Weldability and Welding Procedure

1. INTRODUCTION

Ordinarily, a correctly designed joint and properly made weld do not require special procedures to prevent cracks during welding or in service. The need for special procedures increases, however, with heavy plate structural members and is growing with the expanding use of steels having greater amounts of alloying elements in their chemistry.

This section first provides some insight into the factors that promote weld cracking and makes suggestions for welding procedures to correct or prevent a cracking problem. This section then will present a comprehensive discussion of when to use preheating to eliminate or prevent cracking. It will also present a new approach to establishing the preheat and interpass temperature, based on the heat input of the welding procedure, the critical cooling rate (determined by the chemistry of the steel), and the joint geometry, particularly the plate thickness.

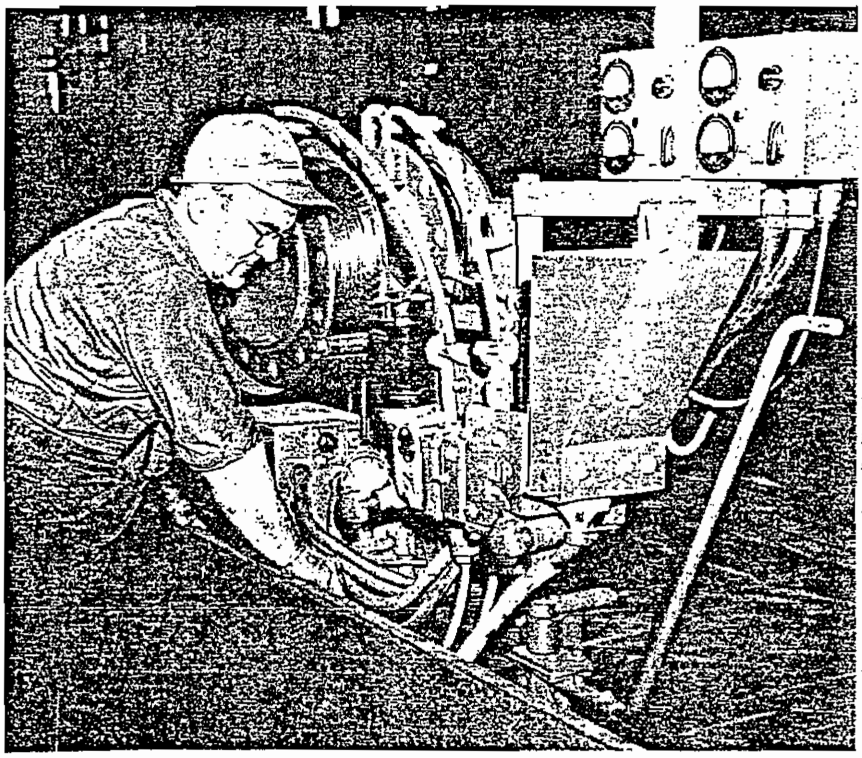
2. WELDABILITY

Most steels can be commercially arc welded, with good results—sound, strong welded joints. The "weldability" of a metal refers to the relative ease of producing a satisfactory, crack-free, sound joint. A steel is said to be ideally weldable if the required weld joint can be made without difficulty or excessive cost.

Some steels are more suited to high-speed welding than others. Analysis of the electrode core wire is accurately controlled to produce good welds, but since the plate metal becomes part of the weld, control of the plate analysis is also important. When higher currents are used to get higher welding speeds, more of the plate metal mixes with the weld. If possible, select an easily welded steel that doesn't require expensive electrodes or complicated welding procedures. Table 1 gives a range of carbon steel analyses for maximum welding speed.

The commonly used mild steels fall within the

Tandem-arc and other modern automatic welding equipment have revolutionized the shop fabrication of large bridge girders, built-up columns, and other special structural members. The welding of thick plates, or of higher-strength alloys, may require preheating or other measures not needed with the more common mild steels.

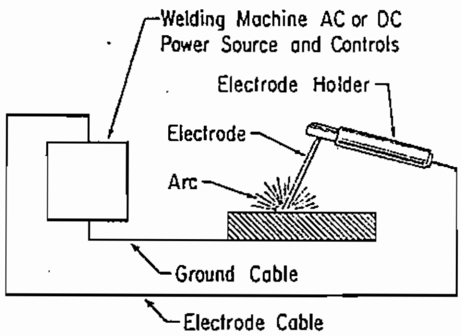


The Shielded Arc Welding Process

In order to evaluate the weldability of steels, a limited knowledge of the basic arc welding process is advisable.

Welding consists of joining two pieces of metal by establishing a metallurgical bond between them. Many different welding processes may be used to produce bonding through the application of pressure and/or through fusion. Arc welding is a fusion process. The bond between the metals is produced by reducing to a molten state the surfaces to be joined and then allowing the metal to solidify. When the molten metal solidifies, union is completed.

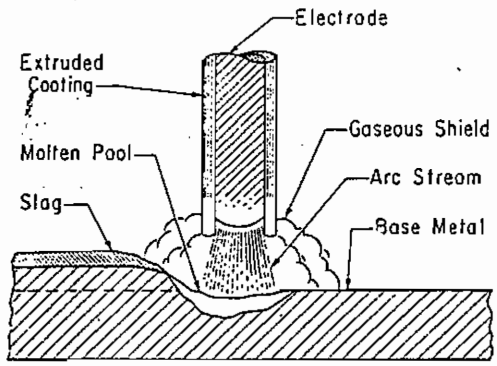
In the arc welding process, the intense heat required to reduce the metal to a liquid state is produced by an electric arc. The arc is formed between the work to be welded and a metal wire or rod called the electrode. The arc, which produces a



temperature of about 6500°F at the tip of the electrode, is formed by bringing the electrode close to the metal to be joined. The tremendous heat at the tip of the electrode melts filler metal and base metal, thus liquifying them in a common pool called a crater.* As the areas solidify, the metals are joined into one solid homogeneous piece. By moving the electrode along the seam or joint to be welded, the surfaces to be joined are welded together along their entire length.

The electric arc is the most widely used source of energy for the intense heat required for fusion welding. The arc is an electrical discharge or spark sustained in a gap in the electrical circuit. The resistance of the air or gas in the gap to the passage of the current, transforms the electrical energy into heat at extremely high temperatures. Electrical power consists of amperes and voltage. The amount of energy available is the product of the amperes and the voltage flowing through the circuit and is measured in watts and kilowatts. The energy used is affected by such variables as the constituents in electrode coatings, the type of current (AC or DC), the direction of current flow, and many others.

In all modern arc welding processes, the arc is shielded to control the complex arc phenomenon and to improve the physical properties of the weld deposit. This shielding is accomplished through various techniques: a chemical coating on the electrode wire, inert gases, granular flux compounds, and metallic salts placed in the core of the electrode. Arc shielding varies with the type of arc welding process used. In all cases, however, the shielding is intended: 1) to protect the molten metal from the air, either with gas, vapor or slag; 2) to add alloying and fluxing ingredients; and 3) to control the melting of the rod for more effective use of the arc energy.



The arc welding process requires a continuous supply of electric current sufficient in amperage and voltage to maintain an arc. This current may be either alternating (AC) or direct (DC), but it must be provided through a source which can be controlled to satisfy the variables of the welding process: amperage and voltage.

* For some applications, filler metal is deposited by a consumable welding electrode; for others, a "nonconsumable" electrode supplies the heat and a separate welding rod the filler metal.

preferred analysis listed. Sulphur content of these steels is usually below 0.035%, although the specification limits permit as much as 0.050%.

Continued progress is being made in metallurgical control of steel, as well as in the development of welding processes, electrodes and fluxes. This tends to broaden the range of "weldability" with respect to steel analysis.

The six basic ASTM-specification construction steels usually do not require special precautions or special procedures.

However, when welding the thicker plates in even these steels the increased rigidity and restraint and the drastic quench effect makes the use of the proper procedure vitally important. In addition, thick plates usually have higher carbon content.

We also have an increase in the use of higher strength low alloy steels and the heat treated very high yield strength steels. These steels have some elements in their chemistry that exceed the ideal analysis, Table 1, for high speed welding.

Frequently pre-planned and proven welding procedures are required to assure the production of crack-free welds when joining thicker plates or the alloy steels. These procedures usually call for one or all of the following:

1. Proper bead shape and joint configuration.
2. Minimized penetration to prevent dilution of the weld metal with the alloy elements in the plate.
3. Preheating, controlled interpass temperature and sometimes even controlled heat input from the welding procedure to retard the cooling rate and reduce shrinkage stresses.

TABLE 1—Preferred Analysis Of Carbon Steel for Good Weldability

Element		Normal Range, %	Steel Exceeding Any One of the Following Percentages Will Probably Require Extra Care
Carbon	C	.06 - .25	.35
Manganese	Mn	.35 - .80	1.40
Silicon	Si	.10 max	.30
Sulphur	S	.035 max	.050
Phosphorus	P	.030 max	.040

3. BASE PROCEDURE ON ACTUAL ANALYSIS

Published standard production welding procedures generally apply to normal welding conditions and the more common, "preferred analysis" mild steels.

