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Effects of Processing Parameters in P/M Steel Forging on Part Properties: A Review

Part II Forging of Sintered Compact

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In the last decade, powder metallurgy (P/M) technology has made marked advances in competitive manufacturing. P/M offers design opportunities that are not possible with other methods, as well as significant cost savings. The processing parameters, material characteristics, individual stages of parts production, deformation and densification mechanics and tooling, and preform design influence the properties of the P/M part and related economics. Therefore, a review of the various parameters involved in the different stages of P/M steel forging in net-shape manufacturing and their implications on resulting properties of the P/M parts is presented in a three-part review. Part I discussed the issues of powder preparation, compaction, and sintering in the stages of preparing a sintered compact. This review (Part II) identifies key parameters in forging the sintered compact that influence the properties of the powder forged part. Part III reviews currently available analysis methods for studying the powder forging process.

1. Introduction

POWDER metallurgy (P/M) has developed from being used primarily for processing refractory and other special materials to compete with classical forming methods. Powder forging is particularly attractive because it blends the cost and material saving advantages of conventional castings and forgings through better dimensional and weight control. In respect to fatigue behavior, powder forged parts can even outperform parts machined from a die forged blank, probably as a consequence of fully dense, absolutely uniform and very fine grained microstructure. The powder forged parts are typically made with zero draft as flashless closed die forgings in one blow, enabling net-shape forming and consequently lowering machining and material costs. Parts containing through holes and complex configurations may be manufactured with little or no material loss, thus eliminating secondary processes such as trimming, hole punching, machining, or grinding.

Fabrication of structural parts and components by deformation processing of sintered powder materials is a process of considerable importance in modern manufacturing technology. The mechanical properties of the powder forged parts such as fatigue strength, tensile strength, and hardness depend on the deformation processing and preform design. Densification characteristics, material flow, flow defects, tooling, friction, microstructure, grain size, strains, strain rates, temperatures, and preform design are some of the parameters that contribute to the resultant properties that are critical for the application. The following sections detail the effects of the characteristics of the forming process for P/M steel parts and the processing conditions on the mechanical properties of the part: the details of deformation mechanics, forming equipment, tooling, etc., are covered elsewhere in the literature and are not presented.

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2. P/M Forging

Figure 1 depicts a typical sequence of some P/M forging processes. Powder metal compacts are forged to achieve improved mechanical properties and full density by three methods:

- Preform for precise weight, hot repress and machine
- Preform for weight and shape, closed die forge flashless and finish machine
- Preform for weight and shape, forge with flash, trim and machine

Some aspects of these three processes are discussed below.

Figure 2 shows a schematic of deformation modes in a cylindrical powder compact upset between rigid flat dies. The friction at the die contact surfaces causes a radial compressive stress, which combined with the axial compressive stress from the die leads to a nearly pure hydrostatic stress near the surface.

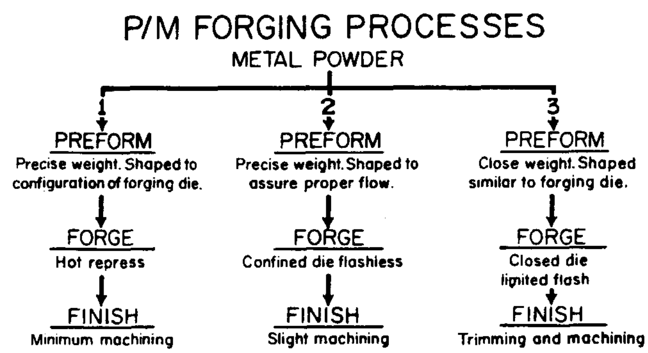

Fig. 1 Typical sequences of P/M forging processes. Process 1 is closely related to the present P/M practice. Process 2 is a new development combining the advantages of P/M and forging. Process 3 is an extension of the present forging practice.[1]

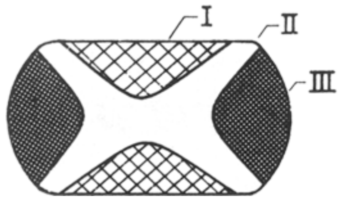

Fig. 2 Schematic of the characteristic modes of deformation as viewed on a longitudinal section through a cylinder upset between flat dies with no lubrication. Region I is under near hydrostatic pressure; Region II is under high shear; and Region III is under small axial compression and circumferential tension.[2]

