5 METAL POWDER COMPACTION

5.1 Introduction

The compaction of metal powders has the following major functions:

(a) to consolidate the powder into desired shape

(b) to impart, to as high a degree as possible, the desired final dimensions with due consideration to any dimensional changes resulting from sintering.

(c) to impart the desired level and type of porosity.

(d) to impart adequate strength for subsequent handling.

Several approaches exist for achieving these goals. In general the techniques can be categorised as (a) continuous vs discontinuous process, (b) pressures – high vs low, (c) compaction velocity – high vs low (d) temperature – room to elevated temperature; (e) uniaxial vs hydrostatic pressures.

In the present chapter only cold compaction methods shall be described.

5.2 Die Compaction

Die compaction represents the most widely used method and is considered as the conventional technique. This involves rigid dies and special mechanical or hydraulic presses. Densities of up to 90 % of full density can be achieved following the compaction cycle, the duration of which may be of the order of just a few seconds for very small parts.

Powders do not respond to pressing in the same way as fluids and do not assume the same density throughout the compact. The friction between the powder and die wall and between individual powder particles hinders the transmission of pressure. A high uniformity in green parts can be achieved depending on:

– the kind of compacting technique
– the type of tools
– the materials to be pressed and the lubricant.

The compacting techniques used may be characterised by references to the movement of the individual tool elements – upper punch, lower punch and die relative to one another.

Pressing within fixed dies can be divided into:

– Single action pressing
– Double action pressing

In the former the lower punch and the die are both stationary. The pressing operation is carried out solely by the upper punch as it moves into the fixed die. The die wall friction prevents uniform pressure distribution. The compact

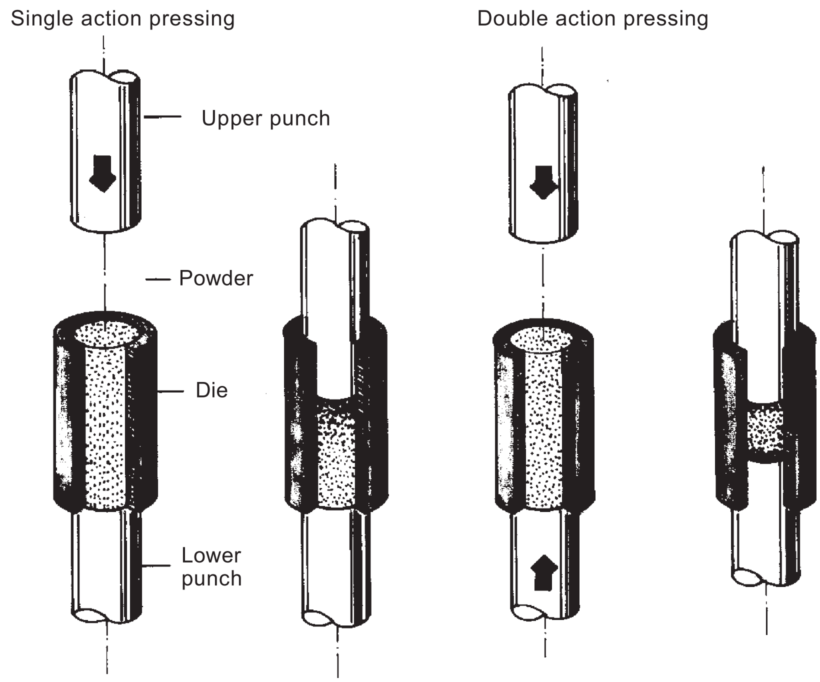


Fig. 5.1 Single and double acting powder compaction.

has a higher density on top than on the bottom. In the latter type of pressing only the die is stationary in the press. Upper and lower punches advance simultaneously from above and below into the die (Fig.5.1). The consequence is high density at the top and undersides of the compact. In the centre there remains a 'neutral zone' which is relatively weak.

5.2.1 Pressing Operation

The pressing operations can be sequenced as follows:

1. **Filling** of the die cavities with the required quantity of powder.

2. **Pressing** in order to achieve required green density and part thickness.

3. **Withdrawal of the upper punch from the compact**: Here the risk of cracking of green parts is felt. As the upper punch withdraws the balance of forces in the interior of the die ends. In the case of parts with two different thicknesses, e.g. flange with a hub, the elastic spring back of the lower punch is the greatest danger. Other problems are protrusions required on the upper face of the part. In the case of thin parts with large projected area, cracking is common due to elastic spring back of the lower punch and the part itself. The former pushes the part still lying in the die cavity upwards, while the latter tends to expand the part.

4. **Ejection**: The tooling must be done in such a manner so that the

ejection of part is feasible. Ejection of a part of complex forms is rather problematic, as it involves friction between the green part and tool walls. The green strength must be high to resist the bending stresses introduced by the ejection force.

There is another type of compaction involving upper punch pressing with floating die. This is characterized by a stationary lower punch the upper punch moves into a die supported by spring. As soon as the friction between the powder and the die wall exceeds the spring power, the die wall is carried down. The friction will vary slightly from stroke to stroke. It also depends on the degree of wear in the tools so that a constant density distribution is difficult to maintain over a period.

During second world war another tooling method was developed in Germany, known as **'withdrawal tooling'**. In this case, the lower punch does not move during compacting cycle. After the upper punch has entered the die cavity, both upper punch and die plate move downwards. After the compact has been pressed, the upper punch moves up, but the die plate and lower coupler move further down until the top of the die plate is flush with the lower punch (Fig.5.2). The compact is ejected and can be moved out of the way by the loading shoe. Die plate and lower coupler then move back into the filling position and the cycle repeats.