When a steel's specification analysis falls outside the preferred analysis, the user often adopts a special welding procedure based on the *extremes* of the material's chemical content "allowed" by the steel's specification. However, since the chemistry of a specific heat of steel may run far below the top limit of the "allowables", a special procedure may not be required, or may require only a slight change from standard procedures and thereby minimize any increase in welding cost.

For optimum economy and quality, under either favorable or adverse conditions, the welding procedure for joining any type of steel should be based on the steel's *actual* chemistry rather than the *maximum* alloy content allowed by the specification. This is because a mill's average production normally runs considerably under the maximum limits set by the specification.

Usually a Mill Test Report is available which gives the *specific* analysis of any given heat of steel. Once this information is obtained, a welding procedure can be set that will assure the production of crack-free welds at the lowest possible cost.

4. WELD QUALITY

The main objective of any welding procedure is to join the pieces as required with the most efficient weld possible and at the least possible cost. "As required" means the weld's size and quality must be consistent with the service requirements. Excessive precautions to obtain unnecessary quality, beyond that needed to meet service requirements, serve no practical purpose and can be expensive.

Because it greatly increases cost without any benefit, inspection should not request the correction of slight undercut or minor radiographic defects such as limited scattered porosity and slag inclusions, unless thorough study shows such defects cannot be tolerated because of specific service requirements.

Why Welds Crack and How to Prevent It

5. WELD CRACKS

A crack in a weld, however, is never minor and cannot be condoned. Good design and proper welding procedure will prevent these cracking problems:

1. weld cracks occurring during welding,
2. cracking in the heat affected zone of the base metal,
3. welded joints failing in service.

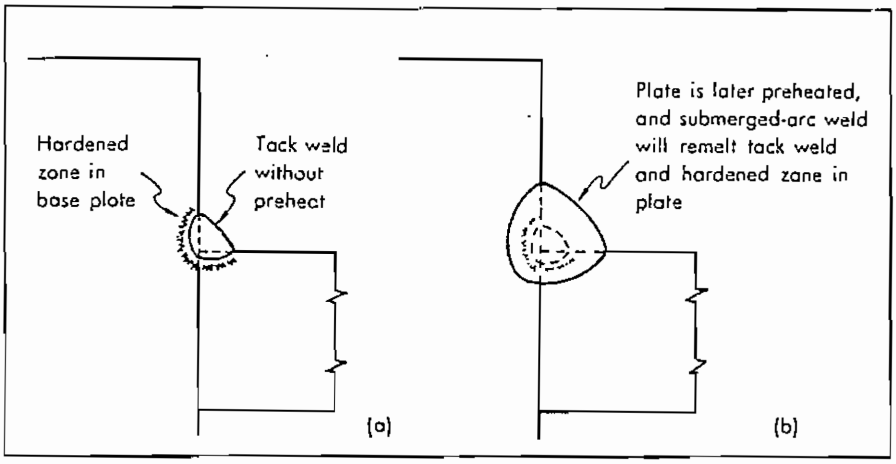


FIGURE 1

Factors that Affect Weld Cracking During Welding

1. *Joint Restraint* that causes high stresses in the weld.

2. *Bead Shape* of the deposited weld. As the hot weld cools, it tends to shrink. A convex bead has sufficient material in the throat to satisfy the demands of the biaxial pull. However, a concave bead may result in high tensile stresses across the weld surface from toe to toe. These stresses frequently are high enough to rupture the surface of the weld causing a longitudinal crack.

An excessively penetrated weld with its depth greater than its width under conditions of high restraint may cause internal cracks.

Both of these types of cracking are greatly aggravated by high sulphur or phosphorus content in the base plate.

3. *Carbon and Alloy Content* of the base metal. The higher the carbon and alloy content of the base metal, the greater the possible reduction in ductility of the weld metal through admixture. This contributes appreciably to weld cracking.

4. *Hydrogen Pickup* in the weld deposit from the electrode coating, moisture in the joint, and contaminants on the surface of the base metal.

5. *Rapid Cooling Rate* which increases the effect of items 3 and 4.

Factors that Affect Cracking in the Heat-Affected Zone

1. *High carbon or alloy content* which increases hardenability and loss of ductility in the heat-affected zone. (Underbead cracking does not occur in non-hardenable steel.)

2. *Hydrogen embrittlement* of the fusion zone through migration of hydrogen liberated from the weld metal.

3. *Rate of cooling* which controls items 1 and 2.

Factors that Affect Welded Joints Failing in Service

Welds do not usually "crack" in service but may "break" because the weld was of insufficient size to fulfill service requirements. Two other factors would be:

1. Notch toughness,* which would affect the breaking of welds or plate when subjected to high impact loading at extremely low temperatures.

2. Fatigue cracking* due to a notch effect from poor joint geometry. This occurs under service conditions of unusually severe stress reversals.

Items to Control

1. *Bead Shape.* Deposit beads having proper bead surface (i.e. slightly convex) and also having the proper width-to-depth ratio. This is most critical in the case of single pass welds or the root pass of a multiple pass weld.

2. *Joint Restraint.* Design weldments and structure to keep restraint problems to a minimum.

3. *Carbon and Alloy Content.* Select the correct grade and quality of steel for a given application, through familiarity with the mill analysis and the cost of welding. This will ensure balancing weld cost and steel price using that steel which will develop the lowest possible overall cost. Further, this approach will usually avoid use of inferior welding quality steels that have excessively high percentages of those elements that always adversely affect weld quality—sulphur and phosphorus.

Avoid excessive admixture. This can be accomplished through procedure changes which reduce penetration (different electrodes, lower currents, changing

* Neither notch toughness nor fatigue cracking are discussed here. See Section 2.1, "Properties of Materials," Section 2.8, "Designing for Impact Loads, and Section 2.9, "Designing for Fatigue Loads."

polarity, or improving joint design such as replacing a square edge butt weld with a bevel joint.)

4. *Hydrogen Pickup.* Select low-hydrogen welding materials.

5. *Heat Input.* Control total heat input. This may include preheat, welding heat, heating between weld passes to control interpass temperature and post heating to control cooling rate. Control of heat input lowers the shrinkage stresses and retards the cooling rate helping to prevent excessive hardening in the heat-affected zone, two primary causes of cracking.

6. TACK WELDS

The American Welding Society's Building Code and Bridge Specifications both require any tack welds that will be incorporated into the final joint, to be made under the same quality requirements, including preheat, as the final welds.

However, this does not recognize the deep penetration characteristics of some welding processes, for example, submerged-arc. If the initial tack welds are relatively small compared to the first submerged-arc weld pass, they will be entirely remelted along with the adjacent heat-affected area in the plate.

In this case, no preheat should be required for small single pass tack welds unless the plates are so thick and restrained that the tack welds are breaking. See Figure 1. If the tack welds are breaking, the corrective measures previously listed relating to bead shape and weld throat should be applied with preheating called for as a last resort. It is always a good idea to use low-hydrogen welding materials for tack welding plates over 1 in. thick.

7. THINNER PLATE

Welds that join thinner plates rarely show a tendency to crack. The heat input during welding and lack of mass of the thinner plate create a relatively slow cooling rate. This, plus the reduced internal stresses resulting from a good weld throat to plate thickness ratio and the fact that the thinner plate is less rigid and can flex as the weld cools and shrinks, controls the factors that induce cracking. Cracking is almost never a factor on thinner plate unless unusually high in carbon or alloy content.

8. THICK PLATES

In the steel mill, all steel plates and rolled sections undergo a rather slow rate of cooling after being rolled while red hot. The red hot thick sections, because of their greater mass, cool more slowly than thin sections. For a given carbon and alloy content, slower cooling from the critical temperature results in a slightly lower strength.

For the normal thicknesses, the mill has no difficulty in meeting the minimum yield strength required. However, in extremely thick mill sections, because of their slower cooling, the carbon or alloy content might have to be increased slightly in order to meet the required yield strength.

