

Forging and Hot Pressing

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POWDER FORGING AND HOT PRESSING processes are similar in terms of their external physical characteristics. Each process involves the simultaneous application of pressure and heat to consolidate powders to full, or nearly full, density. Both processes occur within a die that gives shape to the final densified component.

At a more detailed level, forging and hot pressing are significantly different. Forging involves the deformation of a powder preform in which considerable lateral flow occurs (Fig. 1a). Forging is carried out on high-speed presses that are automated for mass production. Hot pressing, on the other hand, involves compression of loose powder or a powder compact fitted tightly in the die cavity, similar to repressing, resulting in very little lateral deformation, as shown in Fig. 1(b). Hot pressing generally is carried out at very low deformation rates in hydraulic presses.

At an even finer scale, viewing the localized deformation of a representative unit of material containing a pore (or void space) between particles, the lateral flow of forging leads to considerable shear, which breaks up any oxide surfaces on the particles and enhances bonding (Fig. 2a). In hot pressing, pores and voids simply collapse under axial deformation; see Fig. 2(b) (Ref 1). Hot pressing is similar in this respect to cold die compaction.

Because of the differences in speed and deformation mode between forging and hot pressing, the metallurgical mechanisms of densification are different. Forging relies primarily on plastic deformation to close the voids during the few milliseconds that the material is under pressure. Hot pressing involves plastic deformation, creep, and diffusion mechanisms to cause localized flow of material into the pores.

Forging involves only axial compressive stress while the material is undergoing lateral flow, or upsetting. When the forged material reaches the die wall, however, lateral pressure acts on the material much like repressing (Fig. 1a). In hot pressing, the material is subjected to lateral pressure p' in addition to axial pressure p , similar to repressing (Fig. 1b and 2b). The numerical difference between p and p' diminishes as full density is reached. Closure of pores by plastic deformation becomes more difficult as the lateral and

axial pressures approach equality; i.e., a hydrostatic stress state. Therefore, it is important in forging that most of the densification occurs by shear before the material reaches the die walls.

While both powder forging and hot pressing can consolidate most powder materials to full density, forging is applied primarily to high production parts in ferrous alloys, such as automobile connecting rods, transmission parts, and hand tool components. Hot pressing is used primarily for specialty materials such as tungsten carbide, beryllium, and ceramics. Hot pressing is also used as a consolidation process to produce billets for further processing by conventional forging or extrusion of materials such as high strength P/M aluminum alloys, tool steels, and superalloys.

Successful application of forging and hot pressing involves careful consideration of powder preparation (compaction, heating, and atmosphere protection) and forming process parameters (preform design, heating, tooling, and equipment). Computer modeling of these processes has been introduced recently to accelerate the development of the proper process parameters and tooling for new applications and the solution of problems in existing processes. The important process features are described here for both powder forging and hot pressing, along with specific applications and materials.

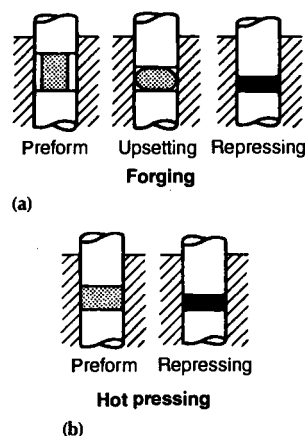


Fig. 1 Deformation mode for (a) forging and (b) hot pressing

Powder Forging

Powder Preparation

The most extensive application of powder forging is automotive drive train parts using high strength steels. Water-atomized low alloy steel 4620 is commonly used as well as iron-copper-carbon blended elemental powders (Ref 2). Powder characteristics, such as size and shape, are unimportant in the forging deformation process itself, but they may have important effects on the compaction and sintering processes prior to forging. For example, whether the powders are spherical or irregularly shaped, fine or coarse in size, they will lose their identity through the extensive deformation and accompanying densification during forging, and will have little effect on the deformation process. For the preform compaction process prior to forging, however, irregularly shaped powders are preferred because of their ability to interlock during compaction and produce compacts with sufficient green strength for handling. Coarse powders might also be preferred over fine powders because of ease of flow during compaction die filling, and because they present less surface area for contamination during sintering or heating for forging.