The major advantage of withdrawal system of tooling is that the lower punches are relatively short and are well supported during compaction and ejection. When there are multiple lower punches, as many of them as possible rest directly on the base plate. Withdrawal tooling can be built for very complex parts. On the other hand, in the tooling system with ejection by the lower punches the motions of the punches are built into the multiple action presses. In many cases no tool holders are required.

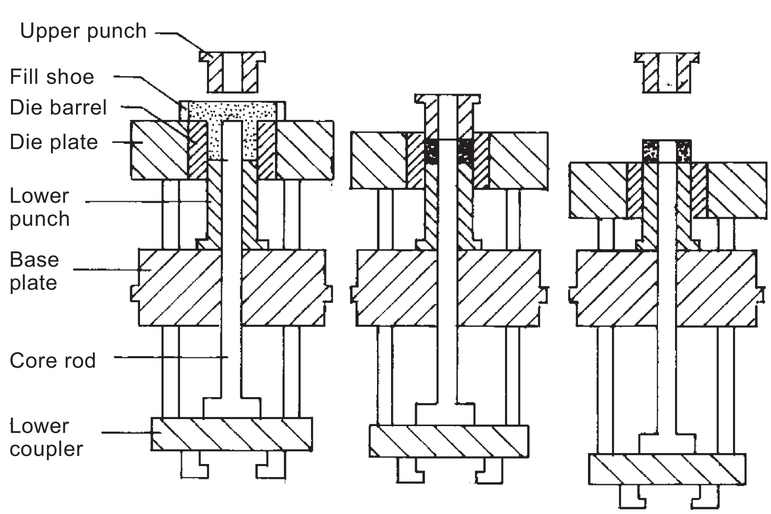


Fig. 5.2 Sequence of operations for pressing with the withdrawal system.

Split Die Systems

Another rigid tooling system is known as split die system. It enables the compaction of parts with completely asymmetric upper and lower sections in the pressing directions. This system requires two die holding plates to carry the upper die and lower die. Each plate is controlled and moved independently [6].

5.2.2 Compaction Presses

Compaction presses for powders are of two types – mechanical or hydraulic. There are others partly hydraulic and partly mechanical. Presses from 3 to 1000 tons capacity are available. The optimum operating speed is dictated by the size and complexity of the P/M parts to be made.

Hydraulic presses produce working force through the application of fluid pressure on a piston by means of pumps, valves, intensifiers and accumulators. Inherent in the hydraulic method of drive transmission is the capability to provide infinite adjustment of stroke speed, length and pressure within the limits of press capacity. Also, full tonnage can be extended throughout the complete length of the stroke.

In **mechanical presses**, a flywheel stores energy, which is then released and transferred by one of a variety of mechanisms (eccentric, crank, knuckle joint, toggle etc.) to the main slide. In most mechanical presses, the movement or stroke of the slide is adjustable within the limit of daylight of the press. Mechanical presses are classified by one or a combination of characteristics viz. sources of power, method of actuating the ram, type of frame and type of clutch, brake and control system.

The energy stored in the flywheel must be sufficient to ensure that the work per stroke required of the press will not reduce the flywheel's speed by more than 10 to 15 percent. The most common type of mechanical press is the eccentric or crank type which converts rotary motion to linear motion. In the toggle type the eccentric or crank straightens a jointed arm or lever, the upper end of which is fixed at the top, while the lower end is guided for controlled accurate punch guidance into the die. In the cam type of mechanical press, pressing speed, timing, and motion are controlled by changing the contours of the cams or cam inserts. A detailed description of such presses are given elsewhere.[1] Figure 5.3 illustrates a general view of the automatic mechanical press.

Rotary Presses

A rotary press is a mechanically operated machine, which uses a number of identical sets of tools to produce parts at high production rates. In this machine, the tool sets normally called tool stations, are held in a head or a turret which rotates continuously. The rotation of the head pulls the upper and lower punches past fixed surfaces called cams, and a set of pressure rolls that impart compression force from above and below. All rotary presses are double action. The design of the cam surface moves the punches up or

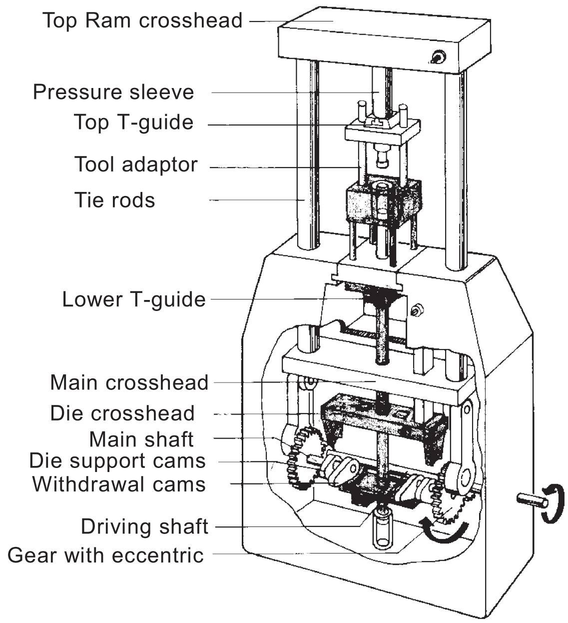


Fig. 5.3 A general view of automatic mechanical press. (Courtesy: Dorst Machinen und Anlagenbau).

down to provide the cycle of die filling, weight adjustment, compression and ejection. Another feature of rotary presses is that all adjustment can be made while the press is in operation. These presses can be furnished in tonnage ranges up to 100 tonnes.