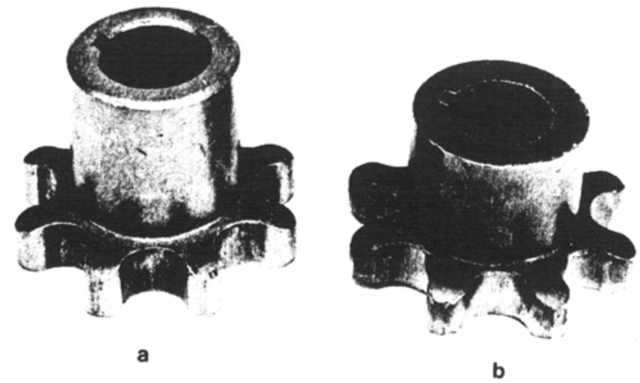

Fig. 3 Hot repressed sprocket showing preform (**a**) and forging (**b**).[3]

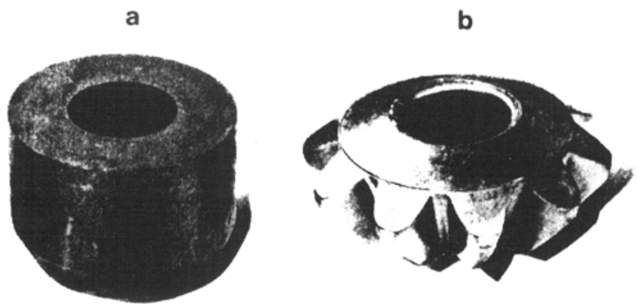

Fig. 4 Differential pinion gear showing sintered preform (**a**) and finished part (**b**).[3]

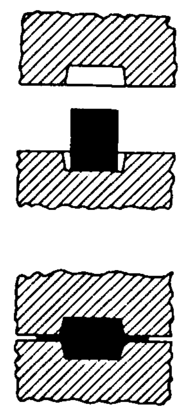

Fig. 5 Forging with flash such as in conventional forging.[3]

Bounding the cones of undeformed material (Region I) are bands of material subject to high shear stresses. Stresses at the barrelled surface are compressive in the axial direction and tensile in the circumferential direction.

The nonuniformity of deformation is reduced by decreasing friction with homogeneous deformation occurring under frictionless conditions. Also voids in Region I are spherical due to nearly pure hydrostatic stress states. They are flattened due to shear stresses in Region II, resulting in greater increase in density and are enlarged in the barrelled outer Region III.

After upsetting in hot forging and subsequent repressing, if the bulge surface comes in contact with the die walls it will cool rapidly, thereby trapping the large pores in this zone. This produces considerable surface porosity, particularly if the deformation rate is low. Therefore, it is essential to produce as much densification prior to repressing and to complement with well-lubricated dies.

3. Hot Forging and Cold Forming of Preforms

In order to obtain similar properties as in wrought materials, porosity must be eliminated. This may be done by producing preforms from metal powders and hot forging these preforms to obtain parts of closely controlled dimensions, microstructure, and completely or near-full density. In powder forging, the blank is a more precise preform than in conventional forging, produced from metal powders by compacting and sintering. Therefore, parts can be forged to net-shape. Three different approaches have been taken in forging these preforms.

The first is hot repressing (Fig. 3), in which the shape of the preform is close to that of the final part except for its height in the forging direction. However, the weight of the preform needs to be tightly controlled. In this process, the friction between die and preform during hot forging is high, and therefore, the pressure needed to get complete densification would also be high, which would involve rapid wear of forging tools. Hot repressing is used in applications where densities on the order of 98% of theoretical density are satisfactory.

The second approach (Fig. 4), the one most widely used in industry, is a precision forging process without a flash, in which the shape of the preform is simpler than that of the final part and the desired final shape is produced to closely controlled dimensions in the hot forging step. The lateral flow during deformation improves densification. Because this process is precise, tight control of preform weight and shape is required.

