranging this equation, defocus spot diameter can be calculated directly as follows:

$$\boxed{d_z = d\,\{1 + (4M^2\lambda z/\pi d^2)^2\}^{1/2}}$$

Example 4.8B: Using *Example 4.8A* above, and having a 7.2 mm (0.29 inch) out of focus condition, $d_z = (0.37)\{1+((4)(5.5)(0.0106)(7.2)/(3.14)(0.37)^2)^2\}^{1/2} = 1.5$ mm (0.060 inch).

Although focused spot diameter increases with increasing focal length (accounting for the decreased welding speeds), the depth of focus also increases, yielding a focal geometry, and therefore focal position, which is more forgiving with respect to part location (refer to *Section 4.5*).

Table 4.1

COMPARISON OF SHIELD GASES USED FOR LASER WELDING

TYPE	PLASMA SUPPRESSION w/ CO_2 LASERS [1] (ionization potential)	PROTECTION AGAINST OXIDATION	RELATIVE COST	TYPICAL FLOW RATES [2] (w/ diffuser nozzle)	WELD PROFILE	LIMITATIONS
Helium	Excellent (24.5 eV)	Good	High	20-30 l/min (44-66 scfh)	Deepest	none
Argon	Lower P_d's only (15.7 eV)	Excellent	Medium	30-45 l/min (66-100 scfh)	Wide	Lower P_d's, nozzle alignment & flow rate critical
Nitrogen (O_2 free)	Lower P_d's only (15.5 eV)	Good	Low	30-45 l/min (66-100 scfh)	Deep	Lower P_d's, embrittlement in certain steels
CO_2	Lower P_d's only (14.4 eV)	Poor	Lowest	30-45 l/min (66-100 scfh)	Nominal	Not good for reactive materials (Ti, Cr-Ni steels), slight oxidation of weld surface
He + Ar mix (20% He min.)	Good	Very Good	Medium	25-35 l/mi (55-77 scfh)	Nominal	He % must increase w/ P_d up to about 50%

[1] The role of plasma suppression for Nd:YAG lasers is negligible due to the different wavelength which appears to limit plasma formation.
[2] Coaxial nozzles and straight tube off-axis nozzles (w/ diameters of about 4-6 mm (0.16-0.24")) require somewhat less flow, perhaps 25-50% less.

4.9 Weld Spatter Protection

The welding process is adversely affected by weld spatter build-up on the focus optic. As weld spatter and debris accumulate on the optical surface of the focusing mirror or lens, an associated increase in power absorbed by the optic and subsequent thermal distortion can greatly reduce weld penetration. As presented in *Section 4.4*, weld zone contamination is one source of weld spatter. In addition, materials with high impurity levels or those with highly volatile constituents (such as lead and sulfur) can be sources for further weld spatter production. Weld joint geometry can also play a role in the amount of molten material expelled from the weld zone. For example, welding a moderately oiled three material stack-up without full penetration through the third layer, yields a condition in which there exists two potential sites for trapped oil to accumulate with only one primary path for spatter expulsion, namely up through the weld zone, and directed at the focusing optic. On the other hand, a two layer overlap weld with through penetration has only one source of trapped oil, while having two primary expulsion paths, both up through the top of the weld and down through the bottom of the weld. This not only minimizes the total amount of spatter produced, but also reduces the amount expelled toward the focusing optic.

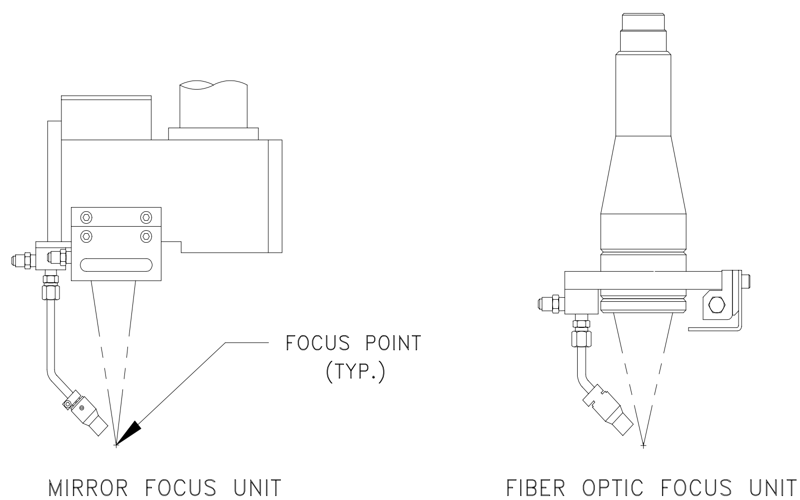
Although weld spatter has many different sources and potential expulsion rates, the primary concern is its rate of adhesion on the focusing optic. The amount of weld spatter that adheres to the focusing optic is primarily dependent on focal length. The closer the focusing optic (or cover slide) is to the source of the spatter, the greater the adhesion rate, and the more likely there will exist subsequent thermal-mechanical damage to its optical surface.

There are a couple of typical approaches used to address this issue. Focus devices (see ***Figure 4.18***) can be equipped with a cross jet air knife. This device provides a plane of air in front of the focus optic, and prevents molten weld spatter from collecting on it. While lighter particles are blown away, heavier particles of molten metal which manage to pass through the air jet will typically be cooled and will solidify, minimizing any potential damage to the optical surface. Also, the optical surface of copper mirrors can be coated with a protective metal. Coated mirrors have two advantages over pure copper mirrors. First, the higher melting point of a protective metal minimizes the potential thermal damage caused by molten weld spatter. Second, the protective metal has a higher abrasion resistance which minimizes potential mechanical damage caused by routine surface cleaning.

In addition, Nd:YAG laser welding using a fiber optic beam delivery and a lens focus module can be equipped with a cover slide. A cover slide is a low cost, disposable transmissive element which prevents spatter from damaging the much more costly focusing optic.

Figure 4.18

EXAMPLES OF FOCUSING DEVICES



4.10 Weld Parameters

An important asset of laser welding is the high level of control which is available over the variables affecting the process. The weld geometry can be tailored to meet requirements of the job and the results can be readily duplicated. The principle parameters are as follows.

4.10.1 Power and Power Density

Lasers are rated by their power output in terms of Watts. Since laser welding is a thermal process, the amount of heat produced is related to its capabilities. Given all other considerations being equal (e.g., power distribution, spot size, etc.), increased power allows for faster processing speeds and the ability to weld deeper. As discussed previously, power density combined with a materials ability to couple with the wavelength of the laser, are the key parameters in determining weld penetration and weld speed. Refer to *Sections 2.3, 2.5, 3.4, 3.5 and 3.6* for a detailed discussion of the parameters affecting power density.

Power density also influences the vaporization of volatile material constituents. Constituents that vaporize at a given relatively high power density (resulting in porosity and/or undercutting, and weld spatter) may not vaporize at a lower power density. Defocusing of the focused beam relative to the weld joint can be used to show if lowering power density reduces vaporization potential. It must be noted, however, that reducing power density (via either defocusing or using a longer focal length focusing optic) must be accompanied by a lower weld speed or a higher weld power, or both. A longer focal length optic is much preferred over defocusing because a longer depth of focus is associated with a longer focal length (refer to *Section 2.4* and ***Figure 4.15***).

4.10.2 Speed

Laser welding speeds have been found to fit empirical formulas based on the available laser power, focused spot size, properties of the material to be welded, weld joint geometry, and shield gas type and optimization (especially for high power density keyhole welding). Above a threshold amount, the speeds are directly proportional to available power density. This takes into account the laser's performance features (e.g. power and mode) in addition to the focusing system's characteristics (e.g. spot size). Given that all other parameters are constant (within process limitations), welding speed (or weld penetration) will increase with:

a) additional power (1500 Watts vs. 600 Watts),
b) improved beam quality (TEM_{00} vs. TEM_{20}), and
c) smaller focused spot size (125 mm vs. 200 mm F.L. focusing optic).

For CO_2 lasers, power (P) per unit spot size (d) is approximately proportional to the welding speed (V). Therefore, power divided by the product of speed and spot size is approximately constant, as follows:

$$P/dV \cong \text{constant}$$

$$\boxed{\mathbf{\{P/dV\}_1 \cong \{P/dV\}_2}}$$

Example 4.10.2: If it is known that a 3.0 mm (0.12 inch) weld penetration can be attained on mild steel with a certain laser at 4.5 m/min (177 in/min) with 6000 Watts, *approximately* what weld speed would be required with the same laser and beam delivery (i.e. $d_1 = d_2$) at 4000 Watts in order to obtain the same weld penetration? Rearranging the above yields $V_2 \cong (P_2)(V/P)_1 = (4000)[(4.5)/(6000)] = 3.0$ m/min *(2.9 m/min actual).*

4.10.3 Focal Length

Since welding speed is a function of available power density, the choice of the focal length of the focusing optic has a great impact on the resulting weld geometry and process requirements. The imaging of a laser beam for welding is accomplished with either focus mirrors or transmissive lenses of focal lengths usually ranging from about 2.5 to 10 inches (6.3 to 25.4 cm). Because the focused spot size is proportional to the focal length, the power density that is produced is proportional to the square of that length. Short focal lengths give very high energy densities, but are limited in their application due to a shallow working depth. However, they are appropriate for use where the weld joint can be held within the depth of focus of the focused beam and if little or no weld spatter is produced. Longer focal lengths yield larger spot sizes and therefore have lower power densities, but are able to maintain those densities over a much broader range. Therefore, longer focal lengths can be used when joint location is less repeatable, provided that there is a high enough energy density to couple with the material.

4.10.4 Tack Weld

When welding low mass to higher mass components (especially on round part welding), thermally induced gaps may result during welding. A high speed, low penetration weld or spot tack welds prior to the full penetration weld can keep these gaps, and the resultant undercut, to a minimum.

4.10.5 Ramping

Ramping power or speed is desirable, especially at the end of a weld, to minimize the localized undercut resulting from the collapse of the keyhole. Typical ramp up schedules increase the laser power from simmer (or low power) to weld power within 0.0-0.2 seconds (zero ramp up time can be accomplished simply by opening the shutter, with the part or focus device in motion, when the laser is already at weld power). Typical ramp down schedules decrease the laser power from weld power to simmer (or low power) within 0.3-0.5 seconds. Ramp down must be long enough to yield a satisfactory keyhole collapse, while being as short as possible to minimize weld cycle time.

4.10.6 Overlap

Weld overlap, especially on round part welding, is usually required for three reasons. First, weld joint designs are normally based on ***full*** 360 degree welds. Second, in order to minimize the undercut resulting from the collapse of the keyhole, ramping is required, and ramping should only occur after a full 360 degree weld has been made. Third, to insure a full 360 degree weld has been made, typically a 3-5 degree overlap is recommended. However, the value used must allow for process control tolerances (ramping times, degrees of rotation, spindle speed, communication delays, etc.) and therefore may be higher.

4.10.7 Weld Angle

As discussed in *Section 2.5*, a weld angle is employed only if the result of the beam being normal to the weld joint would result in beam clipping on any part of the component assembly or adjacent tooling. A beam angle increases the spot area at the surface of the part, and therefore decreases the relative power density, and thereby weld penetration at a given weld speed. Therefore, a beam weld angle should be avoided whenever possible, and minimized when required. The minimum beam angle in degrees (ϑ; which is measured relative to normal to the surface), is dependent on the focal length of the focus optic (f) and diameter of the raw beam at the focus optic (D). The minimum angle required in order to insure the focused beam clears the edge of a mating component (in a butt weld configuration, see ***Figure 4.19***) which has a thicker section, can be calculated from the equation below (which is the half angle of the focused beam plus one degree of clearance). **Note that the clear aperture diameter of the focus unit can be used in place of the raw beam diameter to allow for laser beam misalignment.**

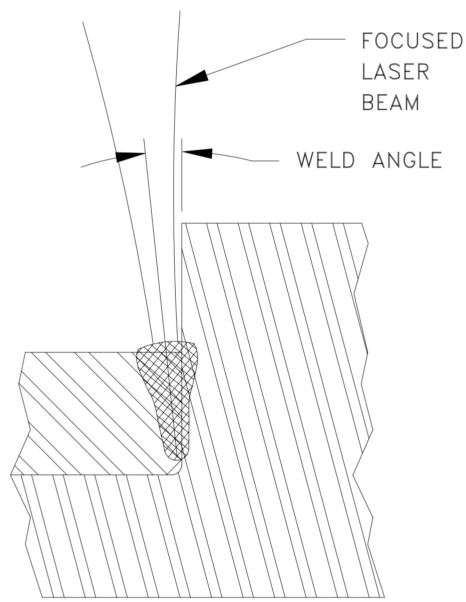
$$\boxed{\vartheta_{min} = \{\tan^{-1} [D/(2f)]\} + 1}$$

<u>Example 4.10.7A:</u> If welding with a 25 mm diameter raw beam at the focus optic and with a 175 mm focal length, what beam angle would be required to avoid clipping on an offset weld joint? Substituting yields $\vartheta_{min} = \{\tan^{-1} [25/350]\} + 1 = 4.1 + 1 = 5.1^\circ$ or about 5°. *See also Example 4.10.7B.*

<u>Example 4.10.7B:</u> If welding with a 45 mm diameter raw beam at the focus optic and with a 200 mm focal length, what beam angle would be required to avoid clipping on an offset weld joint? Substituting yields $\vartheta_{min} = \{\tan^{-1} [45/400]\} + 1 = 6.4 + 1 = 7.4^\circ$ or about 8°. *See also Example 4.10.7A.*

Figure 4.19

WELD ANGLE TO AVOID CLIPPING



4.10.8 Pulsing

When considering laser welding applications (especially Nd:YAG), two primary sub-categories are immediately evident, namely pulsed and continuous wave (CW) applications. A laser which pulses typically produces a beam in the form of a very short, intense burst of energy, while a CW laser produces a beam of constant, steady state power. The primary considerations between pulsed and CW have to do with either product limits (i.e. pulsed vs. CW capability on a given laser) or process limits (focused spot power density requirements for a given application), or both. While there is some overlapping of applications, there are specific areas where either a pulsed laser or a continuous-wave (CW) laser is more suitable.

Pulsing implies that the laser's active medium is excited by a very quick response stimulus. This allows the laser to transmit a burst of energy for a brief length of time (generally in terms of milliseconds). Two types of pulsing are available: normal and superpulse. In normal pulse operation, the current is switched on and off, resulting in a pulsed output for CW lasers in which the peak pulse power is approximately equal to the set CW power. Peak pulse powers for pulsing Nd:YAG lasers can reach values of over 30 times greater than the maximum average power levels. This allows low-to-medium power lasers to achieve enough energy to reach vaporization temperatures for most materials. With superpulse operation of CO_2 lasers, higher amplitude shorter pulses are generated to excite the lasing medium, resulting in peak powers 2-5 times the set CW power.

In some lasers, superpulse schedules can be used in combination with CW power (see *CW Welding Comparison* below). Pulse shaping is also available on some lasers, and can be used to create unique pulse shapes that either enhance coupling efficiency or reduce weld bead roughness, or both. The short duration pulse produced by a pulsable laser guarantees minimum heat input, which is particularly important for parts sensitive to distortion. However, pulsing action slows down welding speeds since duty cycles (the percentage of time that the laser is emitting energy during a weld) are less than 100%. Most welding applications require that the pulses overlap to produce a pseudo continuous, and sometimes hermetic, weld.

CW Welding Comparison

Continuous-wave lasers maintain their output over the entire span of processing (100% duty cycle). The main advantage of CW operation is that there is a greater amount of power per unit time. This generally leads to faster welding speeds than those for the pulsed mode. In some lasers, pulse (or superpulse) schedules can be used in combination with CW power (with perhaps some reduction in pulse peak power, depending on CW power level). The combination of the two can be used for weld seam smoothing (especially on aluminum).

Keyhole welding is dependant on focused spot power density (i.e. laser power and focused spot size), welding speed, material melting temperature, material reflectivity, material conductivity, and the like. In general, CW keyhole welding of steels and stainless steels is possible above 600 watts. For materials such as aluminum and copper, keyhole welding is generally not possible in the CW range below 1000 Watts.

Conduction welding is possible when the absorbed energy is sufficient to melt the weld zone, but insufficient for vaporization and plasma formation. CW conduction welding of steels and stainless steels at low power typically requires a relatively small focused spot (in the range of 250-300 μm) in order to obtain efficient coupling of the energy into the weld joint. In general, CW conduction welding of steels and stainless steels is possible down to about 100 or 200 Watts, while CW conduction welding of materials such as aluminum and copper is only possible to about 500 Watts. In general, conduction welds require higher heat input, which results in a wider weld and makes oxide free welding more difficult to obtain.

Frequency and Overlap

If a pulsed laser is utilized, then pulse rate in Hz (f), average weld spot diameter (d_w – see ***Table 4.2***), and weld speed (V- distance per second) have to be matched to produce the required percent overlap (%OL). The typical %OL values for both hermetic and non-hermetic welds are indicated below. For non-hermetic welding, the lower %OL allows for faster weld speeds, but weld beads can have a rough surface. In general, the larger the %OL, the smoother the weld, but the slower the weld speed. The following relationships may be helpful, especially for Nd:YAG applications where frequency is a limiting factor (about 1000 Hz maximum compared to about 10 kHz for CO_2 lasers):

Overlap = $d_w - V/f$ *(ignoring oblong effect due to travel)*

%OL = $100[(d_w - V/f)/d_w]$, and rearranging yields

$$\boxed{f = 100V/(d_w)(100\text{-}\%OL)}$$

For hermetic welds:	*75 < %OL < 80*
For typical non-hermetic:	*50 < %OL < 70*

$$\boxed{f = 5V/d_w}$$

(for %OL = 80)

Example 4.10.8A: For a weld speed of 100 mm/sec and an average weld spot diameter of 1.5 mm, a frequency of 333 Hz is required for a hermetic weld (80%OL), and a frequency of 167 Hz is required for a 60% overlap. *See also Examples 4.10.8B & C.*

The average weld spot diameter is not a trivial issue, because no weld profile is perfectly parallel. Therefore, the appropriate weld spot diameter must be carefully considered. ***Table 4.3*** gives some recommendations that should be considered when determining the appropriate value of d_w.

Table 4.2

RECOMMENDED VALUES FOR d_w

Weld Joint Configuration	**Recommendations** d_w ***Standard***	d_w ***Conservative***
Overlap Weld	0.9 x average weld width @ interface	focused spot size
Butt Weld *(full penetration)*	focused spot size	0.9 x average weld width @ root
Butt Weld *(partial penetration)*	focused spot size	0.9 x average weld width @ 90% weld depth

Example 4.10.8B: Calculate the pulse frequency required to produce a hermetic pulsed weld on an overlap weld joint configuration, using a weld speed of 30 mm/sec and an average weld width at interface of 1.0 mm. First, calculate d_w using the "Standard" recommended value from ***Table 4.2***, d_w = 0.9 (1.0)= 0.9 mm. Next, substituting into f **= 5V/d_w** yields: $f = (5)(30)/(0.9) = 167$ Hz.

Excursus 2
Overlap Including Travel Affects

If either the beam or part are traveling, a laser pulse at the part becomes an oblong weld spot. In order to account for this effect, the pulse length (t_{on}) must be considered as follows:

$$OL + (V/f) = d_w + (V)(t_{on}), \text{ therefore:}$$

$$OL = d_w + (V)(t_{on}) - (V/f)$$

$$\%OL = 100\{OL/[d_w + (V)(t_{on})]\}, \text{ substituting for OL yields:}$$

$$\%OL = 100\{[d_w + (V)(t_{on}) - (V/f)]/[d_w + (V)(t_{on})]\}$$

$$(\%OL)(d_w) + (\%OL)(V)(t_{on}) = (100)(d_w) + (100)(t_{on}) - (100)(V/f)$$

However, since frequency (f) is equal to $\{1/(t_{on} + t_{off})\}$ and duty cycle (D_c) is equal to $\{t_{on}/(t_{on} + t_{off})\}$, then t_{on} can be seen to equal (D_c/f). Substituting this into the above yields:

$$(\%OL)(d_w) + (\%OL)(V)(D_c/f) = (100)(d_w) + (100)(D_c/f) – (100)(V/f),$$

rearranging and solving for (f) results in:

$$f = [(\%OL)(V)(D_c) - 100D_c + 100V]/[100d_w – (\%OL)(d_w)], \text{ or}$$

$$f = (V/d_w)\{[D_c(\%OL - 100) + 100]/(100 – \%OL)\}$$

If we set %OL to 80%, which would be typically required for hermetic welding applications, then this relationship reduces to the following [compare with ($f = 5V/d_w$) as shown above]:

$$f = V\{[D_c(80 - 100) + 100]/[d_w (100 – 80)]\} = V\{[100 - 20D_c]/20d_w\}$$

$$f = V\{[100 - 20D_c]/20d_w\} = V\{20(5 - D_c)/20d_w\}$$

$$f = V(5 - D_c)/d_w$$

Example 4.10.8C: For a weld speed of 100 mm/sec, an average weld spot diameter of 1.5 mm, an overlap of 80% and a duty cycle of 0.5 (50%), then f = 100(5 – 0.5)/1.5 = 300 (compared with a frequency of 333 Hz if travel is ignored see *Example 4.10.8A*).

Pulse Energy
In pulsable CO_2 and Nd:YAG lasers, energy per pulse, peak power per pulse and pulse width (i.e. laser pulse "on" time) are key weld parameters. Energy per pulse in Joules (E_p) is related to the average laser power (P_{ave}) and pulse rate (f) by the following:

$$\boxed{\mathbf{E_p = P_{ave}/f}}$$

Peak Power
Peak power per pulse (P_p) is the ratio of energy per pulse to pulse width in seconds (t):

$$\boxed{\mathbf{P_p = E_p/t}}$$

Note also:

$$P_p = E_p/t = E_p/t_{on} = (P_{ave}/f)/t_{on} = \{P_{ave}/(1/(t_{on}+t_{off}))\}/t_{on} = P_{ave}\{(t_{on}+t_{off})/t_{on}\} = P_{ave}/D_c$$

For a given energy per pulse, short pulse width times yield high peak powers. When peak power gets too high, the resultant weld can have either undercutting or voids (or both). This occurs because the high peak power results in a high power density per pulse, which can vaporize material constituents out of the molten weld pool that at lower power densities would remain molten (refer to the ***General Guidelines for Normal Pulse Welding Applications*** below). In general, high peak powers produce welds via keyholing, resulting in deeper weld penetration and less overall heat input into the component being welded. On the other hand, the deep and narrow keyhole welds require better part fit-up. If hermetic welds are required, the weld speed may suffer due to the smaller molten spot diameter and because high peak powers occur at lower frequencies (especially for Nd:YAG lasers).

Pulse Width
Long pulse width times yield low peak powers and produce welds via conduction which geometrically tend toward wide and shallow. This geometry is more tolerant to part fit-up, and is also beneficial when overlap welding a thin component onto a thicker component (e.g. diaphragm welding). However, low peak power densities result in greater overall heat input into the welded component, and can yield severe back reflections off the weld joint.

<u>Example 4.10.8D:</u> Calculate the peak power per pulse of a weld utilizing 5 Joules and a 2 ms pulse width. Since peak power is defined as the ratio of energy per pulse to pulse width, then peak power = 5/.002 = 2,500 Watts. To calculate peak power density per pulse, simply divide this value by the area of the focused spot.

4.10.8.1 General Guidelines for Normal Pulse Welding Applications

General guidelines for pulsed welding are difficult to compose because of the interaction between many parameters (e.g. power, focused spot size, weld speed, weld joint geometry, weld joint fit-up, material characteristics, and so on). However, two general situations are worthy of comment, namely adjustment of parameters for increasing or decreasing weld penetration, while minimizing weld spatter. The guidelines below, in combination with ***Table 4.3*** and ***Figure 4.20***, will aid in process parameter determination for Nd:YAG pulsed welding applications.

I. Inadequate Weld Penetration:

   a. With weld spatter expulsion caused by peak power:
      Guideline: Increase pulse width.

   b. Without weld spatter expulsion:
      Guideline: Increase peak power by decreasing pulse width keeping energy per pulse constant.

II. Excessive Weld Penetration:

a. With weld spatter expulsion caused by peak power:
Guideline: Increase speed (and pulse frequency to keep overlap constant), and/or reduce pulse energy by reducing peak power.

b. Without weld spatter expulsion:
Guideline: Increase speed (and pulse frequency to keep overlap constant), and/or reduce pulse energy by reducing pulse width.

Table 4.3

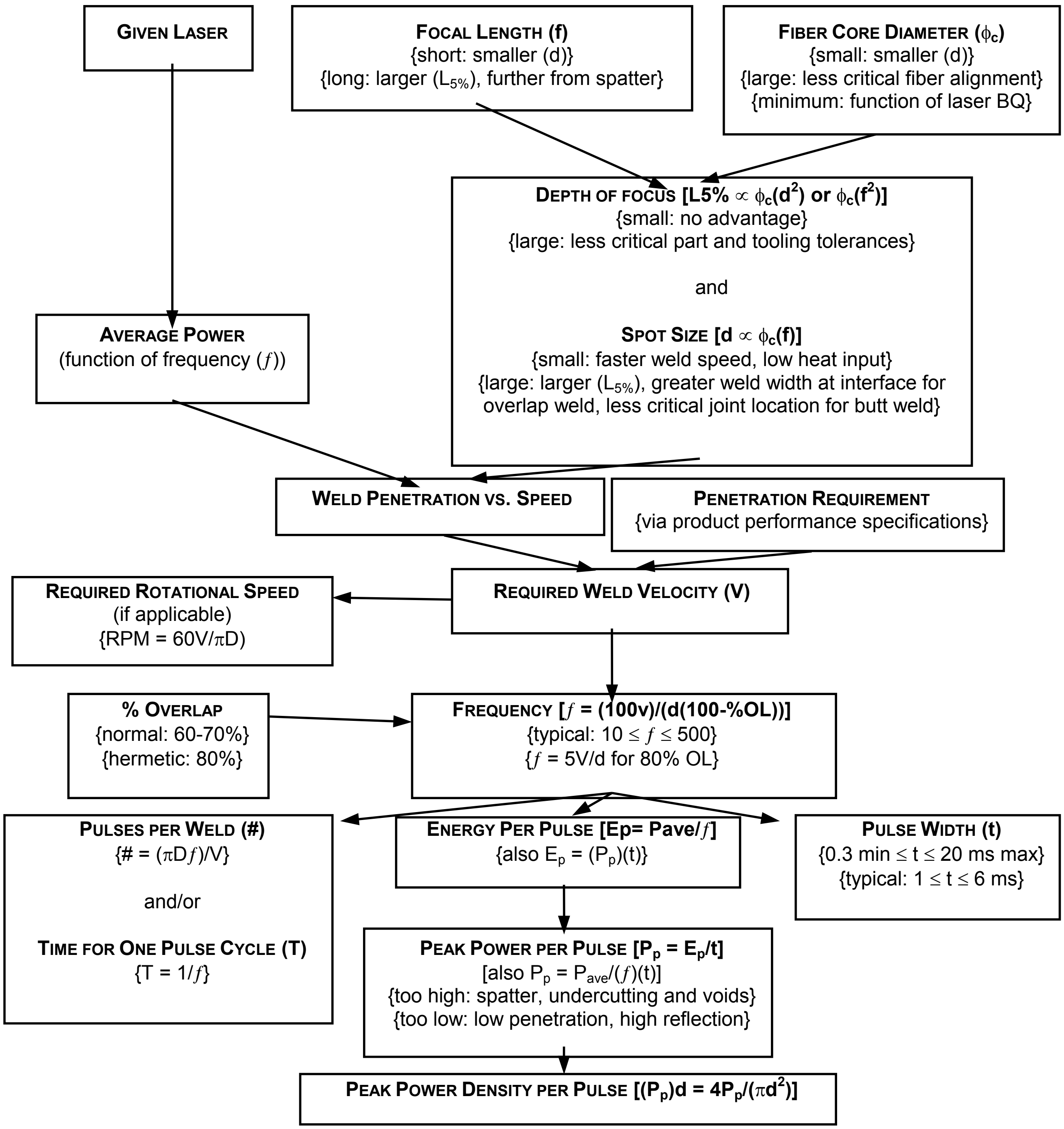
TYPICAL PROCESS PARAMETERS FOR PULSE WELDING

	E_p (Joules)	t (ms)	P_{ave} (Watts)	P_p (kW)	f (Hz)
	material thin thick	material thin thick	material thin thick	material thin thick	material thick thin
Steel	1-20	1-3	10-2000	1-4	10-1000
Aluminum	10-20	1-10 [1]	500-2000	2-10	10-75

[1] typically 6-15 ms if pulse shaping is used.

Figure 4.20

WELD PROCESS DEVELOPMENT FLOWCHART FOR PULSE WELDING



4.10.9 Round Part Welding

4.10.9.1 Weld Speed and Weld Time

In addition to the tack weld, ramping and overlap considerations mentioned above, the following may prove beneficial when considering round part (360 degree) welding. First, converting a weld speed from a linear velocity (V) measured in length per time (e.g. meters/minute) to a rotational speed is essential, since rotational speed is required in order to program or drive a rotary axis. For example, the revolutions per minute (RPM), can be calculated if the linear velocity (for a given weld penetration) and the weld diameter (D) is known:

$$\boxed{\mathbf{RPM = V/(\pi D)}}$$

Example 4.10.9A: Applying this to a linear weld speed of 3000 mm/min (118 in/min), and a weld diameter of 100 mm (3.94 inches), yields (3000)/[(3.14)(100)] = 9.5 RPM. *See also Example 4.10.9B.*

RPM can then be used, along with ramp-up degrees (α), overlap (OL), and ramp-down degrees (β), to calculate the weld time in seconds (t_W):

$$\boxed{\mathbf{t_W = (60/RPM)[1 + (\alpha + \beta)/(360 + OL)]}}$$

Example 4.10.9B: Using an RPM of 9.5, and a ramp-up of 5 degrees, an overlap of 5 degrees, and a ramp down of 15 degrees, t_W = (60/9.5)[1 + (5+15)/(360+5)] = 6.7 seconds. *See also Example 4.10.9A.*

4.10.9.2 Estimating Weld Strength (Ductile Materials)

Strength requirements can be used to ***estimate*** weld penetration and/or weld width requirements. If a torque (T) requirement is known (e.g. lbf-inch or N-mm), the weld cross-sectional shear width (x_W, in inches or mm, note that length unit must be the same as that used for the torque and yield strength values) can be estimated using the ***yield*** strength of the material (S_y, in psi or N/mm^2), the weld diameter (D_W, in inches or mm), and applying a safety factor (K). For butt-weld configurations, the weld cross-sectional shear width may be either equal to, or less than, the weld penetration, depending on the weld cross section that is subject to the torsion (or shear). Consider for example, a transmission shell component welded to a gear component in a butt-weld configuration. If the weld penetrates beyond the shell thickness and into the gear, the strength of the welded assembly is proportional to the shell thickness, not the overall weld penetration. For overlap weld configurations, the weld cross-sectional shear width is equal to the weld width at the weld interface.

Note also, that the safety factor depends on many things, a few of which are; i) the type of loading the component will see (static, fatigue, impact, etc.), ii) the effects of a weld failure on the component in operation (safety to operator, damage of adjacent components, etc.), and iii) the cost of the component.

$$x_w \cong K\{[2(3)^{1/2}T]/(\pi S_y D_w^2)\}$$

$$\boxed{\mathbf{x_w \cong K(1.1T/S_y D_w^2)}}$$

Example 4.10.9C: A mild steel component with a yield strength of 30,000 lbf/in^2 (207 N/mm^2) a torque requirement of 43,000 lbf-in (4,858,347 N-mm), a weld diameter of 4 inches (101.6 mm), and a safety factor of 1.5 requires a weld cross-sectional shear width of ***approximately*** 0.15 inch (3.8 mm) {solving from (1.5)(1.1)(43,000)/(30,000)(4)^2}.

If a push out force (F, in pounds-force or Newtons) is known, the weld cross-sectional shear width can be estimated by:

$$x_w \cong K\{[(3)^{1/2}F]/(\pi S_y D_w)\}$$

$$\boxed{\mathbf{x_W \cong K(0.55F/S_y D_w)}}$$

Example 4.10.9D: Solving for a mild steel component having a push-out requirement of 25,000 lbf (111,206 N), a weld diameter of 4 inches (101.6 mm), and a safety factor of 1.5 yields a required weld cross-sectional shear width of ***approximately*** t_W = (1.5)(0.55)(25,000)/(30,000)(4) = 0.17 inch (4.4 mm).