5.2.3 Press Selection

Hydraulic presses differ from mechanical presses in that fluid pressure rather than a rotated crankshaft is used to actuate the slide. They are slower in operation than mechanical presses. These are generally less economical to operate than mechanical presses that can efficiently perform a specific identical job. One reason for this is that hydraulic presses have no mechanism comparable to the mechanical press's flywheel for storing energy. In a hydraulic system, oil pressure in the cylinder drops after each stroke and has to be build up in a comparatively short time. This requires the use of pumps served by motors, and these pumps draw a large amount of electric power. The motor of a hydraulic press, therefore, has several times the capacity as the motor of a mechanical press of comparable tonnage. Another disadvantage of a hydraulic drive is that the sudden release of pressure with each completed stroke is accompanied by a contraction of the cylinder and its hydraulic conduits, which in turn places great stress on pipe joints, valves, seals etc. Hydraulic presses, however, offer following advantages:

– adjustable tonnage

– Constant pressure can be maintained throughout the entire stroke and applied at any predetermined position. Drawing speeds are adjustable.

In case of mechanical press, the rated tonnage of a press is the maximum force that should be exerted by the ram against a tooling at a given distance above the bottom of the stroke. The higher a press is rated to its stroke, the greater the torque capacity of its drive members and the more flywheel energy it is capable of delivery. Because of the mechanical advantage of the linkage, the force actually transmitted through the clutches to rotating members (cranks or toggles) and reciprocating slides varies from minimum at the beginning of the downward stroke to maximum at the bottom of the stroke. A chart will show the change in tonnage that the drive is capable of delivery at various distances above stroke bottom. Provided its speed is not too high, almost any mechanical press with sufficiently long stroke and large tool mounting space, can be suitably altered for compacting powder, either in spring floated dies or in dies of the withdrawal type.

5.2.4. Factors affecting tooling design

The powder's response to compaction and sintering has a decisive effect on tooling design. Fill, flow, apparent density, fill ratio, compacting pressure and dimensional changes are all contributory in this aspect.

Fill – The terms 'fill' signifies the amount of powder taken into the tool cavity prior to compaction. Proper fill is affected by many variables such as flow, apparent density, part configuration and tool design. The ideal fill should be uniform in density, free of bridging and should be fast enough to allow a reasonable speed in the press cycle. Part configuration has a direct influence on the powder filling into the tool cavity. Thin walled parts have narrow cavity sections, which results in poor powder filling. Powder filling in large areas having thin walls may trap air developing air pockets. Filling can be improved by using the three position air core.[3] Raising and lowering the core during the filling cycle helps in releasing entrapped air. As a minimum period of time is required to obtain adequate powder filling, the speed of the press can appreciably affect the fill.

The amount of powder fill to produce a part is determined by multiplying the finished part thickness by compression ratio of the powder to be compacted to the required green density.

In general term:

$$\frac{\text{Height of filling cacity}}{\text{Compact height}} = \frac{\text{Green density}}{\text{Apparent density}}$$

Components with shoulders or projections will therefore need to have these taken into account in the provision of different filling heights for various sections of the part. If these different filling heights are not taken into consideration, then as shown in an example (Fig.5.4) the flange would be very

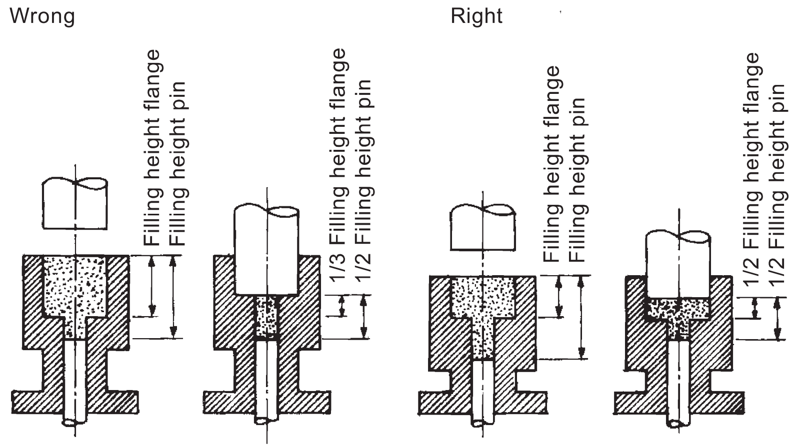


Fig. 5.4 Correct and incorrect die fills for uniform part density.

highly pressed while the remainder of the part was pressed very little.

Flow – Adequate flow of powder is essential for an ideal fill. Many time, the metal powder contains a lubricant, to reduce frictional drag. This prevents galling and cold welding of powder particles to the die and core walls.

Apparent Density and Fill Ratio: The density of the finished part is usually specified. Tooling must be designed to provide enough fill to produce a part to the required compacted density. The ratio of apparent density of powder to green density is used to find the fill depth. The fill ratio accuracy can be improved further if compacts are made at the desired rate of speed for producing green parts on the press. The apparent density is affected by the time allowed for the tool cavity to fill. The true fill ratio should be based after including all the variables. If a fill depth is incorrect because of incorrect tool design, it may be compensated for by a change in powder apparent density. Since apparent density adjustment in powders is limited, it should not be relied upon as a tool design solution. Normal apparent density tolerance limits for powders are 0.1 g/cm^3. In special cases, it can be reduced to ±0.05 g/cm^3.

Compaction Pressure: Although very high forces can be developed in press, there are limits to the load a tool bears, which partially determines the density that can be obtained. Other limits to tool load are (*i*) part configuration which may introduce thin wall sections (*ii*) punch face protrusions which form areas of stress concentration. The tensile strength of the tool steels is the limiting factor to the load a punch will stand. 480 MPa (35 t/sq.inch) is the normal tool pressure allowed for powder compaction or coining. It is advisable to add coining operation, rather than to overload the tool to obtain higher green densities and risk tool breakage. Powder manufacturers have developed improved compressibility powder in order to achieve high green densities. Table 5.1 illustrates compaction pressure requirements for various powders.