A third approach (Fig. 5) considers the process more from the point of view of the conventional forge shop, with the process involving flash and the part is not produced to net shape. In this case, relative to the other two processes, weight and shape control is not as critical. Figure 6 depicts a schematic of the overall deformation in the different processes. Figure 7 shows

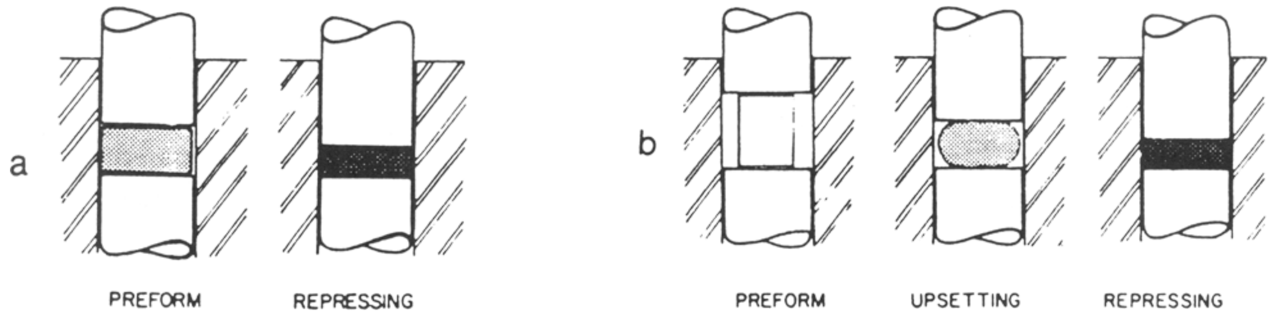

Fig. 6 Schematic of overall deformation in repressing (**a**) and forging (**b**) (upsetting in trap die).[3]

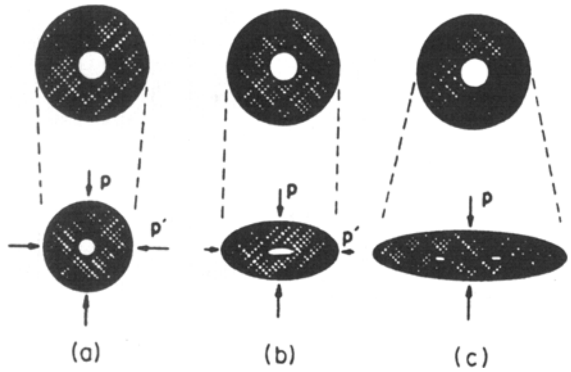

Fig. 7 Schematic of void deformation under isostatic pressure (**a**), repressing (**b**), and true forging (**c**) (with lateral flow).[3]

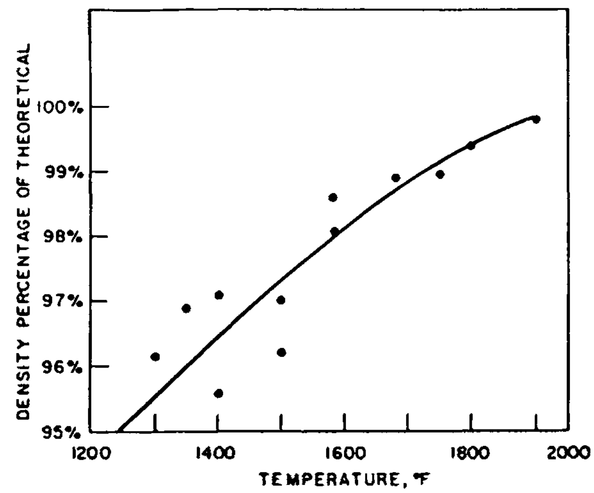

Fig. 8 Hot compressibility of low-alloy steel powder compacts under a forging pressure of 32 tsi.[8]

the schematic of void deformation under the different forging methods.

Preform design, tooling process parameters, etc., are of prime importance in contributing to the mechanical properties of the forged part. For applications requiring combinations of high strength and toughness, one approach[4] has been to add copper powder to a mixture of a prealloyed atomized steel powder with 0.4% Ni and 0.6% Mo to increase hardenability of sinter forged steel and graphite powder to serve as a lubricant to reduce friction. Another approach has been to start with laboratory-prepared atomized alloy powders. P/M structural parts made from iron powder and powders of the alloying ingredients have the advantage of a much wider choice of composition versus prealloyed powders, but the former technique invariably leads to alloys that have inhomogeneous compositions. Therefore, the selection of the powder mix has to be made appropriately for the P/M forging process to produce the required mechanical properties in the parts.