If the above examples are applied to the strength requirements of a transmission shell and gear in a butt-weld configuration, we can conclude that the shell wall thickness must be at least 0.17 inch (4.4 mm) in order to transmit a torque of 43,000 lbf-in (4,858,347 N-mm) and withstand a push-out force of 25,000 lbf (111,206 N). Therefore, if a shell thickness greater than 0.17 inch (4.4 mm) is used, then a partial penetration weld may be adequate. However, if a 0.17 inch (4.4 mm) wall thickness is used, then a full penetration weld is required. Note that if the gear component has a carbon content of greater than 0.3 percent, it is best to minimize the amount of weld penetration which is through the shell and into the gear. This is because the amount of embrittlement of the gear is related to the HAZ of the gear, and an actual decrease in weld strength can result as the weld penetration into the gear is increased.

4.10.9.3 Estimating Weld Strength (Brittle Materials)

Referring to *Section 4.10.9.2*, strength requirements can also be used to ***estimate*** weld penetration/width requirements for brittle materials. If a torque (T) requirement is known, the weld cross-sectional shear width in inches (x_W) can be estimated using the ***ultimate*** strength of the material (S_u), the weld diameter (D_W), and by applying a safety factor (K).

$$x_w \cong K\{[2T]/((2)^{1/2}\pi S_u D_w^2)\}$$

$$\boxed{\mathbf{x_w \cong K(0.45T/S_uD_w^2)}}$$

If a push out force (F) is known, the weld cross-sectional shear width can be estimated by:

$$x_w \cong K\{F/[(2)^{1/2}\pi S_u D_w)\}$$

$$\boxed{\mathbf{x_W \cong K(0.23F/S_uD_w)}}$$

Note: *Although the above formulae can be used to approximate the required weld cross-sectional shear width, the most important aid in determining laser welding requirements begins in the laboratory. As stated previously, up front welding of prototype components and assemblies is the best way of identifying feasibility, required material or part design changes, significant tooling requirements, as well as weld strength requirements. This, followed by component life testing in a test machine (e.g. dynamometer) or in the actual product in which the component is used, will provide the basis for sound engineering design.*

Excursus 3
Static Failure of Ductile Materials in Pure Shear (Circumferential Welds)

Static Failure Model for Ductile Materials

The classic failure model for ductile materials uses the Distortion Energy Theory to predict plastic failure. The model predicts an equivalent tensile stress (σ_e) by combining orthogonal tensile stresses and shear stress as follows:

$\sigma_e = (\sigma_x^2 + \sigma_y^2 - \sigma_x\sigma_y + 3\tau_{xy}^2)^{1/2}$, but
$\sigma_x = \sigma_y = 0$ for pure shear, therefore
$\sigma_e = (3\tau_{xy}^2)^{1/2} = \sqrt{3}\tau_{xy} \leq S_y$ to avoid plastic deformation.

Stress Formulations for Pure Shear

Stress is defined as force divided by area. Therefore, torsional and axial shear stresses can be defined as follows:

Shear Force
Torque = Force * Distance (where Distance equals weld diameter/2), or
$T = F\,(D_w/2)$, therefore
$F = 2T/D_w$ for *torsional shear*, and
F = push-out force for *axial shear*

Shear Area
Shear area = Shear Width * Circumference
$A = x_w\pi D_w$, where:

x_w is equal to the weld width at interface in an *overlap weld* configuration,
x_w is equal to the weld penetration in a *partial butt weld* configuration,
x_w is equal to the minimum material thickness in a *through butt weld* configuration.

Shear Stress
Stress = Force/Area
$\tau = (2T/D_w)/(x_w\pi D_w) = 2T/x_w\pi D_w^2$ for *torsional shear*, and
$\tau = F/(x_w\pi D_w)$ for *axial shear*

Failure Predictions

Substituting the stress formulae back into the failure model above yields the following:

Torsional Shear
$\sigma_e = \sqrt{3}\tau_{xy} \leq S_y$ to avoid plastic deformation, therefore
$\sqrt{3}(2T/x_w \pi D_w^2) \leq S_y$ and solving for x_w yields
$x_w \geq (2\sqrt{3}T)/(\pi S_y D_w^2)$, or
$x_w = K(2\sqrt{3}T)/(\pi S_y D_w^2)$, where K is a safety factor

Axial Shear
$\sqrt{3}(F/x_w \pi D_w) \leq S_y$ and solving for x_w yields
$x_w \geq (\sqrt{3}F)/(\pi S_y D_w)$, or
$x_w = K(\sqrt{3}F)/(\pi S_y D_w)$, where K is a safety factor

5. WELD TROUBLESHOOTING

In partial summary of the prior text, the following laser weld troubleshooting guidelines present a few of the primary causes of production weld degradation in relation to several of the most common weld defects. The weld defects have been separated into those present when penetration is acceptable, and those present when penetration is lacking or inconsistent. In addition, two sample weld troubleshooting checklists are included.

5.1 Weld Defects when Weld Penetration is Good

5.1.1 Cracks or Porosity

i. Is the weld zone free from oil, rust inhibitor, water, cleaning solvent, dust, rust and other debris or contamination?
(may require part wash station, or wash station maintenance- check to see if parts are clean and dry at the parts washer exit)

ii. Is the material impurity levels unusually high?
(has problem occurred on a "new" batch of parts?, high impurity levels increase porosity and weld spatter, similarly, materials such as aluminum may contain highly volatile constituents resulting in molten material expulsion)

iii. For welding of carbon steels, is the equivalent carbon content less than 0.3%?
(high carbon content increases cracking tendency, refer to Section 4.1.1)

5.1.2 Oxidation, Discoloration or Scaling

i. Is shield gas flow adequate? Are all the appropriate valves open? Is the solenoid valve operating properly? Does the shield gas source have sufficient gas? Is the shield gas type correct and of specified purity? Is the shielding directed at the weld with the proper stand-off? Is the shield nozzle clean and free of weld spatter or other debris? Is the shield gas efficiency being disturbed by tooling or by excessive flow rates associated with the exhaust, beam delivery purging or focus optic protection?
(molten metal will oxidize when shielding is inadequate)

5.1.3 Undercutting

i. Is the part geometry and weld joint fit-up consistent? Does the weld joint have acceptable levels of mismatch and gap?
(refer to Section 4.3)

ii. Are machining reliefs or chamfers too large, or inconsistent?
(minimize reliefs and chamfers to insure sufficient weld material)

iii. Is the part clamping adequate and consistent? Check for conditions in the tooling or clamping that would result in poor part fit-up [e.g. burrs, spatter or other damage on tooling, misalignment of tooling, or low clamping force (e.g. air or hydraulic pressure, clamp cylinder binding, etc.)].
(refer to Section 4.6)

iv. Is the shield gas flow rate excessively high?
(extreme shield gas flow rates can displace molten metal from the weld zone)

v. If pulse welding, are peak powers per pulse too high?
(refer to Section 4.10.8)

5.2 Weld Defects when Weld Penetration is Poor

5.2.1 Consistent Lack of Weld Penetration

General Considerations

i. Is the focal position optimized?
(averaged within the weld coupling range, or maximize penetration/weld width, manufacture focus/working distance gauge calibrated to best focus position for quick verification of focus position)

ii. Is the focus optic or cover slide clean from spatter, smoke and other debris, and free from significant dings, scratches and pits?
(clean optic or cover slide, may require an increase in cross-jet or beam delivery purging flow rates to optimize focus optic protection, especially for short focal length applications, replace damaged optics)

iii. Is the power or pulse energy adequate to yield the expected weld penetration at the given process welding speed?
(insure power setting at laser is correct, insure power reading is accurate using power meter calibration, insure process speed is properly calibrated and accurate)

iv. Does the laser power at the focusing optic agree with the expected power loss through the beam delivery optics or fiber?
(use power meter to check power prior to and after each optic in the beam delivery system, or at the input and exit of the fiber optic)

Reflective/Transmissive Beam Delivery System Considerations

v. Does the beam size at the focusing optic agree with the expected mode burn geometry and beam divergence?
(use mode burns to check mode size and geometry just prior to the focusing optic)

vi. Are all the beam delivery bending mirrors clean?
(beam delivery purge air (or inert gas) filters may require changing, or an increase in the purge gas flow rate may be necessary)

vii. Beam alignment: Is the beam "clipping" in the beam delivery system?
(visual inspection of mode burns after each optic in the beam delivery system can be used to identify if clipping is occurring, either fringes or incomplete burns can result from clipping)

viii. Beam alignment: Are the alignment laser and main process beams centered through each optic?
(check via mode burns, and alignment laser)

ix. Beam alignment: Are the alignment and main process beams coaxial?
(near and far field mode burn tests with cross-hair inserts. Note that the far field burn should be at least the distance from the laser output to the focusing optic, the longer the more precise)

x. Beam alignment: Are the alignment and main process beams coaxial to the focal axis of transparent focusing optics, and for parabolic reflective optics are they perpendicular to, and centered with, the line of focus?
(check via retro-reflection test with the alignment laser, insure alignment and main process beams are coaxial)

xi. Has the penetration been decreasing slowly with time (over several days or weeks)?
(thermal focusing of the output optic(s), which decreases the beam size, may be occurring, take a mode burn at weld power at the focus unit with the focusing optic removed and compare the size with what is expected)

Fiber Optic Beam Delivery System Considerations

xii. Beam alignment: Is the focused beam clipping on the part (a flange or an adjacent wall for example), the fixturing, clamping aperati, the shield gas nozzle, etc.?
(establish a graphic clearance cone for the focused beam based on the beam diameter at the focusing optic, or put a small piece of paper or masking tape on the surface in question and take a short burn inspecting for ignition)

xiii. Beam alignment: Is the beam properly aligned into the fiber optic?
(compare power out of the laser with power out of the fiber)

5.2.2 Inconsistent Weld Penetration

General Considerations

i. Is the weld joint location and part fit-up consistent?
(check for conditions such as poor part fit-up, part or tooling run-out, inconsistent chamfer on weld joint edges, damaged tooling or spatter on tooling, etc., an indicator may be used to determine weld joint stability and repeatability)

ii. Is plasma suppression sufficient?
(careful attention required with argon shielding or for helium shielding with high energy density, and for titanium welding)

iii. Does the weld joint fit-up gap increase during the weld?
(tack welding, increased interference fit, enhanced clamping for component cooling and stability, and shorter focal length focusing optic may all help insure stable fit-up for butt welding applications. Refer to Section 4.6)

Reflective/Transmissive Beam Delivery System Considerations

iv. Is the beam delivery purge air (or inert gas) clean and dry, is it connected properly, are there sufficient fittings for the length of the beam delivery system?
(thermal blooming may be occurring, filters may require cleaning or replacement)

v. Does the weld start okay and then after a few seconds it stops coupling?
(thermal blooming may be occurring check step 4.2 b.iv., or thermal lensing of the output optic or focusing optic may be occurring, see Section 3.4.4)

vi. Does the beam delivery system have adequate cooling?
(beam bender and mirror focus mirror mounts should be only warm to the touch, water temperature must be above dew point).

5.3 Sample Weld Troubleshooting Checklists

The following checklists are samples only. Either one may be used as a reference in developing a weld troubleshooting checklist for a particular system or application. Details of procedures referred to in the checklists are not given. Further, safety precautions associated with any of the procedures referenced are not indicated. Detailed procedures and safety precautions are the responsibility of the Laser Safety Officer (see *Section 3.7, Laser Safety* for further information).

5.3.1 Sample Weld Troubleshooting Checklist for CO_2 Lasers

Preliminary Data

a.	Date?	__________	mo/dy/yr
b.	Shift?	__________	shift
c.	Person performing maintenance?	__________	name
d.	Ambient temperature?	__________	degrees: C (F)
e.	Laser model?	__________	RS model #
f.	Laser serial number?	__________	SN
g.	Laser dew point?	__________	degrees: C (F)
h.	Present hours on HV hour meter?	__________	hours
i.	Gas bottle pressure?	__________	N_2: bar (psi)
		__________	CO_2: bar (psi)
		__________	He: bar (psi)
j.	Expected weld power at laser control?	__________	kW
k.	Present weld power at laser control?	__________	kW
l.	Expected weld normal speed?	__________	m/min (in/min)
m.	Present weld speed?	__________	m/min (in/min)
n.	**Expected weld penetration at normal speed?**	__________	**mm (inch) (or full/partial)**
o.	**Present weld penetration at normal speed?**	__________	**mm (inch) (or full/partial)**

Mirror Focus Unit

1. Inspect focus unit optic(s). Is the optic(s) clean and in good condition? (*i.e. free of dings, significant scratches or pits on the surface*).

( ) Yes (go to 2.)
( ) No (clean, go to 12.)
Note: check focus optic protection device if applicable.

Beam Alignment

2. Check alignment at focus unit. Remove focus optic and take mode burn @ weld power with alignment puck inserted. Is the burn centered with cross-hair (within 2 mm (0.08 inch) center to center for 50mm optics, within 1 mm (0.04 inch) for 25mm optics)?
Note that an oblong mode burn (or oblong more than normal if not a round beam) may signify poor internal laser alignment or over tightening of beam bender mirror adjusters.

( ) Yes (go to 3.)
( ) No (perform beam alignment, go to 12.)

Thermal Focusing of Output Optics

3. Remove alignment puck & take mode burn @ weld power. Measure min. dia. If less than a 15% decrease from new, go to 4. If more than a 15% decrease from new, clean or replace output optic(s) & recheck diameter. Recheck step 2., and re-align if required, then go to 12.
The output optic(s) should be replaced if: a) it will not clean-up, b) it has been cleaned once already, or c) damage can be detected with polarizer viewing.

_______ min. dia.: mm (inch)
_______ min. dia. with output optic(s) cleaned or replaced: mm (inch)

Beam Delivery Power Loss

4. Measure power at focus unit with focus optic removed, and record. Measure power in front of laser and prior to first beam delivery optic, and record (*compare with Preliminary Data "k"*). Subtract the first reading from the second, and record. Is the difference greater than 15% (750W for 5kW weld)?

_______ kW @ focus unit
_______ kW @ laser
_______ kW difference

( ) Yes (clean/replace beam delivery optics, re-check steps 2, go to 12.)
( ) No (go to 5.)

Plasma Suppression

5. Measure shield gas flow rate. Does actual shield gas flow rate match expected?
Is the nozzle free from weld spatter and other debris, or is it damaged?

_______ Expected: Nl/hr (scfh)
_______ Actual: Nl/hr (scfh)

( ) Yes (go to 6.)
( ) No (correct, go to 12.)

Nozzle Location

6. Is the shield gas nozzle located properly? (unobstructed, stand-off, aiming, angle)

( ) Yes (go to 7.)
( ) No (correct, go to 12.)

Out of Focus

7. Check focus. Is focus at optimal position?
Note: a gage calibrated to best focus position can be used to confirm this.

( ) Yes (go to 8.)
( ) No (correct, go to 12.)

Thermal Blooming

8. Check beam delivery purge air (or inert gas) flow and quality. Is the flow set properly and is the air (or inert gas) clean and dry?
Inspect purge system filters and flow meter for presence of oil.

( ) Yes (go to 9.)
( ) No (correct, go to 12.)

Thermal Shifting due to Poor Cooling

9. Measure/check beam delivery water flow rate. Does actual water flow rate match expected?

_______ Expected: l/min (gpm)
_______ Actual: l/min (gpm)

( ) Yes (go to 10.)
( ) No (correct, go to 12.)

Poor Part Cleanliness

10. Is the weld zone free from oil, water, dust, rust, or other residue or contamination?
Check that the parts are clean and dry at the exit of the parts washer.

( ) Yes (go to 11.)
( ) No (correct, go to 12.)

Poor Part Fit-up or Poor Weld Joint Location

11. Is the weld joint location and fit-up consistent?
Check for conditions such as poor part fit-up, part or tooling run-out, inconsistent chamfer on weld edges, damaged tooling, weld spatter on tooling, etc.

( ) Yes (go to 12.)
( ) No (correct, go to 12.)

Post Correction Data

12. Indicate step(s) where correction was necessary, and post correction weld penetration. If expected weld penetration is achieved, go to 13. If expected weld penetration is not achieved by correction continue with the step following where the correction was made.

step 1	(	)	__________	mm (inch) *(or full/partial)*
step 2	(	)	__________	mm (inch) *(or full/partial)*
step 3	(	)	__________	mm (inch) *(or full/partial)*
step 4	(	)	__________	mm (inch) *(or full/partial)*
step 5	(	)	__________	mm (inch) *(or full/partial)*
step 6	(	)	__________	mm (inch) *(or full/partial)*
step 7	(	)	__________	mm (inch) *(or full/partial)*
step 8	(	)	__________	mm (inch) *(or full/partial)*
step 9	(	)	__________	mm (inch) *(or full/partial)*
step 10	(	)	__________	mm (inch) *(or full/partial)*
step 11	(	)	__________	mm (inch) *(or full/partial)*

Comments

13. Indicate any comments that may be necessary for detailed explanation of root cause problem:

5.3.2 Sample Weld Troubleshooting Checklist for Nd:YAG Lasers

Preliminary Data

a.	Date?	__________	mo/dy/yr
b.	Shift?	__________	shift
c.	Person performing maintenance?	__________	name
d.	Laser model?	__________	RS model #
e.	Laser serial number?	__________	SN
f.	Number of shots on flash lamps?	__________	shots, lamp 1
		__________	shots, lamp 2
		__________	shots, lamp 3
		__________	shots, lamp 4
g.	Expected weld power at laser control?	__________	W
h.	Present weld power at laser control?	__________	W
i.	Expected weld normal speed?	__________	m/min (in/min)
j.	Present weld speed?	__________	m/min (in/min)
k.	**Expected weld penetration at normal speed?**	__________	**mm (inch) (or full/partial)**
l.	**Present weld penetration at normal speed?**	__________	**mm (inch) (or full/partial)**

Mirror Focus Unit

1.	Inspect cover slide and focus unit optic(s). Are they clean and in good condition?	( )	Yes (go to 2.)
		( )	No (clean, go to 10.) *Note: check focus optic protection device if applicable.*

Beam Delivery Power Loss

2.	Measure power at focus unit with nozzle cone (if used) and cover slide in place, and record. Measure power in front of incoupler, and record. Subtract the first reading from the second, and record. Is the difference greater than 10% (100W for 1000W weld)?	_______	W @ focus unit
		_______	W @ incoupler
		_______	W difference
		( )	Yes (align incoupler, replace fiber optics if required, go to 10.)
		( )	No (go to 3.)
3.	Measure power at focus unit with nozzle cone (if used) and cover slide removed, and record. Compare with that measured at focus unit in step 2. record. Is the difference greater than 1-2%.	_______	W @ focus unit
		( )	Yes (Inspect nozzle cone integrity and alignment, correct and go to 10.)
		( )	No (go to 4.)

Out of Focus

4.	Check focus. Is focus at optimal position?	( )	Yes (go to 5.)
	Note: a gage calibrated to best focus position can be used to confirm this.	( )	No (correct, go to 10.)

Shield Gas Nozzle

5.	Is shield gas nozzle clean and located properly? (unobstructed, stand-off, aiming, angle)	( )	Yes (go to 6.)
		( )	No (correct, go to 10.)

Plasma Suppression

6. Measure shield gas flow rate. Does actual shield gas flow rate match expected?

_______ Expected: Nl/hr (scfh)
_______ Actual: Nl/hr (scfh)

( ) Yes (go to 7.)
( ) No (correct, go to 10.)

Thermal Shifting due to Poor Cooling
(if water cooled beam delivery components are used)

7. Measure/check beam delivery water flow rate. Does actual water flow rate match expected?

_______ Expected: l/min (gpm)
_______ Actual: l/min (gpm)

( ) Yes (go to 8.)
( ) No (correct, go to 10.)

Poor Part Cleanliness

8. Is the weld zone free from oil, water, dust, rust, or other residue or contamination?
Check that the parts are clean and dry at the exit of the parts washer.

( ) Yes (go to 9.)
( ) No (correct, go to 10.)

Poor Part Fit-up or Poor Weld Joint Location

9. Is the weld joint location and fit-up consistent?
Check for conditions such as poor part fit-up, part or tooling run-out, inconsistent chamfer on weld edges, damaged tooling, weld spatter on tooling, etc.

( ) Yes (go to 10.)
( ) No (correct, go to 10.)

Post Correction Data

10. Indicate step(s) where correction was necessary, and post correction weld penetration. If expected weld penetration is achieved, go to 11. If expected weld penetration is not achieved by correction continue with the step following where the correction was made.

step 1	( )	__________	mm (inch) *(or full/partial)*
step 2	( )	__________	mm (inch) *(or full/partial)*
step 3	( )	__________	mm (inch) *(or full/partial)*
step 4	( )	__________	mm (inch) *(or full/partial)*
step 5	( )	__________	mm (inch) *(or full/partial)*
step 6	( )	__________	mm (inch) *(or full/partial)*
step 7	( )	__________	mm (inch) *(or full/partial)*
step 8	( )	__________	mm (inch) *(or full/partial)*
step 9	( )	__________	mm (inch) *(or full/partial)*

Comments

11. Indicate any comments that may be necessary for detailed explanation of root cause problem:

LASER CUTTING

PROCESS FUNDAMENTALS

AND

TROUBLESHOOTING GUIDELINE

(2nd Printing)

Prepared by:

David Havrilla
Mechanical Engineer, Product Support Group

and

Phillip Anthony
OEM Business Manager

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1. INTRODUCTION

Industrial lasers have gained acceptance as effective and reliable production tools. No area of laser processing has grown as fast, with as wide acceptance, as that of laser cutting. The most significant contribution to the growth of the industry can be attributed to both the education and experience that the machine tool builders and end users have gained on the unique advantages of laser cutting. In turn, the end users have pressed the machine tool builders and laser manufacturers for improved reliability and greater processing capabilities. As the use of lasers becomes more widespread, the need to gain greater understanding of the properties, advantages and applicability of the laser cutting process is essential. The fundamental properties of laser light, choice of laser (only CO_2 and Nd:YAG are considered), system considerations, suitable materials, cut quality, component fixturing and cutting parameters are all addressed in the text that follows. A few of the many questions that will be addressed in this paper are:

- What advantages does the laser cutting process offer?
- How does laser cutting compare to conventional methods?
- What makes a laser suitable for cutting?
- How do lasers cut?
- What sort of laser is most suitable?
- What are the basic components of a laser cutting machine?
- What materials are suitable for laser cutting?
- How is cut quality defined and measured?
- What cutting parameters are most important?
- In what ways do these parameters affect cut quality?

The success of any laser cutting process strongly depends on the careful consideration of two primary areas. These areas are the laser process (that is, the laser and how the beam is manipulated and delivered to the workpiece) and the cutting process (the interaction of the laser with the material to be cut). The purpose of this guide is to discuss these considerations and to define the correlation between them. It may be used to build the foundation for sound laser cutting process optimization and troubleshooting.

Each of the areas of consideration are dependent on many factors, some of which are listed below:

i. Laser process considerations:

   a. laser type and wavelength *(e.g. CO_2 or Nd:YAG)*,
   b. laser power and type *(e.g. pulsed or CW)*,
   c. beam quality *(e.g. focusability)*,
   d. raw beam size *(e.g. divergence)*,
   e. focal length,
   f. focused spot size,

g. depth of focus,
h. power density, energy density and cut energy,
i. polarization,
j. beam delivery considerations, and
k. system considerations.

ii. Cutting process considerations:

a. material suitability *(e.g. surface condition, reflectivity, absorptance, thickness, density, heat of vaporization, heat capacity, & diffusivity)*,
b. cut quality *(e.g. kerf width, taper, smoothness/roughness, dross, recast & heat affect)*,
c. material surface condition,
d. part location and fixturing, and
e. cutting parameters *(e.g. power and power density, speed, focal length and focus position, assist gas type and pressure, gas jet nozzle design, orifice size and stand-off, & piercing and pulsing).*

Laser process considerations refer to the group of parameters which influence what type of laser is used and how its power is delivered to the workpiece and focused on it, thus providing a useful source of energy. The cutting process considerations, on the other hand, refer to the factors which influence how successfully the focused energy is coupled with the material and how effectively that energy is used in the cutting process.

1.1 Some Advantages of Laser Cutting

Since the laser can be concentrated to produce a small spot of intense heat energy, laser cutting offers many advantages over other cutting processes (such as shearing or plasma cutting).

First, the tremendous heat energy of lasers is contained in an extremely small area such that it provides for:

- Narrow kerf widths with straight edges and generally good appearance (in most cases parts require no subsequent cleaning operation),
- Minimum heat affected zones adjacent to the cut edge,
- Minimum heat input resulting in minimal distortion of the workpiece,
- Small holes can be cut (diameters smaller than material thickness), and
- Fine control of average power eliminates excess burning during acceleration and deceleration.

Next, since light exerts no force on the workpiece, lasers are non-contact cutting tools which means:

- No mechanical distortion of the workpiece,
- Only light or no clamping required in many cases,
- No cutting tool wear, maintenance or replacement,
- Ability to cut materials regardless of their hardness, and
- Considerably less noise compared with water jet, plasma and mechanical techniques.

Additionally, the beam of light from a laser has a high degree of control and flexibility to offer via:

- Ease of changeover for cutting a variety of material types and geometries (ideal for small lot sizes, prototype development and just-in-time manufacturing),
- Ease of integration and easily controlled with automation equipment (e.g. CNC),
- Unlimited profiling capability (no cutting edge),
- Optimal material utilization (common line sharing and close nesting minimize material waste), and
- Ability to cut in areas difficult to reach with other techniques.

A few of the disadvantages that should be considered are:

- High capital cost relative to other techniques (however, operating costs are lower than many other techniques),
- Hard and often brittle cut edges may occur in hardenable materials,
- Microcracking at the cut edge may occur in some materials, and
- Toxic fumes are generated from laser cutting of some materials.

In light of the above, several key applications of laser cutting are apparent:

- Low to medium production and prototype runs,
- Delicate and tight tolerance parts, and
- High strength or abrasion resistant materials.

1.2 Comparison to Other Cutting Methods

To consider the use of lasers, it is helpful to consider how they differ from other mechanized methods. The key point to note is that the laser effectively competes against the capabilities of a wide range of processing techniques and therefore possesses tremendous flexibility.

1.2.1 Thermal Processes

As with the use of a laser, these methods employ a non-contact source of heat energy to aid in material removal. However, these alternate methods lack the ability to concentrate their heat energy into as small an area as a laser. Therefore, they tend to put excess heat into the material resulting in wider kerfs, larger heat affected zones, and a greater potential for thermal distortion of the workpiece. These thermal methods compete with lasers in cutting of metal components [less than 25 mm (1 inch) thick], but a laser provides the only thermal process which can also be effectively used on non-metals.

Oxyfuel Cutting (OFC)

This cutting process relies on a chemical reaction of oxygen with the base metal that has been heated with a flame (common fuels are acetylene and propane) above the material's ignition temperature [e.g. 870°C (1600°F) is the temperature at which iron will start to burn when in the presence of oxygen]. This limits OFC primarily to use on mild steel even though use of chemical fluxes or metal powder can help to overcome the reduced oxidation of additives such as chromium and nickel in ferrous alloys. Its compact size, low capital cost, and ability to cut steel up to 2 meters (7 feet) thick makes OFC a flexible cutting tool. However, due to its high thermal input, poor dimensional accuracy and slow removal rates, it is rarely chosen for cutting of material less than 25 mm (1 inch). Kerf widths are always a few millimeters or more.

Plasma Arc Cutting (PAC)

This method involves directing a high-current arc transferred through a constricting nozzle from an electrode to the workpiece. The resulting high temperatures are capable of melting most metals while a high velocity jet of partially ionized gas blows the molten metal from the kerf. While the cutting rates are considerably faster than OFC and are on the same range as high power lasers, considerable and frequent care needs to be taken to maintain good cut quality. For example, routine replacement of consumable items (such as nozzles) is required to maintain good cut quality. This leads to running costs which are higher than that of laser cutting. In addition, precautions must be taken in dealing with the ultra-violet radiation generated by the arc.

In general, PAC produces cuts that have wider kerfs and considerable waviness along the edge, resulting in a reduction in overall cut accuracy, as well as limiting the detail that can be cut. Also peculiar to plasma arc cutting of material thicknesses above 6 mm (0.25 inch), is a cut kerf with a bevel on only one edge. This of course, renders impossible common line cutting (i.e. where one cut edge is common to two or more parts).

A recent development in PAC is constricted arc cutting (sometimes referred to as "high definition", "precision" or "fine" plasma arc cutting), which has made considerable improvements in cut quality. However, constricted arc PAC requires not only a higher rate of consumable replacement, but is more sensitive to the quality of the consumables. This in turn, results in a process that is difficult to run unattended.

Plasma arc cutting is generally competitive against lasers for cutting of mild steel greater than 9.5 mm (0.38 inch), and aluminum alloys and stainless steel greater than 6.4 mm (0.25 inch).

1.2.2 Mechanical Processes

Laser cutting systems provide advantages that overcome the problems associated with contacting a part with a cutting edge. Mechanical means (such as punching, shearing, and sawing) are characterized by the need for rigid clamping of the part, difficulty in handling hardened or brittle material, cut edge deformation or burring, and the need for constant sharpening and replacement of the cutting tool. If these problems are a significant concern to the user, lasers can be considered a viable alternative.

Blanking/Stamping
The use of dies to stamp out large quantities of parts carries both a small cost per part and a shorter cycle time (i.e. high production rate). Stamping is not, however, nearly as responsive to design changes as that of programmable laser systems. The lengthy set-up times and high cost of new dies make the laser competitive for short to medium size runs. Furthermore, lasers allow for closer part nesting and less material waste, as compared to stamping which requires die clearance area around each part.

Punching/Nibbling
Punch press equipment offers greater flexibility over blanking, but is limited to lower production rates. It, however, fills a void for fabrication of parts that are too large for a practical size die. The interchangeability of tools when nibbling allows for contouring of even complex shapes, but the resultant “scalloped” edges may require secondary edge preparation. The punching action of the tools creates extremely wide kerfs in comparison to other mechanical methods (as well as lasers), and therefore generates considerable scrap. In addition, some set-up time is required which limits flexibility.

Shears (Straight Edge)
Unless there are obvious problems with contacting the part or problems with the resultant edge that is produced (rounded upper edge with shear tear), lasers are generally not directly evaluated against the capabilities of shears.

Saws
As opposed to lasers, saws and cut-off wheels generally have cutting feed rates that are not dependent upon the thickness of the material. For thin materials those speeds are considerably slower than lasers, but the range of thicknesses that saws can handle is greater. The laser actually is best considered a contouring tool that can be easily manipulated in almost any direction from any point on a piece of material, capability that is usually not required when purchasing a saw (with the possible exception of Jig saws for the cutting of some non-metals).

Water Jet Cutting

High pressure water (or water/abrasive mixture) on the order of 2,700-5,500 bar (40,000-80,000 psi) is pumped through a small diameter nozzle to generate the effect of a cutting tool for fabrication of a wide variety of metals and non-metals. Like a laser, there is no contact between the nozzle tip and the material. However, the jet of water does exert force on the material to be cut (enough to distort a flimsy surface), because a water jet cuts by erosion. With abrasive water jet cutting, high velocity [about 500 m/sec (1,500 ft/sec)] hard particles of silica, garnet or aluminum oxide erode the workpiece. Noise levels are high compared with laser cutting, even high pressure laser cutting. Due to the larger kerf widths resulting from the water jet [generally greater than 2.0 mm (0.08 inch)], cutting of intricate parts is not possible. Since the abrasive cannot be reused, higher operating costs are incurred with water jet cutting relative to laser cutting. A further concern, when cutting metal, is disposal of the abrasive/metal mixture (especially when it is comprised of particulates of heavy metals).

Water jets can be used to cut stacked material, unlike thermal processes wherein the heat generated during the cutting process would fuse the layers together. Water jet cutting is ideal for fibrous and thick non-metals and composites (e.g. foam and fiberglass). Also, when processing titanium, if the imbrittlement caused by the HAZ of thermal processes is intolerable, water jet cutting offers an excellent alternative. Water jet cutting is also a good choice if the recast and/or the HAZ from thermal cutting on aluminum alloys is unacceptable. However, water jet cutting is much slower than laser cutting in thicknesses where the two compete [i.e. up to about 16 mm (0.6 inch)]. For example, 1.6 mm (0.06 inch) thick mild steel can be cut with a 1200 Watt laser at about 8 m/min (315 in/min), compared to only about 0.5 m/min (20 in/min) with an abrasive water jet.