The chemical composition of the powders involved in powder forging is important, primarily

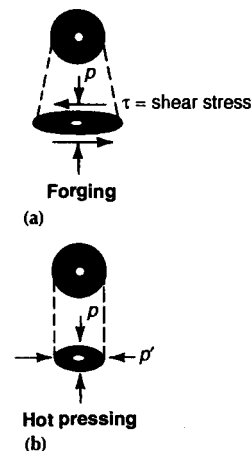


Fig. 2 Stress conditions for (a) forging and (b) hot pressing

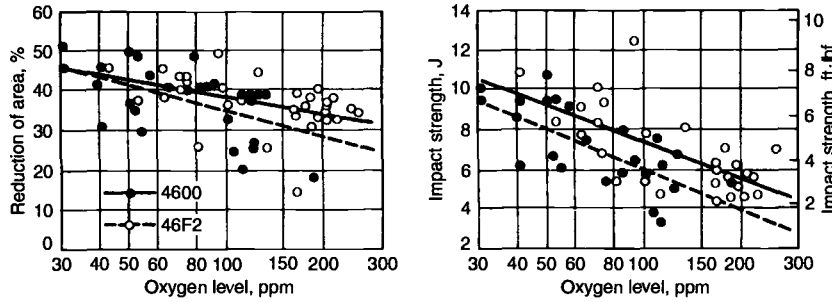


Fig. 3 Variation of reduction of area and impact strength as a function of oxygen content. Source: Ref 3

in terms of oxide content, because the volume fraction of contaminants strongly influences the final properties of the powder forged component. If the oxide appears on the surface of the particles, it can be readily reduced by proper sintering practice or broken up and dispersed by shear deformation during forging.

Preforms for forging are fabricated primarily by conventional die compaction, although dry bag isostatic compaction has also been used for some applications. The overall density of the preform has no significant effect on the density of the forged parts, but variations in density from region to region of the preform are often designed to control metal flow and avoid defects

during the forging process. Another consideration is the influence of preform density on the sintering process. Preforms of low density contain extensive interconnected porosity, allowing the sintering furnace atmosphere to reduce larger amounts of surface oxides on the powder particles. On the other hand, lower density preforms are more prone to internal oxidation and carburization during exposure to air while the preform is transferred from the furnace to the forging press. For this reason, protective coatings are generally applied to the preform before heating.

Control of the preform weight is critical because hot forging is carried out in a trap die without flash, as shown in Fig. 1(a). Excessive preform weight may lead to tool breakage or stalling of the press. Conversely, underweight preforms will not achieve full densification by forging and may not fill extreme corners of the die.

Sintering is the final critical step in preparation of preforms for forging. Sintering not only bonds the powder particles by diffusion, it also provides a protective or reducing atmosphere to prevent contamination and reduce the levels of oxide contamination that may be present in the particles. The oxygen level of the sintered preform, which depends on the sintering temperature, sintering atmosphere, dew point, and furnace type, determines the oxygen level of a

forged part. The oxygen level of sintered preforms decreases with higher sintering temperature and lower dew point. Mechanical properties in general, and dynamic properties (impact and fatigue strength) in particular, are strongly influenced by the oxygen level of the forged part. Low oxygen levels lead to higher dynamic properties because the metallurgical bonds developed between particles during forging are stronger if the particle boundaries are free of oxides; see Fig. 3 (Ref 3).

Forging Process

A major key to successful powder forging is proper preform design because it has a significant effect on the metal flow and distribution of stresses in the material during forging. These factors, in turn, affect the densification and probability of fracture. In general, sufficient metal flow must take place to achieve full density and good bonding across collapsed pores. However, increasing the amount of metal flow also increases the possibility of fracture. Thus, preform shape design involves a tradeoff between the lower limit of deformation to achieve the required properties, and the upper limit that would cause fracture.

As shown in Fig. 1(a) and 2(a), the deformation during forging involves considerable lateral flow and shearing of the powder particles. This shearing action causes any oxide films on the powder particles to be broken up, exposing clean metal, and enabling a strong metallurgical bond across collapsed pore interfaces. As a result, the dynamic properties of the material are enhanced. Figure 4, for example, shows that the impact energy of as-forged alloy steel powder preforms increases steadily with increasing deformation up to ~60% reduction. Similarly, Fig. 5 shows that the fatigue limit for powder forged 4620 steel increases with increased deformation (Ref 4).