The methods of compaction and sintering used for conventional compacting are also used in the fabrication of powder preforms. After sintering, the preforms are cooled in the cooling zone of the sintering furnace and are later reheated to the forging temperature. Powder forging without a separate sintering step may be used in production of parts not transmitting power.[5] Dry bag isostatic pressing of preforms, discussed by Sellors,[6] and high-frequency induction sintering discussed by Vernia,[7] are other variations of powder forging processes.

4. Effects of Residual Porosity on Mechanical Properties of P/M Parts

In powder forging, porosity occurs near part surfaces where die chilling occurs and also where cracking occurs during the early stages of forging due to the presence of tensile stresses. Preform redesign and providing suitable friction conditions aid in eliminating or reducing residual porosity.

The effects of small amounts of residual porosity on the mechanical properties of P/M forgings have been investigated by Kaufman and Mocarski.[8] Their concern lay in pore size distribution, pore concentration, the production of irregularly shaped pores during the P/M process, and pore morphology and their effects on strength and ductility. Compacted preforms of two different size iron powders and 0.57% graphite were forged at a constant pressure of 32 ksi. Density variations were produced by forging between 1300 and 1900 °F. Figure 8 shows almost a linear relationship, with density increasing with an increase in forging temperature. Figure 9 shows that the yield strength decreases rapidly as porosity concentration increases for normalized steel and for samples held at a temperature below the eutectoid and spheroidized condition.

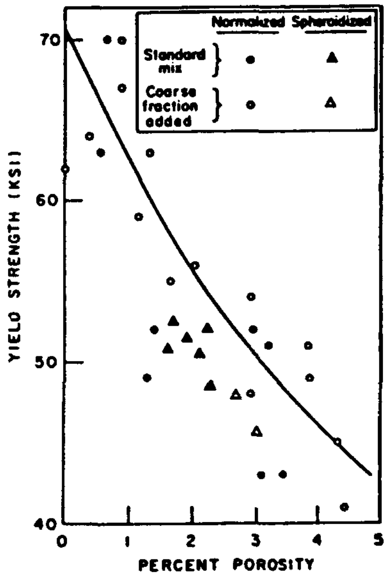

Fig. 9 Yield strength as a function of porosity concentration.[8]

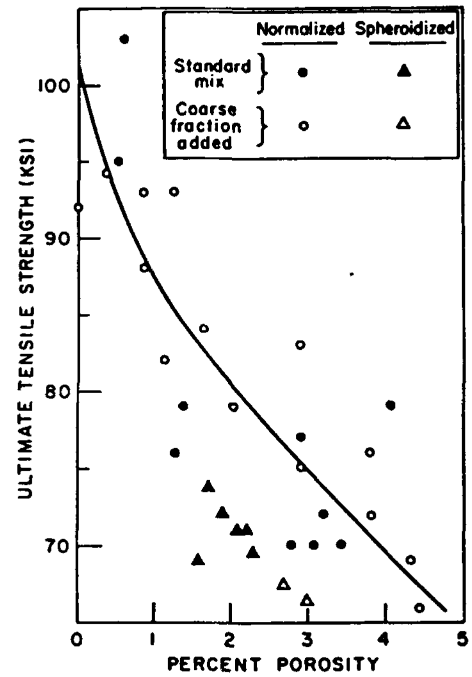

Fig. 10 Ultimate tensile strength as a function of porosity concentration.[8]

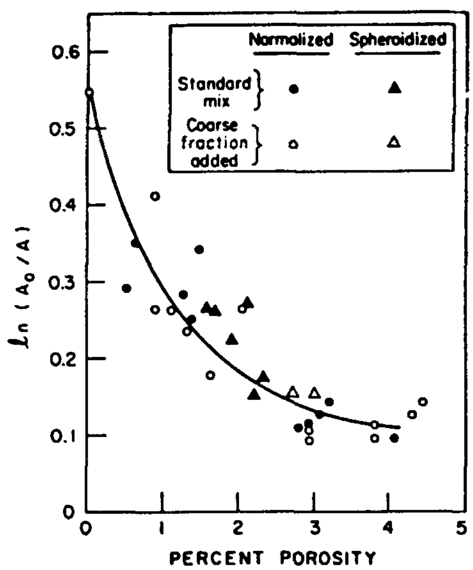

Fig. 11 Apparent ductility as a function of porosity concentration.[8]

Particle size distribution in the initial powder does not have much effect if samples are forged at the same temperature. The effects of porosity and second-phase dispersions were additive, but independent of one another. Tensile strength was found to monotonically decrease at about the same rate as yield strength with pore concentration (Fig. 10). A spheroidized microstructure exerted the greatest influence on tensile strength. True strain at fracture is one of the most common measures of ductility for porous materials. Figure 11 shows a plot of true strain versus porosity concentration; an 80% drop in true strain at fracture was measured for a porosity increase from 0 to 5%. The residual porosity resulting from a powder forging operation is irregular in shape and appears to generate some sort of notch effect, thereby causing deteriorations of mechanical properties. However, the results from the above investigations are difficult to generalize.