1.2.3 Electrical Processes

The use of electrical discharge machining (EDM) and electromechanical machining (ECM) is commonly employed for precision fabrication of hardened metals since these methods, like lasers, make no contact with the workpiece. They use the eroding or dissolving effect of an electrical discharge to carve a cut. While the smoothness of the edge that they generate is superior to that of a laser for thicknesses greater than 3 mm (0.12 inch), speeds are orders of magnitude slower. On the other hand, they have no depth of focus concerns that preclude lasers from cutting thick metal. Faster cutting speeds are possible in some cases with electrical discharge techniques by use of multiple electrodes. Since cutting speeds are faster and edge smoothness is comparable, lasers are preferred for hole cutting in sheet metal components in jet engine turbine manufacturing.

Table 1.1

COMPARISON OF DIFFERENT CUTTING METHODS TO LASER CUTTING

Method	**Material Thickness Practical Maximums** mm (inch)	**Advantages**	**Drawbacks**
Oxyfuel Cutting (OFC)	1,220 (48)	low cost, portable, easy to use	slow, accuracy limit, large kerf, large HAZ, thermal distortion, fumes, metals only
Plasma Arc Cutting (PAC)	50 (2)	lower capital cost, fairly portable,	high consumable cost, accuracy limit, large kerf, large HAZ, thermal distortion, noise, ultraviolet rays, dust and fumes, metals only
Laser	20 (0.75)	high speed and accuracy, flexibility	high capital cost, material restrictions, thickness limitations, fumes
Water Jet	150 (6) non-metals 25 (1) metals	cut any material, cut stacked material, no HAZ, no recast, no dross, no fumes	high operating cost, disposal of metal contaminated abrasive, larger kerf, noise, tool wear
Punching (Nibbling)	13 (0.5)	lowest cost per piece for high volume, accurate, reliable	shear edge distortion, requires fixed tooling and dies, set-up time, noisy, nibbles arcs, metals
Blanking (Stamping)	3 (0.12)	low cost per part, fast	high changeover cost and time, more material waste, metals
Wire EDM	100 (4)	most accurate, high edge quality, non-contact	slow, electrode wear, wire cost, metals only

2. LASER PROCESS CONSIDERATIONS

The laser beam is comprised of electromagnetic radiation which is both highly monochromatic (single wavelength) and coherent (in phase). The ability of a laser to cut is primarily attributed to these two characteristics, which allow the beam to be focused to a very small spot [typically 0.1 mm (0.004 inch) - 0.4 mm (0.015 inch)]. Since the laser power is focused to a relatively small spot, the resultant power density (the ratio of laser power to focused spot area) at the workpiece is typically greater than 10^6 Watts/cm^2 ($6x10^6$ Watts/in^2). At incident power densities of this magnitude, rapid melting, vaporization or decomposition of many materials occurs (those which do not reflect, conduct, or disperse the energy from the focused laser beam), which creates a hole and allows for ejection of the molten material (***Figure 2.1***). As the workpiece moves relative to the beam, the molten, vaporized or decomposed material can continuously be ejected thereby providing the cutting action. This process makes possible cutting thicknesses of several centimeters.

Laser cutting systems combine the energy (heat) of the focused beam with an assist gas which is introduced through a nozzle coaxial to the focused beam. The high velocity gas jet serves to; 1) aid in material removal by blowing out molten, vaporized or decomposed material through the backside of the workpiece, 2) protect the lens from spatter ejected from the cut zone (especially during piercing), and 3) in some material/gas combinations, increases the cutting rate.

2.1 Laser Considerations

2.1.1 General

Although there are many types of lasers, only the CO_2 (carbon dioxide) and Nd:YAG (neodymium:yttrium-aluminum-garnet) lasers are commonly found in industrial applications. Representative cutting speeds for CO_2 and Nd:YAG lasers at various power levels are presented in ***Figures 2.2, 2.3, 2.4 and 2.5***.

The choice of laser type (i.e. wavelength) is typically a function of the type of material to be cut (how well it absorbs laser power of a particular wavelength), as well as the material geometry, material thickness, cut quality, and cutting speed. In general, the Nd:YAG laser wavelength is absorbed better than the CO_2 wavelength by most metals. The use of fiber optics for Nd:YAG beam delivery has taken the important consideration of flexibility into the realm of relatively low cost three-dimensional laser cutting. Several of the primary considerations when choosing between CO_2 and Nd:YAG lasers are listed below:

Carbon Dioxide Laser Considerations

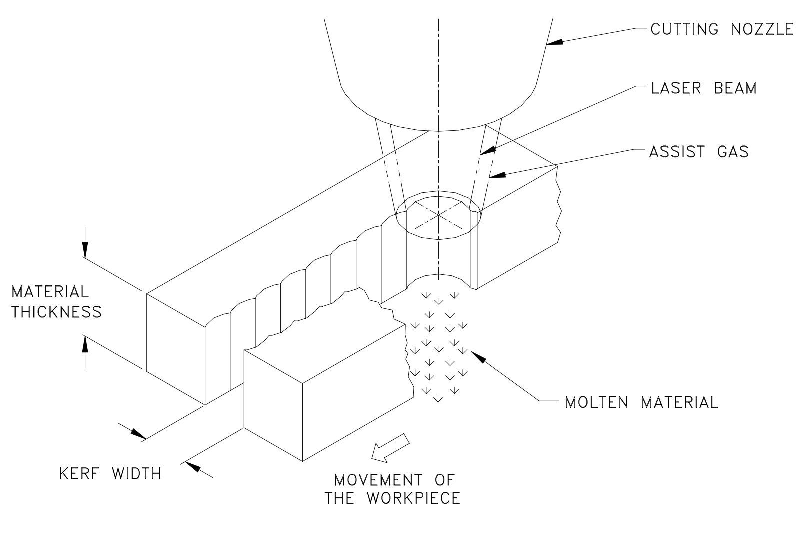
a. Higher powers
b. Better focusability (i.e. beam quality), generally resulting in smaller kerf and superior cut quality
c. Higher cut speeds on materials non-reflective to CO_2 wavelength
d. Greater material thickness on materials non-reflective to CO_2 wavelength
e. Lower capital and operating costs
f. Less expensive safety precautions with CO_2 wavelength

Nd:YAG Laser Considerations (w/ Fiber Optic Beam Delivery)

a. Fiber optic delivery (especially when considering robot applications)
b. Materials reflective to CO_2 wavelength can often be cut
c. Easy beam alignment, beam switching and beam sharing
d. Less extensive and simpler maintenance on laser (solid state device) and beam delivery
e. Less floor space with laser and beam delivery
f. Long and varied fiber lengths with no effect on process
g. High peak powers with high energy per pulse

Figure 2.1

PRINCIPLE OF LASER CUTTING



2.1.2 Pulsed and Continuous Wave Power

Cutting speed is primarily a function of laser power. However, cut quality is strongly dependent on how that power is transmitted into the material to be cut. The laser power can be produced in either a pulsed fashion or a continuous beam [referred to as continuous wave (CW)]. High power CW cutting transfers a significant amount of heat into the kerf walls, causing a deterioration of the cut quality and heating of the workpiece. This effect is especially difficult to overcome on thicker materials, when a narrow kerf width is required, and where workpiece positioning is not achieved at a constant speed. In addition, when cutting oxygen reactive materials using oxygen as the assist gas, uncontrolled self-burning is possible [especially when bulk material temperature rises to over 95°C (200°F), see also *Section 4.6.9*].

Pulsing the laser power can be used to alleviate these problems, and produce better quality cuts under these circumstances. In pulsing, the laser power is cycled on and off, between a high power short pulse time and an off time. Due to this cycling, "average power" rather than CW power is used to define the power of the laser. Average power is simply the laser power multiplied by the duty cycle for normal pulsed operation (where duty cycle is the ratio of on time to the total on plus off time). During the high power pulse, the material is melted, vaporized or decomposed, and ejected. During the off time, the material is allowed to cool while the material or focus module advances, awaiting the next high power pulse. In addition, pulse repetition can be varied with cutting speed. Obviously, the pulse repetition rate is critical and directly dependent on cutting speed. If there is too long of a time between pulses (minimum off time is limited by the laser power supply), a continuous cut cannot be obtained. This situation is typically not encountered with CO_2 lasers. If there is too short a time between pulses the laser power approaches the CW level, and therefore the problems described above are possible. See *Section 4.6.8* for a further discussion of pulsing (including superpulsing).

2.1.3 Mode, Power and Pointing Stability

High quality cuts can be obtained only by the application of consistent laser energy. Therefore, the stability of the laser's output is critical in cutting. This includes maintaining unwavering output energy (power stability), consistent beam quality (mode stability), and fixed energy concentration (pointing stability). Should the power increase or decrease by more than a few percent over short term operation, the beam quality oscillates between a Gaussian (or near Gaussian) and multi-mode profile (see *Section 2.2*), or the location of the beam's direction shifts more than a few tenths of a milliradian, there will result a change in the available power density for cutting, and a resultant change in cut quality.

Figure 2.2

REPRESENTATIVE SPEEDS FOR CO_2 CUTTING OF MILD STEEL WITH OXYGEN ASSIST

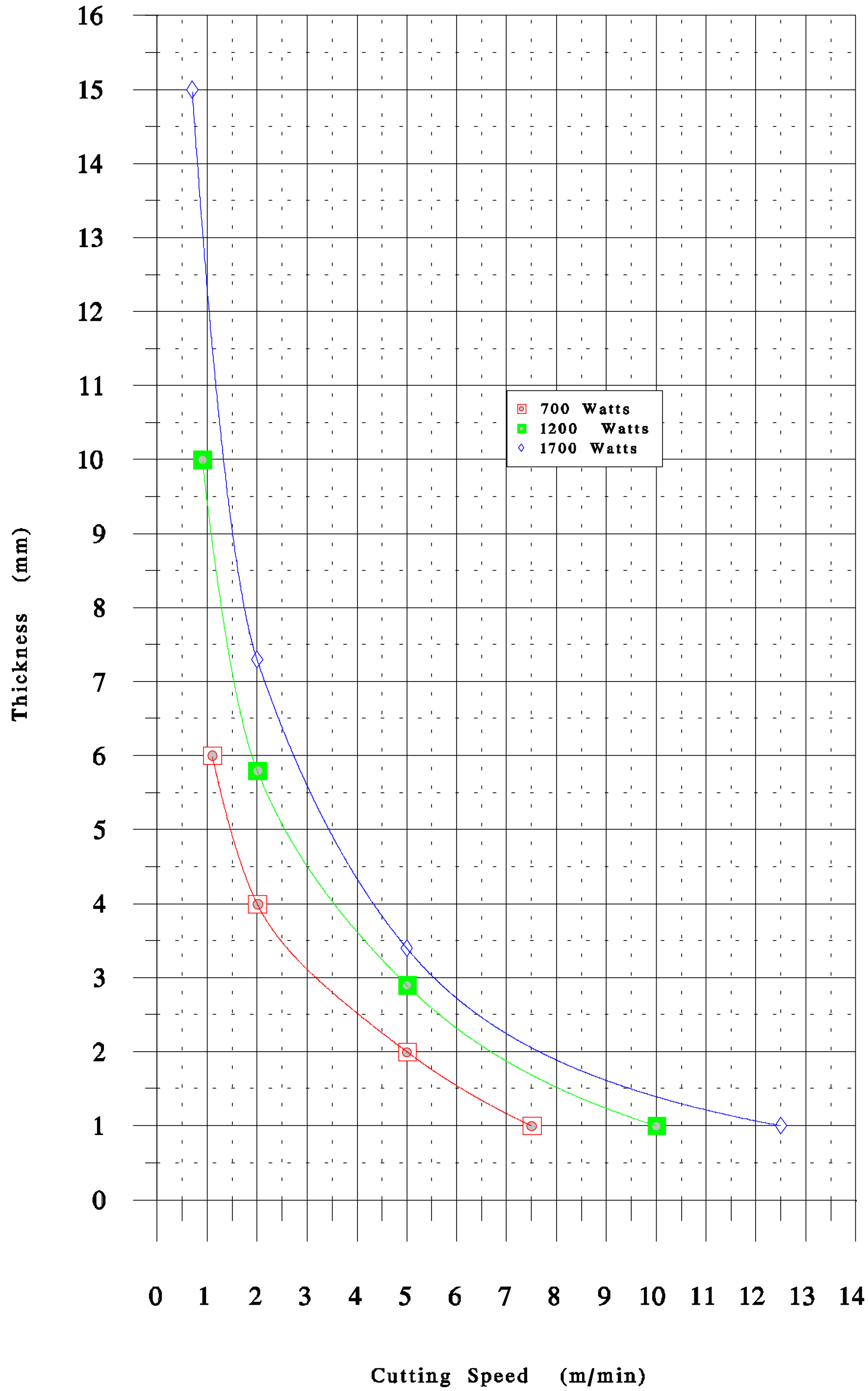


Figure 2.3

REPRESENTATIVE SPEEDS FOR CO_2 CUTTING OF STAINLESS STEEL WITH NITROGEN ASSIST

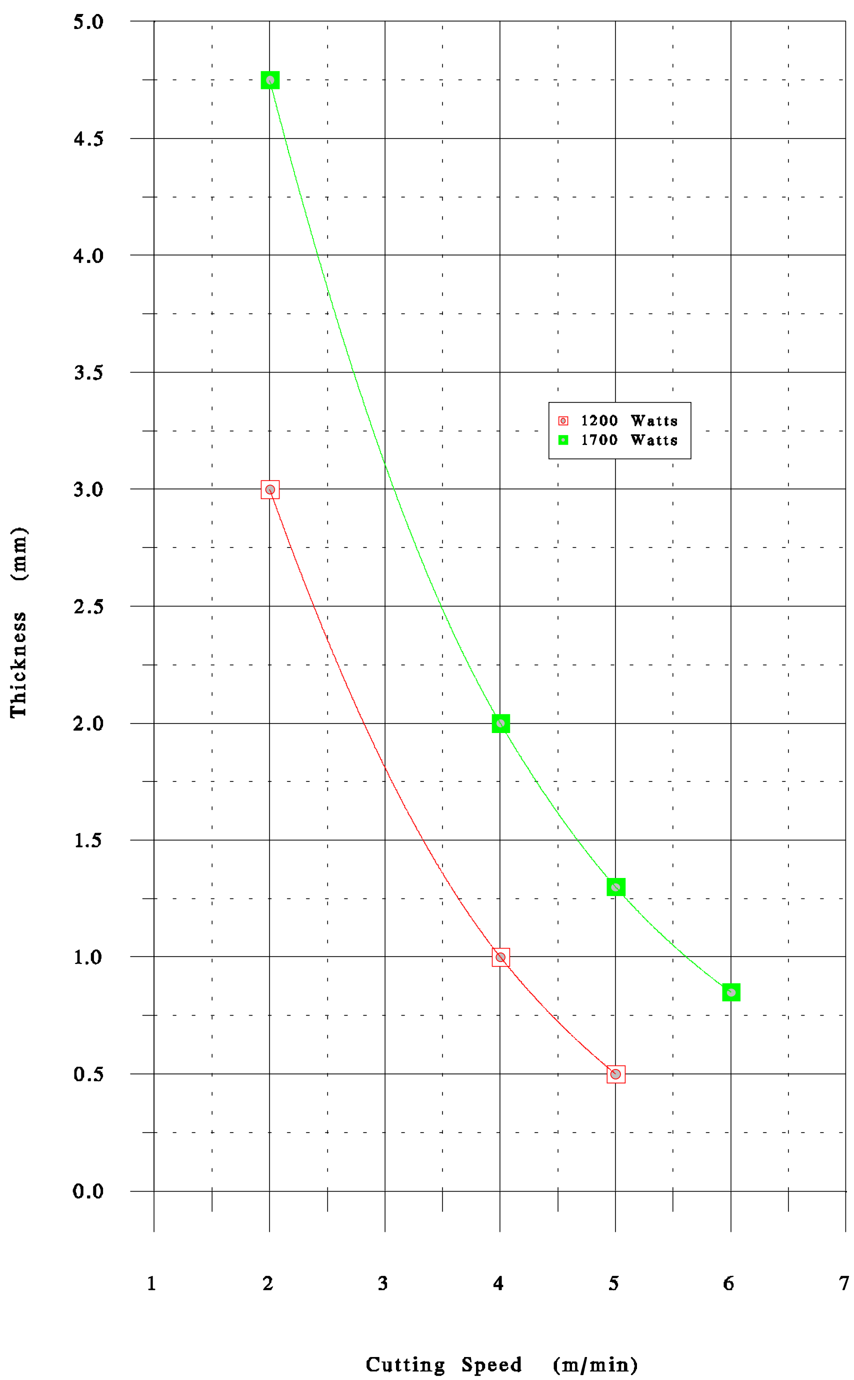


Figure 2.4

REPRESENTATIVE SPEEDS FOR Nd:YAG CUTTING OF MILD STEEL WITH OXYGEN ASSIST

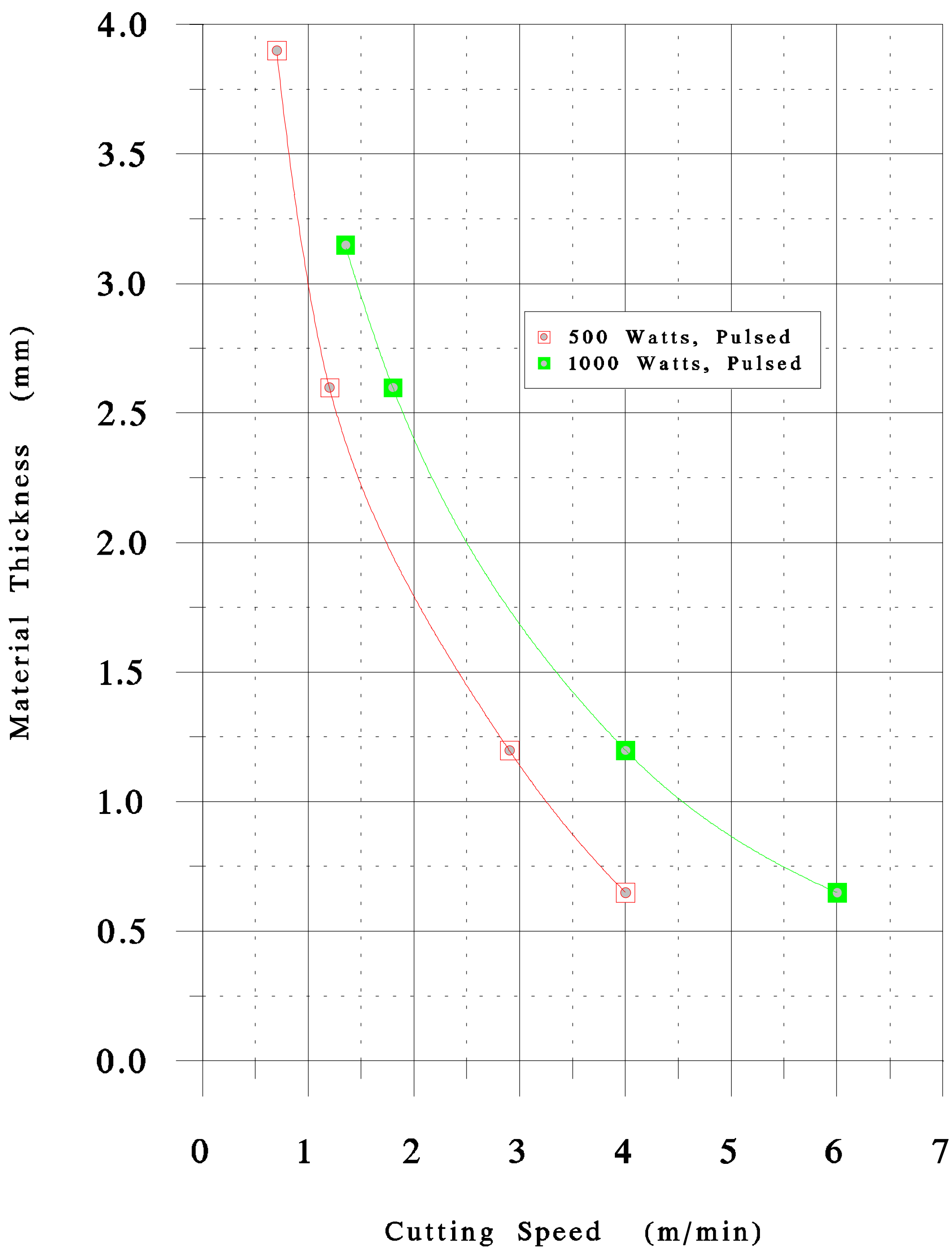
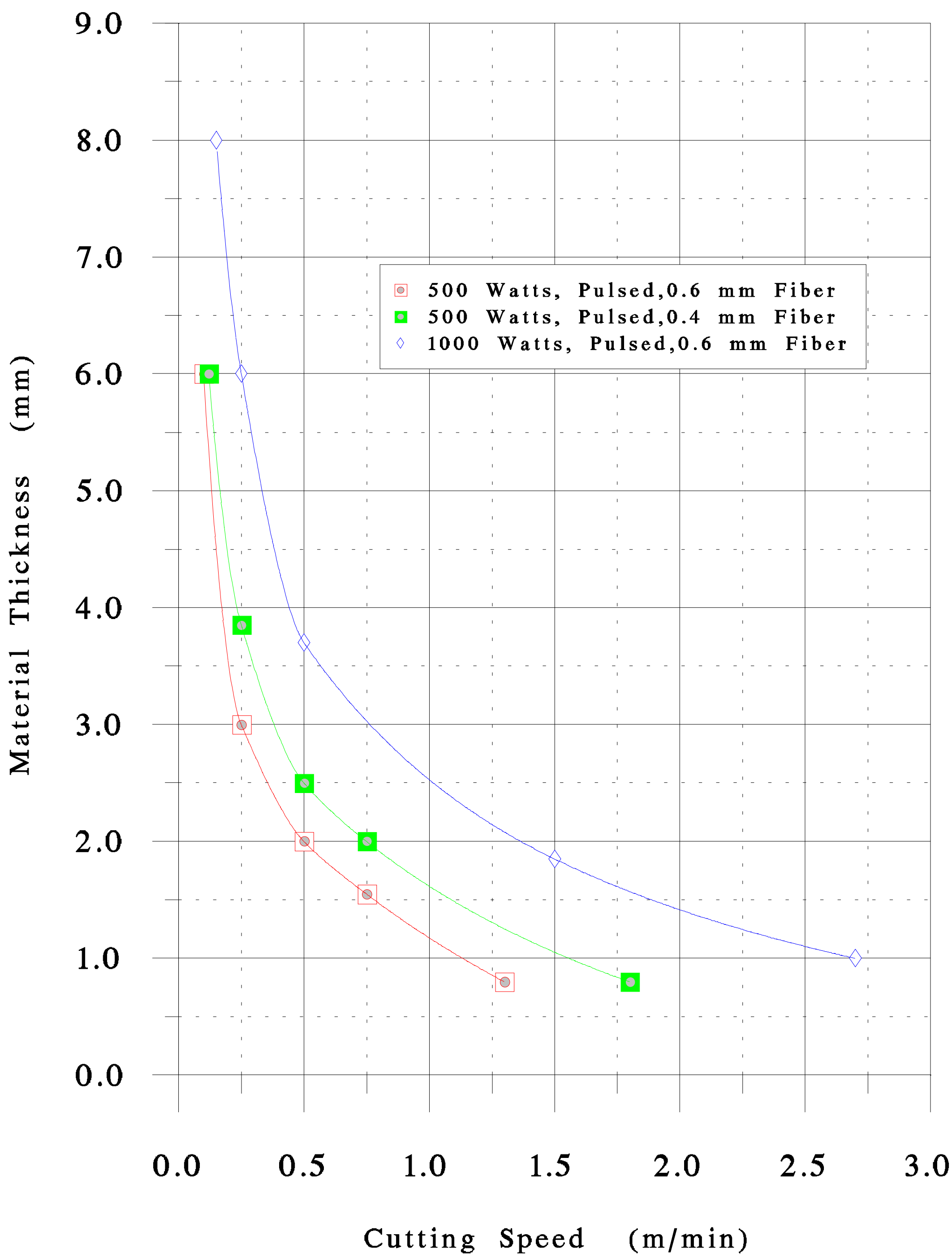


Figure 2.5

REPRESENTATIVE SPEEDS FOR Nd:YAG CUTTING OF STAINLESS STEEL WITH NITROGEN ASSIST



2.2 Transverse Electromagnetic Mode

The focusability of the laser beam is a function of the transverse electromagnetic mode (usually referred to as TEM, or simply "mode"). It is basically a means of describing how the power is distributed within the laser beam. It is comparable to the degree of sharpness of a cutting tool. A "bell" shaped (or Gaussian) power distribution is the most focusable mode (also referred to as TEM_{00}). Modes which approach this power distribution can be focused down to the theoretical minimum spot size. The TEM_{00} mode provides the most concentrated power density, which yields the fastest cutting speeds and narrowest kerf widths in sheet materials. However, because of the concentrated power density, care must be taken to insure the thermal stability of the internal (resonator) and external (beam delivery) optics. From the standpoint of the design of the optical components, this includes considerations such as; 1) appropriate optical material selection (reflectivity or transmittance), 2) optical component mass (thermal mechanical stability), and 3) efficient cooling of the optical component (typically requiring water cooling above 1500 Watts). From the maintenance side, this includes insuring a high degree of optical cleanliness, both from a preventative aspect (see *Section 3.4.3, Beam Delivery Purging*) and from a maintenance aspect (a more vigorous inspection and cleaning schedule).

The mode of a laser is characterized by a numerical value referred to as M-squared (M^2), see also *Section 2.3.1*. The full divergence angle (far field) of the raw laser beam (φ) is directly related to the M^2 value and the laser wavelength (λ), and inversely proportional to the waist diameter of the raw laser beam (D_o) as follows:

$$\boxed{\varphi = M^2(4\lambda/\pi D_o)}$$

Therefore, higher order or multi-mode beam profiles (higher M^2 values) are characterized by a tendency to spread out the energy distribution away from the center of the beam. The resultant focused spot is larger with higher order modes yielding a lower power density or concentration. As a result, higher order mode lasers are considered to be duller cutting tools than low order mode lasers of equivalent power output (see also *Section 4.6.1*).

Furthermore, higher order beam profiles may have a different (asymmetric) power distribution in two axes. This is a result of having differing modes in the two axes. The divergence of the beam effects where the focus spot is located relative to the focus optic (note that the focal length "f" of a focusing optic is the location of the focused spot for a perfectly collimated beam, see *Section 3.4.4*). Therefore, beams with asymmetric modes result in a different focus spot location for each axis. This condition is called astigmatism, and yields a cut quality (e.g. kerf and melt width, and kerf geometry) which is inconsistent and dependent upon cut direction. In general, radially symmetric modes approximating TEM_{00}, TEM_{01^*}, and TEM_{01} (i.e. $1 < M^2 < 3$, see *Section 2.3.1*) are used for CO_2 cutting, while much higher order modes are obtained with fiber optic beam delivery systems (M^2 values as high as 300, however this is offset because the Nd:YAG wavelength is one tenth that of CO_2, see *Section 2.3.1* for how wavelength affects focused spot size).

2.3 Focused Spot Diameter

It is the size of the focused beam, at a given power, which dictates the power density at the workpiece, and therefore controls cut speed, material thickness and kerf width. It is therefore useful to present the factors which influence the size of the focused beam.

2.3.1 Reflective/Transmissive Beam Delivery

The laser parameters that determine the size of the focused spot diameter (d) when focusing a raw laser beam, are wavelength (λ), mode/focusability of the laser beam (M^2), focal length (f), and raw beam diameter at the focusing optic (D), (see ***Figure 2.6***). The wavelength depends on the laser type (i.e. CO_2 , Nd:YAG, etc.). The wavelength of a CO_2 laser is 10.6 micrometers (10.6 microns or 0.0106 mm), for a Nd:YAG laser the wavelength is 1.064 microns (0.001064 mm). As stated in *Section 2.2*, the focusability of the laser beam is a function of the transverse electromagnetic mode. For a perfect "bell" shaped power distribution, M^2 =1 (referred to as high beam quality or low order), for other distribution types, M^2 >1 (referred to as lower beam quality or high order). See ***Figure 2.7*** for M^2 values for several radially symmetric modes. The focal length defines the distance from the focusing optic to the focal plane. Note that it is the diameter of the laser beam at the focusing optic, rather than the diameter of the beam as it exits the laser head, that determines focused spot size. This is important because laser beams are not perfectly collimated. The raw beam either converges to a "waist" region and then diverges, or in some lasers, simply diverges from the output of the laser head (referred to as having an intracavity “waist”). Note that the waist may move with output optic(s) temperature (e.g. laser power and optic(s) absorption). A change in waist location affects the size of the raw laser beam at the focusing optic. See *Sections 3.4.4 and 3.5.4* for further discussion of this topic.

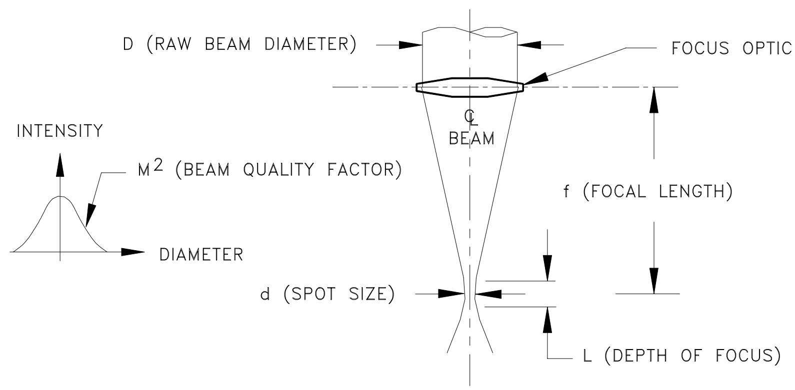
These parameters are related to the focused spot diameter by the following equation:

$$\boxed{\mathbf{d = M^2 (4\lambda f/\pi D)}}$$

Example 2.3.1: Calculate the spot diameter of a CO_2 laser with an M^2 =2.5, a focal length of 127 mm, and a raw beam diameter at the focus optic of 22 mm. Substituting for d = [(2.5)(4)(.0106)(127)]/[(3.14)(22)], and solving yields d = 0.19 mm (0.008 inch). *See also Examples 2.4.1A and 2.5*.