Since a weld cools faster on a thick plate than on

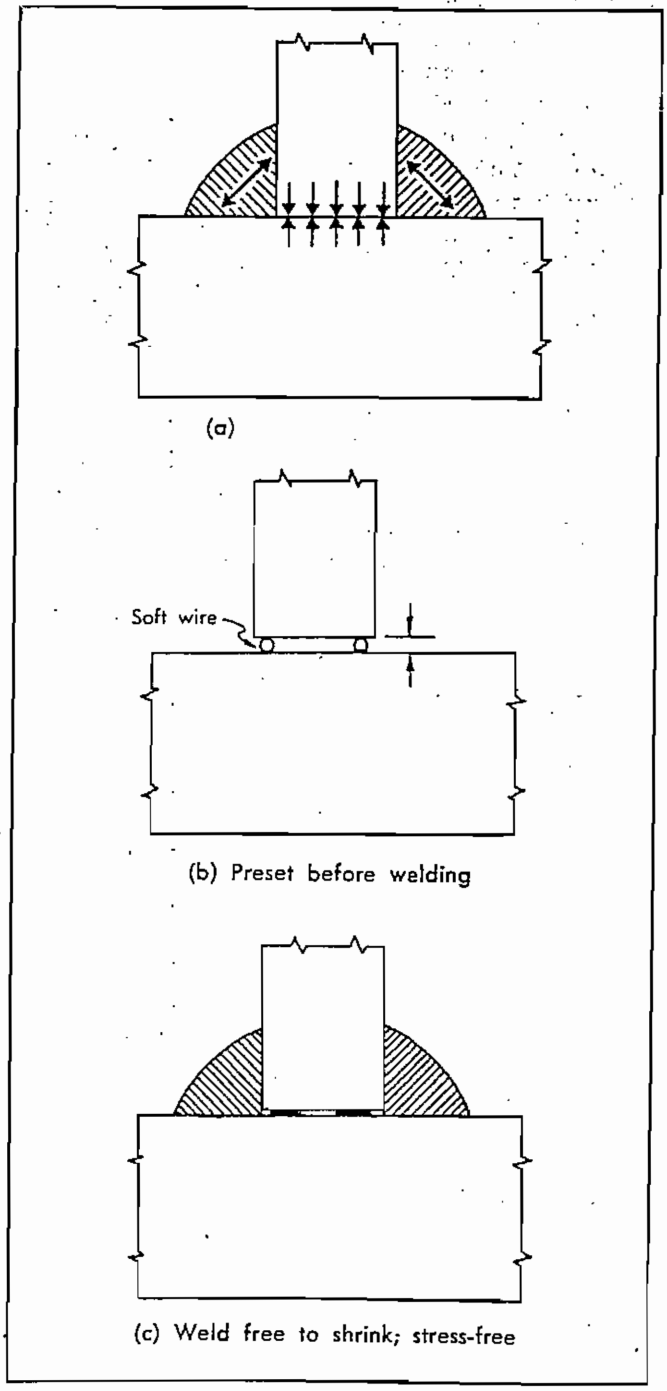


FIGURE 2

a thinner plate, and since the thicker plate will probably have a slightly higher carbon or alloy content, welds on thick plate (because of admixture and fast cooling) will have higher strengths but lower ductility than those made on thinner plate. Special welding procedures may be required for joining thick plate (especially for the first or root pass), and preheating may be necessary. The object is to decrease the weld's rate of cooling so as to increase its ductility.

In addition to improving ductility, preheating thick plates tends to lower the shrinkage stresses that develop because of excessive restraint.

Because of its expense, preheating should be selectively specified, however. For example, fillet welds joining a thin web to a thick flange plate may not require as much preheat as does a butt weld joining two highly restrained thick plates.

On thick plates with large welds, if there is metal-to-metal contact prior to welding, there is no possibility of plate movement. As the welds cool and contract, all the shrinkage stress must be taken up in the weld, Figure 2(a). In cases of severe restraint, this may cause the weld to crack, especially in the first pass on either side of the plate.

By allowing a small gap between the plates, the plates can "move in" slightly as the weld shrinks. This reduces the transverse stresses in the weld. See Figures 2(b) and 2(c). Heavy plates should always have a minimum of $\frac{1}{32}''$ gap between them, if possible $\frac{1}{16}''$.

This small gap can be obtained by means of:

1. Insertion of spacers, made of soft steel wire between the plates. The soft wire will flatten out as the weld shrinks. If copper wire is used, care should be taken that it does not mix with the weld metal.

2. A deliberately rough flame-cut edge. The small peaks of the cut edge keep the plates apart, yet can squash out as the weld shrinks.

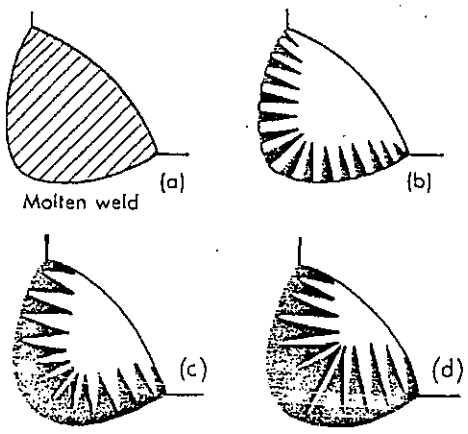


FIGURE 3

3. Upsetting the edge of the plate with a heavy center punch. This acts similar to the rough flame-cut edge.

The plates will usually be tight together after the weld has cooled.

Fillet Welds

The above discussion of metal-to-metal contact and shrinkage stresses especially applies to fillet welds. A slight gap between plates will help assure crack-free fillet welds.

Bead shape is another important factor that affects fillet weld cracking. Freezing of the molten weld, Figure 3(a), due to the quenching effect of the plates commences along the sides of the joint (b) where the cold mass of the heavy plate instantly draws the heat out of the molten weld metal and progresses uniformly inward (c) until the weld is completely solid (d). Notice that the last material to freeze lies in a plane along the centerline of the weld.

To all external appearances, the concave weld (a) in Figure 4 would seem to be larger than the convex weld (b). However, a check of the cross-

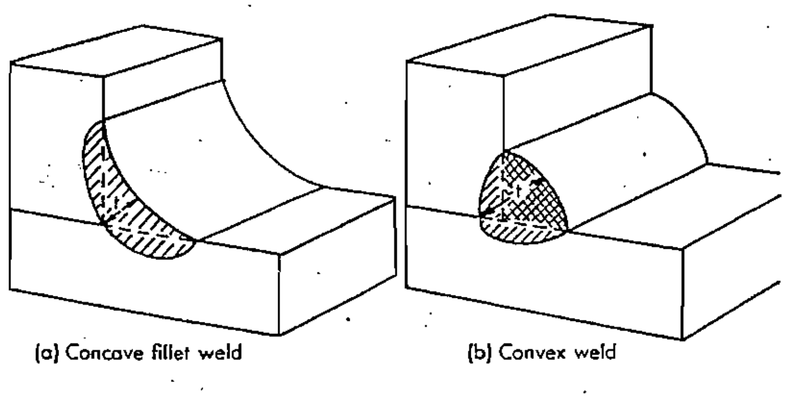


FIGURE 4

section may show the concave weld to have less penetration and a smaller throat (t) than first thought; therefore, the convex weld may actually be stronger even though it may have less deposited metal (darker cross-section).

Designers originally favored the concave fillet weld because it seemed to offer a smoother path for the flow of stress. However, experience has shown that single-pass fillet welds of this shape have a greater tendency to crack upon cooling, which unfortunately usually outweighs the effect of improved stress distribution. This is especially true with steels that require special welding procedures.

When a concave fillet weld cools and shrinks, its outer face is stressed in tension, Figure 5(a). If a surface shrinkage crack should occur, it can usually be avoided by changing to a convex fillet (b). Here the

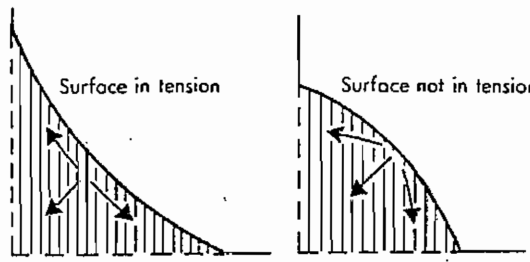


FIGURE 5

weld can shrink, while cooling, without stressing the outer face in tension and should not crack. For multiple-pass fillet welds, the convex bead shape usually applies only to the first pass.

For this reason, when concave welds are desired for special design considerations, such as stress flow, they should be made in two or more passes—the first slightly convex, and the other passes built up to form a concave fillet weld.

9. GROOVE WELDS

On heavy plate, it is usually the first (or root) pass of a groove weld that requires special precautions. This is especially true of the root weld on the back side of a double Vee joint because of the added restraint from the weld on the front side. The weld tends to shrink in all directions as it cools, but is restrained by the plate. Not only are tensile shrinkage stresses set up within the weld, but the weld frequently undergoes plastic yielding to accommodate this shrinkage.

Some idea of the possible locked-in stress and plastic flow of the weld may be seen in Figure 6. Imagine the plate to be cut near the joint, allowing the weld to freely shrink (dotted lines). Then pull the plates back to the original rigid position that they would normally be in during and after welding (solid lines). This necessitates a stretching of the weld.

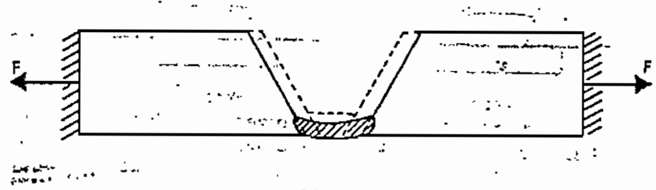


FIGURE 6.