Table 5.1 Compaction pressure requirements and compression ratios for various materials[1]

Type of material	Compaction pressure		Compression ratio
	tsi	N/mm²	
Aluminium	5–20	70–280	1.5 to 1.9:1
Brass	30–50	415–690	2.4 to 2.6:1
Bronze	15–20	205–230	2.5 to 2.7:1
Copper–graphite brushes	25–30	345–415	2.0 to 3.0:1
Carbides	10–30	140–415	2.0 to 3.0:1
Ferrites	8–12	110–165	3.0:1
Iron bearings	15–25	205–345	2.2:1
Iron parts:			
low density	25–30	345–415	2.0 to 2.4:1
medium density	30–40	415–550	2.1 to 2.5:1
high density	35–60	430–825	2.4 to 2.8:1
Iron powder cores	10–50	140–690	1.5 to 3.5:1
Tungsten	5–10	70–140	2.5:1
Tantalum	5–10	70–140	2.5:1

The above pressing force requirements and compression ratios are approximations and will vary with changes in chemical, metallurgical, and sieve characteristics of the powder, with the amount of the binder or die lubricants used and with mixing procedures.

Dimensional Changes

As green parts after sintering usually undergo dimensional changes, this factor must also be included in tool design. Green density variation, material variation, temperature variation, furnace load conditions, furnace atmospheres all combine to affect dimensional change. Alloying many times affects dimensional change. For example nickel blended in iron imparts shrinkage after sintering, while copper does the reverse. In cases where a tool has been incorrectly factored for dimensional change, the powder blend can be changed to obtain a suitable growth or shrinkage. However, it must be borne in mind that the ultimate physical properties of the part are not adversely affected. Sintering temperature can also be adjusted to control growth, the details of which shall be described in the next chapter.

5.2.5 Tooling Materials

Tooling materials can be classed into three categories: steels, carbides and coated steels. Powdered metals are generally abrasive, which cause tool wear. Apart from abrasion resistance, tools must have the properties of high compression strength and toughness. The steels generally used for

Table 5.2 Cemented carbide for powder metallurgy tooling: properties and typical applications.

No.	% of binder	Hard-ness, RA	Trans-verse rupture strength, MPa	Comp-ressive strength, MPa		Tool applications		
						Cores	Punches	Dies
C-4	3%	92.3	1220	5510				
C-9	6%	91.5	1580	4890	WEAR RESIST-ANT			Bearing Dies
C-10	6-9%	90.6	1930	4480		Simple shapes Short lengths		Straight thru dies - simple cavity contour
C-11	12-13%	89.7	2140	4130			Ceramics-Ferrites High polish & No Face projections	
C-12	14-15%	88.5	2340	4000	SHOCK RESIS-TANT	Step cores & complex contours		Complex shapes Gear forms Sectioned dies
C-13	15-20%	87.4	2580	3790		All cores within physical limits of carbides	All within physical limits of carbide	Multi-level dies vulnerable projections
C-14	20-30%	82-86	2510	3240				

All property data represent average for grade

tool making are A2, D2, M2 and SAE 6150 type, the details of which can be seen in any Metal Hand Books. 12% cobalt-containing tungsten carbide is used by many for solid dies and die sections. Modern techniques such as spark erosion machining make this material relatively inexpensive to work. Due to the low pressing forces required for compacting ceramic and carbide powders, punches may be tipped with carbide.

Another application for carbide material is core rods where maximum wear resistance is required. Table 5.2 illustrates various grades of cemented carbides and their typical P/M tooling applications. Among the third category of tools carburized and nitrided coatings are very common. The principle limitations to the use of coated steel tooling is the method of applying the coating to the tool member. Most coatings are difficult to apply uniformly on irregular surfaces. Usually only round core rods are subjected to these coatings, although at present the technology has developed too fast.

Heat treatment of tools is to be controlled to minimize distortion. Heat treatment stresses must be relieved by proper tempering, since untempered tools will warp as they are machined. All tools should be normalized prior to machining operations to relieve heat treatment stresses.

Punches must be tough, and able to take repeated deflections. Although punch wear is important it is sometimes sacrificed to obtain other properties in the tool. Large chamfers on punch faces for examples are subjected to higher loads than the main tool body. Sharp corners at the chamfer root cause stress risers. Punches with these design features should be made of ductile tool steel. On the other hand when punches have fixed steps or depressions for protrusions or pockets in the sintered parts a wear resistant steel is used. A need for auxiliary mechanisms, e.g. floating core arrangement, improves the performance of tool materials. In brief, the tool designer must consider a variety of physical properties of tool materials, selecting the ones which best suit the requirements of the particular design.

The die barrel components of compacting tools usually consist of wear resistant insert or inserts which are held in a retaining ring made of tough steel. Most commonly the insert or inserts are shrunk into the retaining ring which has the advantage that the compression stresses induced in the die-barrel during shrinkage counteract the radial stress during compaction. Although quite complex internal contours can be produced in single piece inserts by electric discharge machining, it is more common to fix several carbide inserts together (Fig.5.5). The entry edges to the die cavity in the die barrel are levelled or radiused. In order to minimize spring back strain during ejection, the die barrels are sometimes made taper, but the taper should be less than the spring back of the part during ejection.

Punch and core rod dimensions are generally relieved behind the forming face making the close fitting portion as short as possible to permit the escape of powder.