Figure 2.6

FOCUSING PARAMETERS
(Reflective/Transmissive Beam Delivery)



An alternate method of describing focusability is in terms of the "F" number (F#), which is defined as the ratio of the focal length (f) to the raw beam diameter at the focusing optic (D). Therefore, the smaller the "F" number, the smaller the focused spot diameter, as shown by the following equation:

$$\boxed{\mathbf{d = M^2\ (F\#)(4\lambda/\pi)}}$$

For a raw Nd:YAG laser beam the "beam quality" (BQ) factor is most often specified and not the M^2 value. The M^2 value, however, can be calculated from the beam quality value (with BQ expressed in millimeter-milliradians) by the following (see *Section 2.3.2, Fiber Optic Beam Delivery* for a further discussion of beam quality):

$M^2 = (\varphi D_o \pi)/(4\lambda)$, (see *Section 2.2*), and

$\varphi D_o = (4BQ)/1000$, (from *Section 2.3.2*, where $\varphi/2 = \Theta$, $D_o = D$ and the factor of 1000 is required to convert from milliradians to radians)

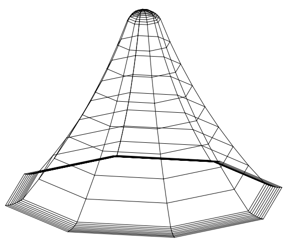
$M^2 = (\pi)(4BQ)/(1000)(4\lambda) = (3.1416)(BQ)/(1000)(0.001064)$
$M^2 = 2.9526\ BQ \cong 3BQ$

Therefore:

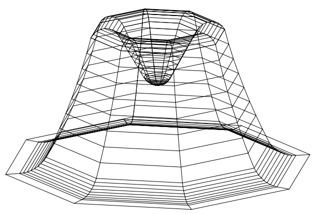
$$\boxed{\mathbf{d \cong 3BQ\ (4\lambda f/\pi D)}}$$

Figure 2.7

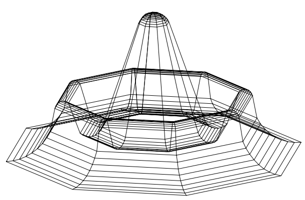
FOCUSABILTY FACTORS FOR SEVERAL MODES



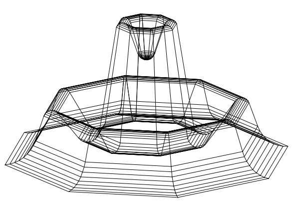
$M^2 = 1$ (TEM_{00})



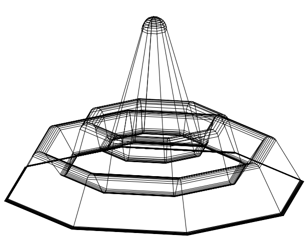
$M^2 = 2$ (TEM_{01*})



$M^2 = 3$ (TEM_{01})



$M^2 = 4$ (TEM_{02*})



$M^2 = 5$ (TEM_{02})

2.3.2 Fiber Optic Beam Delivery

2.3.2.1 Entering the Fiber

With fiber optic beam delivery systems the M^2 value used to described the laser mode in reflective/transmissive systems is replaced by a "beam quality" (BQ) measure (sometimes referred to as "beam product" (BP)), which is expressed in millimeter-milliradians. The beam quality is the product of the half-angle beam divergence (far field) in milliradians (Θ; note $\Theta = \varphi/2$), and the raw beam radius at the beam waist in millimeters (D/2). It also can be defined in terms of the radius of the raw laser beam (D/2), the focal length of any focus optic in millimeters (f_i), and the radius of the focused beam at the specified focal length in millimeters ($d_i/2$), or in terms of the focused beam cone half-angle in milliradians (θ_i) as follows:

$$\boxed{\mathbf{BQ = (\Theta)(D/2)}}$$

$$BQ = (\theta_i)(d_i/2) = \{1000 \tan^{-1}(D/2f_i)\}(d_i/2)$$

Note that the factor of 1000 is to convert radians into milliradians, and that $\tan^{-1}$ must be in radians.

Example 2.3.2A: Estimate the beam quality of a beam that has a diameter of 22 mm at the exit of the laser and a diameter of 31 mm at a distance of 2 meters from the first beam diameter location. First the divergence (Θ) must be calculated, where $\Theta = \tan^{-1}\{[(31-22)/2]/2000\} = 0.0023$ radians = 2.3 mrad. Therefore, $BQ \cong (2.3)(22/2) = 25$ mm-mrad.

In a fiber optic delivery system the raw beam from the laser is focused into the fiber. The ability of the fiber to transmit the input beam is dependent on the "numerical aperture" of the fiber and the beam quality (i.e. focusability) of the raw laser beam. The numerical aperture (N.A.) defines the angle in which the focused input beam must stay within in order to be efficiently coupled into the fiber, and is defined in terms of half-angle (θ). In other words, the cone angle of the focused laser beam ($2\theta_i$) must be smaller than the "acceptance cone" of the fiber optic (2θ) for efficient fiber optic transmission. Therefore:

$2\theta_i < 2\theta$, or simply $\theta_i < \theta$,

$\theta_i = BQ/[1000(d_i/2)]$ in radians from above, and

$\theta = NA/1000$ (1000 to convert from milliradians to radians)

Therefore, $BQ/[1000(d_i/2)] < NA/1000$, which reduces to

$BQ/(d_i/2) < NA$, or $BQ/NA = (d_i/2)_{minimum}$

If we let $(d_i/2)_{minimum}$ = $(\Phi_c/2)$ *fiber core radius in millimeters*, then

$(\Phi_c/2) \geq BQ/NA$

Furthermore, if the focused spot diameter of the input beam to the fiber optic is set to a predetermined maximum allowable size relative to the core diameter [based on a percent fiber fill (%Fill), typically set at about 70-90% of the fiber core diameter in order to accommodate misalignment and optical distortion (aberration) effects], then the minimum fiber optic core diameter (Φ_c min) can be determined for a given laser beam quality and fiber optic numerical aperture using the following equation:

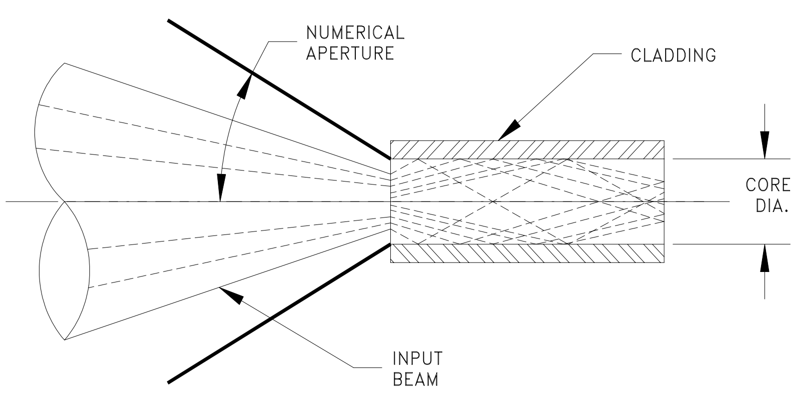
$(\%Fill/100)(\Phi_c/2) \geq BQ/NA$, therefore

$$\boxed{\mathbf{\Phi_c \text{ min} = (200/\%Fill)\ (BQ/N.A.)}}$$

Example 2.3.2B: For 70% fill, a beam quality of 25 mm-mrad, and a N.A. of 220 mrad, yields a minimum fiber core diameter of Φ_c min. = (200/70)*(25/220) = 0.325 mm. Therefore, the smallest standard fiber optic core diameter that can be used in most cases is about 400 micron.

Figure 2.8

FIBER OPTIC TRANSMISSION



2.3.2.2 Exiting the Fiber

Within the fiber the beam is transmitted via internal reflections within the fiber optic core (see ***Figure 2.8***). Typical fiber core diameters range from 0.3-1.0 mm. The beam exits the fiber optic at an angle limited by the N.A. of the fiber optic. The exit beam is then focused by one or more lenses (typically a collimating lens and a focus lens) to a small spot diameter. The parameters that determine the size of the focused spot (d) when focusing a laser beam that has been delivered through a fiber optic, are; i) fiber optic core diameter (Φ_c), ii) collimator focal length (f_c), and iii) focal length (f) of the focusing optic (***Figure 2.9***).

These parameters are related to the focused spot diameter by the following equation:

$$\boxed{d = (f/f_c)\Phi_c}$$

Example 2.3.2C: Utilizing a collimator with a focal length of 120 mm, a focusing optic with a focal length of 80 mm, and a fiber optic with a core diameter of 600 micron (0.6 mm), yields a focused spot diameter of d = (80/120)(0.6) = 0.4 mm (0.016 inch). *See also Examples 2.4.2A and 2.4.2B.*

Notice that the smaller the fiber optic core diameter, the smaller the focused spot diameter. However, reducing the fiber core diameter is limited by the beam quality of the input laser beam.

2.3.2.3 Exit Beam Quality

At present, there are two basic types of fibers used for high power Nd:YAG transmission, namely, step index and graded index (see *Section 3.5.1* for a further discussion of graded index fibers). The step index fiber is comprised of a core material (typically quartz) and an outer cladding material. In a step index fiber optic, all internal reflections of the transmitted beam occur at the core/cladding interface. The numerical beam quality of an exit beam (BQ_{exit}) that has passed through a step index fiber optic can be significantly greater than the numerical beam quality of the input raw beam (BQ_{input}). The resulting exit beam has a power distribution that is, in general, uniformly distributed (i.e. "top-hat" distribution) and less focusable. The actual exit beam quality is dependent on several factors, including: i) the length of the fiber optic, ii) the number and severity of bends in the fiber optic, iii) the core diameter of the fiber optic (smaller core diameters preserve the input beam quality better than larger core diameters), iv) the input cone angle (larger input cone angles preserve the input beam quality better through the fiber because your closer to the N.A.), and v) the angular alignment of the input beam relative to the centerline of the fiber (i.e. the input beam and the fiber should be coaxial, the quartz block surface should be perpendicular to the fiber, ...).

In general, however, the ***worst case*** exit beam quality can be approximated knowing the fiber core radius ($\Phi_c/2$) and the numerical aperture of the fiber optic (N.A.) by the following (i.e. the input cone angle is not preserved through the fiber, and in the worst case scenario the cone angle at the fiber exit is equal to the fiber numerical aperture):

$$\boxed{\mathbf{BQ_{exit} \cong (\Phi_c/2)(N.A.)}^{[1]} \quad \textit{\textbf{worst case}}}$$

[1] Note that the optical aperture of the collimator should be used if it is smaller than the numerical aperture of the fiber. For example, a collimator with a focal length of 120 mm and a clear aperture of 50 mm, yields an optical aperture of 205 mrad {from: $1000 \tan^{-1}[(50/2)/120]$}.

The ***best case*** exit beam quality can be approximated by assuming the input beam cone angle (θ_i) is preserved through the fiber so that the exit cone angle is the same as the input cone angle (as opposed to the numerical aperture of the fiber optic) by the following:

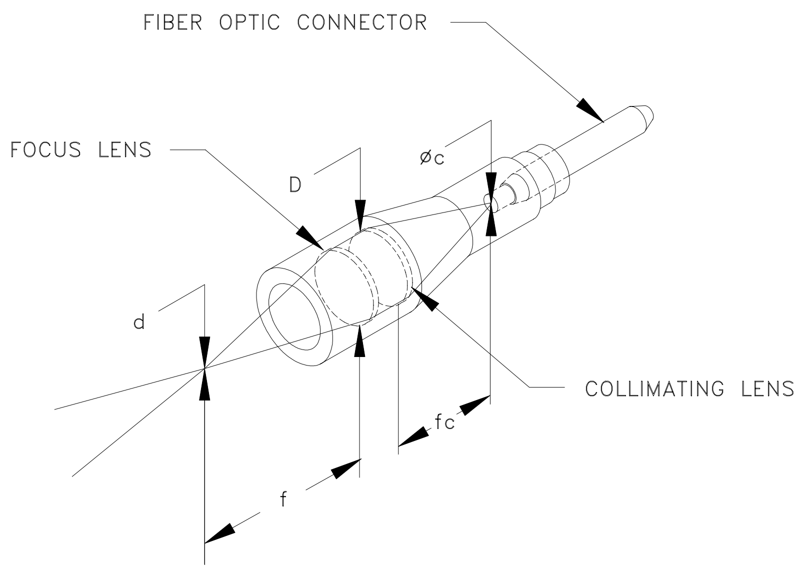
$$\boxed{\mathbf{BQ_{exit} \cong (\Phi_c/2)(\theta_i)} \quad \textit{\textbf{best case}}}$$

$\theta_i = 1000 \tan^{-1}(((D_i\text{-}d_i)/2)/f_i) \cong 1000 \tan^{-1}((D_i/2)/f_i)$ *in milliradians*, where D_i is the beam diameter at the incoupler with incoupler focal length of f_i and where the 1000 is required to convert radians to milliradians (because the focus spot size at the fiber $d_i << D_i$, d_i has a negligible effect on the incoupling angle and therefore can be ignored in this computation).

<u>Example 2.3.2D:</u> With an input cone angle of 110 mrad, a fiber optic core diameter of 600 microns (0.6 mm), a fiber numerical aperture of 220 milliradians, and an optical aperture of 125 milliradians. The best case and worse case exit beam quality would be approximately $BQ_{exit} \cong (0.6/2)(125) = 38$ mm-mrad (worst case, using the optical aperture since it is smaller than the NA, see Note [1] above) and (0.6/2)(110) = 33 mm-mrad (best case). Note also that $M^2_{exit} \cong 3BQ_{exit}$ yields a range of 99 to 198 (see *Section 2.3.1*).

Figure 2.9

FOCUSING PARAMETERS
(Fiber Optic Beam Delivery)



2.4 Depth of Focus

Another characteristic of the focused spot is the depth of focus (L), which defines the full range at which the focus spot size increases no more than a preset percentage (p), i.e. p=0.05 for 5%. In practice, the depth of focus defines the range in which the cut kerf width does not significantly increase. As a result, the depth of focus is one of the primary factors which influences the consistency of the cut (especially if the nozzle stand-off varies), and it is directly related to the set-up time (the larger the depth of focus, the shorter the time required to optimize the focus position). See *Section 4.6.3, Lens Type and Focal Length* for further discussion.

2.4.1 Reflective/Transmissive Beam Delivery

The depth of focus can be approximated by the following relationship:

$$L = [(p+1)^2 - 1)]^{1/2}(\pi d^2)/2\lambda M^2$$

Note: For raw Nd:YAG beams, beam quality values may be substituted by setting M^2 = 3 BQ.

Typically, the value of "p" is set at 5% (0.05), which reduces this equation to (with the value of "p" set at 5%, the power density within the depth of focus region decreases no more than about 9.3%, see *Excursus 1* below):

$$\boxed{\mathbf{L_{5\%} \cong d^2/2\lambda M^2}}$$

Example 2.4.1: Using the factors from *Example 2.3.1*, $L_{5\%} \cong (0.19)^2/(2)(.0106)(2.5)$ = 0.68 mm (0.027 inch).

Excursus 1
Depth of Focus Derivation

One of the fundamental beam propagation relationships that describes the beam diameter at any location along the propagation axis is generally presented as follows:

$$2W_Z = 2W_O \{1+ [(Z-Z_O)/Z_R]^2\}^{1/2} \qquad \textbf{(1)}$$

The terms in this equation are defined below, and can be correlated to the terms presented in this paper:

$2W_Z = d_Z$ = beam diameter @ reference location (Z) from waist
$2W_O = d$ = beam diameter @ waist location (Z_O)
$Z_R = \pi d^2/4M^2\lambda$ = Rayleigh range
$Z-Z_O = \Delta Z$ = distance between reference and waist locations

Substituting these terms back into equation (1) yields:

$$d_Z = d \{1+ (\Delta Z 4M^2\lambda/\pi d^2)^2\}^{1/2} \qquad \textbf{(2)}$$

Rearranging and solving for ΔZ yields:

$$\Delta Z = \pi d (d_Z^2 - d^2)^{1/2}/4M^2\lambda \qquad \textbf{(3)}$$

Depth of Focus (5% Definition)

If we allow the spot size to change 5% (i.e. $d_Z = 1.05d$), then equation (3) becomes:

$$\Delta Z_{5\%} = \pi d (1.1025d^2 - d^2)^{1/2}/4M^2\lambda = \pi d^2 (1.1025 - 1)^{1/2}/4M^2\lambda$$

However, the quantity $\{\pi(1.1025 + 1)^{1/2}\}$ approximately equals unity, therefore:

$$\Delta Z_{5\%} \cong d^2/4M^2\lambda$$

As defined above, ΔZ represents only half of the depth of focus:

$$\Delta Z_{5\%} = L_{5\%}/2 \cong d^2/4M^2\lambda$$

Therefore, multiplying $\Delta Z_{5\%}$ by two is equivalent to the 5% depth of focus as given in *Section 2.4.1*:

$$L_{5\%} = 2\Delta Z_{5\%} \cong 2(d^2/4M^2\lambda) = d^2/2M^2\lambda$$

Depth of Focus (Rayleigh Length Definition)

The Rayleigh length is often referred to in the context of depth of focus. If we allow ΔZ to equal one Rayleigh length, (rather than defining it by a 5% change in spot size) then:

$$Z_R = \Delta Z$$

$$\pi d^2/4M^2\lambda = \pi d\,(d_Z^2 - d^2)^{1/2}/4M^2\lambda$$

In order for this to be true:

$$d^2 = d\,(d_Z^2 - d^2)^{1/2}$$

Therefore, by rearranging, we find that at one Rayleigh length away from focus, the diameter of the spot is:

$$d_Z = (\sqrt{2})d = 1.414\,d$$

In other words, at one Rayleigh length away from focus, the spot diameter has increased about 41%, which correlates to a 50% reduction in power density as shown by the following:

$$P_d(d_Z) = 4P/\pi d_Z^2 = 4P/\pi(1.414d)^2 = 0.5\,(4P/\pi d^2)$$

Whereas with the 5% depth of focus ($L_{5\%}$), in which the spot diameter increase is 5%, the corresponding reduction in power density is 9.3% (or 90.7% of the focused spot power density):

$$P_d(d_{5\%}) = 4P/\pi d_{5\%}^2 = 4P/\pi(1.05d)^2 = 0.907\,(4P/\pi d^2)$$

2.4.2 Fiber Optic Beam Delivery

Recall that the depth of focus can be approximated by the following relationship:

$$L = [(p+1)^2 - 1)]^{1/2}(\pi d^2)/2\lambda M^2$$

As before, if the value of "p" is set at 5% (0.05), and using the mode value associated with the beam exiting the fiber optic $[(M^2)_{exit}]$, this equation reduces to:

$$L_{5\%} = 1.0058 \ d^2/2\lambda(M^2)_{exit} \cong d^2/2\lambda(M^2)_{exit}$$

For Nd:YAG lasers, beam quality values may be substituted by setting M^2 = 2.9526 BQ. Using this, and by setting λ equal to 0.001064 mm, results in:

$$L_{5\%} = 1.0058 \ d^2/(2)(.001064)(2.9526 \ BQ)_{exit} = 160.08 \ d^2/BQ_{exit}$$

From *Section 2.3.2.3, Exit Beam Quality*, we see that the beam quality of the exit beam is not known exactly, but can be bracketed between "best case" and "worst case" values, as follows [knowing the fiber core radius ($\Phi_c/2$), the numerical aperture of the fiber optic (N.A.), the radius of the beam at the incoupling lens ($\Phi_i/2$) and the focal length of the incoupling lens (f_i)]:

$BQ_{exit} \cong (\Phi_c/2)(N.A.)$ *Worst Case*

$BQ_{exit} \cong (\Phi_c/2)\{\tan^{-1}[(\Phi_i/2)/f_i]*1000(\pi/180)\}$ *Best Case*

Substituting these values back into $L_{5\%} \cong 160.08 \ d^2/BQ_{exit}$, the following relationships result:

$\boxed{\mathbf{L_{5\%} \cong 320 \ [d^2 / \Phi_c \ N.A.]}}$ ***Worst Case***

$L_{5\%} \cong 320.16 \ \{d^2 / \Phi_c \{\tan^{-1}[(\Phi_i/2)/f_i]*1000(\pi/180)\}\}$ *Best Case*

$\boxed{\mathbf{L_{5\%} \cong 18.34 \ \{d^2 / [\Phi_c \tan^{-1}((\Phi_i/2)/f_i)]\}}}$ ***Best Case***

Example 2.4.2A (Worst Case): Using the factors from *Example 2.3.2C* & assuming a NA of 220 mrad, $L_{5\%} = 320 \ [(0.4)^2/(0.6)(220)] = 0.39$ mm (0.015 inch).

Example 2.4.2B (Best Case): Using the factors from *Example 2.3.2C*, a beam diameter at the incoupling lens of 22 mm and a incoupling focal length of 60 mm, $L_{5\%} = 18.34 \ \{(0.4)^2 / [(0.6) \tan^{-1}((22/2)/60)]\} = 0.47$ mm (0.019 inch).

These values can be significantly different from each other depending on the incoupling beam diameter and focal length. It is important to note that because of the reduced beam quality of a Nd:YAG beam that has been transmitted through a fiber optic (especially a step index fiber, see *Section 3.5.1*), the depth of focus for a given spot diameter is much smaller than that of a reflective/transmissive beam delivery system.

In summary, note that the depth of focus is dependent on the exit beam quality (which is dependent on the fiber N.A., the fiber core diameter and the incoupling configuration, see *Section 3.5.1*) and the spot diameter. Therefore, if the numeric value of the ratio (f/f_C) remains constant, it has no influence on either spot diameter or depth of focus. For example, a fiber optic beam delivery system having f = 60 mm and f_C = 60 mm has the same spot size and depth of focus as a system having f = 120 mm and f_C = 120 mm.

Additionally, since $L_{5\%}$ is directly proportional to (d^2/Φ_c), and since d is directly proportional to ($f\Phi_c$), the following relationship proves insightful:

$$L_{5\%} \propto d^2/\Phi_c \propto (f\Phi_c)^2/\Phi_c \propto f^2\Phi_c$$

What this relationship indicates is that, under normal circumstances, the fiber core diameter should be minimized for a given laser in order to maximize the focal length (which maximizes the depth of focus and the distance the focus lens is away from smoke and spatter). This also allows for more flexibility when choosing the focal length (in other words, different focal lengths can be used to alter the focused spot size).

2.5 Power Density, Energy Density and Cut Energy

Power Density

Power density is defined as the ratio of laser power to the area of the focused spot and is directly related to the thickness of the material that can be cut. It is critical in that it encompasses both the laser power and the area in which that power is concentrated (see *Section 3.6.1* for a summary of factors which affect power density at the cut point). Neither a high power unfocused laser beam nor a low power focused beam is of much use for laser cutting. Power density (P_d), is related to laser power (P) and to the area of the focused spot (d) by the following (assuming a focused spot which is circular):

$$\boxed{\mathbf{P_d = 4P/\pi d^2}}$$

<u>Example 2.5:</u> For a raw beam of 2000 Watts, with a diameter of 0.8 inch, the $P_d = (4)(2000)/(3.14)(0.8)^2$ = 3,980 W/in^2. On the other hand, for the focused beam used in *Example 2.3.1*, with a power of 2000 Watts, the $P_d = (4)(2,000)/(3.14)(0.008)^2$ = 39,808,917 W/in^2!

Table 2.1

SPOT SIZE AND DEPTH OF FOCUS INTER-RELATIONSHIPS

Process Parameter	Short Focal Length	Long Focal Length
Spot size	smaller	larger
	higher cut speed *smaller kerf* *lower heat input* *thinner materials*	*lower cut speed* *larger kerf* *higher heat input* *thicker materials*
Depth of focus	shorter	longer
	higher part tolerance [1] *higher tooling tolerance* *longer time to find focus* *thinner materials*	*lower part tolerance* *lower tooling tolerance* *shorter time to find focus* *thicker materials*
Focus optic maintenance	higher	lower
	closer to smoke & spatter	*further from smoke & spatter*

[1] May require height following even on "flat sheet" applications.

Notice that doubling the focused spot diameter (by doubling the focal length for example), results in only one fourth the power density. However, doubling the focal length yields four times the depth of focus. This trade off between spot size and depth of focus is at the center of all focus optic choices when considering kerf width, molten material ejection and material thickness.

Energy Density

Energy density is related to the speed at which the power density is imparted into the material to be cut. A high speed cut of thin material imparts less energy into the material than does a low speed cut of thicker material (at a given power density). The available energy density is directly proportional to the power density (P_d) and the spot size (d), and inversely proportional to the cutting speed (V):

$$\boxed{E_d = d(P_d/V)}$$

Note that: $E_d = d(P_d/V) = d(4P/\pi d^2 V) = 4P/\pi dV \propto \mathbf{P/dV} \propto \mathbf{DP/fV}$

(where "D" is the diameter of the raw laser beam at the focus optic, and "f" is the focal length of the focus optic).

Therefore, if P/dV (or DP/fV) is held constant, the energy density into the material to be cut is constant.

The energy density along with coupling efficiency (the ability of the material to be cut to absorb the energy density of the focused beam), determines the cut energy from the laser. The cut energy from the laser along with the exothermic energy from oxygen cutting (when applicable) establishes the required cut speed for a desired cut thickness (provided the minimum kerf for efficient ejection is obtained). The coupling efficiency is dependent on many things, a few of which are; laser type, power density, material reflectivity and conductivity, material surface condition, and the amount of volatile constituents in, or coatings on, the material.

Cut Energy

While the ***energy density*** is related to the ***power density*** and ***spot size***, the **cut energy** is related to the **power** and **cut length**. The cut energy (E, i.e. how much energy has been utilized for a given cut length) is directly proportional to the power (P) and cut length (w), and inversely proportional to the cutting speed (V):

$$\boxed{\mathbf{E = w(P/V)}}$$

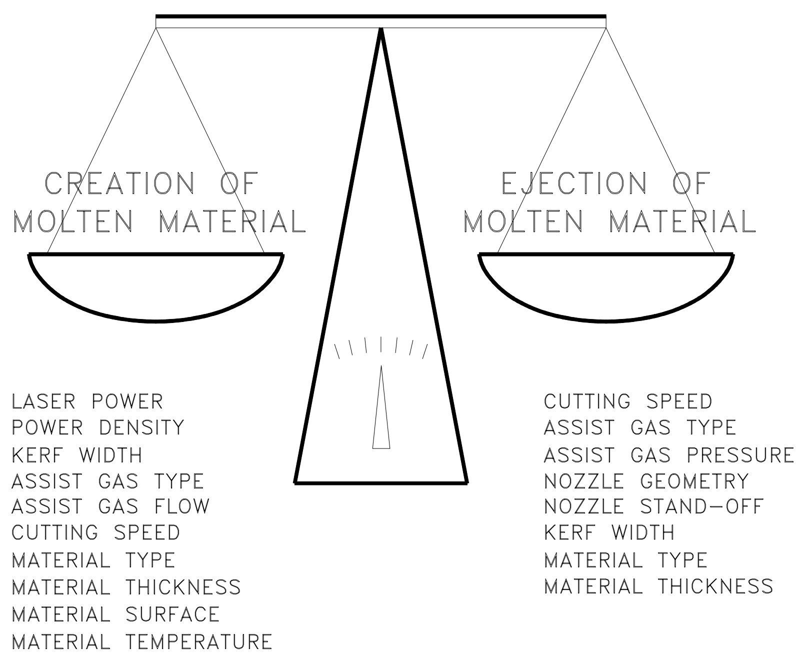
The total cut energy (laser and reactive gas) is responsible for the creation of molten (and/or vaporized or decomposed) material, which must be ejected from the kerf. This forms the most basic relationship of laser cutting, which is:

Creation of molten/vaporized/decomposed material	**=**	***Ejection of molten/vaporized/decomposed material***

A good laser cut involves the adjustment of parameters to insure this equilibrium. Many of the parameters, however, affect both the creation and ejection simultaneously (see ***Figure 2.10***). Therefore, the adjustment of parameters in laser cutting is often not straight forward. This complexity also influences troubleshooting, because for many of the symptoms there can be more than one cause.

Figure 2.10

CREATION AND EJECTION BALANCE



Finally, from an energy standpoint, the following energy balance shows some of the additional complexities encountered in laser cutting:

ENERGY IN	**=**	**ENERGY OUT**		
energy supplied to to cut zone	**=**	**energy used to generate cut**	**+**	**energy losses from the cut zone**
laser (electromagnetic energy) **+** *reactive gases (chemical/exothermic energy)* **+** *gas dynamics (kinetic energy)*		*heat of vaporization & fusion* + *ejected material & assist gas*		*radiated and reflected light (including plasma)* + *transmitted light (through kerf)* + *conducted & convected heat* + *noise*

Table 2.2

SUMMARY OF LASER PARAMETER CALCULATIONS

Process Parameter	Reflective/Transmissive Beam Delivery	Fiber Optic Beam Delivery
Spot Size	$d = M^2 (4\lambda f/\pi D) = M^2 (F\#)(4\lambda/\pi)$ $d = 3BQ (4\lambda f/\pi D)$	$d = (f/f_c)\Phi_c$
BQ of Focus Spot	$BQ_{spot} \cong$ BQ of raw beam	$BQ_{exit} \cong (\Phi_c/2)(N.A.)$ *worst case* $BQ_{exit} \cong (\Phi_c/2)(\theta_i)$ *best case*
Depth of Focus	$L_{5\%} \cong d^2 /2\lambda M^2$	$L_{5\%} \cong 320\ (d^2/\Phi_c N.A.)$ *worst case* $L_{5\%} \cong 18.34\ \{d^2/[\Phi_c \tan^{-1}(D_i/2f_i)]\}$ *best case*
Power Density	$P_d = 4P/\pi d^2$	$P_d = 4P/\pi d^2$
Energy Density	$E_d = dP_d/V$	$E_d = dP_d/V$
Cut Energy	$E = wP/V$	$E = wP/V$

3. SYSTEM CONSIDERATIONS

3.1 Basic Components

Recall that the laser is a device that generates a nearly collimated beam of light energy. The laser by itself has extremely limited potential. However, when its beam is directed, manipulated and focused with respect to a workpiece, it has a consistency that is ideally suited for automated processing.

3.1.1 Beam Delivery System

The beam delivery system is comprised of components that accept the beam from the laser (and enclose it), direct it to the workpiece, and condition it into a useable form of energy. These generally include; i) beam bending mirrors, interconnecting beam guard tubes, and may include a beam collimator for moving beam or long beam delivery systems in a reflective system, or ii) a coupling module, fiber optic cable and a collimator in a fiber optic delivery system. In addition, both systems require a focus module with a lens, and a gas jet nozzle.

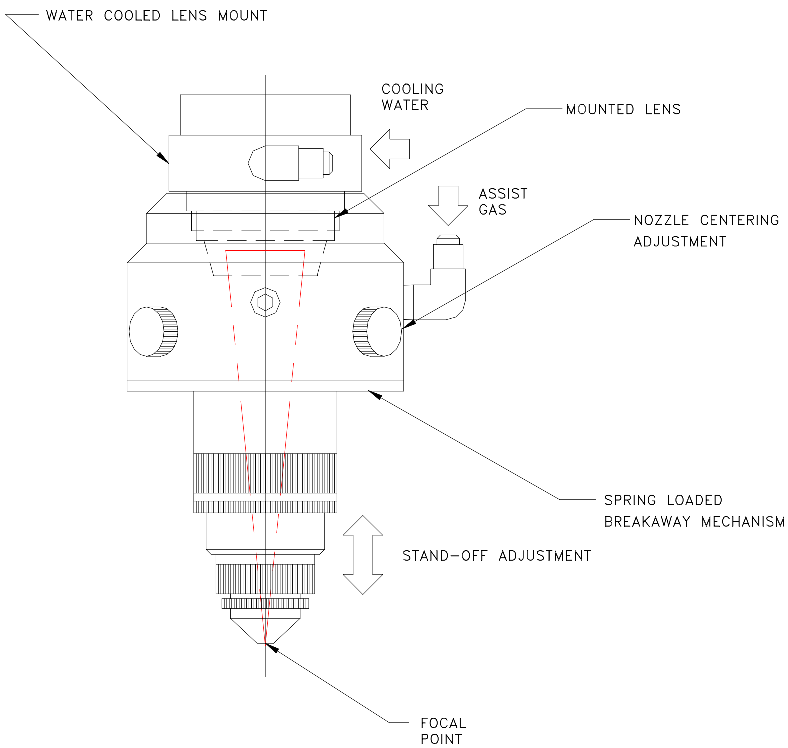
Focus modules provide a housing for the focusing lens. These assemblies generally provide a means to adjust the focal position relative to the part while maintaining a desired stand-off gap. In addition, they typically provide the adjustments required to center the focused beam through the nozzle orifice. These assemblies must generally be attached to a rigid, linearly adjustable axis (e.g. dove-tail slide, THK style rails, etc.) which can be used to adjust the focus position relative to the part [usually about ± 25 mm (± 1 inch) is all that is required if only one focal length and one part geometry is to be cut with the system]. This axis may be controlled either manually or via automation (i.e. servo motor, etc.). The adjustable axis may be designed to allow for various focal lengths (such as on a lab or development system), or various part geometries, thus significantly increasing the range of adjustment required. The focus adjustment axis, if manual, should have a lock down provision, as well as an integrated dial indicator (for both tracking and holding the focus position). If multiple part geometries are to be cut on the same system with frequent changeover, a servo controlled axis (with a brake if this axis is parallel to gravity) can be considered.

Nd:YAG focus modules typically use inexpensive, expendable glass cover slides to protect the focus optic from spatter and smoke from the cutting process. With CO_2 lasers, glass cover slides cannot be used, and the cover slide materials which can be used cost almost as much as the focus optic and hence are generally not used. Height sensing devices (either mechanical or electronic) can be incorporated to automatically maintain the proper focal point position and stand-off gap regardless of undulations in the workpiece surface.

Gas jet nozzle assemblies (see ***Figure 3.1***) are usually integrated with the focusing assembly below the lens in order to direct the desired assist gas into the cut point. A properly designed nozzle tip is very important to the cutting process (see *Section 4.6.6, Gas Jet Nozzle* for further discussion). It can maximize feedrates and cut quality with minimum gas consumption.