In actual practice all of this stretch or yielding can occur only in the weld, since the plate cannot move and the weld has the least thickness of the joint. Most of this yielding takes place while the weld is hot and has lower strength and ductility. If, at this time, the internal stress exceeds the physical properties of the weld, a crack occurs which is usually down the centerline of the weld.

The problem is enhanced by the fact that the first (or root) bead usually picks up additional carbon or alloy by admixture with the base metal. The root bead thus is less ductile than subsequent beads.

A concave bead surface in a groove weld creates the same tendency for surface cracking as described for fillet welds, Figure 7. This tendency is further increased with lower ductility.

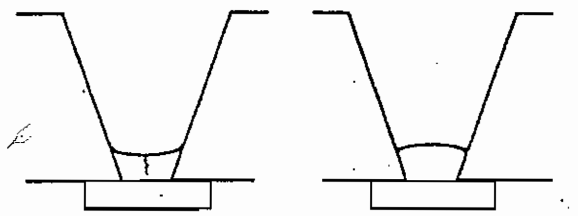
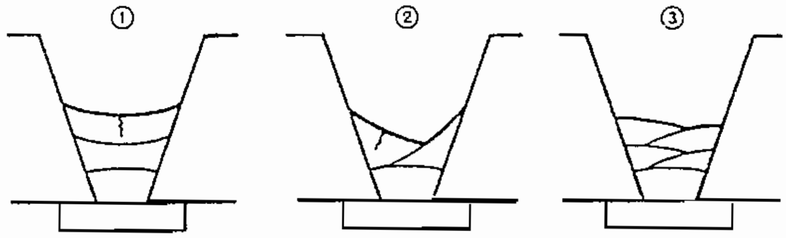


FIGURE 7

Increasing the throat dimension of the root pass will help to prevent cracking; use electrodes or procedures that develop a convex bead shape. Low hydrogen welding materials are sometimes useful and finally preheat can be specified. Obviously preheating should be adopted as a last resort since it will cause the greatest increase in weld cost.

The problem of centerline cracking can even occur in the succeeding passes of a multiple pass weld if the passes are excessively wide or concave. Corrective measures call for a procedure that specifies a narrower slightly convex bead shape, making the completed weld two or more beads wide, side by side, Figure 8.



Wrong
Too wide and concave
(Also poor slag removal)

Wrong
Washed up too high
and concave

Right
Flat or slightly convex
not quite full width
(Also good slag removal)

FIGURE 8

10. INTERNAL CRACKS AND WELD WIDTH TO DEPTH OF FUSION RATIO

Where a cracking problem exists due to joint restraint, material chemistry or both, the crack usually appears at the weld's face. In some situations, however, an internal crack can occur which won't reach the weld's face. This type of crack usually stems from the misuse of a welding process that can achieve deep penetration, or poor joint design.

The freezing action for butt and groove welds is the same as that illustrated for fillet welds. Freezing starts along the weld surface adjacent to the cold base metal, and finishes at the centerline of the weld. If, however, the weld depth of fusion is much greater than width of the face, the weld's surface may freeze in advance of its center. Now the shrinkage forces will act on the still hot center or core of the bead which could cause a centerline crack along its length without this crack extending to the weld's face, Figure 9(a).

Internal cracks can also result with improper joint design or preparation. Figure 9(b) illustrates the results of combining thick plate, a deep penetrating welding process, and a 45° included angle.

A small bevel on the second pass side of the double-V-groove weld, Figure 9(c), and arc gouging a groove too deep for its width, led to the internal crack illustrated.

Internal cracks can also occur on fillet welds if the depth of fusion is sufficiently greater than the face width of the bead, Figure 9(d).

Although internal cracks are most serious since they cannot be detected with visual inspection methods, a few preventive measures can assure their elimination. Limiting the penetration and the volume of weld metal deposited per pass through speed and amperage control and using a joint design which sets reasonable depth of fusion requirements are both steps in the right direction.

In all cases, however, the critical factor that helps control internal cracks is the ratio of weld width to depth. Experience shows that the weld width to depth of fusion ratio can range from a minimum of 1 to 1 to a maximum of 1.4 to 1.

$$\frac{\text{Width of Weld}}{\text{Depth of Fusion}} = 1 \text{ to } 1.4$$

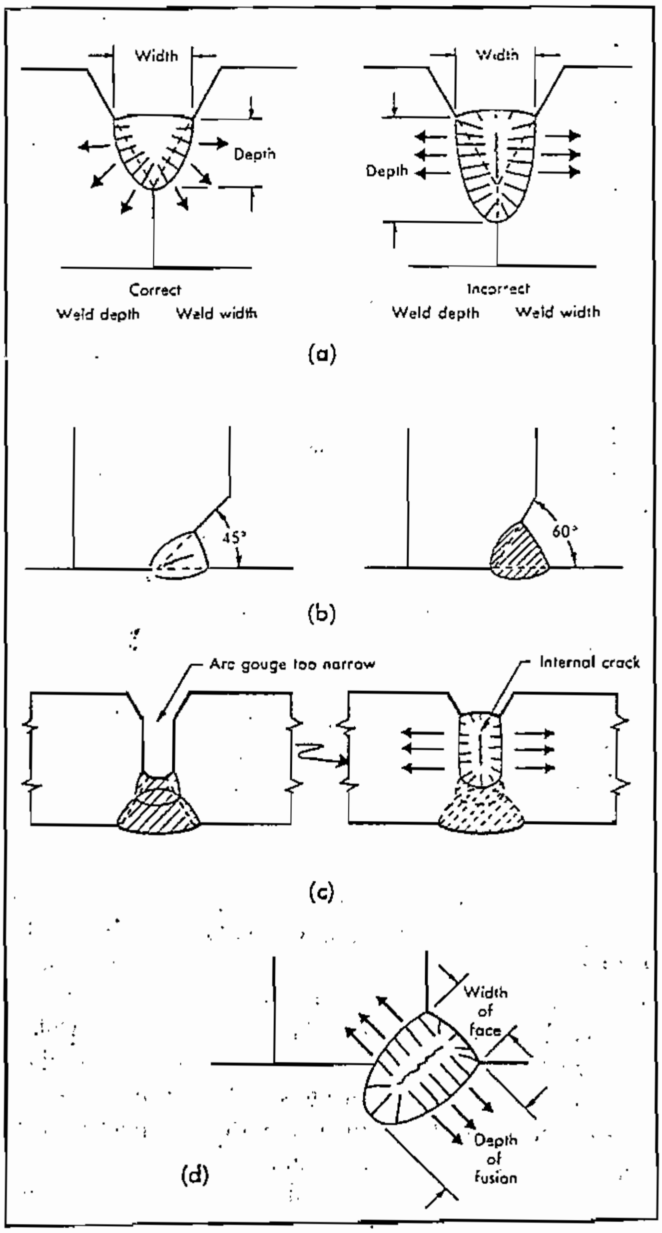


FIGURE 9

11. UNDERBEAD CRACKING

Underbead cracking is not a problem with the controlled analysis low carbon steels. This problem if it occurs is in the heat-affected zone of the base metal. It can become a factor with thick plate as the carbon or alloy content of the steel increases. As an example, this can occur with the heat treatable very high strength, high carbon low alloy steels like 4140 or 6150. The construction alloy steels which have over 100,000 psi tensile strength and are heat treated before welding, also can experience underbead cracking in thick plates. When armour plate was used, underbead cracking (toe cracks) was a problem. The point is that the problem is only important on hardenable steels.

Low-hydrogen processes should be used to join these materials since one cause of underbead cracking is hydrogen embrittlement in the heat-affected zone. Hydrogen in the welding arc, either from the electrode coating or from wet or dirty plate surfaces, will tend to be partially absorbed into the droplets of weld metal being deposited and absorbed into the molten metal beneath the arc.

As the welding arc progresses along the plate, the deposited hot weld metal (which has now solidified) and the adjacent base metal heated by the weld above the transformation temperature are both austenitic at this elevated temperature, and have a high solubility for hydrogen. Fortunately, a considerable amount of hydrogen escapes through the weld's surface into the air; however, a small amount may diffuse back through the weld into the adjacent base metal. (The rate of diffusion decreases with decreasing temperature.)

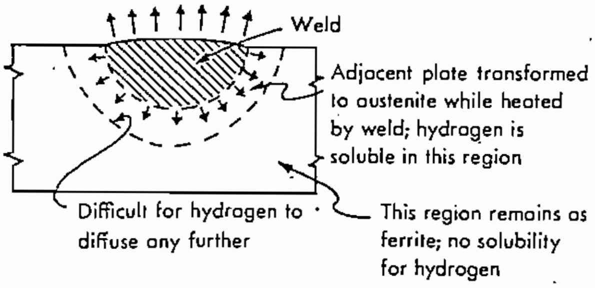


FIGURE 10

Beyond the boundary of the heat-affected zone, the base metal is in the form of ferrite, which has practically no solubility for hydrogen. This ferrite boundary becomes an imaginary fence, and the hydrogen tends to pile up here, going no farther. See Figure 10.