Large deformation of sintered powder material can easily lead to fracture because tensile stresses usually develop, and pores in the material provide many sites for concentration of these stresses, leading to fracture. To overcome this limitation a fracture criterion has been developed for predicting fracture during powder forging. Based on the occurrence of fracture during

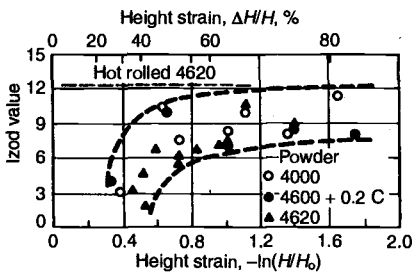


Fig. 4 Increase in impact resistance with increasing forging deformation of sintered nickel steel (4600 series) powder

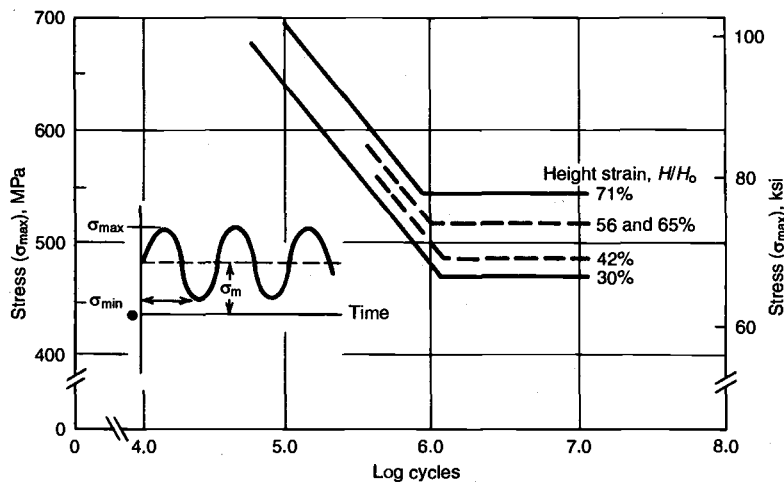


Fig. 5 Axial fatigue of P/M forged 4620 steel for various levels of forging deformation. Fatigue limit increases as deformation level (height strain) increases. Source: Ref 4

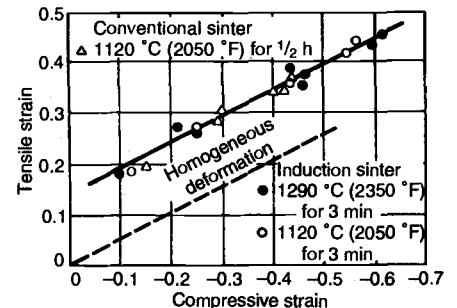


Fig. 6 Tensile strain vs. compressive strain at fracture of 4620 steel powder cylinders and sintered under various conditions. Dashed line represents homogeneous deformation (zero tensile stress).

upset compression testing, a locus of surface strains at fracture can be generated, as shown in Fig. 6 (Ref 5). For a given material, strain combinations in the material above this line will lead to fracture, while strain combinations below the line are safe. Such fracture lines can be generated for any material.

To illustrate the important role of preform design on defect-free powder forging, consider the part shown by shading within the tooling configuration in Fig. 7. This part is axisymmetric, consisting of an outer rim (upper section) formed by the upper punch, and a hub (lower section) formed by the lower punch. A flange is formed between both punches, and an outer die and core rod complete the tool set. A preform containing the rim and hub features is not considered because metal flow would be limited, leading to incomplete densification. Rather, the preform for this part would simply be a cylinder with a hole at the center. Forging the part from a cylindrical preform will involve various combinations of back extrusion of metal into the rim, forward extrusion into the hub, and lateral (radial) flow in the flange. However, as seen in Fig. 8, for a given volume of material, the inside and outside diameters of a cylindrical preform can have a variety of combinations. Using the fracture criterion in Fig. 6 and knowledge of the stresses in the various modes of deformation, the proper preform can be determined.