Figure 3.1

EXAMPLE OF GAS JET NOZZLE



3.1.2 Motion System

Lasers must be integrated as part of larger systems. In addition to the laser, each system features beam delivery components (see *Section 3.1.1*), a method of material handling, and a control system to govern its action. The relative motion of the focused laser beam with respect to the material can be accomplished by movement of the beam, movement of the part, or a combination of the two. This choice is somewhat dependent upon the material that is to be cut. If simple edge clamping can be used to move the material about freely, a rigidly mounted focus assembly in position above a moving X-Y table is an effective and reliable approach. Conversely, difficulty in mobilizing material such as uncoiled bolts of flimsy fabric or large sheets of thick armor plate steel at speeds commensurate with the chosen laser's capabilities point toward motion of the beam.

Systems range from simple set-ups where material is moved linearly under a fixed beam, to sophisticated multi-axis motion systems used for three-dimensional contour cutting. Two dimensional cutting systems come in the following three configurations; 1) fixed beam (where the optical delivery system remains fixed), 2) moving beam (where the workpiece remains fixed), and 3) hybrid system (where one optical axis and one table axis moves). Each have strengths and weaknesses which must be weighed. Presented in ***Table 3.1*** below is a summary of a few of the more important considerations for two-dimensional cutting systems.

Three dimensional contouring systems presently make-up less than ten percent of the installed base. Three dimensional cutting systems are comprised of primarily two types of five (or six) axis gantry systems. One type has all the motion in the optical axes, while the other has one table axis motion, which may allow for easier loading and unloading of fixtures. Robots are also used for 3-D cutting. However, they are, in practice, limited to Nd:YAG lasers with fiber optic beam delivery (see ***Figure 3.2***). Robot rigidity and accuracy must be considered, along with the basic laser considerations (e.g. the effect of wavelength on material interaction, and the effect of fiber optics on spot size and kerf width).

Dynamic positioning accuracy poses the most significant problem in maintaining the cutting system's overall precision. This concerns the dynamic response in movement of the positioning system's drives rather than the system's point to point positioning and repeatability capabilities. Inadequate encoder line count and mechanical deficiencies such as low motor torque, excessive backlash, excessive system inertia, and insufficient mechanical rigidity can all contribute to erratic contouring. High precision systems utilize mechanical assemblies compatible with the system's anticipated changes in inertia. They use precision components such as low inertia high torque servos, high resolution encoders, rigid low mass structural parts, and high-efficiency, high accuracy ball screw, rack and pinion or linear motor assemblies.

The laser is capable of continuously delivering a consistent amount of light energy that is directed at the workpiece. The interaction of the beam with the material occurs at a predictable rate. To achieve consistent cut performance, the focused spot must move smoothly at a constant velocity throughout the desired cut contour. Any dwell, acceleration or deceleration during the cut at constant laser power will result in inconsistent kerf and/or dross. Therefore if a constant cutting velocity cannot be maintained by the motion system or the system control, decreased power or pulsing during transition velocities is required (see *Section 3.2, System Control*).

Table 3.1

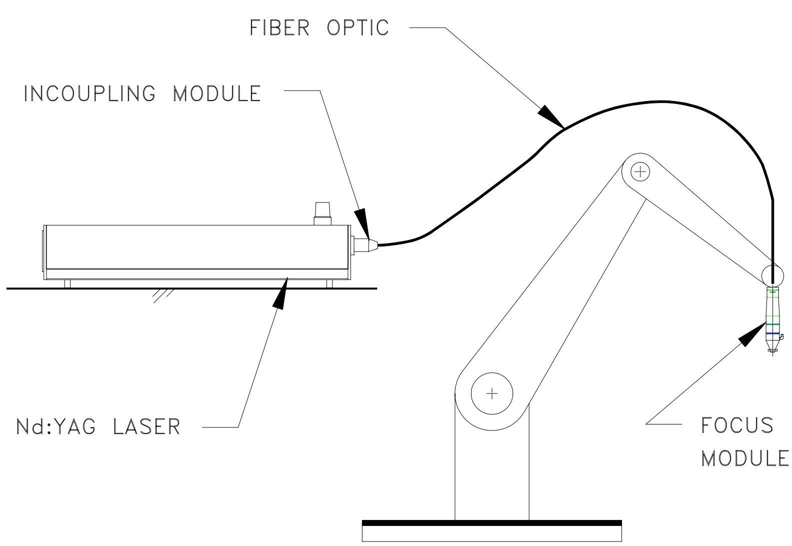
SUMMARY OF 2-D MOTION SYSTEM CONSIDERATIONS

Parameter Considered In Design of Machine	Fixed Beam (moving x-y table)	Hybrid (x table, y optics)	Moving Beam [1] (flying x-y optics)
Cost	lowest	medium	highest [2]
Laser Beam Alignment Time	shortest	moderate	longest [3]
Effects of Divergence on Cut	none	some	most [4]
Material Handling Time *(as a proportion of per sheet cycle time)*	higher	higher	lower [5]
Inertia Effects on Accuracy & Speed *(also vibration)*	highest	medium	lowest
Material Weight Restriction	highest	medium	lowest
Foot Print	largest	medium	smallest
Part Clamping & Handling Requirements	highest	medium	lowest
Optical Power Loss	lowest	medium	highest
Ability to Keep Optics Clean *(Due to particulate migration [6] & number of optics)*	highest	medium	lowest

[1] Including moving laser (e.g. Nd:YAG with reflective/transmissive beam delivery, and "no flow" CO_2 slab laser).
[2] Cost is relatively high due primarily to [3] and [4] below.
[3] Orthoganality of beam delivery and mirror stability become critical, design and cost increase.
[4] Collimating of laser beam may be required, this adds optics and associated maintenance and alignment issues.
[5] With pallet changer.
[6] Especially in the case of bellows w/o proper venting, or telescoping tubes w/o proper sealing.

Figure 3.2

ROBOT WITH FIBER OPTIC BEAM DELIVERY



3.1.3 Gas Delivery System(s)

Laser gases (if required) and the cutting assist gas must be delivered to the laser and gas jet nozzle respectively (see ***Figure 3.3*** for example of assist gas delivery panel). Gas bottles, liquid gas containers or bulk vessels are utilized. A few of the many considerations when specifying a gas delivery system are:

Laser Gas Delivery Considerations

a) pressure regulation,
b) pressure adjustment and setting,
c) pressure sensing (e.g. detect when gases are low), and
d) in process bottle or vessel changeover.

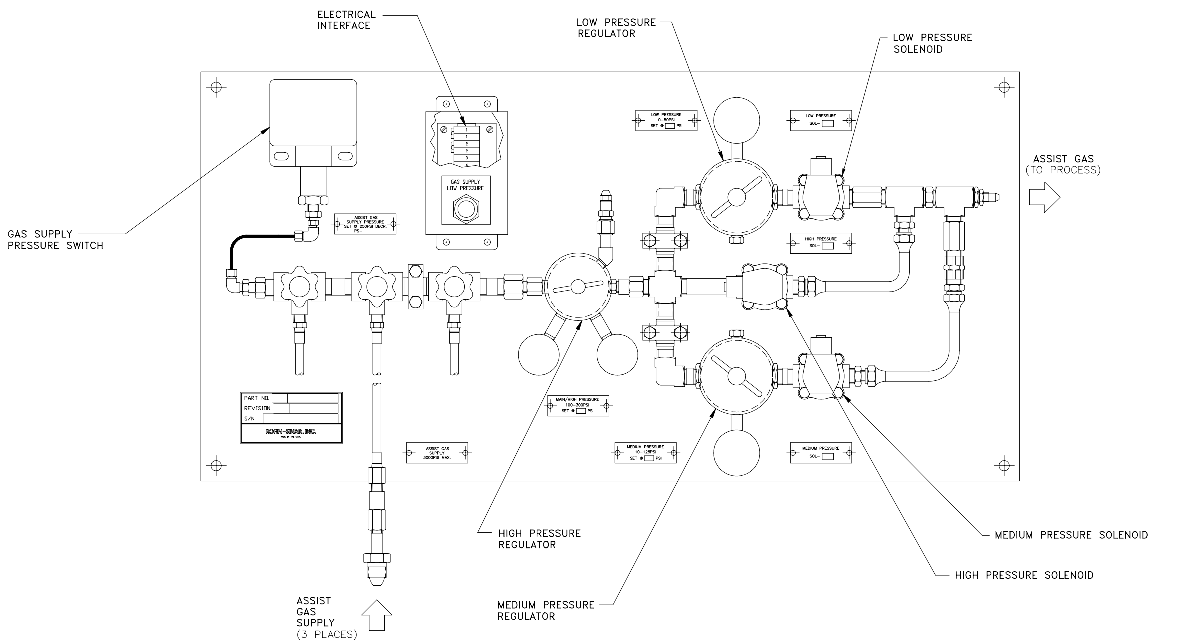
Assist Gas Delivery Considerations

a) pressure regulation and adjustment/setting (e.g. via CNC part program and servo valve),
b) high pressure and flow component selection (e.g. solenoids, hoses and focus lens),
c) pressure sensing (e.g. detect when gases are low),
d) pressure and flow monitoring at cutting head,

e) solenoid life cycle specification and cycle rate (e.g. ball valve with pneumatic actuator may be desirable for high cycle requirements), and
f) supply hose materials which can withstand reflected power (e.g. stainless steel braided hose), especially when cutting highly reflective materials such as aluminum.

Figure 3.3

EXAMPLE OF ASSIST GAS DELIVERY PANEL
(Three Pressure)



3.1.4 Exhaust System

An exhaust system for removing vaporized and/or decomposed material is required. When cutting materials that can emit toxic vapors (such as plastics, or materials containing beryllium or lead), fumes must be collected and filtered, and the filters must be safely handled and properly disposed of. In general, the type of exhaust system (including volumetric flow rate and filtering capacity) must be considered along with cutting cycle time requirements, material(s) to be cut and filter changeover options. In addition, careful attention must be given to the location of the inlet and exhaust ports, to insure optimum smoke and fume removal. In this regard, flexible exhaust tubing may be used to exhaust closer to the cutting process.

The cross sectional area of the inlet and exhaust ports should be appropriate for the volumetric flow rate required. The inlet port should incorporate a filter, and be baffled in order to maintain a light tight enclosure. The effect of a filter and the baffle on air flow rate must be considered. In addition, it may be useful to electronically monitor filter cleanliness (via flow or pressure drop sensing) so that filter exchange/cleaning occurs at intervals designed to ensure optimum smoke and fume removal. This will help keep the optics and enclosure as clean as possible, thereby maximizing process performance and uptime.

The material's Material Safety Data Sheet (MSDS), can be helpful for identifying hazards. Federal, state and local laws should be researched for regulations concerning fume handling. In addition, users must work closely with the cutting system manufacturer to design a fume removal system appropriate for all materials intended to be laser cut. See also *Section 3.7, Laser Safety*.

3.1.5 Chiller

Lasers and many beam delivery components require water cooling to maintain consistency and function. Using city water for this purpose is cost prohibitive, therefore an industrial water chiller is typically required. The chiller can be either water cooled (using city water or a cooling tower) or air cooled via integral fans. The laser and beam delivery may require cooling water at two temperatures to avoid condensation on moisture sensitive components, in which case either a dual circuit chiller, or a chiller and an auxiliary cooler may be used. A few of the considerations for proper chiller selection and installation are listed below:

Cooling Water Flow

A flow rate equal to or greater than the specified total minimum flow rate is required for the laser as a stand alone system. If water cooled accessories (e.g. beam benders or focus module) are integrated into the system, a flow rate greater than the specified total minimum flow rate will be required for adequate cooling. Installing a flow meter on the chiller supply line will help identify maintenance requirements (e.g. filter replacement, chiller flushing). Note that water additives can increase viscosity and therefore change chiller pump requirements. In addition, manual water by-pass systems on chillers (to prevent pump from dead heading) will also reduce water flow to the system. Automatic by-pass systems (which open only during a dead head condition) are preferred but are more costly.

Pumping Supply Pressure

A supply pressure (flowing not static) equal to or greater than equivalent to the sum of the maximum total pressure drop across the laser (ΔP_{laser}) plus the pressure drop from the chiller to the laser inlet ($\Delta P_{supply\ line}$) and the pressure drop from the laser outlet to the chiller ($\Delta P_{return\ line}$), must be available at the chiller [P_{supply}, not to exceed the maximum supply pressure allowed at the laser inlet ($P_{laser\ max.}$)]. Consult the chiller manufacturer for the pressure drop in the supply line (including filters and/or strainers) and the pressure drop in the return line, to insure adequate chiller supply pressure. Note that the pressure drop in the supply and return lines is dependent on many factors, a few of which are; i) flow rate, ii) water additive, iii) line material, inner diameter and length,

v) quantity and geometry of all fittings (e.g. elbows, reducer bushings), vi) filter quantity and mesh size, and vii) straightness of hose (if used).

$$\boxed{\mathbf{P_{supply} \geq \Delta P_{laser} + \Delta P_{supply\ line} + \Delta P_{return\ line} < P_{laser\ max.}}}$$

Temperature Control

Note that an increase in supply water temperature to the laser results in a decrease in maximum laser power output. Therefore, it is critical to operate at the nominal water temperature, and within the temperature stability, specified for the laser. The temperature set point and stability must be maintained regardless of laser and accessory heat load. This can range from 10-100% of the maximum cooling requirement. An adjustable temperature control on the chiller (and the resonator circuit for models requiring dual circuit cooling) is recommended to avoid operating at conditions below dew point (see *Section 3.4.5*).

Cooling Capacity

Review the cooling requirements with the chiller manufacturer to insure that the chiller will give the desired temperature control when running the laser at low power and will give adequate cooling on hot days. Note that water additives generally reduce heat transfer, and chillers must be sized to accommodate this. Also, consider the increased heat load from the chiller (particularly with an air cooled chiller) on facility air conditioning.

Water Quality

Typically, clean tap water can be used for filling the chiller (providing it meets the water quality specifications required for each laser). Sometimes distilled or deionized water is specified. Note that water additives may also be recommended. Filters should be provided on the chiller supply line to decrease contamination particulates in the water system (filter sizes are typically given for each laser). Filters and/or strainers must be routinely cleaned/replaced to avoid flow restriction. A viewing port for confirming water quality is recommended. The water system should be flushed and refilled regularly.

Plumbing

Non-corrosive materials (e.g. CPVC, PVC, copper, stainless steel, and brass) should be used for all wetted surfaces within the chiller and the field installed plumbing components. Do not use carbon steel, black iron or galvanized pipe due to their high rust and corrosion potential which may result in water system blockage and subsequent heat damage to laser components. Review plumbing requirements between laser and chiller with the chiller manufacturer to insure minimum pressure drop and adequate flow rate. Keep in mind that as the distance between the laser and the chiller increases, and as the flow rate requirements increase, the inner diameter of the plumbing which connects the laser with the chiller must also increase. ***Note:*** for CO_2 systems, if hard plumbing is used (e.g. copper or PVC), a flexible connection to the laser is required to allow the laser to be moved for beam alignment.

Accessories Cooling
In general, water cooled beam delivery accessories are cooled via the industrial chiller used to cool the laser. Accessories should be connected in parallel with the main laser cooling circuit in single circuit cooling systems, and connected in parallel with the resonator cooling circuit in dual circuit cooling systems. For systems with many water cooled accessories, and with accessories requiring different flow rates, several parallel branches may be necessary to achieve the required flow rates. A flow meter and flow switch should be installed in each parallel water circuit so that the water flow rate can be monitored both visually and via the system controller. Also, the material for the water hoses in the proximity of the cutting head should be selected which can withstand reflected power (e.g. stainless steel braided hose), especially with when cutting highly reflective materials such as aluminum.

3.2 System Control

The entire cutting system should be under the direction of a central controller capable of actuating the laser in coordination with the motion system. It is key that the controller have sufficiently high sampling rates to effectively deal with the encoder signals to maintain accuracy and smoothness of motion. In order to process information at high speeds for smooth continuous motion, the controller should be able to pre-read blocks or program information in advance to determine the accelerations required to maintain constant velocity during a change of direction. Refer to ***Table 3.2*** for a typical laser system interface.

Dynamic Power Control
In the event that a constant velocity cannot be maintained throughout the cut (e.g. during the contouring of sharp radii), a system which employs interactive laser power ramping can be used. However, much better results are obtained when direct pulsing is employed by varying the duty cycle of pulsing, on the fly. By utilizing frequency modulation of pulses of predetermined pulse energy (i.e. a given peak power and pulse length, and therefore constant power density), the cutting performance of the laser can be matched to the actual feedrate with a linear relationship. Once this relationship is established for a given material and thickness, this technique leaves the programmer free to set feedrate purely on the basis of machine performance and the required accuracy of the cut part.

For multi-purpose processing, cutting systems normally use computer numerical controllers (CNC). These devices provide flexibility for multi-axis control. Hardware features to assist in programming generally include a CRT display, keyboard, manual axis controls, feedrate overrides, and a variety of input/output devices such as tape readers, disk drives, DNC links and other communication interfaces. While programming features tend to distinguish one controller from another, most offer features including; linear and circular interpolation, axis scaling, inch or metric programming, absolute and incremental dimensioning, axis rotation, sub-routines, calculation blocks, and insert/modify/delete capabilities of stored part programs. Off-line programming allows for maximum laser utilization.

There is a strong trend to control in real time all the typically user addressable cutting parameters from the CNC part program. This includes, but is not limited to; i) laser power, ii) power/feedrate relationship (i.e. Dynamic Power Control), iii) cutting gas type, and iv) cutting gas pressure. This leaves only the focal length, focus position, stand-off distance and nozzle diameter as manually settable.

3.3 Polarization

As discussed previously (see *Section 2*), laser light is comprised of electromagnetic waves. This means that laser beams possess electric and magnetic components (i.e. vectors) which are at right angles to one another and are perpendicular to the laser beam's direction of travel. It is the orientation of the electric vector that determines the direction of the beam's polarization.

The significance of the orientation of polarization is related to the role it plays in the relative degree of absorption of the laser's energy into some materials, most notably metals and ceramics. A cut made parallel to the beam's polarization produces a narrow kerf and sharp, straight edges. As the direction of travel of a cut angles away from the direction of polarization, there is an associated decrease in energy absorption. In addition, the cutting speed is slower, the kerf widens, and the edges tend to be rougher and not square to the material's surface. Once the direction of travel becomes perpendicular to the direction of polarization, the edges are no longer sloped but speeds are even slower, the kerf is widest, and the cut quality appears even rougher yet.

While in theory it is desirable, it has not been found feasible to maintain the orientation of polarization parallel to the direction of travel for complex cut geometries. Circular polarization of the laser beam has been successfully employed to negate the unfavorable traits of a linearly polarized beam, thereby allowing the user to consistently obtain high quality cuts regardless of cut direction. Typically, CO_2 cutting lasers emit linearly polarized light, which must be transformed to circularly polarized light. If the plane of the linear polarized light is set at 45° (to the horizontal), then circular polarization is normally achieved via one external beam bending mirror which has a special coating (referred to as either ¼ wave or 90° phase shift mirror). Once circular polarization is achieved, care must be taken to preserve this condition. This is accomplished by using optical components that induce a minimal change in polarization (0° phase shift) to the reflected or transmitted beam.

Table 3.2

TYPICAL LASER SYSTEM INTERFACE

Program Controlled Outputs from System Controller	Status Inputs to System Controller
Laser	
Emergency Stop to Laser	Emergency Stop from Laser
	HV is ON (Ready)
HV Enable	System Safety Interlocks are Open/Closed (e.g. beam delivery components to enable HV)
Shutter Enable	System Safety Interlocks are Open/Closed (e.g. guards and access doors to enable shutter)
Open/Close Shutter	Shutter is Opened/Closed
Laser Discharge On/Off	
Select: a) Power Level (analog or digital) or b) Preprogrammed Power Level	
Select Preprogrammed Pulse Program	
Other Associated System Components [1]	
Chiller Start/Stop [2]	Chiller Status (may require several inputs)
Select Assist Gas Type (may require two or more)	
Set Assist Gas Pressure (analog or digital) (e.g. via servo valve)	Assist Gas Pressure/Flow Status
Exhaust System On/Off	Exhaust System is On/Off
Height Following Control (may require several outputs)	Height Following Status (may require several inputs)

[1] Does not include I/O required for material handling.
[2] Laser may have chiller remote start/stop capability.

Nd:YAG lasers typically produce higher order modes with random polarization, which in most applications does not require circular polarization, especially in view of the high cost that would be required to produce circular polarization. However, for a Nd:YAG laser integrated to multiple beam share modules, a ½ wave (i.e. 180° phase shift) transmissive element may be required to insure the desired power distribution to the individual fibers. An adjustable energy share module may be able to ensure equal power distribution without the use of a $\lambda/2$ element providing the adjustment range is adequate (e.g. > ±5%).

3.4 Beam Delivery Considerations for Reflective/Transmissive Beam Delivery

3.4.1 Beam Alignment

Beam benders use mirrors at a 45° angle which can redirect an unfocused “raw” beam at right angles to its incident axis. Typically, one to four beam benders are used in a beam delivery system, each additional unit adding more freedom of adjustment at the expense of some power loss and increased alignment time. The final mirror typically projects the beam vertically downward through the focusing assembly. While not required from a cutting standpoint, vertical orientation minimizes concerns about laser beam safety and simplifies protection against beam hazards since the beam is directed downward and can be absorbed and/or diffusely reflected by the cutting box or supporting tooling. Vertical orientation also simplifies containment of the molten material blown through the cut. The raw laser beam must be aligned through all of these components (see also *Section 3.1.1*).

Improper beam alignment accounts for many of the instances in which cut quality degradation occurs. There are two primary effects from improper alignment which decrease cut quality. First, if the beam alignment is such that beam obstruction or "clipping" occurs, the power at the cut point will be reduced (with a resultant loss of power density) and there is the possibility that the beam delivery components may be damaged by the misaligned laser power. The beam can be obstructed by (or at) the beam benders, focus unit, or the assist gas nozzle. Loss of power due to clipping generally results in loss of through cut or cutting speed. Misalignment and clipping at the nozzle orifice may additionally produce inconsistent dross or an angled cut. Even if power clipping is not significant, the interference patterns that would be caused from the focused beam reflecting off the internal nozzle cone result in a larger spot size than minimal, and a corresponding loss of power density at the cut point.

Secondly, in order to minimize spot size (and thereby minimize kerf and maximize processing speed) alignment of the laser beam through the focusing optic requires that the incident beam be parallel with the optical axis. For transmissive focusing optics, this typically requires the incident beam to be parallel with, and generally central to (i.e. coaxial), the optical axis. For reflective focusing optics, this requires the incident beam to be perpendicular to, and centered with, the optical axis. If these conditions are not met the resultant spot can be either distorted or elongated, which increases the focused spot area, and therefore reduces the power density at the workpiece. An increased spot size increases the kerf width and dross, and reduces the cut speed. Additionally, an angled cut may result. For moving beam systems where the laser beam is not coaxial (or parallel) with the optical axes of the beam delivery system (especially at the focus lens), it is difficult, if not impossible, to have the focused beam centered through the nozzle orifice at all locations of the cutting head within the work envelope of the beam delivery system.

3.4.2 Beam Delivery Stability

Another factor which influences beam alignment is the stability of the supporting structure or foundation for the laser and its beam delivery system. If the laser and beam delivery system are not located on a solid, stable floor, or a robust single superstructure, beam misalignment can occur. Avoid branching across expansion joints (between laser generator and system) and avoid locating systems in areas of significant vibration. When branching across expansion joints, unequal motion of foundation sections, due to settling or thermal shifting, can cause severe misalignment of the beam delivery system. Similarly, when locating systems in close proximity to vibration source (e.g. near a press area), vibration induced misalignment can adversely affect process performance and quality. Failure to comply with either of these requirements can result in either; i) poor alignment at the focusing optic resulting in a larger focus spot size and therefore a lower power density, or ii) poor alignment through the beam delivery system resulting in a "clipping" and therefore a loss of power density at the cut point. Consult the system manufacturer for specified foundation and/or maximum shock specifications. See *Beam Alignment, Section 3.4.1* for a further discussion.

3.4.3 Beam Delivery Purging

Beam delivery systems must be well sealed. Aluminum tubes (fixed or telescoping), reinforced bellows, and other metal safety enclosures are generally used for this purpose. This limits the amount of contamination which can migrate onto the optical components, as well as provides a safety enclosure for the invisible laser beam. In addition to this, the beam delivery system should be purged with an inert gas (such as nitrogen) or clean, dry air {air quality to be at least (unless otherwise specified); *Water vapor* < 550 ppm @ 35°F; *Solids* < 1,000/ft^3, < 0.2 μm; *Oil aerosols* < 0.0005 ppm by weight; *Oil vapors* < 0.003 ppm by weight}. This maintains a positive pressure inside the sealed system which minimizes the ingress of ambient contamination (oil mist, water vapor, smoke, dust, solvent fumes, etc.) into the beam delivery system.

Purging helps keep the beam delivery components clean and dry prior to and during operation. A build-up of debris and foreign matter on the optical components has two primary detrimental effects. First, any debris (dust or oil for example) that contaminates any of the optical surfaces will absorb laser beam power. Second, as the surfaces absorb power they will distort due to that thermal load. Focusing optics are particularly sensitive to thermal loading because they are generally smaller (less thermal mass) than output optics and beam delivery mirrors, and they are most susceptible to contamination (especially from the cutting process). They distort due to the thermal load, which will cause the focus position to drift (referred to as thermal lensing). This results in an increase of the spot size at the cut point, and an accompanying loss in power density. Insufficient cooling of the beam delivery components, especially the focus lens, can result in a similar phenomena.

Additionally, if contamination or moisture is present in the path of the beam in the beam delivery system, a condition referred to as "thermal blooming" may result. Thermal blooming occurs when foreign matter (i.e. oil mist, or hydrocarbons such as paint thinners, acetone or alcohol fumes, etc.) in the path of the beam absorbs some of the beam energy, thus heating up. The rise in temperature is accompanied by a change in the refractive index of the air, which in-turn can redirect and cause divergence of the laser beam resulting in internal beam clipping (with an accompanying loss of power and power density at the cut point), and potential damage to beam delivery components. Purging helps prevent thermal blooming from occurring.

3.4.4 Raw Beam Size and Thermal Lensing

The raw beam has differing sizes within the beam delivery system, and therefore will exhibit a different focusability depending on where the focusing optic is located. As discussed in *Section 2.3*, the size of the raw beam at the focusing optic is inversely proportional to the focused spot size. Therefore, for moving beam systems, or for systems where the beam is shared (shuttled) between two or more work stations, a difference in cut performance may be evident from one position (or station) to another.

Similarly, as the temperature of the lasers output optic(s) increases, the optic(s) refractive index and/or geometry changes (i.e. behaves more like a lens). This changes the location of the waist, and therefore changes the raw beam size (i.e. propagation characteristics). Generally, beam divergence is greater with a “cold” optic than it is with a “hot” optic. An increase in temperature of the output optic(s) occurs with; i) an increase in laser power, ii) an increase in the optic(s) absorptance (e.g. if the output optic(s) become dirty or damaged), or iii) a decrease in cooling of the optics. For example, a build up of debris (carbon deposits for example), or damage (cracks or pits) on the output optic can cause it to absorb additional energy and increase in temperature, thus resulting in thermal distortion (thermal lensing) and thermal focusing of the output beam. Insufficient cooling (e.g. low flow rate or higher cooling water temperature) of the output optic can result in the same phenomenon. Thermal focusing of the raw beam will yield a beam size at the focusing optic which can be significantly different from that of the raw beam which has not been thermally focused, which in-turn will result in inconsistent cut quality.

Additionally, not only does thermal focusing effect the spot size of the focused beam, but because the raw beam divergence changes during thermal focusing, the focus plane shifts. A converging raw beam will cause the focus plane to move toward the focusing optic (with respect to the theoretical focal length of the focus optic), while a diverging raw beam will cause the focus plane to move away from the focusing optic. In practice, all raw laser beams go through thermal focus cycles (from when the output optic(s) is new to when it requires replacement). Replacement intervals are determined by the optic quality, exposure to contamination, laser power, and cutting/ process sensitivity to the increasing spot size. The rate of degradation can be minimized with timely and correct routine maintenance of the output optic(s) (inspection and cleaning) and insuring the integrity of the output optic(s) gas shroud protection and the beam delivery purging (quality and flow, see also *Section 3.4.3*).

Since the focused spot size almost always increases as the output optic ages, either the laser power will have to be increased, or the cut speed decreased, in order to maintain a through cut. Adjustments in focus position to account for the shift in focus plane during the thermal focusing cycle will help maximize the cut speed and quality. Note that contamination on, or insufficient cooling of, the focus optic can result in the same sort of spot size changes and focus plane shifting.

Similar effects can also occur with Nd:YAG lasers. This is caused by thermal distortion of the Nd:YAG rod(s), as well as thermal lensing of the laser output optics. Consequently, the raw laser beam generally has differing beam quality with respect to power, and therefore, differing focused spot diameters at the cut point with respect to power. As noted above, the same is true of focusing optics.

3.4.5 Dew Point

If moisture is present on optical surfaces, the violent vaporization of the water as the beam impinges them can cause surface damage (similar to a cavitation erosion condition). This situation is typically associated with water cooled components which are cooled to temperatures below the dew point. When operating at this condition, water will condense on the optical surfaces that are exposed to the ambient environment. To avoid this situation: i) insure that the system purge gas (see *Section 3.4.3*) is clean, dry and properly functioning in order prevent ingress of moisture into the beam delivery, and ii) insure that any water cooled beam delivery components that are exposed to the atmosphere (such as the nozzle side of the focus lens) are cooled at temperatures above dew point.

3.5 Beam Delivery Considerations for Fiber Optic Beam Delivery

3.5.1 Fiber Types

As presented in *Section 2.3.2*, there are two basic types of fibers used for high power Nd:YAG transmission, namely, step index and graded index. Graded index fibers are infrequently used at high laser powers because; i) they are expensive to manufacture, ii) they are highly sensitivity to alignment of the input beam into the fiber, and iii) Nd:YAG lasers typically have such a low beam quality that graded index fibers yield only marginal improvements of spot diameter and depth of focus as compared with a step index fiber.

The numerical beam quality of an exit beam (BQ_{exit}) that has passed through a step index fiber optic can be significantly greater than the numerical beam quality of the input raw beam (BQ_{input}). The resulting exit beam has a power distribution that is, in general, uniformly distributed (i.e. "top-hat" distribution) and less focusable.

3.5.2 Alignment

Improper alignment of the focused input beam into the fiber optic reduces the power transmitted through the fiber, and therefore reduces available cut energy. Additionally, misalignment at the fiber input can severely damage, and in many cases damage beyond repair, the fiber optic. Water cooled fiber connectors can greatly reduce the risk of fiber damage caused by misalignment.

Related to alignment, note also that the focused beam at the workpiece can also be obstructed by (or at) the focus unit and the assist gas nozzle or nozzle orifice. See also *Section 3.4.1* for further discussion.

3.5.3 System Stability

As with the transmissive/reflective beam delivery systems, the stability of the supporting structure or foundation for the laser and its work station influences cut quality. If the laser is in a location where intense vibration is present (e.g. near a press area) random misalignment at the fiber optic input can occur. Similarly, vibration induced movement of the focus module and the component to be cut can cause a cyclical out of focus condition (and a changing stand-off gap if no height following is used), which changes the focused spot size at the part, and thereby adversely affects the cut quality. This is especially critical when utilizing a robot to manipulate either the focus module or the component to be cut. The rigidity of the robot (in all orientations, and at all expected velocities, accelerations and decelerations) coupled with the fixture or cutting module, must be carefully considered. See *Section 3.4.2* for further discussion.

3.5.4 Raw Beam Effects

As discussed in *Section 3.4.4*, the raw beam at the laser head generally has differing beam quality with respect to power for a Nd:YAG laser. Transmissive/reflective beam delivery systems are significantly affected by this because a change in beam quality results in a change in focused spot size, and therefore a loss of power density. With fiber optic beam delivery systems however, especially step index fibers, this effect is normally insignificant. The reason is that the fiber optic delivery system produces a nearly "top hat" power distribution at the exit of the fiber regardless of the input beam quality. While this keeps the cut quality consistent, the “top hat” mode is not as focusable as the raw beam (see *Section 3.5.1*). Therefore, the cut quality with a fiber optic beam delivery will be less than that of a reflective/transmissive beam delivery. The flexibility of the fiber optic, however, in many cases outweighs this effect.