Upon further cooling, the heat-affected area transforms back to ferrite with almost no solubility for hydrogen. Any hydrogen present tends to separate out between the crystal lattice and builds up pressure. This pressure, when combined with shrinkage stresses and any hardening effect of the steel's chemistry, may cause tiny cracks. Since weld metal is usually of a lower carbon than the base plate, this trouble occurs mainly just beyond the weld along the austenite-ferrite boundary and is called "underbead cracking" See Figure 11. If some of these cracks appear on the

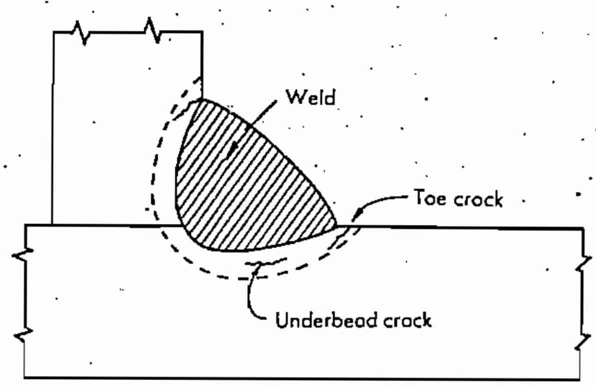


FIGURE 11

plate surface adjacent to the weld, they are called "toe cracks". Slower cooling by welding slower and preheating allows hydrogen to escape and helps control this problem.

The use of low-hydrogen welding materials eliminates the major source of hydrogen and usually eliminates underbead cracking.

12. SUMMARY ON CRACKING

The first requirement of any welded joint is to be crack-free. Cracking may occur in either the weld metal or the heat-affected zone of the base plates.

Most steels can be welded in the average plate thickness without worrying about weld cracking.

As plate thickness increases, and as the carbon and alloying content increase, weld cracks and underbead cracks may become problems and require special precautions for their control.

This necessitates in order of importance: a) good welding procedure, especially in respect to bead shape, control of admixture, b) reducing rigidity by intentional spacing of plates, c) use of low-hydrogen welding materials, and d) controlled cooling rate, including welding current and travel speed, and if needed control of preheat and interpass temperature.

Why Preheat and How to Determine Correct Preheat Temperature

13. WHEN AND WHY TO PREHEAT

Preheating, while not always necessary, is used for one of the following reasons:

1. To reduce shrinkage stresses in the weld and adjacent base metal; especially important in highly restrained joints.

2. To provide a slower rate of cooling through the critical temperature range (about 1800° F to 1330° F) preventing excessive hardening and lowered ductility in both weld and heat-affected area of the base plate.

3. To provide a slower rate of cooling through the 400°F range, allowing more time for any hydrogen that is present to diffuse away from the weld and adjacent plate to avoid underbead cracking.

4. To increase the allowable critical rate of cooling below which there will be no underbead cracking. Thus, with the welding procedure held constant, a higher initial plate temperature increases the maximum safe rate of cooling while slowing down the actual rate of cooling. This tends to make the heat input from the welding process less critical.

Cottrell and Bradstreet* show the following critical cooling rates (R_{cr}) for a given steel at 572°F (300°C) using low-hydrogen electrode in order to prevent underbead cracking for various preheats to be:

T_o (°F)	R_{cr} (°F/sec)
—58	6.8 — 9.9
68	8.6 — 11.7
212	21.6 — 37.8

5. To increase the notch toughness in the weld zone.

6. To lower the transition temperature of the weld and adjacent base metal.

Normally, not much preheat is required to prevent underbead cracking. This is held to a minimum when low-hydrogen welding materials are used. Higher preheat temperature might be required for some other reason, e.g. a highly restrained joint between very thick plates, or a high alloy content.

Preheating makes other factors less critical, but since it invariably increases the cost of welding, it cannot be indulged in unnecessarily.

* Cottrell and Bradstreet, "Effect of Preheat on Weldability", BRITISH WELDING JOURNAL, July 1955, p. 309.

14. AWS MINIMUM REQUIREMENTS

The AWS has set up minimum preheat and interpass requirements given in Table 2.

These minimum preheat requirements may need to be adjusted, according to welding heat input, specific steel chemistry, the joint geometry, and other factors.

TABLE 1—AWS Minimum Initial and Interpass Temperatures[1,2] (1966)

Thickness of Thickest Part at Point of Welding (inches)	Welding Process: Shielded Metal-Arc Welding with Other than Low-Hydrogen Electrodes A36[3], A7[3], A373[3]	Welding Process: Shielded Metal-Arc Welding with Low Hydrogen Electrodes and Submerged Arc Welding A36[4], A7[4], A373[4], A441[5] A242[5] Weldable Grade
To ¾, Incl.	none[6]	none[6]
Over ¾ to 1½, Incl.	150°F	70°F
Over 1½ to 2½, Incl.	225°F	150°F
Over 2½	300°F	225°F

[1] Welding shall not be done when the ambient temperature is lower than 0°F.
[2] When the base metal is below the temperature listed for the welding process being used and the thickness of material being welded, it shall be preheated for both tack welding and welding in such manner that the surfaces of the parts on which weld metal is being deposited are at or above the specified minimum temperature for a distance equal to the thickness of the part being welded, but not less than 3 inches, both laterally and in advance of the welding. Preheat temperature shall not exceed 400°F. (Interpass temperature is not subject to a maximum limit.)
[3] Using E60XX or E70XX electrodes other than the low-hydrogen types.
[4] Using E60XX or E70XX low-hydrogen electrodes (EXX15, -16, -18, -28) or Grade SAW-1 or SAW-2.
[5] Using only E70XX low-hydrogen electrodes (E7015, E7016, E7018, E7028) or Grade SAW-2.
[6] When the base metal temperature is below 32°F, preheat the base metal to at least 72°F.

15. HEAT INPUT DURING WELDING

One factor that would reduce preheat requirements is the use of greater welding heat input; for example, the welding heat input for vertical welding with weave passes at an arc speed of 3 in./min. is greater than that of horizontal welding with stringer beads at 6 in./min. The heat input (J) for a specific welding procedure can be determined using the formula:

$$J = \frac{E\ I\ 60}{V} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where:

- J = Heat input in Joules/in. or watt-sec/in.
- E = Arc voltage in volts
- I = Welding current in amps
- V = Arc speed in in./min

Since all of the welding heat input at the arc does not enter the plate, the following heat efficiencies are suggested for use with this formula and subsequent formulas, charts or nomographs:

75-80% manual welding

90-100% submerged arc welding

Most preheat and interpass temperature recommendations are set up for manual welding where there is a relatively low heat input. For example, a current of 200 amps and a speed of 6 in./min. would produce a welding heat input of about 48,000 joules/in. or watt-sec./in., assuming an efficiency of 80 percent. Yet, it might be necessary to weld a 12-gauge sheet to this plate in the vertical down position with 180 amps and a speed of 22 in./min. This would reduce the welding heat input to 9800 joules/in. If this were a thick plate, it would indicate the need, with this second procedure, for more preheat, although existing preheat tables do not recognize the effect of different welding heat inputs.

On the other hand, some downward adjustment in preheat from the value listed in the preheat tables should be made for standard welding procedures which provide a much greater welding heat input. We are considering here a stable heat-flow condition after some welding has progressed.

This does not consider the more severe cooling conditions at the moment welding commences. Undoubtedly, some initial heat could be supplied to a localized area at the start of the weld on thick plate. The question now becomes how much, if any, preheat is needed for the remaining length of joint.

For example, it is standard practice today to use submerged-arc automatic welding to build up columns and girders from heavy plate. One method of fabrication uses a single-arc, submerged-arc automatic weld at 850 amps and a speed of 20 in./min. (for a ⅜" fillet weld), with the girder positioned for flat welding. This would provide a heat input of 86,000 joules/in. An alternate method positions the girder with its web vertical so that both welds are made simultaneously in the horizontal position, and uses two sets of tandem arcs (each set with two welding heads); the heat input from each arc would be 73,600 joules/in.—a total of 147,000 joules/in. of weld for each fillet. Because of the resulting lower cooling rate, less preheat should be required once the weld has been started. This may be a considerable advantage for the comfort of welding operators, especially when welding inside large box girders.

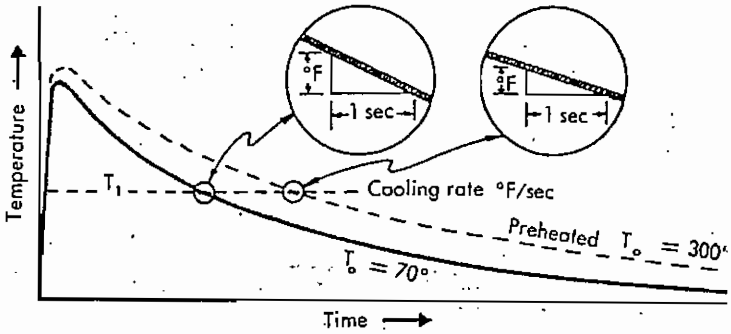


FIGURE 12

16. COOLING RATE

When a weld is made, the weld and adjacent plate cool very rapidly. The rate of cooling depends *first* on the combination of initial plate temperature (T_o) (including effects of preheat or interpass temperature) and the welding heat input (J), and *secondly*, on the plate's capacity to absorb this heat in terms of plate thickness and joint geometry.