Solanki[9] pointed out that, although overall porosity levels may be as low as 0.5%, local levels could be as high as 3 to 5% due to flow, etc., during forging. In this study of the effects of surface porosity on fatigue resistance and fracture toughness, he showed that mechanical properties improve when the local porosity levels are reduced.

Crawson[10] studied the effects of preform temperature, die temperature, forging pressure, and flow level on residual porosity of 4640 steel forgings. The surface layer of 0.2 mm (0.008 in.) contained the bulk of the porosity. The experiments consisted of repressing operations, and the following conditions were concluded as near optimal:

- Forging temperature of 2200 °F
- Die temperature of 450 °F
- Forging pressure of 40 ksi
- Lateral flow of 5%

Stromgren and Lochon[11] showed that, for producing gear teeth with residual porosity levels of less than 0.4%, a preform temperature of 2010 °F and a forging pressure of 145 ksi were required. However, it must be noted that the above data are applicable only to the particular gear and preform shape.

The effects of porosity on fatigue resistance are depicted in Fig. 12. In ferrous compositions, the *S-N* curves exhibit a sharp knee similar to that in cast and wrought steels. As the last traces of porosity are removed, fatigue strength increases more rap-

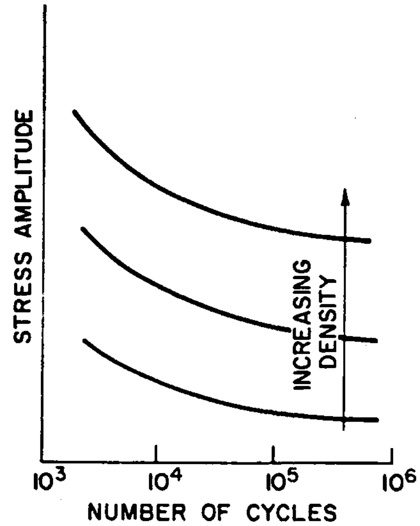

Fig. 12 Dependence of response to cyclic loading on density.[2]

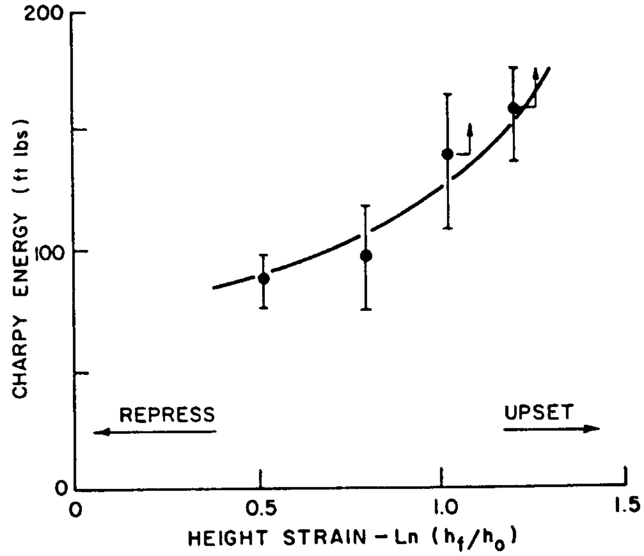

Fig. 13 Charpy impact response (standard test piece) for fully dense as-forged 1000 iron powder preforms as a function of extent of height strain (and hence lateral flow).[13]