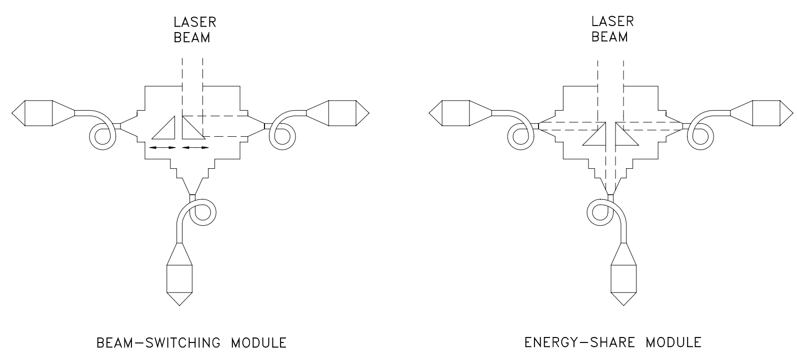
However, if thermal distortion of the Nd:YAG rod(s) or thermal lensing of the output optic(s) results in an input spot size that overfills the fiber optic core diameter (see *Section 2.3.2*), then the cutting process would be affected. This is because overfilling the fiber optic means absorption of the beam into the fiber clad material, and therefore a loss of power and power density at the cut point. This can occur if either; a) there is significant thermal affects in situations where the spot size is normally very close to the diameter of the fiber core, or b) there is extreme thermal affects in situations where the spot size is normally much smaller than the fiber core diameter.

3.5.5 Fiber Configurations

One of the many advantages offered by fiber optic beam delivery systems is the ability to switch or share the laser between many modules (see ***Figure 3.4***). With reflective/transmissive beam delivery systems, only switching is practical, and then only between two work cells. Maintaining beam alignment and raw beam divergence (and therefore beam delivery length) are two primary limitations. However, with a fiber optic beam delivery system, fiber length has virtually no affect on the power transmitted or on the exit beam quality.

Figure 3.4

EXAMPLES OF FIBER CONFIGURATIONS



3.6 Summary of Beam Delivery Effects on Cut Energy Density

3.6.1 Energy Density

i. Cut energy (along with coupling efficiency) determines the maximum cut thickness and it is directly proportional to power density (and the focused spot size), and inversely proportional to cutting speed.

ii. There is always a trade off between the focused spot diameter and depth of focus with focal length.

iii. Power density is decreased when:

   a. Power is decreased via:

      i. beam clipping due to poor alignment or installation site vibration/shifting,
      ii. beam clipping due to thermal blooming *(reflective/transmissive systems)*,
      iii. contamination on beam delivery optics or damaged optics,
      iv. spatter on focus optic or cover slide, and
      v. thermal lensing of Nd:YAG rod or optics resulting in an overfill of the fiber optic core *(fiber optic systems)*

   b. The focused spot diameter is increased via:

      i. out of focus,
      ii. alignment not coaxial to focus optic *(reflective/transmissive systems)*,
      iii. reduced raw beam size through thermal focusing of output optics or moving beam/beam shuttling because of beam propagation characteristics *(reflective/ transmissive systems)*,
      iv. part location drifts in and out of focus due to part tolerance or fixturing repeatability/stability (assuming no height following capability), and
      v. thermal shifting of focal point due to insufficient cooling or contamination on focus optic or cover slide.

3.6.2 Coupling Efficiency

i. Coupling efficiency determines how much of the available energy density is transferred to, and absorbed at, the cut point (and thus becomes cut energy).

ii. Coupling efficiency is affected by:

   a. laser type (i.e. wavelength),
   b. power density, and
   c. material reflectivity and conductivity.

3.7 Laser Safety

Safety concerns can be grouped into many categories, a few of which are; 1) high voltage and related electrical hazards, 2) laser beam hazards to skin and eye (alignment laser and main beam, direct and reflected), 3) hazards from laser generated fumes, 4) handling of hazardous materials (e.g. filters from exhaust system, laser optics, and vacuum pump oil), 5) fire and explosion hazards, 6) noise hazards, and 7) the hazards associated with compressed gases.

The standard pertaining specifically to the laser that every end user in the United States must comply with is ANSI Z136.1-latest revision. This standard is the American National Standard for *Safe Use of Lasers*, and is approved by the American National Standards Institute. In general, all laser users must appoint a Laser Safety Officer (LSO) that takes responsibility for compliance to this standard (which requires not only the identification and evaluation of hazards, but also criteria for control measures, training and medical surveillance, all of which are outlined in Z136.1). A summary of a ***few*** of the pertinent standards and references are listed below:

1) American National Standards Institute (ANSI), 11 West 42nd Street, New York, New York 10036.
   National Fire Protection Association (NFPA), 1 Batterymarch Park, Quincy, Massachusetts 02269.

   i) ANSI Z136.1, *Safe Use of Lasers*
   ii) ANSI Z49.1, *Safety in Welding and Cutting*
   iii) ANSI Z87.1, *Practice for Occupational and Educational Eye and Face Protection*
   iv) ANSI Z117.1, *Safety Requirements for Confined Spaces*
   v) ANSI/NFPA 70, *National Electric Code*
   vi) ANSI/NFPA 79, *Industrial Machinery*

2) Occupational Safety & Health Administration (OSHA), Department of Labor, Washington, DC 20210.

   i) US Department of Labor, *Code of Federal Regulations*, Title 29-Labor, Part 1910, "Occupational Safety and Health Standards"
   ii) Instruction Publication 8-1.7, *Guidelines for Laser Safety and Hazard Assessment*

3) Center for Devices and Radiological Health (CDRH), FDA, Department of Health and Human Services, 8757 Georgia Avenue, Silver Spring, Maryland 20910.

   i) US Department of Health and Human Services, *Code of Federal Regulations*, Title 21, Subchapter J, Part 1040.10 (latest edition), "Performance Standards for Laser Products"

4) Laser Institute of America (LIA), 12424 Research Parkway, Suite 130, Orlando, Florida 32826.

   i) LIA, *Laser Safety Guide*
   ii) LIA, *Guide for Selection of Laser Eye Protection*

3.8 Operating Costs

Laser cutting system operating costs can be estimated if the application data is known. One way to calculate cost is calculating it per hour (or per unit length of cut), while amortizing some of the more significant maintenance costs into an hourly figure. The following examples are given primarily as an aid. They may be altered and enhanced to suit individual products and applications.

3.8.1 Conventional CO_2 Cutting System

Typical cutting systems utilizing carbon dioxide lasers have operating costs generally falling into the categories listed below. However, recent developments in CO_2 laser technology has made available a CO_2 laser which does not use a continuous flow of laser gases, but rather uses a static volume of gas. For this style of laser, the laser gas consumption data and costs would differ from that listed below.

Example 3.8.1: A 2000 Watt CO_2 laser (with $M^2 \cong 2.5$) cutting 3 mm (0.12 inch) thick carbon steel with oxygen assist @ 2.5 bar (37 psi) with a 127 mm (5 inch) lens, and a 1.5 mm (0.06 inch) diameter nozzle orifice:

Cutting speed:	5.2 m/min (205 inch/min)	
Laser electrical power:	(25 kVA)(0.8 pf)($0.08/kWhr)=	1.60
Laser gas, Carbon Dioxide:	(0.15 scf/hr)($0.12/scf)=	0.02
Laser gas, Helium:	(2.30 scf/hr)($0.14/scf)=	0.32
Laser gas, Nitrogen:	(1.10 scf/hr)($0.08/scf)=	0.09
Chiller electrical power:	(10 kW)($0.08/kWhr)=	0.80
Chiller additive:	(.35)(60 gal)($10/gal)/(6000 hr)=	0.04
Laser optics:	($2340)/(6000 hr)=	0.39
Assist gas (see *Figure 4.5*):	(2.3 scf/min)(60 min/hr)($0.03/scf)=	4.14
Focus lens:	($400)/(1000 hr)=	0.40
Nozzle tip:	($30)/(200 hr)=	0.15
Exhaust system power:	(5 kW)($0.08/kWhr)=	0.40
Exhaust system filters:	($5)/(100 hrs)=	0.50
Maintenance labor (with overhead):	(12 hrs/2000 hrs operation)($45/hr)=	0.27

Total approximate operating cost per hour (full power continuous operation): $9.12/hr

Cost per unit length of cut *(assuming 85% utilization)*:
[($9.12/hr)/((0.85)(5.2m/min)](hr/60min) = $0.034/m
($0.034/m)(m/39.37inch) = $0.0009/inch

3.8.2 Conventional Nd:YAG Cutting System

Typical cutting systems utilizing Nd:YAG lasers have operating costs generally falling into the categories listed below. Note that the laser arc lamp life is strongly dependent on laser power and duty cycle (assumed below as 500 hours at 85% power and 100% duty cycle).

Example 3.8.2: A 2500 Watt CW Nd:YAG laser with 0.6 mm fiber optic beam delivery cutting 3 mm (0.12 inch) thick stainless steel with nitrogen assist @ 7 bar (103 psi) with a 80 mm (3.15 inch) focal length, and a 1.5 mm (0.06 inch) diameter nozzle orifice:

Cutting speed:	2.3 m/min (90 inch/min)	
Laser electrical power:	(90 kW)($0.08/kWhr)=	7.20
Chiller electrical power:	(45 kW)($0.08/kWhr)=	3.60
Chiller additive:	(.35)(75 gal)($10/gal)/(4000 hr)=	0.07
Laser arc lamps:	($250)(8)/(500 hr)=	4.00
Assist gas (see *Figure 4.5*):	(5.2 scf/min)(60 min/hr)($0.03/scf)=	9.36
Cover slide:	($50)/(500 hr)=	0.10
Nozzle tip:	($30)/(200 hr)=	0.15
Exhaust system power:	(5 kW)($0.08/kWhr)=	0.40
Exhaust system filters:	($5)/(100 hrs)=	0.50
Maintenance labor (with overhead):	(5 hrs/2000 hr operation)($45/hr)=	0.11

Total approximate operating cost per hour (full power continuous operation): $25.49/hr

Cost per unit length of cut *(assuming 85% utilization)*:
[($25.49/hr)/((0.85)(2.3m/min)](hr/60min) = $0.217/m
($0.217/m)(m/39.37inch) = $0.0055/inch

4. CUTTING PROCESS CONSIDERATIONS

4.1 Materials Suitable for Laser Cutting

Many ferrous and non-ferrous materials can be laser cut. Each material has its own unique response to the effects of CO_2 and Nd:YAG lasers, some of which are not suitable for laser cutting. Therefore, the question of suitability of any material to laser cutting depends on the response of the material to the laser wavelength and energy. That interaction is dependent upon four key factors:

1) *Surface condition*: how well the material initially absorbs the energy.

2) *Heat flow properties*: the material's coefficients of thermal diffusivity and conductivity.

3) *Heat phase-change requirements*: the amount of excess energy required to induce a phase change as a function of the material's density, specific heat, and latent heat of fusion and vaporization.

4) *Reflectivity of the cut zone:* this depends on many things, including i) base material reflectivity at ambient temperature, ii) molten cut zone geometry (macroscopic), iii) liquid melt surface geometry (microscopic), iv) physical state of the molten material in cut zone (solids, liquids, gases, plasma), v) chemical state of material in cut zone (e.g. oxidized), and v) temperature and temperature uniformity of the cut zone.

However, high power densities (e.g. obtained via high power, excellent beam quality, short focal length, or high pulse peak power) can overcome the energy requirements of 1) and 3) above, even though the material may not generally couple well with the wavelength. For example, aluminum cannot be cut consistently with most CO_2 lasers operating at 500 Watts CW, with a 127 mm (5 inch) focal length. However, if a 63.5 mm (2.5 inch) focal length is used cutting is possible, because the decreased focal length increases the power density of the focused beam. The same is true of CW cutting of copper with a 1000 Watt CO_2 laser.

The following information in intended to provide general guidelines for cuttability on the major categories of materials, keeping in mind these factors.

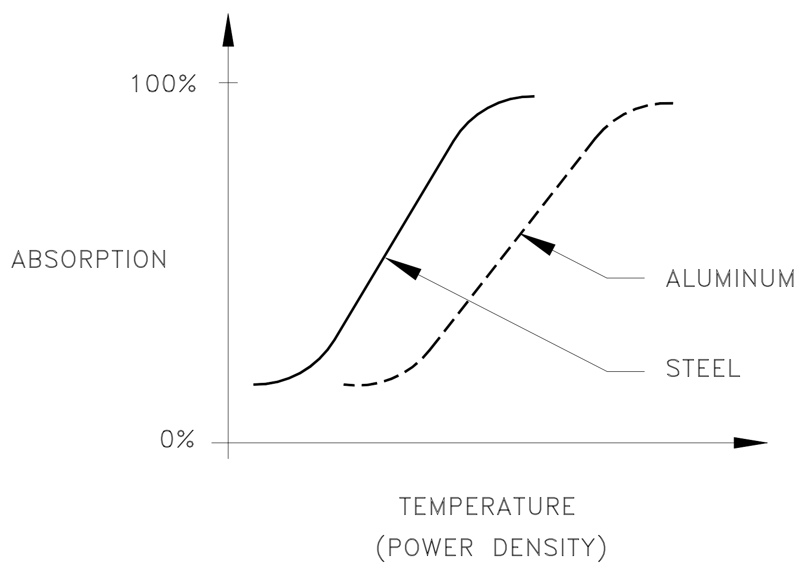
4.1.1 Metals

Although at room temperature almost all metals are highly reflective in infrared energy, the CO_2 laser with its 10.6 micron wavelength (far infrared) is successfully employed in many metal cutting applications. The initial absorptivity can range from only 10% to as little as 0.5% of the incident energy. However, the focusing of the laser beam, which provides power densities in excess of 1 million Watts per square centimeter (6 million Watts per square inch) can quickly initiate surface melting (in a matter of microseconds). The absorption of most molten metals increases dramatically with temperature, raising the absorptivity of energy to as much as 80-100% (see ***Figure 4.1***).

Mild and Carbon Steel *(CO_2 = excellent, Nd:YAG = excellent)*
Conventional steels of up to 20 mm (0.79 inch) lend themselves reasonable well to oxygen-assisted laser cutting. The kerfs are narrow [as little as 0.1 mm (0.004 inch) for thin material] and the resultant heat affected zones are negligible, particularly for mild and low carbon steel. At the same time, the cut edges are smooth, clean, and square. In some rare cases, it has been found that the presence of impurities (such as pockets of carbon, phosphorous and/or sulfur) within mild steel can cause blow outs, and therefore roughness along the cut edge. As such, the use of low impurity steel (e.g. cold-rolled) will result in improved edge quality over results obtained with hot-rolled material.

Figure 4.1

ABSORPTION VERSUS TEMPERATURE



A higher carbon content within the steel does yield a slight improvement in edge quality, but will result in an increase in hardness of the cut edge and an increased HAZ. This may be problematic if the cut component requires post-cut machining or forming. In addition, an increase in edge hardness increases the potential for cracking, which will reduce the fatigue life of the cut component. Post-cut annealing may be employed to minimize these problems. Increased carbon content also reduces the cut speed and maximum material thickness that can be cut with oxygen assist. The reason is that carbon combustion occurs in the oxygen jet to form carbon dioxide gas (CO_2) which in-turn dilutes the oxygen at the cut front. See also discussions on thermal runaway and the use of coolant (see also *Sections 4.6.5 and 4.6.9*).

Stainless Steel *(CO_2 = excellent, Nd:YAG = excellent)*
Lasers have been shown to be viable cutting tools for the fabrication of sheet metal components made from stainless steel. The controlled heat input of the laser beam serves to minimize the HAZ along the cut edge, thereby helping the material to maintain its corrosion resistance. Since stainless steels do not react with an oxygen assist as efficiently as does mild steel [due to passive chromium oxide layer (Cr_2O_3), which seals the molten iron fairly well from the flow of oxygen, thereby inhibiting exothermic oxidation], cutting speeds for stainless steels with oxygen assist are slightly lower than those for comparable thicknesses of plain steel.

As for the resultant cut quality, martensitic and ferritic stainless steels (400 series) provide clean smooth edges. The presence of nickel within austenitic stainless steels (300 series and precipitation hardened) affects the energy coupling and transfer within the material. Specifically, the high viscosity and surface tension of molten nickel or nickel/chromium oxides (greater than that of the more extensively oxidized melt in mild steel cutting) generated during the cutting action causes it to migrate and adhere as slag to the backside of the cut. While the use of high velocity gas jets can effectively eliminate slag for material up to 1.0 mm (0.040 inch) thick, oxide deposits up to 0.5 mm (0.020 inch) are generally present on thicker cross sections, when cutting with oxygen. In addition, a chromium and iron oxide layer (i.e. Cr_2O_3 and Fe_2O_3) is present on the edge of the cut. Because chromium oxidizes vigorously, chromium in the melt migrates to the surface to react with oxygen. This results in a resolidified melt region just beneath the oxide layer that has less chromium than the bulk material. Microcracks in the hard and brittle oxide layer expose this region resulting in a cut edge with less corrosion resistance in a corrosive environment.

If cut edges are to be butt welded, the edge oxides would be trapped in the weld metal and remain as inclusions which would reduce the static and fatigue strength of the weld. If cut edges are to be welded in lap configurations, dross inhibits intimate contact with mating parts. At the expense of up to 50% of the speed for oxygen assisted cutting, an inert assist gas (no exothermic energy) can be employed to obtain a “weld ready”, oxide and dross free cut edge, which has the same corrosion resistance as the bulk material. High pressure nitrogen cutting is most common, and although it is not completely inert, it can produce high quality, oxide and dross free edges in thickness up to 10 mm (0.39 inch), and it is less expensive than a true inert gas such as argon. An increased gas consumption and cost is associated with high pressure inert gas cutting. In addition, the gas jet nozzle, lens and gas delivery components must be suitable for high pressure.

Alloy Steel *(CO_2 = excellent, Nd:YAG = excellent)*
Since care is taken to control the amount and distribution of additives to the base iron, as well as generally lower impurity levels, most alloy steels are considered ideal candidates for the laser cutting process and allow improved cut quality compared to cold-rolled carbon steel. The primary alloying elements (e.g. carbon, silicon, manganese, chromium, nickel and molybdenum) have only a minor (and usually positive) affect on cut quality, but generally interfere with the iron oxidation reaction. As a result, alloy steels generally cut at a slower rate as compared to mild steels. Dross is sometimes present, but generally less than that on stainless steels.

Silicon is often added (up to about 4%) for improved electrical performance (i.e. reduces eddy current losses and improves resistance to high temperature oxidation). However, silicon inhibits the oxidation of iron and also increases the viscosity of the molten metal, resulting in slower cut speeds and increased dross. In the case of motor laminations, which require stacking, dross is undesirable. Pulsed cutting and auxiliary gas jets help minimize dross adherence. The auxiliary gas jets are located under the cut zone and are positioned such that the dross is blown to the scrap side of the cut, thereby leaving one edge of the cut dross free. The addition of manganese, sulfur and carbon to improve machinability has little affect on cutting if the compositions are low ($Mn < 0.3\%$, $S < 0.1\%$ and $C < 0.1\%$). However, as compositions approach the typical maximums ($Mn \sim 1.6\%$, $S \sim 0.3\%$ and $C \sim 0.5\%$), cut speeds decrease, because the formation of the gases CO_2 and SO_2 dilute the oxygen in the cut front and thereby reduce the iron oxidation process. Dross also increases as a result of a higher viscosity melt.

High strength materials such as AISI-SAE 4130 (chrome molybdenum steel) and 4340 (chrome nickel molybdenum steel) display exceptional laser cut edges that are square and clean. Hardenable alloy steels, however, will have martensitic edges which are brittle, but generally crack free.

Tool Steel *(CO_2 = excellent, Nd:YAG = excellent)*
Similar in many ways to alloy steels, most tool steels respond well to the cutting action of a laser. The most notable exceptions are tool steels with high levels of tungsten [e.g. tungsten high speed (Group T) and tungsten hot work (part of Group H)] materials which retain heat in a molten state, thereby resulting in slower cut speeds with cuts that have burned edges and some slag.

Aluminum and Aluminum Alloys *(CO_2 = fair-good, Nd:YAG = good)*
Due to its high thermal conductivity and high reflectivity to a CO_2 laser's wavelength, aluminum requires considerably higher laser energy density in order to initiate cutting compared to steel. This means the need for a laser possessing exceptional beam quality (see *Sections 2.1.3, 2.2 and 4.6.1*) and capable of outputting at least 500 Watts in addition to precise focus control. Due to the reduced coupling efficiency, even 1-2 kilowatt lasers are limited to cutting of thicknesses under 4 mm (0.16 inch). Although pulsable CO_2 lasers with high peak powers can be used for cutting of aluminum and aluminum alloys, high power Nd:YAG lasers are generally better suited.

During the cutting process, the assist gas serves primarily to blow the molten material away from the cut zone. Even if oxygen is used as the assist gas, the oxidation of aluminum to form Al_2O_3 is self extinguishing because it forms an impermeable oxide layer which seals the molten metal surface from oxygen (note that the affinity to oxidize, even at room temperature, is what gives aluminum its corrosion resistance, by the formation of a transparent passive oxide layer).

However, due to the high surface tension of the liquid melt [because of rapid cooling due to the high thermal conductivity of aluminum and the high solidification temperature of aluminum oxide, about 2017°C (3663°F)], a continuous dross forms on the lower edge of the cut. An auxiliary gas jet can be used to blow the dross to the waste side of the cut. Air can be used for this purpose since aluminum requires no chemical shielding. High pressure inert gas cutting can be used to minimize dross, because the absence of aluminum oxide reduces the solidification temperature of the molten aluminum [which freezes about 659°C (1218°F)]. Even without these techniques, the slag is easily removable (via grinding or scraping), but residual tensile stresses accompanied by intergranular cracks may be present on the cut surface. Concern over the presence of this microcracking (and the associated large HAZ due to aluminum's high thermal conductivity) has prevented the use of lasers for manufacturing structural components such as those encountered in the aerospace industry. See *Paint and Chemical Coatings* in *Section 4.3* for how anodizing affects cut performance.

Copper and Copper Alloys *(CO_2 = difficult, Nd:YAG = fair)*
Copper has less ability than aluminum to absorb energy from a CO_2 laser. With the exceptions of gold and silver, copper has the highest conductivity, and reflectivity to CO_2 light. However, copper can be readily cut with kilowatt class CO_2 lasers having good beam quality. Oxygen cutting of copper and copper alloys is more successful than inert cutting because the oxidation reaction (CuO) generates more cut energy and the oxide layer which coats the cutting zone improves absorption. Common copper alloys include bronze and brass. Bronze is rarely found in sheet form and therefore generally not laser cut. Brass, on the other hand, is common in sheet form. The presence of zinc makes brass more suitable for laser cutting (with respect to pure copper) in three ways; i) zinc reduces thermal conductivity, ii) zinc reduces reflectivity, and iii) zinc oxidizes (ZnO) thereby increasing the cut energy in oxygen cutting. Typical laser cutting of copper alloys will result in slag adhering to the backside of the cut, with rough cut edges (even with the use of an inert assist gas). High power Nd:YAG lasers generally are better suited for cutting of copper and copper alloys.

Titanium *(CO_2 = good, Nd:YAG = good)*
Pure titanium responds well to the concentrated heat energy of a focused laser beam. The use of oxygen as an assist gas is avoided because of the potential for dangerous burning (the reaction between titanium and oxygen to form TiO_2 is extremely exothermic). The use of argon and nitrogen are most prevalent. Nitrogen reacts with titanium to form brittle compounds on the cut edge. Helium or argon can be used to avoid this. Helium is used in the aerospace industry to cut thicknesses less than 6 mm (0.24 inch), but is generally cost prohibitive. Heat treatment can be used to minimize

any problem associated with the HAZ. Although inert gas cutting prevents titanium from oxidizing with the assist gas, the hot edges can still oxidize when exposed to the ambient air. Auxiliary underside inert gas jets can be used to cool the hot edges and protect them from oxygen and nitrogen contamination. The auxiliary jet(s) can also be used to propel dross toward the waste side of the cut.

4.1.2 Non-Metals

In general, non-metallic materials are good absorbers of the infrared energy produced by CO_2 lasers and poor absorbers of the energy produced by Nd:YAG lasers. Likewise, they are generally poor conductors of heat and have relatively low vaporization temperatures. As such, the energy intensity of a focused beam is almost totally absorbed by the material at the focused spot. This absorption results in predominantly one of the following three cutting mechanisms for non-metals, namely; i) melt shearing, ii) vaporization, and iii) chemical degradation. The predominant cut mechanism, to a large extent, determines the cut edge quality possible for a given material. Melt shearing describes the cutting process whereby molten material is continuously blown out of the kerf by a gas jet (typically air). This results in a high quality edge with some microscopic ripples due to the fluid dynamics of melt ejection. Vaporization yields a high quality edge (superior to flame polished edge). Acrylic and polyacetal are two materials commonly cut by vaporization. In chemical degradation, energy from the beam breaks chemical bonds, resulting in the slowest and highest temperature cutting mechanism of the three. Resultant edges are flat and smooth but are generally covered with a fine carbon residue.

4.1.2.1 Organics

Plastics (Polymers) *(CO_2 = good-excellent, Nd:YAG = poor)*
Most clear plastics are not cut with Nd:YAG lasers because of their high transparence to the Nd:YAG wavelength. CO_2 lasers, however, have found their way into many plastic machining operations because of their ability to cut complex geometries at high feedrates without contacting the workpiece. Since the laser is an intense heat source, it uses its energy to melt or vaporize the binder and quickly breaks down the material's polymer chains. Its suitability hinges on the desirability of its heat affected cut.

Thermoplastics with relatively low melting temperatures typically display clean cuts with fire-polished edges as a result of resolidified melting. Flame polished edges are more likely with amorphous thermoplastic polymers via vaporization cutting (e.g. acrylic), than with crystalline thermoplastic polymers (e.g. polypropylene, polyethylene and polystyrene) which are cut via melt shearing. Process control can be exercised to minimize or eliminate bubbling or the presence of small burrs on the backside of the cut. However, burr formation is a function of the surface tension of the liquid melt and the shrinkage of the resolidification material, and is therefore sometimes unavoidable. The flame polished cut edge typical of acrylic cutting can be prone to cracking due to, among other reasons, residual stresses associated with resolidification. High pressure cutting reduces the tendency for edge cracking, but produces a cut with a frosted edge. Annealing can also be used to reduce crack sensitivity.

Thermosetting plastics are often applied as composite structures comprised of either multicomponent laminates or blends of polymer and particulate or fibrous fillers (e.g. phenolic or epoxy resins, and rubber products). Thermosetting plastics are heat resistant, and generally dissociate (chemically degrade) rather than melt, resulting in carbon residues on the cut edges (e.g. charred). Carbon residues can be removed if required (e.g. bead blasting).

Decomposition products of many laser cut polymers are hazardous [e.g. PVC emits highly toxic and corrosive hydrogen chloride (HCl) which readily combines with moisture to become hydrochloric acid]. Careful attention must be given to the removal and filtering of potentially hazardous, corrosive and/or explosive fumes that are generated as the result of burning or decomposition (see *Sections 3.1.4 and 3.7*).

Composites *(CO_2 = poor-excellent, Nd:YAG = poor-fair)*
New lightweight, fiber reinforced polymers are difficult to machine with conventional cutting tools. This has led many users to the non-contact cutting capabilities of a laser. Organic composites (such as Kevlar® fibers in an epoxy matrix) are readily cut up to 6 mm (0.25 inch). Inorganic fibers (such as fiberglass or graphite) in an organic epoxy are more difficult to laser cut. Process speeds and thicknesses are limited by the fiber material, which often results in an over decomposition of the epoxy. Pulsed cutting can be used to minimize matrix degradation. Inorganic composites, such as metal-matrix composites, are successfully cut by both CO_2 and Nd:YAG lasers.

Prior to the curing of laminated stacks, thin prepreg sheets in thicknesses up to 0.5 mm (0.020 inch) can be trimmed or sized at speeds up to 40 m/min (1,600 in/min), without the problem of gumming up a cutting tool. The heat from the laser's cutting action fuses the edges, thus preventing fraying of the fibers. For thicker sections and fully cured composites, particularly boron and carbon fiber material, there is a probability of charring, delamination, and thermal damage along the cut edge, thus reducing the acceptability of laser cutting for structural members. As with the cutting of polymers, care should be exercised in the removal of fumes.

Rubber *(CO_2 = good, Nd:YAG = poor)*
Both natural gum and synthetic rubber materials in thicknesses up to 20 mm (0.79 inch) readily degrade or vaporize from the heat of a focused laser beam. This allows precision sizing of items such as gaskets. Material with fiber or steel cord reinforcement can be cut with a laser at considerably slower speeds due to the higher energy necessary to laser cut the steel cords. However, due to the slow speeds there is a higher probability of poor finish due to heat effects.

The advantage of laser cutting is the simplicity of handling without having to worry about stretching or distorting of the material due to the impact/friction of a cutting tool. Fresh cut samples tend to exhibit slight stickiness along the edge and therefore require care in post-process handling. Additionally, some rubber, particularly those containing carbon, may require a clean-up operation to wipe clean any edge charring. Since carbon doesn't melt (but degrades at a high temperature) and because carbon increases the thermal conductivity of rubber, cutting speeds are reduced and cut edges are covered with carbon residue. Vulcanized rubber (sulfur added) when laser cut generates a dense, sooty smoke which has a very unpleasant odor.

Wood *(CO_2 = excellent, Nd:YAG = poor)*
The laser offers a number of advantages for the cutting of cellulose based materials (e.g. lumber, plywood, and particleboard). In particular, it provides narrow kerfs of 0.3-1.0 mm (0.01-0.04 inch), it does not produce sawdust, it has the ability to contour cut in any direction, there is no tool wear and noise is minimal. While the use of a laser likewise eliminates the rough, torn-out, and fuzzy edges associated with conventional sawing techniques, laser cuts on wood are characterized by "burned" edges (i.e. carbon residue) which are parallel, flat, smooth and splinter-free. The residual carbon layer is a function of both thickness and cellulose density, both of which decrease cut speed as they increase (note also that cellulose is cut via chemical degradation). Increased assist gas pressure reduces the amount of carbon deposited on the cut edges. Cut speed, for a given thickness, is a function of composition. Wood is composed primarily of cellulose, water, lignin and trapped air. If the density of cellulose, lignin (e.g. wood type or the presence of a knot) or water increases (e.g. stored in a damp environment), cut speed decreases.

While lasers are used for cutting slots in dieboards for mounting of steel rule dies and for certain contour cutting applications (such as puzzles and decorative materials), their acceptance for other industrial applications has been hampered by process limitations and relatively high initial cost. Since practical power outputs are limited to a few kilowatts, lasers are limited in their ability to cut up to 75 mm (3 inch) thick for lumber and 25 mm (1 inch) for particleboard and plywood. Using some of the highest power lasers that are available with these thicknesses, cutting rates fall to less than 2.4 meters per minute (8 feet per minute).

Paper, Leather, Synthetic Textiles *(CO_2 = excellent, Nd:YAG = poor-good)*
Paper products and leather, as well as natural and synthetic textiles, can easily be cut with a CO_2 laser. The lack of thickness coupled with their high combustibility minimizes the power output requirements of a laser to no more than a few hundred Watts. In many instances, several layers of material may be cut simultaneously. The resultant edges are clean and free from fraying. However, some charring due to hydrocarbon decomposition may be present. No significant fire hazard exists with paper or cardboard cutting because the material is vaporized by the laser, and removed from the kerf and cooled by the assist gas (which is usually air).

4.1.2.2 Inorganics

Quartz *(CO_2 = good-excellent, Nd:YAG = not possible)*
Since it has a relatively low coefficient of thermal expansion, quartz responds well to the cutting action of a CO_2 laser. However, quartz is transparent to the 1.06 micron wavelength of the Nd:YAG laser. Though there is the presence of a shallow heat affected zone adjacent to a cut, the resultant edges are often crack-free and have a smooth appearance thereby eliminating clean-up operations required by saw cutting. Thicknesses up to 10 mm (0.39 inch) can be cut at speeds that are a couple orders of magnitude greater than sawing and without imparting force to the workpiece. Annealing is sometimes required (if cracking occurs and is not tolerable) to avoid post-cut cracking. In general, cracking is a function of heat input and is therefore directly proportional to material thickness.