5.2.6 Part Classification

P/M parts usually are classified by evaluating the complexity of part design on a range of I though IV. They are signified by:

Class I parts: Single level components with the compacting force applied from one direction only. In this case the part thickness is generally limited to a maximum of 6–7 mm.

Class II parts: Single level components with the force applied from two directions.

Class III parts: Two level components pressed with forces from two directions.

Class IV parts: Multilevel parts pressed with forces from two directions.

A detailed discussion on tooling details of parts of varying complexities has been made elsewhere.[2,5] Figures 5.6–5.9 illustrate such classes of P/M parts.

5.2.7. Guidelines of Part Geometry:

The following guidelines related to conventional die compaction would be highlighted.

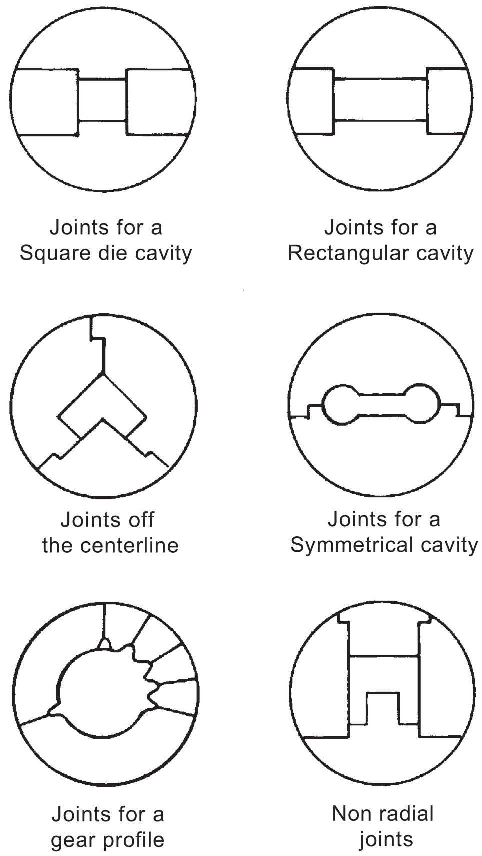


Fig. 5.5 Design of carbide inserts for fitting into retaining ring of die barrel

1. **Wall thickness** – Minimum wall thickness is governed by overall component size and shape. Where the ratio of length to wall thickness is 8:1 or more, special precautions must be taken to achieve uniform fill. The tooling required for long, thin walls is quite fragile and has low life.

2. **Holes** – Holes in the direction of pressing, produced with core rods extending up through the tools can be readily incorporated in the tooling. While round holes are least expensive, other shaped holes, including splines, keys, keyways, D-shapes, squares and hexagonals, can also be produced. Blind holes on blind steps in holes, and tapered holes which could be difficult to machine, are also readily produced. Side holes or holes not parallel to the direction of pressing cannot be made in the pressing operation and are produced by secondary machining. In big heavy parts many times holes are intentionally incorporated in order to make them light.

3. **Tapers and drafts (Fig.5.10)** – Draft is generally not required on straight-through P/M parts. Tapered sections usually require a short, straight level to prevent the upper punch from running into the taper in the die wall

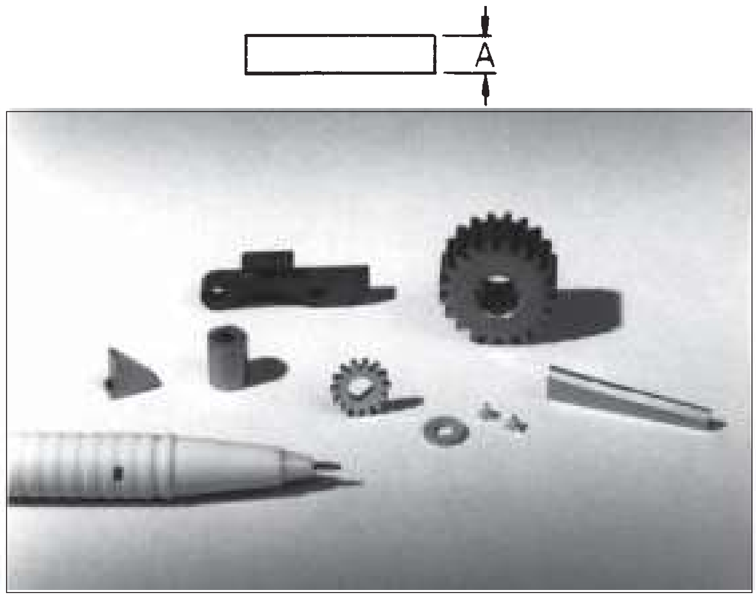


Fig. 5.6 Class 1 components (reprinted with permission from The Powder Metallurgy Design Manual, 1995 edition Metal Powder Industries Federation, Princeton, New Jersey, USA, 1995).

Fig. 5.7 Class 2 components (reprinted with permission from The Powder Metallurgy Design Manual, 1995 edition Metal Powder Industries Federation, Princeton, New Jersey, USA, 1995).