In Fig. 8(a), the preform leads to successful forging because radial expansion of the outer surface is prevented, forcing inward flow to form the hub. This inward flow is in compression and does not lead to fractures. Meanwhile, the rim forms by backward extrusion without radial expansion and is also safe from fracture. The preform in Fig. 8(b) allows considerable radial expansion and flow of material around the upper corner radius into the rim, which easily leads to fracture on the inside of the rim. In Fig. 8(c), the preform is constrained from lateral flow on both the inner and outer diameters; the resulting forward extrusion into the hub section causes large tension on the surface of the hub, leading to fracture. The preform in Fig. 8(d), like Fig. 8(b), leads to fracture on the inside surface of the rim as material flows around the upper corner of the punch into the rim.

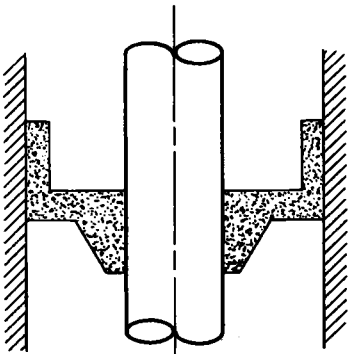


Fig. 7 Prototype part for illustration of preform design

It is clear that, even though a cylindrical preform is the obvious choice for this part, the specific dimensions of the preform must also be determined. Subtle changes in the preform dimensions mark the difference between successful and unsuccessful forging. This observation is true in preform design for nearly every part.

For more complex shapes, preform design is a major challenge, since a wide variety of deformation modes and combinations may occur. Preform design for connecting rods, for example, requires specification of the preform dimensions for the circular sections at the pin end and the crank end, as well as the beam section connecting these ends. Lateral flow and extrusion occur locally in all three sections, and material flow may occur across the intersections as well. Preform design for this complex case requires careful determination of the weight of material in each section and detailed analysis of the localized metal flow in each section. Unlike most preforms, it is necessary to specify different densities in each of the three sections of the preform to ensure full densification and avoid defects in the finished connecting rods.

The tooling for powder forging is based on the trap die concept, an example of which is shown in Fig. 7. The material is completely trapped between the punches and die, with no flashland. While the trap die concept produces a near-net shape that does not require removal of excess metal in a flashland, it does lead to high stresses on the tooling. Combined with the high temperatures of forging, these stresses and metal flow lead to high wear rates on the punches and die. The most commonly used material for the dies is H13, a hot-working die steel. With proper preform design and cooling of the tools between press strokes, 50,000 to 100,000 parts can be produced before die refurbishment is required.

The temperature of the preform as it enters the forging process influences the mechanical properties of the forged parts as well as the life of the forging tooling. Higher forging temperatures enhance densification of the forged part because

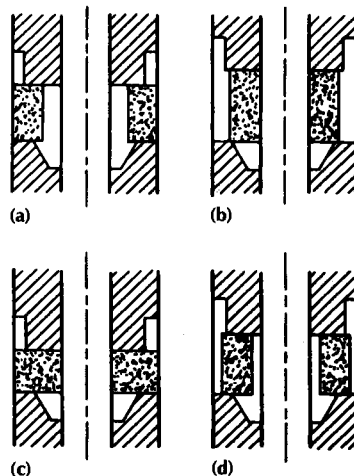


Fig. 8 Preform options for forging the part shown in Fig. 7. See text for discussion of (a) through (d).

plastic flow occurs more easily, as shown in Fig. 9 (Ref 6). On the other hand, higher forging temperatures lead to greater die wear. Typically, steel powder preforms are forged at 980 °C (1800 °F) as the optimum temperature to minimize die wear and ensure part densification.

The speed of forging also affects the quality of parts produced by powder forging. Since the preform is porous, rapid cooling of the hot preform surface by contact with the colder die surface will lead to residual porosity at these surfaces. To minimize this effect, the contact time between the preform and die must be as short as possible. For this purpose, screw presses with a very stiff frame are widely used for powder forging. The screw press motion ensures rapid withdrawal of the forging punch from the die, and the stiff frame minimizes contact time between the part and die at the peak load. The total contact time for forging by a screw press is ~30 ms, while the contact time for a typical mechanical crank press is 80 ms. This difference has a very large effect on local cooling of the preform and, consequently, residual surface porosity in the forged part.