Figure 12 illustrates the temperatures in the heat-affected zone of the plate as the welding arc passes by. Under a given set of conditions, the cooling rate will vary as represented by the changing slopes of both curves.

For a particular chemistry, at a given temperature level (T_1) there is a critical cooling rate (R_{cr}) which should not be exceeded in order to avoid underbead cracking. This temperature level is in the range of 400°F to 750°F. American investigators tend to use a higher value such as 750°, while English and Canadian investigators favor a lower value such as 300°C, or 572°F. In this discussion, we have placed this temperature level (T_1) at 572°F.

The investigation of cooling rates has been based largely on two extreme conditions, which have been developed mathematically.* These are:

1. The *thin plate*, in which the combination of

heat input and plate size permit assuming the temperature to be uniform throughout the thickness at any point; in other words, heat flows transversely in only two axes. See Figure 13.

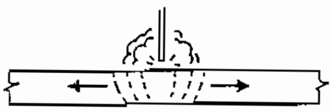


FIGURE 13

thin plate

$$\boxed{R = K_1 \left(\frac{t}{J}\right)^2 (T_1 - T_o)^3} \quad \ldots\ldots\ldots\ldots (2)$$

2. The *thick plate,* in which the combination of heat input and plate size permit assuming the bottom surface of the plate does not increase in temperature; in other words, heat flows transversely in three axes. See Figure 14.

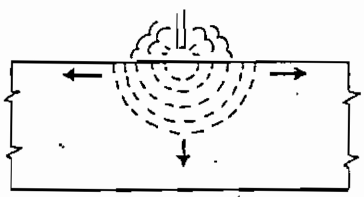


FIGURE 14

thick plate

$$\boxed{R = \frac{K_2}{J}(T_1 - T_o)^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

where:

R = cooling rate at temperature (T_1), °F/sec

T_1 = temperature at which cooling rate is considered, 572°F

T_o = initial plate temperature or preheat temperature when preheating is used, °F

K = thermal conductivity (the BTU loss per hour per square foot of surface divided by the temperature gradient of °F per foot of thickness.)

(K = 25.9 for mild steel at 572°F)

K_1 = constant, representing K, ρ, C at T_1

(K_1 = 161.48 for mild steel at 572°F)

K_2 = constant, representing K at T_1

(K_2 = 5.961 for mild steel at 572°F)

ρ = density, lbs/ft³

(ρ = 489.6 lbs/ft³ for mild steel)

C = specific heat, BTU/lb/°F

(C = .136 BTU/lb/°F for mild steel)

t = actual plate thickness, in.

J = welding heat input (formula 1)

Unfortunately, there is no clear definition of what is a "thin plate" and what is a "thick plate" relative to cooling rate. The actual condition often lies somewhere between these two extremes, and for this reason a certain amount of judgment is needed. For example, welding on a 1" plate with submerged arc at a current of 1000 amps and a speed of 10 in./min. would approach a "thin plate" condition; yet manual welding vertically down on a ¾" plate at a current of 120 amps and a speed of 12 in./min. would approach a "thick plate" condition.

In Figure 15, these two basic formulas are plotted for a given set of conditions: heat input (J), and preheat and interpass temperature (T_o).

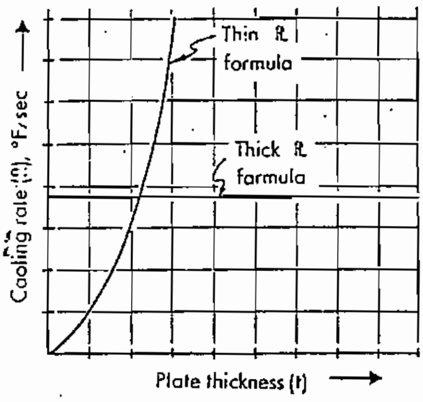


FIGURE 15

The formula for a "thin plate" recognizes the effect of plate thickness (t); and the resulting cooling rate (R) increases rapidly as the square of the plate thickness. When the cooling rate characteristics of a thick plate are studied, however, it soon becomes apparent that for a given welding procedure and an initial temperature, increasing the plate thickness beyond a certain dimension will not cause further change in the rate of cooling. For this reason, the formula for "thick plate"—Formula No. 3—does not include actual plate thickness (t) and the value of (R) does not vary with thickness but remains constant for a given

* D. Rosenthal, "Mathematical Theory of Heat Distribution During Cutting and Welding", WELDING JOURNAL, May 1941, p. 220-s.

heat input, preheat and interpass temperature. For a given heat input, the cooling rate indicated by the "thick plate" formula is the maximum (R_m) that can occur regardless of the plate thickness.

At any given plate thickness the lower cooling rate value is the more nearly correct. Using the two curves of Figure 15 as a limit and a guide, a new curve (solid line) has been drawn in Figure 16.

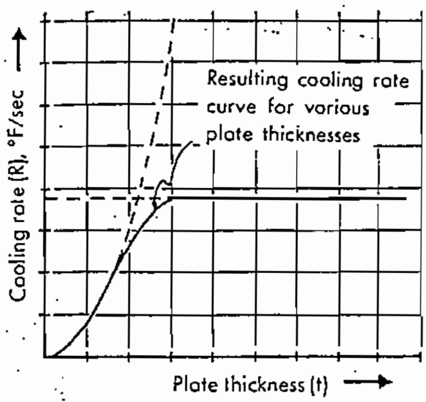


FIGURE 16

Notice, Figure 16, that the upper half of the variable part of this curve is almost a perfect reversal of the lower half, and the lower half belongs to the curve for the "thin plate". Therefore, the curved portions will be expressed mathematically as—

lower portion

$$\boxed{R = 161.48 \left(\frac{t}{J}\right)^2 (572 - T_o)^3} \qquad (4)$$

upper portion

$$\boxed{R = 5.961 \frac{(572 - T_o)^2}{J}\left(-27.09\, t^2 \frac{(572 - T_o)}{J} + 14.72\, t \sqrt{\frac{572 - T_o}{J}} - 1\right)} \qquad (5)$$

If a welding procedure for a given plate thickness lies in the lower portion of the curve, it is easy to solve directly for the required preheat (T_o) using formula (4); however, this would be very difficult for the upper portion using formula (5).

The chart is further limited in use since it only covers a single value of preheat and heat input. Therefore, to expand the application of this approach, we will put both formulas (4) and (5) into more usable non-dimension formulas (6) and (7). This calls for inclusion of the maximum effective plate thickness (t_{me}), and the corresponding maximum effective preheat ($T_o/_{me}$) for this thickness.

lower portion

$$\boxed{\frac{t}{t_{me}} = \sqrt{\frac{1}{2}\left(\frac{T_1 - T_o/_{me}}{T_1 - T_o}\right)^3}} \qquad (6)$$

upper portion

$$\boxed{\frac{t}{t_{me}} = \sqrt{\frac{T_1 - T_o/_{me}}{T_1 - T_o}}\left(1 - \frac{1}{\sqrt{2}}\sqrt{1 - \left(\frac{T_1 - T_o/_{me}}{T_1 - T_o}\right)^2}\right)} \qquad (7)$$

where:

t = actual thickness of the plate, in.

t_{me} = maximum effective plate for given values of (J) and (R)

$$\boxed{t_{me} = .4246 \sqrt[4]{\frac{J}{R}}} \qquad (8)$$

T_1 = elevated temperature at which cooling rate is considered (572°F)

T_o = preheat temperature for given values of (J), (R), and (t), °F

$T_o/_{me}$ = maximum effective preheat temperature for a given value of (J) and (R), °F

$$\boxed{T_1 - T_o/_{me} = \sqrt{\frac{R\,J}{5.961}}} \qquad (9)$$

Formulas (6) and (7) produced the curve shown in Figure 17. This can be used to determine T_o the required preheat temperature.

17. BI-THERMAL VS. TRI-THERMAL HEAT FLOW

This work is based upon bi-thermal heat flow where the heat has two avenues for escape; for example, a conventional butt joint consisting of two plates, Figure 18(a).

Tri-thermal heat flow has three avenues for escape, an example is a tee joint made of three plates, Figure 18(b).

Where tri-thermal heat flow condition exists, the above work should be modified either by:

1. Using ⅔ of the actual heat input (J), or
2. Adjusting the plate thickness (t) to allow for the extra plate by using ½ of the sum of three thicknesses.