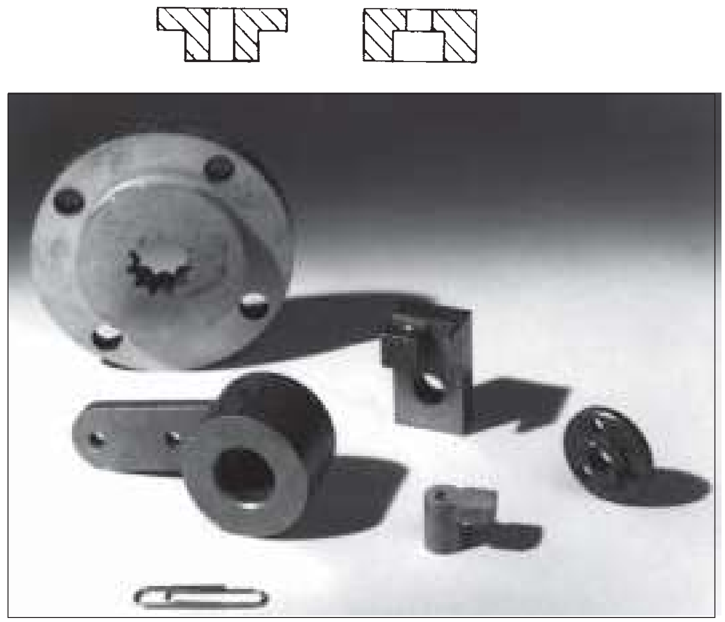
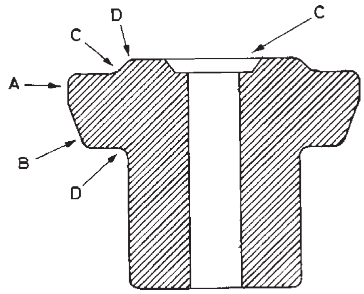


Fig. 5.8 Class 3 components (reprinted with permission from The Powder Metallurgy Design Manual, 1995 edition Metal Powder Industries Federation, Princeton, New Jersey, USA, 1995).

Fig. 5.9 (right) Class 4 components (reprinted with permission from The Powder Metallurgy Design Manual, 1995 edition Metal Powder Industries Federation, Princeton, New Jersey, USA, 1995).



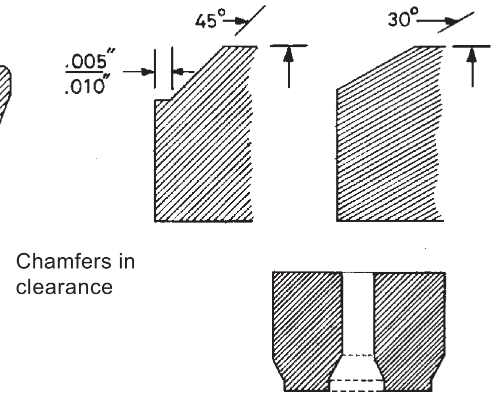


Fig. 5.10 Tapers and drafts.
Fig. 5.11 (right) Chamfers in P/M parts.

or on the core rod. When a flange type section is made on a step in the die, a draft is desirable to assure proper part ejection. Similarly drafts on the sides of bosses or counterbores made by the punch face aid tool withdrawal and minimize possible chipping of part.

4. **Fillets and Radii**: Generous radii fillets are desirable for most economical design of tools and production (D, Fig.5.10). A true radius is not possible at the junction of a punch face and a die wall. A full radius is, therefore, approximated by hand finishing or some other processes such as tumbling.

5. **Chamfers and Bevels**: Chamfers, rather than radii are preferred on part edges to prevent burring. A 45° angle and 0.125 mm minimum flat is common practice to eliminate feather edges (Fig.5.11). The preferred chamfer and most economical to produce is 30° maximum from radial, so as to minimize the chance of breaking the punch protrusion. When chamfers with a large angle from horizontal are required for punching of a part or when a step would create a problem (Fig.5.11), the chamfer may be produced by a bevel in the core rod or die. Chamfers on irregular shapes are more costly than on a plain round part or on two sides of a square part.

6. **Countersinks**: A countersink is a chamfer around a hole for a screw or bolt head. A flat of about 0.25 mm is essential to avoid fragile, sharp edges on the punch (Fig.5.12).

7. **Bosses**: A boss can be located on top or bottom of a part. To produce bosses with perpendicular sides, special punches are required to give positive part ejection.

8. **Hubs**: Hubs, which provide for drive or alignment rigidity in gears, sprockets and cams, can be readily produced by the P/M process. A generous radius between the hub and flange is preferred, as well as maximum permissible material between the outside diameter of the hub and the root diameter of components (Fig.5.13).

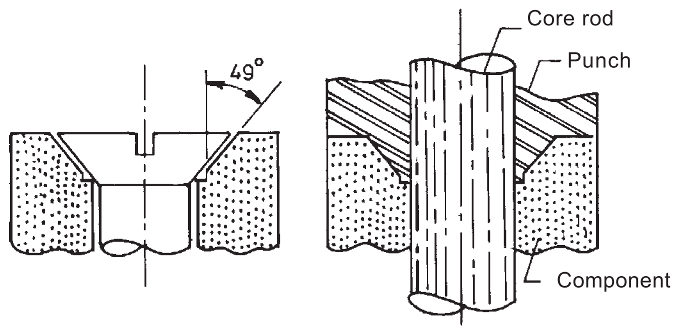


Fig. 5.12 A standard countersink.

9. **Studs**: Shallow studs with drafted sides are made in the regular tools.

10. **Knurls**: Vertical, but no diamond or angled, knurls can be made on inside and outside diameters because they interfere with ejection.

11. **Under Cuts**: Undercuts on the horizontal plane, cannot be produced, as they prevent the part from ejecting from the die.

A part with a reverse taper (large on bottom than on top) cannot be ejected from the die.

12. **Slots and Grooves**: Grooves can be pressed from projections on the punch into either end of a component, within the following limits. (a) curved or semicircular grooves to a maximum depth of 30 % of overall component length, (b) rectangular groovers to a maximum depth of 20 % of the overall component length.