Applications

Forging of P/M preforms to near-net shape or net shape parts has several advantages: material utilization is increased by eliminating or substantially reducing machining operations, energy efficiency is greater than conventional forging because operations such as hot rolling of bar stock are eliminated, and powder forging uses lower temperatures than conventional forging for the same alloys. As an example, a machine gun accelerator is conventionally produced by hot forging billets of 4340 steel to a rough shape in six operations, followed by 27 machining operations. Powder forging of the same part consists of compacting a preform from atomized 4600 steel powder, sintering the preform, and hot forging, followed by just seven machining steps. This leads to a net cost savings of >50% compared to the conventional approach.

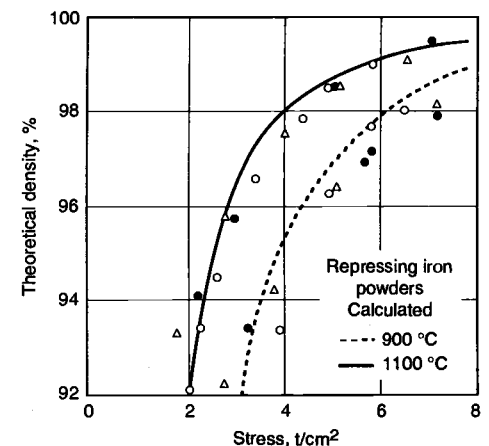


Fig. 9 Experimental and predicted increase in forging pressure with density during hot repressing of steel powder

Powder forging for mass-produced structural parts was developed to meet performance requirements beyond that available from conventionally pressed and sintered powder parts. A number of parts have been attempted by powder forging; however not all of these parts were successful, primarily for economic reasons. Currently, powder forged parts are produced mainly for automotive drive train applications. Powder forged connecting rods have been in use in U.S. automobiles since 1987, starting with the Ford Escort 1.9 liter engine. Powder forged connecting rods are now used in at least 13 engines among major U.S. automakers and are also used in some European and Japanese engines. The rods are typically forged from Fe-Cu-C powders to a minimum density of 7.84 g/cm³. At this density they have an ultimate strength of 760 MPa (110 ksi), a yield strength of 550 MPa (80 ksi), and endurance limit of 275 MPa (40 ksi). Powder forged connecting rods eliminate the surface defects inherent in conventional forging, have a uniform microstructure, are dimensionally consistent, and have superior machinability. The uniformity of microstructure and material distribution also minimizes the amount of material removal required for balancing the connecting rods.

Powder forging has also been used for specialty materials, such as tungsten, molybdenum, and beryllium. Since these materials cannot be cast easily, powder forging is the best option for processing fully dense net shapes. Powder forging concepts are also emerging for the fabrication of ceramic parts. With the recent development of superplastic ceramic materials, forming of complex shapes from simple ceramic preforms has been developed for high temperature bearing and seal applications (Ref 7).

scribed for each region. Finally, the design details are determined through limited applications of a finite element simulation code (Ref 9).

Hot Pressing

Material Preparation

Hot pressing is similar to powder forging in that powder material is compressed at high temperature between opposing punches, but hot pressing occurs at a much lower rate than forging. Also, lateral flow of material does not occur in hot pressing, whereas this is an important requirement in powder forging. Hot pressing is also similar to conventional powder compaction at room temperature since powder is placed in a die and compacted by uniaxial compression.

Unlike powder compaction, feeding loose powder into the die is not practical. Since hot pressing is carried out with dies heated to the pressing temperature, loose powder particles entering the die cavity heat up rapidly, causing particles to bond together or weld to the tool cavity and impede further flow of powder into the die. In addition, the large free surface area of loose powder increases the likelihood of oxidation of the powder at the high temperatures of hot pressing.

One option is to fill the cold die with loose powder at a separate station, and then move the filled die to the press where the die and powder are heated simultaneously before pressing. A second option is to preform the powder into a porous green compact for easy handling. This approach eliminates powder flow at high temperatures and minimizes oxidation problems, which outweighs the additional step of preform pressing. The compact, which may be preheated or at room temperature, is placed in the die, which may also be at room temperature or preheated to the hot pressing temperature. With the powder compact in the die, the powder and die must be heated to the hot pressing temperature. Heating can be done directly through induction or electrical resistance heating, or indirectly by heat transfer from the die, which is heated by other means.