Glass *(CO_2 = difficult, Nd:YAG = not possible)*
As opposed to quartz, most types of glass are prone to thermal shock and solidification cracking, and are therefore generally not suitable candidates for laser cutting. Like quartz, glass is transparent to the 1.06 micron wavelength of the Nd:YAG laser, but absorbs the 10.6 micron wavelength from the CO_2 laser very well. Both full penetration cutting and scribing are used. In many cases, full penetration cuts are made by multiple overlap passes to minimize thermal shock.

Heat resistant glass, such as boro-silicates and Pyrex, are less susceptible to cracking during cutting. However, most other forms of glass (including soda lime) experience thermal shock which results in crack propagation along the cut edge. Also, because of the high viscosity of the molten glass, there will be significant resolidified material (recast) that will adhere to the edges and underside of the cut.

Ceramics *(CO_2 = fair-good, Nd:YAG = fair)*
Most of the ceramic cutting and scribing for the electronics industry is via CO_2 lasers. Common ceramics include alumina (AL_2O_3), tungsten carbide (WC), titanium nitride (TiN) and titanium carbide (TiC). Ceramics are hard and brittle, and therefore difficult to cut mechanically (especially complex shapes). Full penetration cutting is not required in many cases, especially straight line cuts. If only scribing is required, speeds can be quite high [15 m/min (600 in/min) or more].

Full penetration cutting is generally required for complex or curved profiles. In such cases pulsed cutting is preferred in order to reduce the heat into the area surrounding the cut. Cutting of contours in tile for decorative applications is also done with CO_2 lasers. High power pulses are required to melt and vaporize the material, and to minimize the damage to the surface glaze. The high melting temperature of ceramics result in rather slow speeds for full penetration cutting [typically less than 0.5 m/min (20 in/min)]. Nd:YAG is typically transmitted by most ceramics unless power densities are extremely high.

Stone and Rock *(CO_2 = poor, Nd:YAG = poor)*
While they tend to absorb the heat energy from a laser, granite, concrete, rock, stone, and various minerals are not suited for laser cutting. The explosiveness from heating moisture within these materials can lead to undesirable cracking. Aside from the lack of uniformity in their structures, stone and rock are typically found in thicknesses greater than 25 mm (1 inch), far in excess of the practical limit of laser cutting.

Table 4.1

SUMMARY OF PROCESSING CAPABILITY

Material	CO_2 Laser	Nd:YAG Laser
Metals		
Mild Steel	excellent	excellent
Stainless Steel	excellent	excellent
Alloy Steel	excellent	excellent
Tool Steel	excellent	excellent
Aluminum & Aluminum Alloys [up to 6 mm (0.24 inch)]	fair-good	good
Copper & Copper Alloys	difficult [1]	fair
Titanium	good	good
Gold & Silver	poor [2]	difficult
Non-Metals, Organics		
Plastics (Polymers)	good-excellent	poor [3]
Composites	poor-excellent	poor-fair
Rubber	good	poor
Wood	excellent	poor
Paper and Cardboard	excellent	poor-good
Leather	excellent	poor-good
Synthetic Textiles	excellent	poor-good
Non-Metals, Inorganics		
Quartz	good-excellent	not possible
Glass	difficult [1]	not possible
Ceramics	fair-good [4]	fair
Stone and Rock	poor	poor

[1] Fair with enhanced pulsing up to 3 mm (0.12 inch).
[2] Fair with enhanced pulsing up to 1.5 mm (0.06 inch).
[3] Strongly dependent on color and filler material.
[4] Good with enhanced pulsing up to about 6 mm (0.24 inch), depending on type of ceramic.

4.2 Cut Quality for Metals

It is often wondered what type of cut edge finish is generated by a laser. That appraisal usually entails an evaluation of both the roughness and visual appearance of the edge. Each piece of conventional cutting equipment provides a consistent, known degree of quality which can serve as a reference for subjectively comparing results. In so much, a laser cut can be said to fall somewhere between a sawed edge and that of an EDM cut. When considering metal cutting, a laser cut has the following characteristics (see ***Figure 4.2***):

4.2.1 Kerf

In the thinnest of materials, cut kerf widths can be as little as 0.1 mm (0.004 inch). As material thickness increases, more material is removed from the cut zone. In the end, kerf width is just about linearly proportional to material thickness. A kerf of 0.15 mm (0.006 inch) is typical for 3 mm (0.12 inch) steel, while the kerf width for 19 mm (0.75 inch) steel is about 0.38 mm (0.015 inch). Kerf width is increased purposely (via defocusing or longer focal length) for thicker materials to enhance molten material ejection. This is especially true for oxygen cutting of carbon steels, where higher pressure and flow velocity cannot be employed without inducing excessive heat. In general, kerf widths for metals cut with a Nd:YAG through a fiber optic beam delivery will be larger than the kerf widths produced by a CO_2 laser. The kerf width must be compensated for when designing and programming a cutting pattern.

4.2.2 Taper

The channeling effect of a focused beam used for cutting through a piece of material minimizes taper of the cut in metals to less than 2 degrees (including rounding of the top edge), depending on material type and focal length. That equates to roughly 0.2 mm (0.008 inch) for a quarter-inch thick section. In general, longer focal length focusing optics yield more parallel edges than shorter focal lengths.

4.2.3 Smoothness/Roughness

Measured in terms of the average difference between high and low spots along an edge, the rating for a laser cut piece of metal typically falls between 0.8 and 6.3 μm (30 and 250 μ-inch) with carbon steel having better quality than a comparable thickness of 300 series stainless steel or aluminum. Stainless steel cut with nitrogen assist gas has about half the peak to peak roughness as does the same cut with oxygen. The control of laser processing parameters such as focal length, travel speed, assist type and pressure, pulsing frequency, and focus position serves to optimize the desired quality. For a given material, smoothness is typically a function of overall thickness, depth, composition and quality (e.g. grade of steel), and surface quality (e.g. rust).

Table 4.2

FACTORS INFLUENCING KERF WIDTH
(with a given material thickness)

Factor	Comments/Primary Issues
Spot Size	***Minimize with respect to molten material ejection and depth of focus*** *(Section 2)*
Focusability	Recall: $d = M^2 (4\lambda f/\pi D)$ [$d = (f/f_c)\Phi_c$, *fiber optic*]
Beam Quality (M^2)	Low M^2 values are best (*Section 2.2*)
Wavelength (λ)	Type of material to be cut & fiber optics (*Section 2.1*)
Focal Length (f)	Minimize: balance spot size & depth of focus (*Section 4.6.3*)
Raw Beam Diameter (D)	Large: minimizes spot size and power density on optics (*Section 2.3.1*)
Fiber Optic Diameter (Φ_c)	Minimize: function of laser mode (*Section 2.3.2*)
Focus Position	Requires optimization (*Section 4.6.4*)
Beam Alignment	Beam parallel (and typically coaxial) to optical axis and Mechanical axes and perpendicular to work piece (*Section 3.4.1*)
Thermal Focusing	Affects raw beam size (D): optics quality and cleanliness, cooling efficiency (*Section 3.4.4 & 3.5.4*)
Polarization	***Circular to avoid kerf width variations with direction*** (*Section 3.3*)
Travel Speed	***Constant and repeatable*** (*Section 3.1 & 3.2*)
Power	***Optimize with respect to molten material creation*** *(Section 2.5)*
Gas Pressure/Flow ***Nozzle Geometry/Stand-off***	***Optimize with respect to molten material ejection*** *(Section 4.6.5 & 4.6.6)*

4.2.4 Dross and Recast

In most instances, laser cutting is successful in completely removing material from the kerf. In some materials however, a deposit of material slag (referred to as dross) can appear along the backside of the cut. The formation of this slag is primarily a function of the viscosity and oxidation resistance of the molten material that was not able to be blown away by the gas assist. Additionally, since laser cutting is generally exposed to air, a thin [usually less than 0.1 mm (0.004 inch)] oxide film can be found along the edge of materials that react with oxygen.

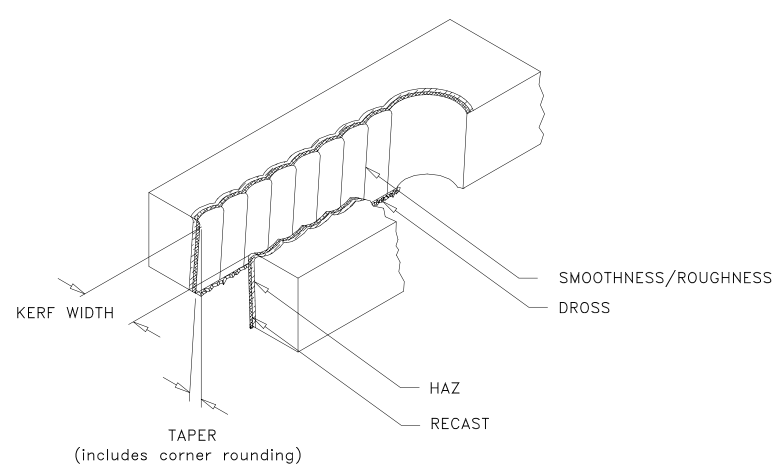
Recast on mild steels is generally less than 0.13 mm (0.005 inch) because the viscosity (and therefore surface tension) of the molten metal is low, enabling good material ejection. With non-ferrous materials, viscosity is generally higher, resulting in poorer ejection of the molten material. This is accompanied by thicker recast zones, especially when oxygen is used as the assist gas. If nitrogen or argon are used, recast can be less than 0.13 mm (0.005 inch). Processing speed with inert gas cutting of mild steels, however, is compromised.

4.2.5 Heat Affect

For materials that combust, such as wood and paper, the laser's heat energy may char the cut edge. With other organic materials, the molten material adjacent to the kerf resolidifies to provide either a fused edge such as with synthetic cloth and prepreg composites or a fire-polished edge as is the case with some plastics. The heat affected zone on metals is generally contained within 0.13 mm (0.005 inch) of the edge. As a general rule of thumb, the thinner the material or the faster the cutting speed, the smaller the heat affected zone. The use of a coolant during cutting can be used to reduce the HAZ (see *Section 4.6.9* for other uses of coolant).

Figure 4.2

LASER CUT QUALITY PARAMETERS FOR METALS



4.3 Material Surface Condition

Surface Finish

For highly reflective materials (such as aluminum, copper, and gold) with an excellent surface finish, the initial coupling of laser energy is reduced. In these materials, if the surface finish is extremely smooth, inconsistent cut quality may result. For such materials, it must be noted that reflected light can cause damage; i) within the laser cavity, ii) to the raw beam or fiber optic beam delivery system, iii) to the cutting head, and iv) to water and gas lines in the proximity of the cutting head (see *Section 3.1.3* and *Accessories Cooling* in *Section 3.1.5*), and personnel (see *Laser Safety, Section 3.7*). Special optic coatings, back reflection sensing, and water cooling in fiber optic beam delivery systems are used to decrease potential for damage within the cavity or beam delivery system. A lightly sanded surface (matte finish) helps reduce reflectivity. Sometimes special coatings are used to increase surface absorption [e.g. ceramic dust (Al_2O_3) particles suspended in a fluid, which can be washed off after cutting].

Paint and Chemical Coatings

In general, paint increases the absorption of the laser into the material (in particular, highly reflective materials such as aluminum), but often leaves unattractive residues in the finished cut area. In addition, the paint near the cut zone may experience degradation. The use of a coolant can be used to minimize this effect (see *Section 4.6.9*). Some heat resistant paints (e.g. ceramic based paints) impede cutting. Some paints ignite with pure oxygen cutting, and therefore in such cases air is used.

Aluminum is often anodized (black and silver-white are most common) for reasons of strength, hardness, corrosion resistance or aesthetics. Anodized aluminum may be pierced and cut more easily and rapidly than bare aluminum because the anodized surface absorbs the laser energy much better than the bare aluminum. Although the anodized surface absorbs nearly all of the power from a CO_2 laser (compared to about 2% on bare aluminum), speeds for CO_2 cutting of anodized aluminum increase only about 30% over bare aluminum, because the reflectivity of the liquid melt is unchanged by the anodizing. In addition, the increase in surface absorptivity of anodized aluminum yields a process which is much less sensitive to variations in process parameters (e.g. focus position and stand-off). However, anodizing is relatively expensive (and therefore would not be used only to improve cuttability) and anodized aluminum cannot be easily formed or welded (therefore, in most cases, anodizing is done after the workpiece or component is completely fabricated).

Zinc coating of mild steel is used for corrosion resistance. Zinc is applied to the surface via the process of galvanization (hence, galvanized steel) or by hot dipping. While galvanized steel has a consistent zinc layer of minimal thickness, hot dipped often has a significant thickness of zinc which inconsistently coats the surface of the steel. Hot dipped zinc coatings of greater than a few microns may cause a reduction in cut quality. Note also that zinc fumes (zinc oxide) are harmful. Cadmium plated steel cuts well, but like zinc, cadmium oxide fumes are harmful.

Protective Films
Sheets of acrylic, and stainless and aluminum used for decorative purposes, often have films of plastic or paper to protect the highly finished surfaces. The presence of the protective layer has little affect on the cutting process or the cut quality. However, the assist gas can lift the protective layer off the surface, which can foul the cutting nozzle or mechanical following head. With acrylic, the hot vapor from the cutting process can get between the protective layer and the surface which may melt damage or distort the workpiece.

Rust, Scale and Contaminants
Carbon steel may often have rust on the surface, especially hot rolled steel which has surface oxides (mill scale) as a result of the hot rolling process. The surface oxides retain moisture, and iron oxide and water inhibit the cutting process yielding an inconsistent cut with poor edge quality (sporadic burning and dross adhesion). Also, because surface oxides are already present (and thus decrease the exothermic potential), oxygen blow piercing times can be longer and oxygen assist cut speeds can be slower. Rust should be removed prior to laser cutting. Pickled and oiled hot rolled steel has improved cuttability over untreated hot rolled steel. Pickling is a chemical etching process which removes the oxide layer. Oil is used to prevent oxidation during storage. In general, the presence of oil and grease have little affect on the cutting process, however, excess oil and grease should be wiped off before cutting.

4.4 Part Location

The relative part location in relationship to the cutting nozzle is a function of primarily three factors; i) the manufacturing and/or assembly tolerances of the component or component assembly to be cut (this may include flatness of sheet metal), and ii) the contouring accuracy, repeatability and stability of either the beam and/or part manipulation, and iii) the repeatability, stability and accuracy of the part fixturing. The cut point location must be held within a tolerance which is dependent upon several factors, a few of which are the sensitivity of the cutting process to stand-off height, nozzle diameter, assist gas type and pressure, depth of focus of the focused beam (see ***Figures 4.3, 4.4 and 4.5***), laser power and cutting speed. If the component location is not properly maintained, the result is either; i) prominent striations or gouges (high cut pressure resulting in violent ejection from stand-off to small), or ii) dross and/or loss of cut (loss of cut pressure and loss of ejection from stand-off too large).

Example 4.4: Cutting 3 mm (0.12 inch) sheet metal with a 1350 Watt CO_2 laser [D = 22 mm (0.87 inch) and M^2 = 2.5] with oxygen assist at 2.5 bar (37 psi), a 1.5 mm (0.060 inch) nozzle orifice, a 127 mm (5 inch) focal length focusing optic with no height following, and a cutting speed of 4 m/min (157 inch/min), requires a part location tolerance of about ±0.25 mm (±0.010 inch).

Figure 4.3

EFFECT OF FOCAL LENGTH ON SPOT SIZE & DEPTH OF FOCUS

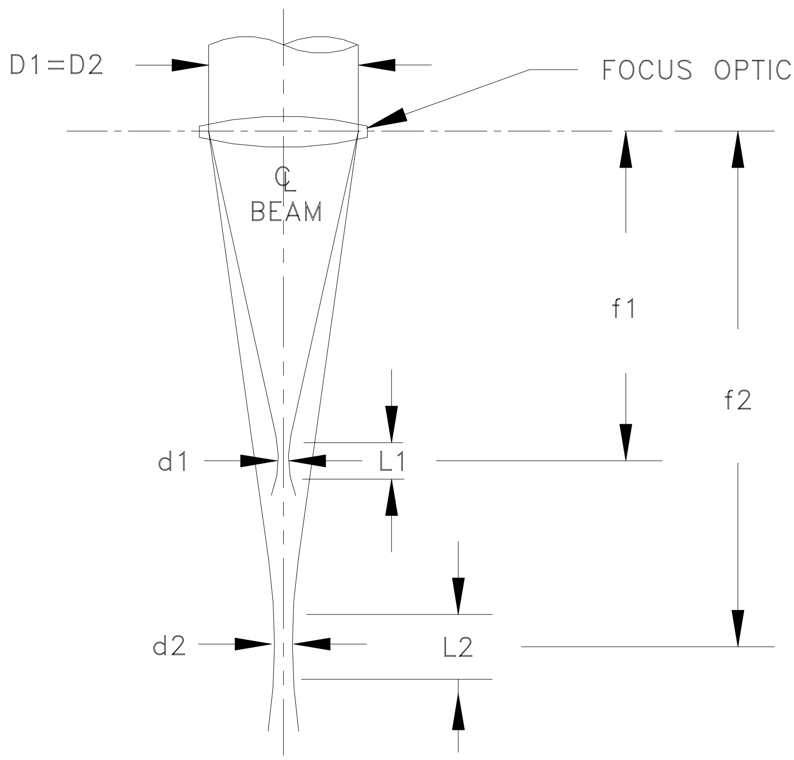


Figure 4.4

EFFECT OF BEAM DIAMETER ON SPOT SIZE & DEPTH OF FOCUS

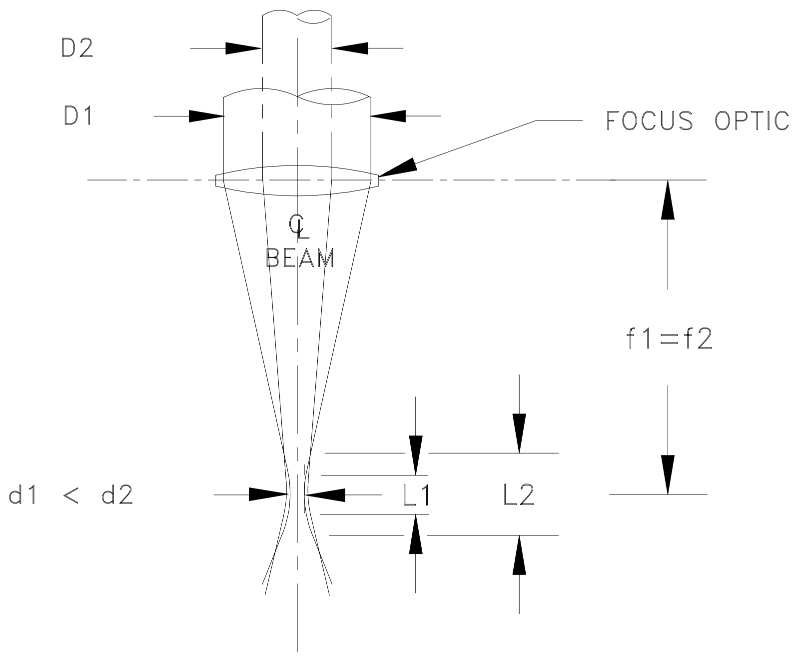
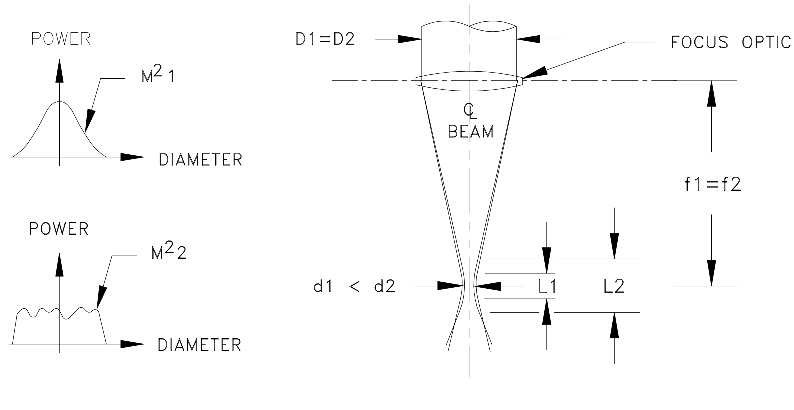


Figure 4.5

EFFECT OF LASER MODE ON SPOT SIZE & DEPTH OF FOCUS



4.4.1 Height Following

Height following is used to maintain a constant stand-off distance during processing. Either mechanical or electrical capacitive methods are used. While flat sheet cutting may not require a height following head, most cutting systems are provided with a means of height following as standard equipment. However, all other geometries cannot be consistently cut without a height following head. Selection criteria must include the height following performance when considering material type, cutting speed, nozzle pressure, material geometry, and workpiece vibration. Additionally, mechanical following systems (generally roller ball) can be used with coolant (see *Sections 4.6.9*).

Table 4.3

HEIGHT FOLLOWING METHOD COMPARISON

Comparison	Capacitive	Mechanical
Positives	three dimensional cutting non contact (no marking)	simpler and less expensive can use coolant all materials
Negatives	more expensive no coolant conductive materials only	flat sheet only may mark material

4.5 Part Fixturing

Due to the relatively small focused spot size and depth of focus of the laser beam, accuracy and repeatability of production tooling must be carefully examined prior to implementation. Although laser cutting produces less heat than conventional thermal cutting processes, it is a thermal process, and may induce thermal distortion of the cut components which may result in deterioration of cut performance in components requiring several cuts (particularly if no height following is used). When considering component clamping, bear in mind the following factors:

a. Avoid off-sets or force moments when designing clamp and fixture tooling. This will minimize unequal loading which may induce distortion of the component at the cut point,

b. Bowing of cut components or fixture “skeletons”, from heating or residual stresses in the material,

c. Force exerted on material and fixturing from assist gas (especially with high pressure cutting),

d. Flexing/distortion of the material and fixturing due to the inertia of the motion system (fixed beam and hybrid motion systems only, see *Section 3.1.2, Motion System*),

e. Allow for assist gas nozzle access when designing clamping geometry,

f. Design for transmitted beam containment (beam dump, cutting box, etc.), and access/maintenance of containment device (e.g. access drawer in cutting box to remove spatter and slugs),

g. Flammability of fixture material(s), and

h. Spatter and heat resistant materials or coatings (i.e. high melting temperature materials) may be considered for fixtures.

4.6 Cut Parameters

An important asset of laser cutting is the high level of control which is available over the variables affecting the process. The cut can be tailored to meet the exact requirements of the job and the results can be readily duplicated. The principle parameters are as follows.

4.6.1 Power and Power Density

Lasers are rated by their power output in terms of Watts. Since laser cutting is a thermal process, the amount of heat produced is related to its capabilities. A 300 watt laser with a high quality output is more than adequate for the cutting of paper products, but lacks the power and power density to effectively couple into aluminum. Given all other considerations being equal (e.g., power distribution, spot size, etc.), increased power allows for faster processing speeds and the ability to cut thicker sections of materials.

As discussed previously, power density combined with a materials ability to couple with the wavelength of the laser, are the key parameters in determining cut thickness and speed. Refer to *Sections 2.5, 3.4 and 3.5* for a detailed discussion of the parameters affecting power density.

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Power density describes the average power per unit area. While this is a very helpful parameter to know (since it is essentially directly related to cutting speed and maximum material thickness), it doesn't describe the profile of the laser power within the focus spot. This can be described by the term "intensity". A laser beam with a low order mode (high beam quality) has a high intensity, with a TEM_{00} mode having the highest

relative intensity. Cutting with high intensity has a couple primary affects. First, longer focal lengths may be required to produce an appropriate focused spot size (depending primarily on the material thickness). Increasing focal length has a positive effect on the Rayleigh length (and therefore reduces kerf angle) on thicker sections, as compared with a shorter focal and higher order mode. However, a longer focal length means a larger focus module, which may reduce the work envelope and flexibility (especially for three dimensional gantry style cutting systems). Secondly, the cut dynamics of a TEM_{00} mode are somewhat different than that of higher order modes, which influences a few of the cutting parameters (e.g. power/speed, pierce parameters, focal length, maximum material thickness).

Laser cutting of thin section aluminum can be given as an illustration of the influence that beam intensity has on the cutting process. For high beam quality (near Gaussian/TEM_{00}) cutting of aluminum, it is possible to cut thin sections (thicknesses less than 2.5 mm (0.10 inch)) faster than carbon steel because; i) the high intensity yields good coupling, ii) the molten material has lower viscosity than steel (therefore, the molten material is easy to eject in thin sections), and iii) as speed increases, the kerf becomes even narrower when cutting with a TEM_{00} beam (compared with a TEM_{01^*} for example), yielding an even greater ejection efficiency. The narrowing kerf is due to the slope of the TEM_{00} power distribution, as compared with the TEM_{01^*}, which is closer to a "top hat" power distribution. As speed is increased (when using a TEM_{00} mode), the energy used for cutting shifts more and more to the center of the power distribution, thus reducing kerf width.

4.6.2 Speed

Laser cutting feedrates are related to the laser power density and the properties of the material to be cut. Above a threshold amount, the feedrates are directly proportional to available power density. This takes into account the laser's performance features (e.g. power and mode) in addition to the focusing system's characteristics (e.g. spot size). Cutting rates are likewise inversely proportional to the material's density and thickness. Given that all other parameters are constant (within process limitations), feedrates will increase with:

a) additional power (i.e. 1500 Watts vs. 600 Watts),
b) improved beam quality (i.e. TEM_{00} vs. TEM_{20}),
c) smaller focused spot size (i.e. 63.5 mm (2.5") vs. 127 mm (5") focal length lens),
d) less required energy to initiate vaporization (i.e. plastic vs. steel),
e) lower material density (i.e. white pine vs. hickory), and
f) decreased thickness [i.e. 3 mm (.12") vs. 6 mm (.24")].

Feedrates can be varied for a particular set of parameters in order to obtain different edge quality results. Particularly for metals, the plot of cutting speed versus thickness for a material has two curves. The upper curve reflects the top speed at which through cuts are achieved while the lower curve shows the limit below in which either inconsistent cuts occur or self-burning with oxygen assist occurs. The resultant window of acceptable cut speeds is usually wider at the thinner range of a material.

For CO_2 lasers, power (P) per unit thickness (z) is approximately proportional to the cutting speed (V). Therefore, power divided by the product of speed and thickness is approximately constant, as follows:

$$P/Vz \cong \text{constant}$$

$$\boxed{\{P/Vz\}_1 \cong \{P/Vz\}_2}$$

Example 4.6.2: If it is known that 3.2 mm thick mild steel can be cut at 4.5 m/min with 1700 Watts, *approximately* how fast can 4.8 mm thick mild steel be cut with 1700 Watts (assuming the same laser and beam delivery system)? Rearranging the above yields $V_2 \cong \{P/z\}_2\{Vz/p\}_1$ = (1700/4.8)[(4.5)(3.2)/1700)] = 3.0 m/min. *(3.2 m/min actual)*

In general, if speed is too low, the kerf width, dross, recast and HAZ increase. If speed is too fast, an incomplete cut will result. Increased reflectivity of the surface to a particular wavelength (e.g. aluminum to the CO_2 wavelength) will reduce the range in which cutting speed can be altered without significantly affecting cut quality. For cutting of plastics, too slow of a cutting speed can result in heat warpage or melting due to reflection off the cutting box or workpiece fixturing, even though the edge quality may still be okay.

It is important to note that cut time is only in part related to linear cut speed, especially when considering contour cutting. Total cut time must include pierce time, times associated with lead in or out cuts, reduced velocity portions of the cut profile (e.g. sharp radii), and delay times. The equation below summarizes some of the most significant factors which determine total cut time:

$$\text{Total cut time} = \sum(\text{assist gas on/off delay}) + \sum(\text{pierce time}) + \sum(\text{plasma stabilization time, if req'd}) + \sum[(\text{cut length})/(\text{cut speed})]$$

In practice, production cutting speeds are set below the maximum possible cut speed. For example, cutting of mild steel is normally accomplished at speeds 80-90% of the maximum cutting speed. This allows for a reliable process which is more tolerant of variation or fluctuation in the cut parameters (i.e. power, focus position, material thickness, assist gas flow, cutting speed).

4.6.3 Lens Type and Focal Length

Focusing lenses come in a variety of types and materials. Only a few materials are used for focusing optics with CO_2 lasers based on their ability to transmit the 10.6 micron wavelength. Zinc selenide (ZnSe) is almost always used with high power CO_2 lasers. Gallium arsenide (GaAs) and potassium chloride (KCl) are also used for CO_2 lenses. However, gallium arsenide has a higher absorption than ZnSe, and it is opaque in the visible spectrum (i.e. will not transmit the red beam from a helium neon alignment laser), and potassium chloride is hygroscopic, water soluble and has a low index of refraction.

When considering lens type (e.g. plano-convex, meniscus, aspheric, diffractive), a trade-off between cost and ability to focus (i.e. focus spot size) is generally the issue. However, plano-convex lenses are generally acceptable for most CO_2 cutting applications. The focusability of a lens is related to F# [the ratio of lens focal length (f) to the size of the raw laser beam at the lens (D), see *Section 2.3.1*]. ***Table 4.4*** below summarizes the considerations for lens types used for CO_2 lasers. Lenses for Nd:YAG lasers are typically made of fused silica.

Since speed is a function of available power density, the choice of the focusing lens has a great impact on the resulting cut quality. Imaging of lasers beams is usually accomplished with transmissive lenses of focal lengths ranging from 2.5 to 10 inches (6.3 to 25.4 cm). Because the focused spot size is proportional to the focal length, the power density that is produced is inversely proportional to the square of that length.

Short focal lengths give very high energy densities, but are limited in their application due to a shallow depth of focus and to thinner materials (because kerf width must be larger in thick materials to allow efficient ejection of the molten material). Short focal lengths are appropriate for use with thin materials and in high speed operations where the material can be held within the depth of focus of the focused beam. Longer focal lengths have lower power densities, but are able to maintain those densities over a much broader range and therefore produce straighter edges on thicker materials, than do shorter focal lengths, given that they have enough energy initially. In addition, short focal lengths produce rough cut edges in the lower region of the kerf on thick materials (providing the kerf width is large enough to allow efficient ejection of molten material). Therefore, focal length (for a given laser) has to be optimized with respect to the material thickness to be cut (see also ***Table 2.1***).

Thick, organic materials produce high concentrations of decomposition particulate and gaseous hydrocarbons in the kerf. Absorption and reradiation of the laser beam via these particulates increase the kerf width in the central region of the cut. High assist gas pressure, or slow cutting speeds in combination with a long focal length lens, minimize this effect.

The choice of an appropriate lens entails a compromise between power density and depth of focus. While shorter focal lengths provide smaller spot sizes, with a higher power density, they have a much shorter depth of focus. The following chart gives typical values for maximum material thickness and focus tolerance relative to focal length.

Table 4.4

CONSIDERATIONS FOR LENS TYPE
(for CO_2 lasers)

Type	F# (f/D) for near diffraction limited spot	F# (f/D) generally acceptable	Relative Cost
Plano-convex	> 8	> 5	Lowest
Meniscus	> 6	> 2.5	Medium
Aspheric	Any	Any	High
Diffractive [1]	Any	Any	Highest

[1] Diffractive optics allow for a longer focal length for a given spot size, as compared with an inferior lens.

Table 4.5

RELATIONSHIP BETWEEN FOCAL LENGTH AND MATERIAL THICKNESS
[for CO_2 lasers with $2 < M^2 < 4$, and 20 mm (0.79 inch) < D < 25 mm (0.98 inch)] [1]

Lens Focal Length	Maximum Material Thickness	Focus Tolerance
127.0 mm (5.0 inch)	< 10 mm (0.39 inch)	± 0.25 mm (0.010 inch)
190.5 mm (7.5 inch)	> 10 mm (0.39 inch)	± 0.50 mm (0.020 inch)

[1] Material thickness and focus tolerance are a function of focused spot size and depth of focus, which in addition to focal length, are a function of mode and wavelength. Therefore, these values will differ depending on mode and wavelength.