13. **Threads**: These cannot be incorporated in holes or outside diam-

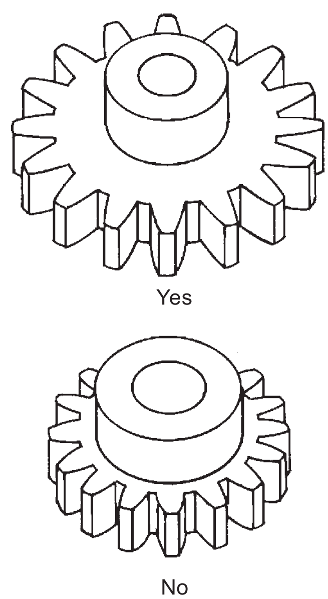


Fig. 5.13 Hubs' location for gear's root.

eters, as they prevent the part being ejected from the die. They are produced by secondary machining operations.

5.3 Cold Isostatic Compaction

In cold isostatic compaction a flexible mould is filled with the powder and pressurised isostatically using a fluid such as oil or water. Compaction pressures up to 1400 MPa have been achieved in this manner, however, cold isostatic compaction is usually performed at pressures below 350 MPa. The use of rubber mould provides a means of creating complex shapes. Cold isostatic compaction has following advantages:

1. Uniform density of compacted bodies.
2. High green density, about 5–15 per cent higher than that achieved with die compaction at the same pressure.
3. High green strength and good handling properties of the powder body.
4. Reduction in internal stresses.
5. Possibility to compact powder without binding or lubricant additives.
6. Possibility to compact bodies having complex shapes or with a large length to cross-section ratio and achieve a high, uniform density.
7. Composite structures can easily be obtained.
8. Low tool costs through the use of rubber or plastic moulds.
9. Low material and finish machining costs.

On the other hand, isostatic compaction has some disadvantages too. They are:[2]

1. Dimensional control of the green compacts is less precise than in rigid die pressing.
2. The surfaces of isostatically pressed compacts are less smooth.
3. In general the rate of production in isostatic pressing is considerably lower.
4. The flexible moulds used in isostatic pressing have shorter lives than rigid steel or carbide dies.

5.3.1. Isostatic Press Equipment

The main sub groups of isostatic presses are described below (Fig.5.14):

Pressure Vessel or Cavity: The pressure vessel is the most important element of an isostatic press. Of all the various high pressure structures known, the monolith forged type is preferred. While forging, care is taken that the grain structure is similar in all directions so that with a closely controlled heat treatment the high mechanical properties obtained in tangential, radial and longitudinal directions of the forging will be as desired and with in close tolerance of each other. The pressure vessel must be designed to withstand the severe cyclic loading imposed by rapid production rates and must take into account fatigue failure. Pressure vessels designed and constructed per section VIII, Division 2, of the ASME Code are available for pressures up to approximately 276 N/mm^2 (40,000 psi). Devices, including an absolute closure control, absolute pressure restrictor and an energy

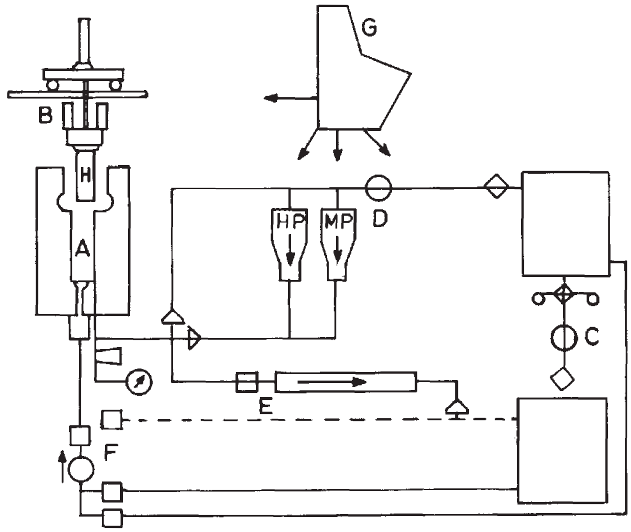


Fig. 5.14 Principal schematic of the composition of an isostatic press. A – pressure vessel, B – closure with mechanism; C – reservoir(s) with filtering system; D – high pressure generator group; E – depressurisation system; F – fluid transfer system; G – controls; H – tooling.

absorption protection shield, should be installed in direct combination with the pressure vessel.

Closure System: This seals the pressure vessel cavity. Threaded covers are extensively used. However proper design must be made, otherwise any stress concentration at the root of the first thread could restrict the life of the vessel assembly. Quicker and more economical automated closing mechanisms can be effected by closure with interrupted threads.

Reservoir with filtering system: In case of dry bag the contamination of the fluid is avoided by the use of normal hydraulic systems reservoirs and good conventional filters. For wet bags, where mostly water is used, the contamination is very acute, which adversely affects the pumps and seal life.

High Pressure Generator: From small high pressure hand pumps, pressure generators have developed by the use of small air hydraulic intensifiers. In these, large air driven piston moves a small high pressure hydraulic piston which pumps the liquid to the desired pressure. The surface ratio of the low pressure air piston versus the hydraulic piston can reach 600:1 and more.

Depressurisation System: There are various depressurisation systems capable of almost any decompression profile to help eliminate compact breakage that may occur by too rapid depressurisation.

Fluid Transfer System: After the compaction step, the superfluous quantity of liquid in the pressure vessel must be evacuated as rapidly as possible at the end of depressurization stage. All such transfer can be accomplished by an appropriate standard transfer pump and the correct valving between the reservoirs and the pressure vessel.

Controls: Most simple units have manual control of the pumps, valves and cover mechanisms. However, automatic controls by servo-operated valves with identical closing and opening forces are used. This enhances the service life of high pressure valves.