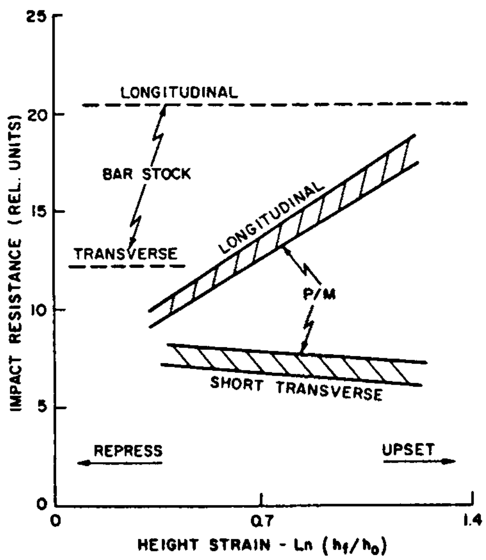

Fig. 14 Izod impact response (standard test piece) for fully dense as-forged 4620 steel powder preforms as a function of extent of height strain (and hence lateral flow).[13]

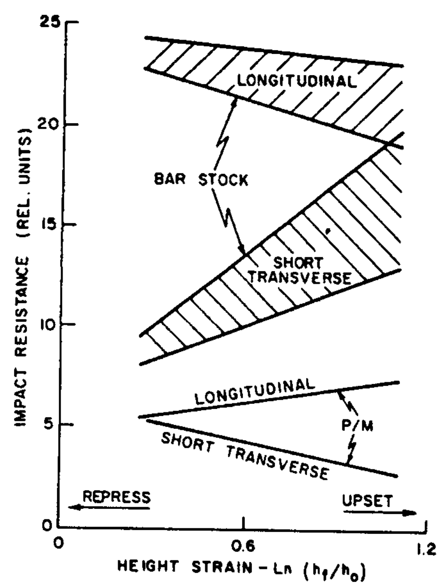

Fig. 15 Izod impact response (standard test piece) for fully dense heat treated 4620 steel powder preforms as a function of extent of height strain (and hence lateral flow).[13]

idly than tensile strength. According to Brown,[12] with increasing density a transition point is reached, beyond which inclusions probably become more dominant in controlling fatigue strength and crack propagation resistance than residual porosity.

5. Mechanical Behavior at Full Density

The forging process (repressing, upsetting, coining, etc.) determines the mechanical properties of the final product. Repressed and forged preforms are fully dense for practical purposes, and in this section, the relationships of mechanical properties of such parts are discussed.

Tensile strength is comparable for forgings that are repressed and those that are upset forged. In low-alloy steels, scanning electron microscopy confirms microporosity along particle boundaries, which remain open in the repressed condition. However, with increasing levels of lateral flow, this source of porosity is eliminated, and consequently, impact resistance increases. Ductility, on the other hand, is improved significantly by shearing due to metal flow.

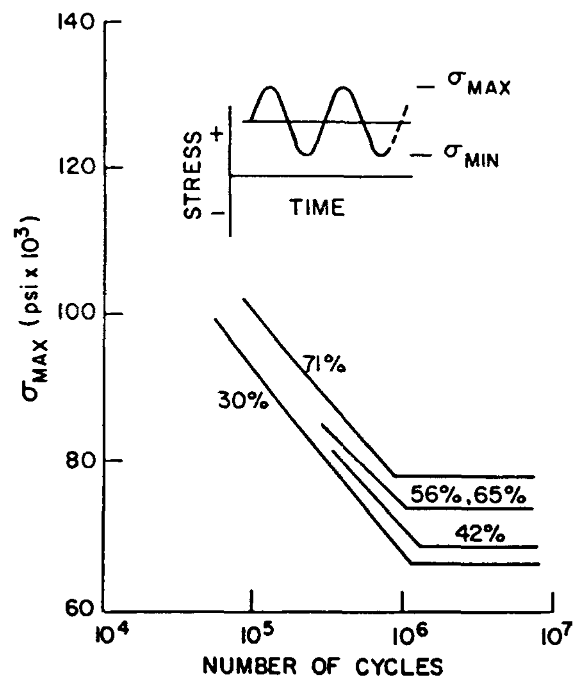

Fig. 16 Axial fatigue *S-N* curves for full-density powder forgings of 4620 as a function of height strain, as-forged condition.[2]