4.6.4 Focus Position

During the laser cutting process, the focal point of the lens should be consistently positioned in order to provide the best cutting results. See the table below for an overview of focus position for three common cases. Above or below this point (see Focus Tolerance in ***Table 4.5*** above), cut quality deteriorates. Cutting systems that employ short focal length lenses must insure constant lens-to-workpiece distance.

Optimum focus position is dependent on material thickness and material type. Sensitivity of the cut quality to focus position is also dependent on material type and thickness, as well as laser power. One technique which can be used to determine the optimum focus position is to adjust the focal position (while keeping the stand-off distance constant) until the kerf width is minimized.

Table 4.6

FOCUS POSITION

Material	Assist Gas	Focus Position
Carbon steel	Oxygen	@ or above material surface (up to about 30% above)
Metals	Nitrogen	@ or near bottom surface of material
Non-metals	Any	@ or below surface of material [1] (up to about 30% below)

[1] Except dieboard cutting, where focus is above material.

4.6.5 Assist Gas

(see also Section 3.1.3)

Reactive or Inert

Recall that assist gas is supplied coaxial with the focused beam to protect the lens and aid in the material removal process. Generally, compressed air (used primarily for organic materials) or inert gas is used to exhaust melted and evaporated material from the cut zone while minimizing any excess burning. For most metal cutting applications, a reactive gas assist (e.g. oxygen) can be employed to promote an exothermic (heat generating) reaction. Oxygen creates a radial combustion front (exothermic reaction) ahead of the beam which can improve cutting speeds by 25-40% over the results obtained with use of air. The oxidation reaction in mild steels can make up as much as 40% of the total cut energy for thick sections. For thicknesses less than 2 mm (0.080 inch), nitrogen cutting with a TEM_{00} laser @ 2,500 Watts is actually faster than oxygen cutting. At these higher speeds, the exothermic reaction contributes increasingly less energy to the cutting process, and eventually hinders it.

On the other hand, when the exothermic energy input is much greater than the molten material ejection, uncontrolled self-burning is possible [especially when bulk material temperature rises to over 95°C (200°F)]. Several techniques may be employed to reduce bulk material temperatures and therefore the potential for self-burning:

a. *Corner Overshooting*: Since constant velocity cannot be maintained at a sharp corner, the corner can be overshot and the cut direction can be changed by a loop cut outside of the cut component. This loop cut prevents the increase of temperature that would occur at a corner and decreases geometric inaccuracies at the corners due to acceleration and deceleration, but increases material waste.

b. *Pulse Frequency Modulation*: See *Dynamic Power Control, Section 3.2.1*.

c. *Power Ramping*: Reducing power as speed is reduced (see *Section 3.2*). This technique is inferior to pulse frequency modulation because as power is reduced, the power density is reduced, and therefore energy coupling with the material changes.

d. *Cooling*: See *The use of Coolant, Section 4.6.9*.

e. *Cut Planning*: Organize cut routine to maximize cooling of component. Examples of this are; i) for components that require the cutting of many small details in close proximity to one another, do not cut adjacent details one right after the other, and ii) if the heat input from piercing results in burning when cutting small details (e.g. diameter holes), accomplish other cutting on the component while the pierce area is cooling, then return and cut the detail.

f. *Air Assist Cutting*: Cutting with air suppresses the exothermic oxidation reaction that occurs with oxygen cutting, and thereby eliminates the problem of self-burning. However, the maximum material thickness that can be cut and the speed at which a particular thickness can be cut are both reduced as compared to oxygen cutting (less than half the thickness can be cut and speeds are reduced by as much as 30%). In addition, because the speed is reduced the HAZ increases. Also, cutting with air requires higher pressure and therefore, higher consumption. Three cautions are worthy of mentioning in regard to cutting with air supplied by a compressor; i) maximum pressures available are lower than required for many applications, ii) pressure can fluctuate as much as 20% (depending on air demand), iii) compressed air is often contaminated with oil and water which can contaminate the focus lens (which can lead to lens damage, power loss and thermal shifting of focus).

Argon is used as an assist gas for laser cutting of titanium and typically nitrogen is used for other oxygen sensitive metals to avoid the formation of a hard oxide next to the kerf (e.g. chromium oxide when cutting Cr-Ni stainless steel). However, inert gas cutting is somewhat slower (10-50%) than oxygen cutting, but is employed especially when a “weld ready”, oxide-free cut edge is required. See ***Table 4.7*** for a summary of assist gas types and uses.

Pressure

In addition to gas type, delivery pressure is an important consideration. In light of the narrow kerf produced by laser cutting, the required assist gas pressure is often quite high because only a portion of the gas flows through the narrow kerf. Typically, pressures of 3-4 bar (45-60 psi) developed in the gas jet nozzle are used in oxygen cutting of thin material at high speeds to help prevent the clinging of slag or dross to the back edge of the cut. In addition to high pressure, using reactive gases (when metallurgically acceptable) with metallic materials minimizes the amount of dross. In general, the pressure is reduced as the material thickness increases or process speeds slow. However, in the cases of stainless steel and aluminum, a higher assist gas pressure is required as the material thickness increases. Pressure gauges should be installed directly to (or as close as possible to) the assist gas nozzle to insure accurate indication of actual cutting pressure.

In some cases, oxide free cutting for example, assist gas pressures (nitrogen) can be as high as 27 bar (400 psi). In such extreme cases, thicker focus lenses must be used in order to withstand the higher pressure. Laser cutting often requires two (or more) gas pressures (e.g. piercing and cutting), in which case an assist gas supply system must be used which incorporates a servo valve or multiple solenoids and regulators (see also *Section 3.1.3*, and ***Figure 3.3*** for an example of a three pressure assist gas delivery panel).

For plastics cut via melt shearing (e.g. polypropylene, polystyrene and polyethylene), too low of a gas pressure can result in melt droplet ignition which, via the flames produced, can melt, ignite or distort the workpiece. In addition, the molten material is ejected less effectively, therefore cut speeds are reduced. Too high of a gas pressure, on the other hand, increases the roughness of the cut edge due to assist gas turbulence. In addition, fine filaments rather than droplets are ejected, which can clog the fume elimination system (i.e. filters). Plastics cut via vaporization (e.g. acrylic) respond differently to assist gas pressure changes. If the assist gas pressure is too high, the normally flame polished edge changes to an edge with a frosted appearance. If the assist gas pressure is too low, the vapor in the cut zone may ignite into a yellow, sooty flame which damages the workpiece.

Flow

The assist gas should be turned on and flowing prior to piercing or cutting to protect the nozzle and lens. The assist gas solenoid(s) and supply line size(s) must be selected for the maximum pressure and flow rate required. Note that in high pressure cutting, the assist gas type (inert gas) and consumption yield processing costs that are significantly higher than low pressure oxygen cutting.

For supersonic flow [i.e. nozzle pressures greater than 0.9 bar (13 psi) for oxygen, nitrogen and air; and greater than 1.1 bar (15 psi) for argon and helium], assist gas consumption (Q) in liters per minute can be readily calculated knowing the nozzle orifice diameter (ϕ) in millimeters and the nozzle gauge pressure (P_g) in bar (*Note*: to convert assist gas consumption to cubic feet per minute, multiply liters per minute by 0.0353; divide pounds per square inch by 14.7 to convert to bar). Refer to ***Figure 4.6*** for assist gas consumption data for supersonic flow through various nozzle diameters.

$$\boxed{Q = 8.2\,(\phi)^2\,[P_g + 1]}$$

<u>*Example 4.6.5:*</u> To calculate the assist gas consumption for oxygen cutting at 7 bar (103 psi) and a 1.5 mm (0.06 inch) nozzle orifice diameter, $Q = (8.2)(1.5)^2(7+1) = 148$ liters/min. To convert to scfh, (148 liters/min)(0.0353 scf/liter) = 5.2 scfh (see also ***Figure 4.6***).

4.6.6 Gas Jet Nozzle

The coaxial assist gas required for laser cutting is delivered to the cut point via a cutting nozzle (incorporating a replaceable tip which is usually made of copper). The nozzle tip is a consumable part, especially when cutting metals (due to spatter). However, the tip may last indefinitely when cutting polymers. As stated above, the assist gas should be turned on and flowing prior to piercing or cutting to protect the nozzle and lens. Copper is typically used as the material for the nozzle tip because; i) copper reflects the laser radiation and is not easily damaged by the focused beam if misaligned, and ii) spatter does not readily adhere to copper.

Since the nozzle tip is a consumable; i) it must be easy to replace, ii) it must be accurately manufactured, and iii) it must have a repeatable, self-centering means of attachment. The performance parameters of the cutting nozzle are the internal nozzle geometry (orifice size and flow geometry) and stand-off distance (distance from bottom of nozzle tip to top of material to be cut).

Table 4.7

ASSIST GAS TYPES AND COMMON USES

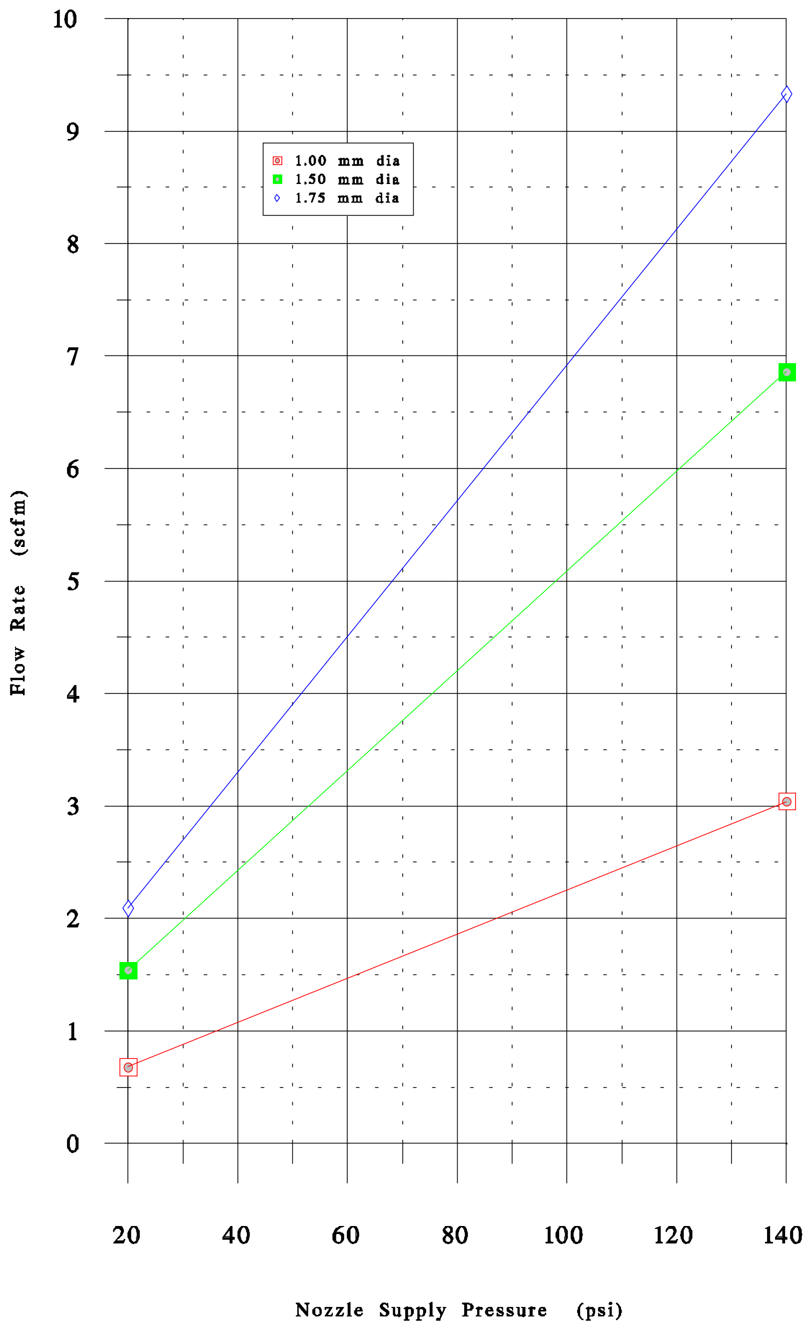
Assist Gas	Common Applications	Comments
Oxygen	mild steel (comments 1 & 2), stainless steel (comment 2), copper (comment 3),	(1) O_2 increases cut speed/ O_2 burning possible (2) oxide layer on cut edge (3) good finish up to 3 mm (0.12 inch)
Nitrogen	stainless steel, aluminum, nickel base alloys, mild steel (clean cut)	slower cut speeds, clean cuts *(no oxide layer, suitable for welding)*
Air	thin aluminum (air reactive) (comment 1), alumina (air inert), plastics, wood, composites, glass, quartz	inexpensive when applicable (1) up to 1.5 mm (0.06 inch)
Argon/Helium	titanium	argon relatively expensive *(oxygen reacts violently & nitrogen yields imbrittlement)*, helium or helium/argon mix minimizes HAZ & reduces argon plume problems

Stand-off

The ratio of stand-off distance to orifice size is typically in the range of 0.2 - 0.8. Stand-off distances greater than the diameter of the nozzle generally result in turbulent flow of the assist gas. This, in combination with a narrow kerf, yields large pressure fluctuations in the stand-off gap, which causes inconsistent cut quality. In these applications special laminar flow nozzles can be used to minimize the effects of turbulence. With a short stand-off, the kerf acts as an extension of the cutting nozzle and makes the flow geometry of the nozzle tip much less critical. Maintaining stand-off distance is often more critical than maintaining focus (in other words, the depth of focus is often larger than the tolerance of the cutting process to changes in stand-off). Stand-off distances are generally in the range of 0.5 - 1.0 mm (0.02 - 0.04 inch). On occasion stand-off distances less than this are required for good cut quality [e.g. oxide-free cutting of 6 mm (0.24 inch) stainless steel]. However, in this case, the stand-off distance must be maintained very accurately during cutting [about ± 0.1 mm (± 0.004 inch)], because ejection pressure varies significantly with small changes in stand-off, thereby affecting cut quality.

Figure 4.6

ASSIST GAS CONSUMPTION [1]



[1] For supersonic flow, see *Flow* in Section 4.6.5.

Orifice Size
Generally, the nozzle orifice is more than twice the kerf width, which means the pressure drop between the nozzle tip and the workpiece is negligible. The gas jet, however, over expands within the keyhole cavity after only a few nozzle diameters. This limits the effective length of the gas jet, the cut thickness limit and the length over which the cut surface quality can be maintained. Small nozzle orifice diameters make nozzle alignment more critical, and makes the process more sensitive to misalignment and changes in pressure, but minimize gas consumption. Typical nozzle orifice diameters are in the range of 1.0 - 2.2 mm (0.040 - 0.087 inch). However, for some plastics cutting, nozzle orifice diameters can be as large as 3.0 mm (0.12 inch). This is done to reduce gas jet velocity, and thereby minimizes gas turbulence and cut edge surface roughness.

Alignment and Damage
The nozzle orifice and focused spot must be centered within about 0.2 mm (0.008 inch), otherwise a tapered cut and/or inconsistent dross will result. Additionally, the nozzle and laser beam centerlines must be coaxial and, whenever possible, perpendicular to the surface of the material to be cut. If not, a tapered cut and/or inconsistent dross will result. Damaged nozzles, such as those which are dented or burned, also has a serious affect on cut quality. Damage resulting in an asymmetric orifice produces inconsistent cut quality (e.g. dross, roughness, taper) as a function of cut direction.

4.6.7 Piercing

Piercing is a term used to describe the creation of the initial hole through the material to be cut. Almost all cuts begin with piercing. Only cuts that can be initiated off the edge of the material to be cut do not require piercing. Except for very thin materials and non-metals, piercing is accomplished while the material is stationary, and generally falls into two categories; 1) controlled pulse piercing, and 2) blow piercing. Controlled pulse piercing uses a series of pulses to "peck" through the material. The piercing schedule is accompanied by low pressure assist gas [less than 1 bar (15 psi)] to displace the molten material as it is melted. For mild steel, air can be used for controlled pulse piercing since material displacement and protection of the lens and nozzle are the functions of the assist gas (i.e. oxygen does not accelerate the piercing process).

Blow piercing uses a much more aggressive pulsing schedule (high average power) in order to punch through the material faster, with typically an accompanying increase in stand-off distance. Controlled pulse piercing is slower, but results in a pierce hole diameter which is less than, or equal to, the kerf width. Blow piercing is much faster, but results in a pierce hole diameter which is significantly greater than the kerf width [up to about 3 mm (0.12 inch)]. In addition, blow piercing creates significant spatter, therefore lens and tip maintenance is increased [even though assist gas pressures of up to 3.5 bar (51 psi) are used to minimize this problem]. Blow piercing also imparts more heat to the workpiece than does pulse piercing. Oxygen is generally used for mild steel, and does accelerate the blow piercing process. Air can be used to reduce the pierce hole size on mild steel, but blow pierce time is increased (about two to three times).

Table 4.8

COMPARISON OF PULSE AND BLOW PIERCING
(for mild steel with oxygen assist)

Pierce Parameter	Controlled Pulse Piercing	Blow Piercing
Hole Diameter	less than or equal to kerf width	greater than kerf width
Pierce Time for 6.4 mm (1/4 inch)	about 1.5 seconds	about 0.25 second
Pierce Time for 12.7 mm (1/2 inch)	6-8 seconds	less than 2.0 second
Assist Gas Pressure	less than 1 bar (15 psi)	2.5-3.5 bar (37-51 psi)
Spatter Produced	low	high

4.6.8 Pulsing

When considering laser cutting applications (especially Nd:YAG), two primary sub-categories are immediately evident, namely pulsed and continuous wave (CW) applications. A laser which pulses typically produces a beam in the form of a very short, intense burst of energy, while a CW laser produces a beam of constant, steady state power. The primary considerations between pulsed and CW have to do with either product limits (i.e. pulsed vs. CW capability on a given laser) or process limits (focused spot power density requirements for a given application), or both. While there is some overlapping of applications, there are specific areas where either a pulsed laser or a continuous-wave (CW) laser is more suitable.

Pulsing implies that the laser's active medium is excited by a very quick response stimulus. This allows the laser to transmit a burst of energy for a brief length of time (generally in terms of milliseconds). Two types of pulsing are available; normal and superpulse. In normal pulse operation, the current is switched on and off, resulting in a pulsed output for CW lasers in which the peak pulse power is approximately equal to the set CW power. Peak pulse powers for pulsing Nd:YAG lasers can reach values of over 30 times greater than the maximum average power levels. This allows low-to-medium power lasers to achieve enough energy to reach vaporization temperatures for most materials.

With superpulse operation of CO_2 lasers, higher amplitude shorter pulses are generated to excite the lasing medium, resulting in peak powers 2-5 times the set CW power. In some lasers, superpulse schedules can be used in combination with CW power (*see below*). Pulse shaping is also available on some lasers, and can be used to create unique pulse shapes that either enhance coupling efficiency or reduce cut burr, or both.

The short duration pulse produced by a pulsable laser guarantees minimum heat input, which is particularly important for parts sensitive to distortion. However, pulsing action slows down feedrates since duty cycles (the percentage of time that the laser is emitting energy during a cut) are less than 100%. Cutting further requires that the pulses overlap to produce sharp, straight edges. Continuous-wave lasers maintain their output over the entire span of processing (100% duty cycle). The main advantage of CW operation is that there is a greater amount of power per unit time. This generally leads to faster feedrates than those for the pulsed mode. While there is more heat input to the workpiece, resultant edge quality (25-250 micro-inches) is comparable to a pulsed cut on most materials.

Frequency and Overlap

If a pulsed laser is utilized, then pulse rate in Hz (f), average kerf width (k_W), and cut speed (V- distance per second) have to be matched to produce the required percent overlap (%OL). The following relationships may be helpful, especially for Nd:YAG laser applications where frequency is a limiting factor (about 1000 Hz maximum compared to about 100 kHz for CO_2 lasers):

$$\text{Overlap} = k_w - V/f \quad \textit{(ignoring oblong effect due to travel)}$$

$\%OL = 100[(k_w - V/f)/k_w]$, and rearranging yields

$$\boxed{f = 100V/(k_w)(100\text{-}\%OL)}$$

For low striation cuts: *75 < %OL < 80*

For typical cuts: *50 < %OL < 70*

$$\boxed{f = 5V/k_w}$$

Example 4.6.8: With a cut speed of 80 mm/sec and an average kerf width of 0.2 mm, a frequency of 2 kHz is required for a low striation cut [(100)(80)/(0.2)(100-80)], and a frequency of 1 kHz is required for a typical 60% overlap cut [(100)(80)/(0.2)(100-60)].

Pulse Energy

In pulsable CO_2 and Nd:YAG lasers, energy per pulse, peak power per pulse and pulse width (i.e. laser pulse "on" time) are key cutting parameters. Energy per pulse in Joules (E_p) is related to the average laser power (P_{ave}) and pulse rate (f) by the following:

$$\boxed{E_p = P_{ave}/f}$$

Peak Power

Peak power per pulse (P_p) is the ratio of energy per pulse to pulse width in seconds (t):

$$\boxed{P_p = E_p/t}$$

For a given energy per pulse, short pulse width times yield high peak powers. When peak power gets too high, the resultant cut can have prominent striations, especially if the cut speed is too fast or too slow. In general, high peak powers can cut thicker materials with less overall heat input into the component being cut. However, the cut speed suffers (as compared with CW cutting) because high peak powers occur at lower frequencies (especially with Nd:YAG lasers), and the speed must be matched to the frequency to insure a continuous cut.

Pulse Width

Long pulse width times yield low peak powers and produce cuts which have excessive kerf widths. However, low peak power densities result in greater overall heat input into the component, and can yield severe back reflections off the surface of the material.

4.6.9 The use of Coolant

The coolant (usually water or water with a corrosion inhibitor) is most commonly delivered to the cut zone via the cutting head (coaxial to the assist gas) and removed by vacuum, or recirculated within the cutting system, or both. Mechanical following systems (generally roller ball) can be used with coolant, while capacitive height following systems cannot. A slightly higher assist gas pressure [about 2 bar (30 psi)] is typically needed to keep the coolant out of the kerf. Due to the assist gas pressure and flow displacing the coolant away from the immediate kerf zone, the presence of water does not significantly affect the cut speed. However, cut components must be dried after cutting to avoid corrosion. The use of coolant in laser cutting has several primary uses and benefits:

a. Cooling prevents thermal runaway (uncontrolled oxygen self-burning) on carbon steels where cutting results in parent material temperatures greater than 95°C (200°F). The increased assist gas flow rate (due to higher pressure) can make the process window smaller, as thickness increases. This is due to higher heat generated from the increased exothermic effect. This additional heat must be removed successfully by the coolant. Cooling allows cutting of intricate contours using relatively high average power (compared to pulsed cutting with no coolant) and high feedrate, without regard to material temperature issues. Cooling makes the process more forgiving at thicknesses less than 6.25 mm (0.25 inch), and allows intricate cutting in thicknesses up to 13 mm (0.5 inch).

b. The use of cooling during cutting can be used to reduce the HAZ in carbon steels, aluminum and titanium.

c. Cooling reduces thermal distortion of the sheet when cutting thin metals.

d. The use of a coolant can be used to minimize paint and/or coating degradation near the cut zone on painted or coated materials.

5. CUT QUALITY TROUBLESHOOTING CHECKLIST FOR METALS

In partial summary of the prior text, the following laser cutting troubleshooting guidelines present a few of the primary causes of production cut quality degradation in relation to several of the most common cut defects when cutting metal materials. The cut defects have been separated into those present when the cut is a through cut, and those present when the cut is intermittent or lacking.

5.1 Cut Defects with Through Cut

5.1.1 Large Kerf

i. ***Spot Size via Focus-*** Is the focus position optimized?
(Recast and dross will also increase. Set by cut trials keeping stand-off constant and minimize kerf.)

ii. ***Power-*** Is the average power too high?
(Recast and dross will also increase.)

iii. ***Speed-*** Is the speed too low?
(Recast and dross will also increase. Insure process speed is properly set, calibrated and accurate. Check % feedrate override if applicable.)

5.1.2 Angled Kerf

i. ***Beam Alignment-*** Is the laser beam coaxial to the focal axis of the focusing optic?
(If the alignment laser is used to aid in determining this, insure alignment and main process beams are coaxial.)

ii. ***Polarization-*** Is the laser beam circularly polarized?

5.1.3 Excess Dross

i. See 5.1.1, i. through iii.?

ii. ***Assist Gas-*** Is the assist gas pressure too low or too high?
(Inadequate expulsion. Check pressure regulator setting and bottle pressure. Also check for pressure leaks caused by loose fittings, or gas supply lines damaged by spatter, flames or reflected laser power.)

iii. ***Stand-off Gap-*** Is the stand-off gap too large?
(Inadequate expulsion because assist gas is not directed through the kerf.)

iv. ***Gas Jet Nozzle-*** Is the assist gas nozzle diameter too large?
(Inadequate expulsion because assist gas is not directed through the kerf.)

5.1.4 Inconsistent Dross

i. ***Beam Alignment-*** Is the focused beam centered with the nozzle orifice?
(Uncentered can cause dross on one side of the cut and cut quality will change with cut direction.)

ii. ***Nozzle Blockage-*** Is the nozzle orifice partially blocked by spatter or other contamination?
(Blockage can cause dross on one side of the cut and cut quality will change with cut direction.)

iii. ***Nozzle Damage-*** Is the nozzle tip damaged due to crash or laser misalignment (especially with high pulse power)?
(Tip damage can cause dross on one side of the cut and cut quality will change with cut direction.)

iv. ***Poor Mode Symmetry-*** Is the mode oblong or asymmetrical?
(Asymmetry can cause dross on one side of the cut and cut quality will change with cut direction. Poor laser cavity optical alignment or distorted external beam delivery mirrors can cause asymmetry of the laser beam.)

5.1.5 Prominent Striations/Gouging

i. ***Assist Gas-*** Is the assist gas pressure too high?
(Violent/turbulent expulsion.)

ii. ***Stand-off Gap-*** Is the stand-off gap too small?
(Violent/turbulent expulsion.)

5.1.6 Oxygen Burning

i. ***Assist Gas-*** Is the assist gas pressure too high?
(Oxygen self-burning possible.)

ii. ***Speed-*** Is the speed too low?
(Oxygen self-burning possible, especially at corners and small details.)

5.2 Intermittent or No Cut

5.2.1 Consistent Lack of Cut

General Considerations

i. ***Inadequate Power-*** Is the average power too low? Is the power or pulse energy adequate to yield a cut at the given process cutting speed?
(Power may have degraded due to contaminated laser gas supply, flash/arc lamp deterioration, poor laser cavity optical alignment due to service or vibration, or contamination laser cavity optics. Insure power reading at laser is accurate using power meter calibration.)

ii. ***Energy Loss via Speed Increase-*** Is the speed too high? Is the process speed set properly to yield a cut at the given process laser power?
(Insure process speed is properly set, calibrated and accurate. Check % feedrate override if applicable.)

iii. ***Spot Size Increase via Improper Focus Position-*** Is the focus position optimized?
(Recast and dross will also increase, set by cut trials keeping stand-off constant and minimize kerf. If focus optic has been replaced, the focus position may need to be re-optimized.)

iv. ***Improper Focal Length-*** Is the focus optic focal length correct?
(Especially at locations where many lasers are used with varying focal lengths.)

Reflective/Transmissive Beam Delivery System Considerations

v. ***Power Loss via Absorption-*** Are all the beam delivery bending mirrors clean?
(Purge gas filters may require changing, or an increase in the purge gas flow rate may be necessary.)

vi. ***Power Loss via Clipping-*** Is the beam "clipping" in the beam delivery system? Are the alignment laser and main process beams centered through each optic? If the alignment laser is used for beam alignment, is the alignment and main process beams coaxial?
(Visual inspection of mode burns after each optic in the beam delivery system can be used to identify if clipping is occurring, either fringes or incomplete burns can result from clipping. Near and far field mode burn tests with cross-hair inserts can be used to check if alignment and process laser beams are coaxial. Note that the far field burn should be at least the distance from the laser output to the focusing optic, the longer the more precise.)

Fiber Optic Beam Delivery System Considerations

vii. ***Power Loss via Clipping-*** Is the beam properly aligned into the fiber optic?
(Compare power out of the laser with power out of the fiber.)

5.2.2 Inconsistent Lack of Cut

General Considerations

i. ***Stand-off Gap-*** Is the stand-off gap constant throughout the cut?
(Check gap with feeler gauge at several points during a dry run.)

Reflective/Transmissive Beam Delivery System Considerations

ii. ***Spot Size Increase via Thermal Lensing of Raw Beam-*** Has the cut quality been decreasing slowly with time (over several days or weeks)? Does the beam size at the focusing optic agree with the expected mode burn geometry and beam divergence?
(Thermal focusing of the output optic, which increases the focused spot size, may be occurring, take a mode burn at the work station with the focusing optic removed and compare the size with what is expected. Also check quality of purge gas and output optic shroud gas, laser gas quality, internal cavity oil or water/additive.)

ii. ***Spot Size Increase via Thermal Distortion of Beam Delivery Optics-*** Does the beam delivery system have adequate cooling?
(Beam bender and focus lens mounts should be cool to the touch, water temperature must be above dew point.)

iii. ***Power Loss/Spot Size Increase via Thermal Distortion of Focus Optic/Cover Slide-*** Is the focus optic and/or cover slide clean?
(Purge gas filters may require changing, or an increase in the purge gas flow rate may be necessary, insure assist gas is coming on prior to laser on/shutter open.)

iv. ***Power Loss by Clipping via Thermal Blooming***- Does the cut start okay and then after a few seconds the cut quality deteriorates?
(Is the purge air clean and dry, is it connected properly, are there sufficient fittings for the length of the beam delivery system? Filters may require cleaning or replacement.)

5.2.3 Oxygen Burning

i. ***Assist Gas-*** Is the assist gas pressure too low?
(Burning due to incomplete ejection of molten material.)

Table 5.1

SUMMARY OF CUT PERFORMANCE VS. PROCESS PARAMETERS FOR METAL

Process Parameter	**Cut Performance** *Too High*	*Too Low*
Power	kerf increases recast & dross increase increased taper wavy striations/some dross	kerf decreases loss of cut *(see also Section 3.6.1, iii.a)*
Speed	kerf decreases loss of cut increased surface roughness wavy striations/some dross	kerf increases recast & dross increase increased taper
Focus Position	kerf increases recast & dross increase deep striations loss of cut *(see also Section 3.6.1, iii.b for factors increasing spot size)*	kerf increases recast & dross increase loss of cut
Assist Gas Pressure	prominent striations erosion at bottom of cut (excessive burning) O_2 self-burning possible	dross inadequate ejection (partly closed kerf)
Stand-off Gap	dross	prominent striations
Nozzle Orifice Diameter	dross high gas consumption	centering critical [1] inadequate ejection (partly closed kerf)

[1] Focused beam not centered with nozzle orifice yields dross on one side and clean on the other.

ROFIN-SINAR LASER

ROFIN-SINAR, Inc.
40984 Concept Drive, Plymouth, MI 48170, USA
Tel: (734) 455-5400, Fax: (734) 455-2741

ROFIN-SINAR Laser GmbH
Marking Division,
Neufeldstrasse 16/Guending, D-85232 Bergkirchen, Germany
Tel: (8131) 704-0, Fax: (8131) 704 100

ROFIN-SINAR France S.A.
10, Allee du Cantal, Z.I. La Petite Montagne Sud,
F-91018 Evry Cedex, France
Tel: (1) 69 11-36 36, Fax: (1) 69 11-36 39

ROFIN-SINAR UK Ltd.
York Way, Willerby, Kingston upon Hull,
HU106HD, United Kingdom
Tel: 44-1482-650088, Fax: 44-1482-650022

ROFIN-SINAR Laser GmbH
Berzeliusstrasse 83, D-22113 Hamburg, Germany
Tel: (40) 733 63-0, Fax: (40) 733 63 100

ROFIN-MARUBENI Laser Corp.
Sun-Intelligent Building 4F, 3162 Sakai Atsugi-shi,
Kanagawa-ken, 243 Japan
Tel: (462) 29-8655, Fax: (462) 29-8541

ROFIN-SINAR Italiana S.r.l.
Via Galilei, 1, 1-20090 Rovagnasco di Segrate (MI), Italy
Tel: (2) 269 20-446, Fax: (2) 269 20 549

DILAS Diodenlaser GmbH
Galileo-Galilei-Strasse 10, D-55129 Mainz, Germany
Tel: 49-6131-9226-0, Fax: 49-6131-9226 55