Tooling: There are various factors[4] to be considered when designing a proper tooling, for example:

1. Type of press
(a) wet or dry bag
(b) automatic, semiautomatic or manual
(c) top or bottom ejection
2. Properties and type of powder:
(a) metal, ceramic etc.
(b) flowability
(c) compression ratio
(d) green strength
(e) adhesion to bag or punches
(f) density
3. Bag Material
(a) dipped latex, natural rubber, Neoprene
(b) PVC
(c) moulded natural rubber, Neoprene, nitrile
(d) polyurethane Table 5.3 summarises main properties of flexible die materials [7].
4. Production Rate
5. Life of Tooling
6. Accuracy of compact
7. Shape of compact
8. Operator's skills

In the **wet bag** tooling, the filled and sealed mould is immersed into a fluid chamber which is pressurized by an external hydraulic system (Fig.5.15). After pressing, the wet mould is removed from the chamber and the compact removed from the mould. In case of **dry bag** tooling, both powder filling and ejection are performed without removing the bag assembly. Sealing is achieved by an upper punch which enters the bag before pressurization. The compaction stresses are generated by isostatic compression of the bag through a fluid without loading the punch. The dry bag method is much more rapid because the bag is built directly into the pressure cavity. In general, the more versatile wet bag process is used for the batch production of small number of shapes whereas the dry bag process is used for the semiautomatic or automatic production of large number of shapes often of smaller dimensions.

5.3.2 Isostatic Pressing Cycle

A typical isostatic pressing cycle comprises of the following:

(i) Insertion of compact – The material filled with the material to be

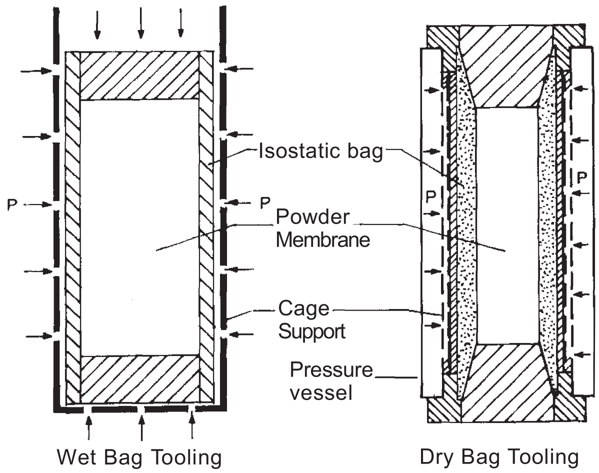


Fig. 5.15 Wet bag and dry bag tooling in cold isostatic pressing.

Table 5.3 Type of mould materials and their properties[7]

Water resistance	G	G	G	G	G	F	P → Ex
Oil resistance	P	P	G	Ex	G	F	G → Ex
Aging resistance	P	F	G	G	G	P	P → Ex
Toughness	VG	VG	VG	VG	P	P	G → Ex
Tear resistance	VG	VG	VG	VG	VP	P	G → Ex
Cut resistance	VG	VG	VG	VG	VP	P	G → Ex
Resilience	Ex	Ex	G	G	VG	P	P → Ex
Set resistance	Ex	Ex	VG	VG	G	P	VP → Ex
Availability	R	S	R	S	S	R	S
Cost	L	M	L	M	H	L	L → M → H

R = Readily available; S = Subject to mould;
L = Low; M = Medium; H = High;
VP = Very poor; P = Poor; F = Fair; G = Good;
VG = Very good; Ex= Excellent.

pressed is sealed and placed in the partially filled vessel. This causes the liquid level in the vessel to rise.

(ii) Filling and Venting – The upper closure is installed and locked. Any air remaining above the fluid level is removed. Otherwise greater amount of energy would be used before the vessel reaches operating pressure, because of the fact that air is highly compressible. The displaced air is vented through the valve in the top closure.

(iii) Pressurizing – The high pressure pumping system pressurises the water to the operating pressure. Water is added during pressurization in order to compensate for the volume reduction of the powder being pressed and the compressibility of water at these pressures. Table 5.4 gives some typical values for pressures required for isostatic pressing.

(iv) Depressurizing – During this stage, the extra amount of water is expelled from the vessel.

(v) Compact removal and draining system – The green part and mould are now removed from the pressure chamber. The water level drops, but subsequently gets overflown if another uncompacted mould is inserted.

5.3.3. Defects due to Tooling Limitations

The major defects associated with the improper tooling are :

1. **Elephant's Footing**: If the modulus of the bag is less than that of the closure then the bag will distort or compress more than the closure. The result is the elephant footing. Figure 5.16 shows the problem and a suggestion for it's remedy.
2. **Poor consolidation**: If the modulus of the bag is too high or the wall thickness is too great then insufficient pressure will be exerted on to the powder. Altering the hardness of the bag and or its gauge normally eliminates the problem.
3. **Radial Cracking**: When a very thick wall bag is used the pressing pressure causes the material to 'ruckle'. This gives differing radial pressures along the length of the form and the resultant differing densities can cause cracking on decompression. Thinner gauge sections are usually required to reduce or eliminate this problem.
4. **Preform Cracking**: If the bag properties are poor, then powder sticking can be a major problem. On decompression a surface layer can be turn out of the preform resulting in cracking which is noticed on sintering. A change in the grade of bag material is called for.

Table 5.4 Typical pressures required for isostatic pressing powders

	Ksi	N/mm^2
Aluminium	8-20	55-138
Iron	45-60	311-414
Stainless steel	45-60	311-414
Copper	20-40	138-276
Lead	20-30	138-207
Tungsten carbide	20-30	138-207

These pressures are approximate since every application presents its own requirements of density, configuration and size.