Resistance heating of the powder is accomplished by passing a low voltage, high amperage current through the powder while pressure is applied. A variation of resistance heating involves discharging an electric spark through the powder. High temperatures generated at the points of contact between adjacent powder particles cause bonding. Heating of the die and then indirect heating of the powder compact is the most common method for heating. In this case the entire tool set may be heated by induction or a resistance wire heated muffle furnace.

As with other high temperature processes involving metal powders, a controlled environment must surround the powder material during hot pressing. This atmosphere can be a gas contained in the die cavity, or the gas can surround the entire die assembly inside a chamber. A vacuum can also be used as the hot pressing envi-

Process Modeling

As with many other manufacturing processes, several computer models have been developed for analysis of powder forging, including finite element analysis and expert design systems. These computer tools aid design of the process, including preform design. Such models were difficult to develop because of the complications introduced by porosity in the material. The existence of porosity and accompanying density change during deformation preclude the use of conventional plasticity equations, which are based on zero volume change. In addition, heat transfer rates in the material depend on the local density level, which changes throughout the preform during the forging process. Recently, material models giving accurate representations of porous material behavior during plastic deformation have been developed. Coupled with modern numerical methods, these material models have led to reliable simulations of the deformation during powder forging (Ref 8). The fracture criterion given in Fig. 6 has also been embedded in the computer code so that fracture predictions can be made.

A reliable simulation code is particularly useful for preform design for powder forging of new parts. Starting with an initial guess of the preform shape, a finite element simulation of the forging of that shape will indicate areas of incomplete densification as well as locations at which fracture may occur. Then modified preform shapes can be attempted in an iterative approach to eventually derive a preform shape that leads to defect-free forged parts. This trial-and-error procedure, however, can be very tedious, especially for complex parts. For this reason, an expert design system was devised to provide an initial guess for the preform design, based on experience with previously forged parts. The part to be forged is first subdivided into regions of primary metal flow, such as back extrusion, forward extrusion, and lateral flow (Fig. 10). This subdivision into regions is done automatically by the program, using geometric reasoning applied to computer-aided design (CAD) data representing the part. Preform design rules accumulated from experience on other parts are then applied to each region. An additional set of rules is applied to evaluate material flow between regions. Next, a decision tree methodology is followed to optimize the preform shapes in each region, based on the objective of minimizing defects, wear, and tool loads. Smoothing functions then blend the preform shapes pre-

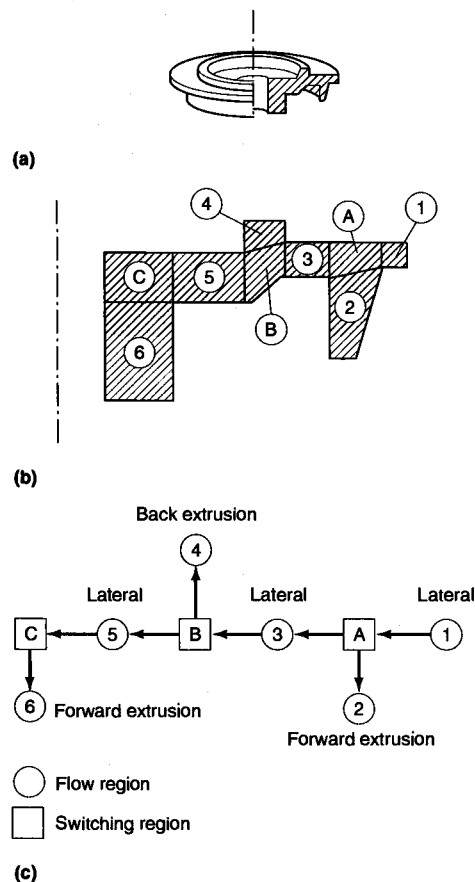


Fig. 10 An example of an axisymmetric part. (a) Isometric view. (b) Cross section showing regional subdivisions. (c) Link-node network representation of the part topology for expert system design decisions

ronment. Inert gases (such as argon) can be used when hot pressing powders such as beryllium or titanium that are particularly sensitive to contamination by oxygen or nitrogen.