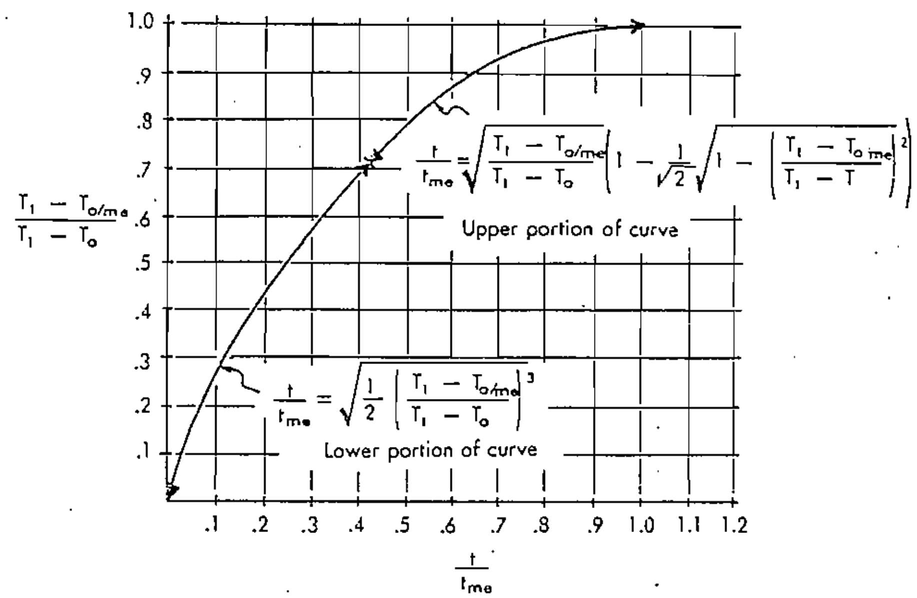


FIGURE 17

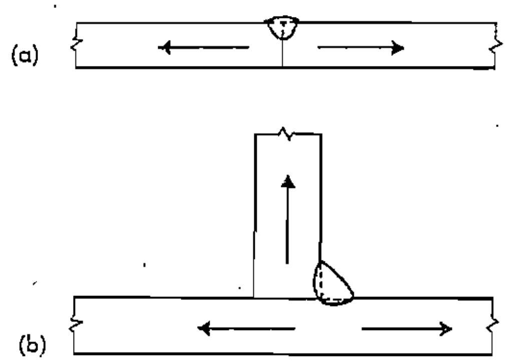


FIGURE 18

18. CARBON EQUIVALENT

As a result of recent experiments and studies, it is possible to simplify the relationship of all chemical elements in a steel to the occurrence of underbead cracking. The simplification is expressed in a single formula known as the carbon equivalent. This formula expresses the influence of each element relative to that of carbon.

Investigators* have shown a definite relationship in the percent of underbead cracking to the carbon equivalent. Figure 19 shows a 1" thick test plate on which a single bead was deposited using ⅛" E6010 electrode at 100 amps, 25 v, reversed polarity, at 10 in./min. The chart, Figure 20, shows the percentage of underbead cracking for different carbon equivalents that occurred with this test. A deposit made with low-hydrogen E6015 electrodes on a specimen of this thickness did not have underbead cracks. The AWS E6015 electrode is comparable to today's E7018. The results were plotted, Figure 20, to give curves for three different preheat temperatures (T_o).

K. Winterton* has listed 14 different carbon equivalent formulas and recommended the following:

$$\boxed{C_{eq} = C\% + \frac{Mn\%}{6} + \frac{Ni\%}{20} + \frac{Cr\%}{10} - \frac{Mo\%}{50} - \frac{V\%}{10} + \frac{Cu\%}{40}} \qquad (10)$$

This formula is applicable to the low-carbon low-alloy steels for construction and machinery manufacturing.

19. COOLING RATE AND CARBON EQUIVALENT

Although not too well defined, for a given analysis of steel there is a maximum rate at which the weld and adjacent plate may be cooled without underbead cracking occurring.

* Stout and Doty, "Weldability of Steels", Welding Research Council, 1953, p. 150; Williams, Roach, Martin and Voldrich, "Weldability of Carbon-Manganese Steels", WELDING JOURNAL, July 1949, p. 311-s.

* K. Winterton, "Weldability Prediction from Steel Composition to Avoid Heat-Affected Zone Cracking", WELDING JOURNAL, June 1961, p. 253-s.

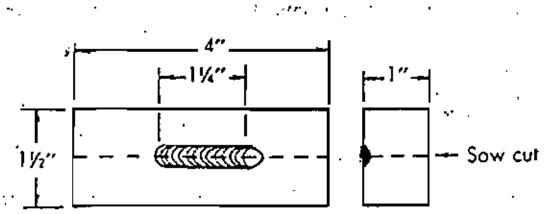


FIGURE 19

The higher the carbon equivalent, the lower will be this critical (allowable) cooling rate. Thus, the higher the steel's carbon equivalent, the more important becomes the use of low-hydrogen welding and preheating.

Cottrell and Bradstreet* have used a type of Reeve Restraint test, called the CTS (Controlled Thermal Severity) test. For any given steel, three thicknesses are tested — ¼, ½, and 1". Each test requires

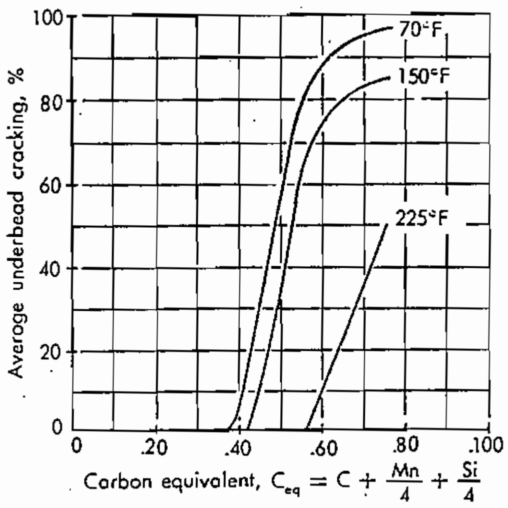


FIGURE 20

two fillet welds—one a bi-thermal weld (two avenues for heat to escape), the other a tri-thermal weld (three avenues for heat to escape). This gives a total of 6 different values for TSN (Thermal Severity Number), and for the given welding heat input (about],000 joules/in.) produces 6 different cooling rates. It is then observed at what cooling rate cracking does or does not occur, and the subsequent welding procedure is adjusted so this critical cooling rate will not be exceeded.

Both of these men have produced tables in which relative weldability has been expressed along with the critical cooling rate. More recently, Bradstreet** has tied in this relative weldability with carbon equivalent. By working back through this information, the carbon equivalent—critical cooling rate curve shown in Figure 21 has been produced to use as a guide in case the CTS test on the particular steel is not made. This curve may be expressed by the following formula:

$$\boxed{R_{cr} = \frac{6.598}{C_{eq} - .3074} - 16.26} \quad \text{.............(11)}$$

This is the critical cooling rate at T_1 — 572°F.

The critical cooling rate (R_{cr}) can be determined by a) actual test of the particular steel to see what cooling rate will not cause cracking, or b) using formula (11) based upon Canadian investigations.

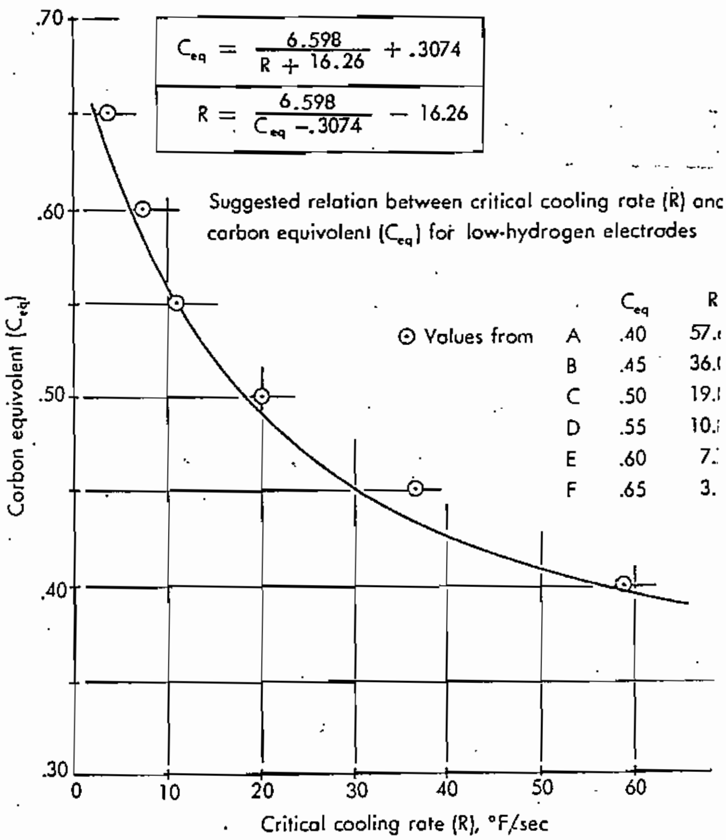


FIGURE 21

20. FINDING REQUIRED PREHEAT TEMPERATURE

To calculate the required preheat temperature (T_o) that will produce the required cooling rate (R) for a given heat input (J) and plate thickness (t), the following mathematical computations must be made:

a) Determine from formula (9) the value of ($T_1 - T_o/_{me}$).

b) Determine from formula (8) the value of (t_{me}).

c) From this (b) determine (t/t_{me}).

d) From the chart, Figure 17, using (c) read the value for

* C. L. M. Cottrell, "Controlled Thermal Severity Cracking Test Simulates Practical Welded Joints", WELDING JOURNAL, June 1953, p. 257-s; Cottrell and Bradstreet, "A Method for Calculating the Effect of Preheat on Weldability", BRITISH WELDING JOURNAL, July 1955, p. 305; Cottrell and Bradstreet, "Calculating Preheat Temperatures to Prevent Hard Zone Cracking in Low Alloy Steels", BRITISH WELDING JOURNAL, July 1955, p. 310.