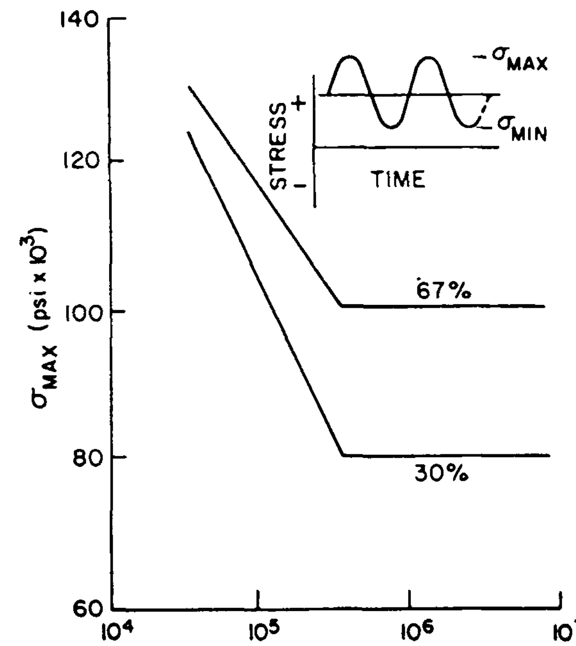

Fig. 17 Axial fatigue *S-N* curves for full-density powder forgings of 4620 as a function of height strain, heat treated condition.[2]

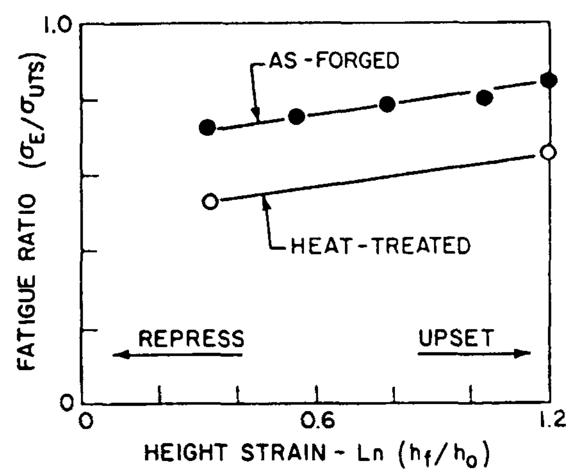

Fig. 18 Endurance ratio of 4620 powder forgings in axial fatigue as a function of height strain.[2]

In steels, the lower initial preform density (75 to 83% of theoretical) results in optimum toughness in fully dense forgings. This is attributed to the fact that the lower density preforms have a significantly larger amount of interconnected porosity; during sintering, the oxide reducing gas can penetrate the lower density preforms to a greater extent, thus lowering the final oxide content prior to forging and thereby raising the final toughness after forging. Observations of Ferguson *et al.*[13] have shown that toughness (Charpy energy) is enhanced by lateral flow produced by upsetting in fully dense ferrous powder forgings. Figure 13 depicts the increase in Charpy impact resistance as the compressive height strain of the preform, otherwise lateral flow, is increased. However, the flow causes material anisotropy, resulting in the divergence in longitudinal and transverse values (Fig. 14). In the as-forged condition, Izod impact resistance in the longitudinal direction approach that of bar stock tested in the same operation. After heat treatment, however, the toughness of the powder forgings is well below that of bar stock (Fig. 15). The powder forgings are anisotropic with respect to impact resistance in both the as-forged and post-heat-treated conditions.

The fatigue strength and resistance to crack propagation under conditions of cyclic loading are enhanced by lateral flow at full density. An extensive experimental study and analysis were conducted by Ferguson *et al.*[14,15] in terms of microstructure and stress state using specimens hot forged in plane-strain conditions. Figures 16 and 17 represent the increase in fatigue strength with increased strain (lateral flow) in as-forged and heat treated conditions from axial fatigue tests. Figure 18 represents the increase in endurance ratio in the case of upset versus repressed specimens in the forged and heat treated conditions. Figure 19 compares the *S-N* curves for a high-flow P/M prototype part with corresponding parts made by repressing and parts machined from a cast and wrought stock. Axial and rotating bend fatigue data are discussed in Ref 2, p 160-165. Figures 20 and 21 show the rotating bend fatigue curves for 4620 steel in as-forged and heat treated conditions for P/M and cast and wrought parts, respectively.