Hot Press Equipment

A wide variety of hot pressing equipment configurations have been devised for both production and laboratory applications. These installations combine indirect or direct heating with various tooling configurations and means for containing the tooling in a controlled atmosphere. Several examples are given in Ref 10. Two examples are shown in Fig. 11 and 12. Figure 11 shows graphite tooling, heated by resistance, with a telescoping enclosure for containing an atmosphere. The entire fixture is fitted to a hydraulic press (Ref 11). Figure 12 is an example of a vacuum hot press used for beryllium consolidation. Graphite tooling is again used inside an induction coil for heating the tooling and powder. The assembly is mounted inside a double-walled chamber with vacuum seals for the rams and utility connections (Ref 12).

The material selected for hot pressing punches and dies is critical because these parts are subjected to high pressure and temperature for a sustained period of time. The punches must resist plastic deformation under the axial loads of pressing, while the die body must constrain the lateral pressure of pressing without yielding. As pointed out in the description of Fig. 2(b), as full density is approached, the lateral pressure nearly equals the applied axial pressure. As a result, the die must have a wall thickness great enough to withstand the circumferential stresses developed at peak axial loading.

Metals used for hot pressing tooling include molybdenum, a molybdenum alloy TZM (Mo-0.5Ti-0.1Zr), tungsten, superalloys, and alloy steels that are highly heat resistant. If steel or superalloy dies and punches are used, they must be kept at lower temperatures by water cooling through internal passages. Ceramic or graphite tooling is frequently used without cooling, but

overloading must be prevented to avoid catastrophic failure of these brittle materials. Because thermal expansion occurs during heating, the dies and punches should be made of the same material. If the die expands at a greater rate than the punches, a gap will form between the die and punches into which pressed powder material will extrude, and lead to difficulty in ejecting the hot pressed material from the die. Conversely, if the punches expand at a greater rate than the die, the die will fit tightly around the punches, again preventing ejection of the hot pressed material.

The sustained processing time at high pressure and temperature during hot pressing also requires consideration of chemical reactivity between the powder material and tooling. Diffusion at the interface between the powder and tool surfaces may lead to welding of material to the die cavity. Graphite tools and molybdenum alloys require a controlled atmosphere to prevent oxidation. To avoid reactivity between the tooling and powder, as well as improve ejection of the pressed material from the die, die wall lubricants are frequently used. Colloidal graphite suspension in water or oil is applied to the die wall to reduce friction and wear. Ceramic or mica suspensions in hydrocarbons spray coated on the punch and die also inhibit diffusion bonding and welding.

Since hot pressing involves plastic deformation, creep, and diffusion, pressing times are extended to several minutes or even hours. For this reason hydraulic or pneumatic presses are used rather than mechanical presses. Generally a hydraulic press with a simple single action ram will suffice, as long as a means for ejecting the hot pressed material is provided. Hydraulic presses with side rams enable the use of split dies for easy extraction of hot pressed materials, particularly parts having multiple levels. In all cases, precise control of the axial load is necessary to ensure that a constant pressure or the required pressure-time profile is maintained during the pressing operation.

Applications

The material produced most widely by hot pressing is tungsten carbide. While small tungsten carbide parts, such as cutting tool inserts, are made by pressing and sintering, the density gradients resulting from such processes preclude their use for large parts. Tungsten carbide powders are hot pressed generally in graphite molds induction heated to 1400 °C (2550 °F) and pressed at pressures up to 17 MPa (2500 psi). Higher pressures may crack the graphite tooling, or cause the cobalt binder phase to extrude between the punches and die. If the pressure is too low, high levels of porosity remained and distortions will result during sintering to full density. Hot pressing is widely used for producing forming dies and wear resistant parts of simple geometries.

Hot pressing is also the preferred process for shapemaking of beryllium. Hot pressing of beryllium powders prevents grain coarsening, which is the major limitation in casting this material. Beryllium is hot pressed at 1050 °C (1920 °F) in graphite tooling in a vacuum. Hot pressed beryllium parts are used primarily in nuclear reactor modulators and in missile and aerospace applications.

Superalloys and titanium alloys have also been hot pressed to full density for simple geometry parts. However, serious problems occur due to reactions between these alloys and the tool materials. Such problems can be overcome by using hot isostatic pressing, where these interactions are more easily controlled.