** B. J. Bradstreet, "Methods to Establish Procedures for Welding Low Alloy Steels", ENGINEERING JOURNAL (Engineering Institute of Canada), November 1963.

$$\left(\frac{T_1 - T_o/_{me}}{T_1 - T_o}\right)$$

e) Knowing this value (d) and the value of $(T_1 - T_o/_{me})$ from item (a), determine the required preheat temeprature (T_o).

An easier and faster method for determining the required preheat uses the nomograph, Figure 22. This nomograph is actually two nomographs superimposed upon each other. The first nomograph (subscript a) will provide a value for $\left(\frac{T_1 - T_o/_{me}}{T_1 - T_o}\right)$. The second nomograph (subscript b) will provide the required preheat and interpass temperature (T_o).

A set of eight graphs, Figure 23, will also provide this same information.

Example Using Chart (Fig. 17)

Given:

$$J = 20{,}000 \ \frac{\text{watt-sec}}{\text{inch}}$$

$R = 25$ °F/sec

$t = 1.0''$

find required preheat temperature (T_o):

a) Determine $T_1 - T_o/_{me} = \sqrt{\frac{R\ J}{5.961}}$

$$= \sqrt{\frac{(25)\ (20{,}000)}{5.961}}$$

$$= 289.6°\text{F}$$

b) Determine $t_{me} = .42457 \sqrt[4]{\frac{J}{R}}$

$$= .42457 \sqrt[4]{\frac{20{,}000}{25}}$$

$$= 2.26''$$

c) Determine relative thickness: $\frac{t}{t_{me}} = \frac{1''}{2.26''}$

$$= .4429$$

d) From chart, Figure 17, read relative preheat temperature: $\frac{T_1 - T_o/_{me}}{T_1 - T_o} = .73$

e) Therefore: $T_1 - T_o = \frac{T_1 - T_o/_{me}}{.73} = \frac{289.6}{.73}$

$$= 396.7$$

$$572 - T_o = 396.7$$

or $T_o = \underline{175.3}$ °F

Example Using Nomograph (Fig. 22)

Given: $J = 20{,}000 \ \frac{\text{watt-sec}}{\text{inch}}$

$R = 25$ °F/sec

$t = 1.0''$

find preheat temperature (T_o):

1st nomograph

(1) $R = 25$ °F/sec

(2a) $J = 20{,}000 \ \frac{\text{watt-sec}}{\text{inch}}$

(3a) Read $t_{me} = 2.26''$

Use this number as a pivot point

(4a) $t = 1.0''$

(5a) Read % $\frac{T_1 - T_o/_{me}}{T_1 - T_o} = 73\%$

2nd nomograph

(1) $R = 25$ °F/sec

(2b) $J = 20{,}000 \ \frac{\text{watt-sec}}{\text{inch}}$

(3b) Read $T_o/_{me} = 282$ °F

Use this number as a pivot point

(4b) % $\frac{T_1 - T_o/_{me}}{T_1 - T_o} = 73\%$ (from 1st nomograph)

(5b) Read $T_o = 175$ °F

21. OTHER POINTS OF CONSIDERATION

Test data has indicated that thin plates result in slightly higher cooling rates than calculated. It is believed this is because thin plates have a relatively greater surface area for heat loss per volume than thick plates.

Normally, in the investigation of a groove weld, the pass completing the joint is considered rather than the root pass. This is because the face pass usually has a slightly higher cooling rate due to the larger cross-section of the joint (assuming the same interpass temperature).

There is some indication that fillet welds have slightly higher cooling rates than the bead-on-plate welds used in the investigative work. This is because the 90° intersection of the two plates presents a larger area of contact with the weld, therefore absorbing heat at a slightly greater rate. A groove weld similarly would offer a larger area of plate contact with the weld than a bead-on-plate weld.

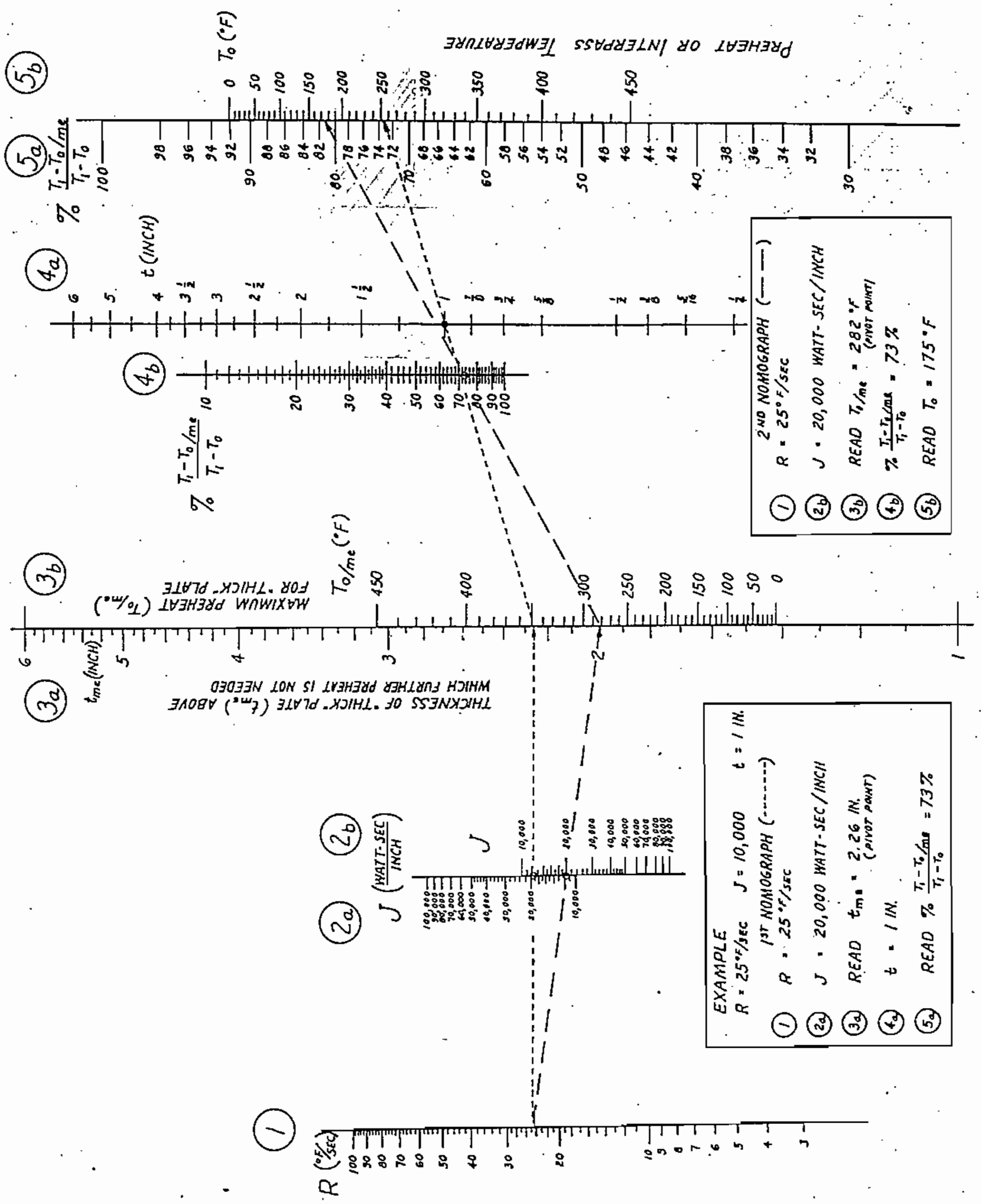


FIGURE 22—Estimated Preheat for Given Heat Input, Cooling Rate and Plate Thickness

FIGURE 23—Estimated Preheat for Given Cooling Rate, Heat Input & Plate Thickness