Currently, hot pressing is a very important process in the development of new ceramics and metal matrix or ceramic matrix composites for a wide variety of applications. Materials include silicon carbide and silicon nitride in various metal

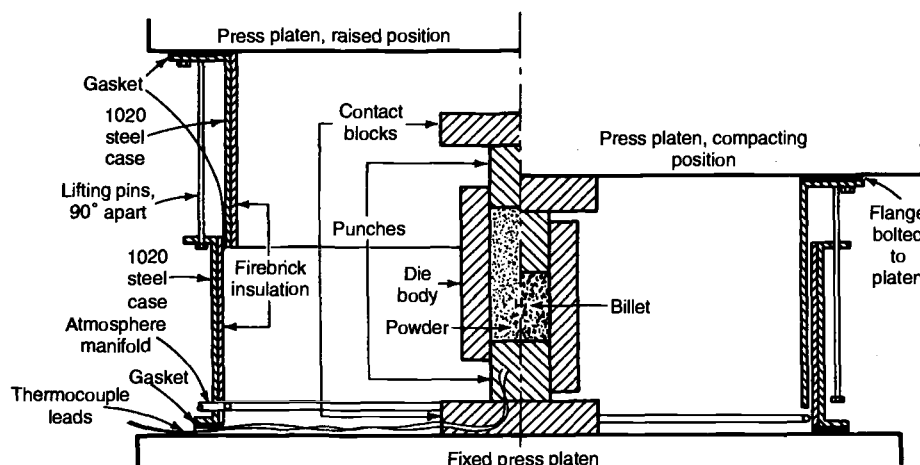


Fig. 11 Cross section of resistance heated graphite die assembly built into hydraulic press. Arrangement provides for telescoping controlled atmosphere enclosure and double-action hot pressing for steel, nickel alloy, and titanium alloy powders. Source: Ref 11

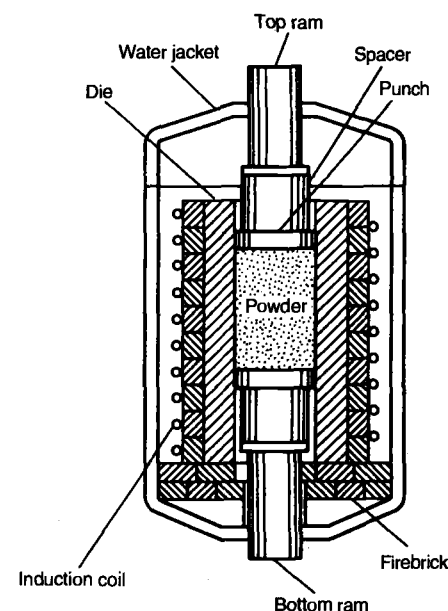


Fig. 12 Cross section of hydraulically activated, induction-heated graphite die assembly inside vacuum chamber. Arrangement permits double-action hot pressing of beryllium powder into blocks. Source: Ref 12

or intermetallic matrices. A relatively new material known as System 2 has been produced by the U.K. Atomic Energy Authority for protection of the next generation space shuttle, Skylon. The material consists of 40% silicon carbide continuous fibers in a refractory glass ceramic matrix that has been processed by hot pressing (Ref 13). The material is self healing at high temperatures and is ideal for hot structures where weight reduction is required. This material serves as an effective substitute for titanium- and nickel-base alloys for advanced aerospace applications. Alumina-aluminum silicon composites have been fabricated by in situ reaction of molten aluminum with aluminosilicate ceramics (Ref 14). This reactive metal penetration process is driven by a strongly negative Gibbs energy for reaction. In the aluminum-mullite system, aluminum reduces mullite to produce alpha alumina and elemental silicon. Ceramic-metal composites containing up to 30 vol% Al(Si) were prepared by reacting molten aluminum with dense aluminosilicate ceramic preforms, or by reactively hot pressing aluminum and mullite powder mixtures. Bulk metal matrix composites have also been produced by hot pressing blended prealloyed powders of aluminum alloy 6061 with 15 vol% of silicon carbide particles (Ref 15). In the T6 heat treated condition, yield strengths of 400 MPa (58,000 psi) were obtained with elongations of 2.5%. Sliding wear resistance of the metal matrix composite was also greatly superior to that of monolithic aluminum alloy 6061. A variety of ceramic components such as heat

shields for space reentry vehicles are also produced by hot pressing in graphite molds heated by induction. Aluminum silicon carbide composites produced by hot pressing are used for kiln fixtures as well as high performance aerospace vehicle structures.

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