Thus, provided full density is achieved, the strength and ductility levels of powder forgings will match or exceed those of conventional cast and wrought materials. In contrast, full density is not a sufficient criterion for the toughness or fatigue

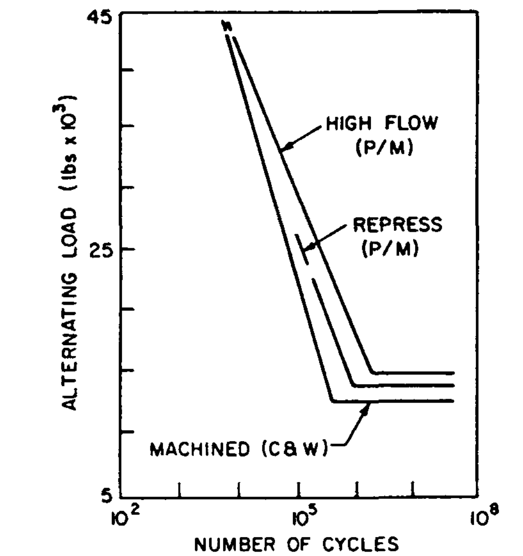

Fig. 19 *S-N* curves for simulated axial fatigue on prototype powder forged parts. C and W indicate cast and wrought, respectively.[2]

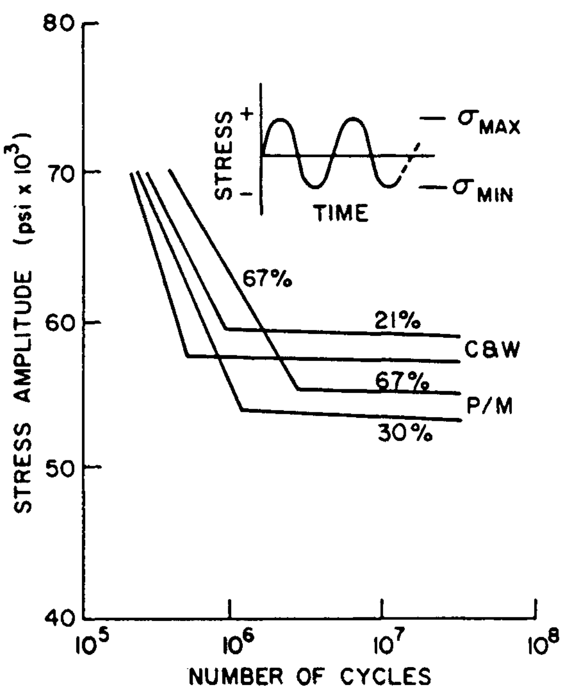

Fig. 21 Rotating bend *S-N* curves for full-density powder forgings of 4620 as a function of height strain, heat treated condition. C and W indicate cast and wrought, respectively.[2]

resistance of the powder forging to be as good as that of the cast or wrought material. In considering dynamic properties, the method or route taken to achieve full density is a further critical factor. As a general rule, lateral flow (as in upset forging) enhances dynamic property levels by virtue of improved bonding

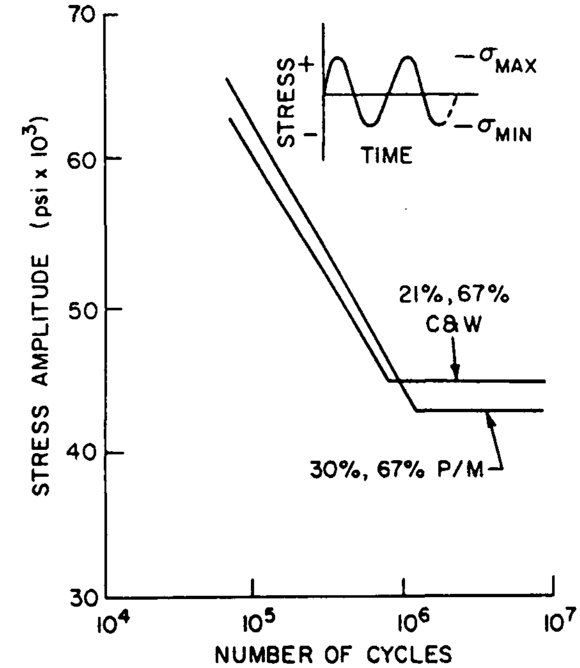

Fig. 20 Rotating bend *S-N* curves for full-density powder forgings of 4620 as a function of height strain, as-forged condition. C and W indicate cast and wrought, respectively.[2]

across collapsed pore interfaces. The effects of lateral flow on inclusion morphology and anisotropy must also be considered in evaluation of mechanical response. An analysis of state of stress developed around residual pores, collapsed pores, and inclusions for differing regimes of external loading provides a basis for understanding fatigue response. The endurance limit increases with increasing lateral flow. In rotating bend fatigue tests, *i.e.*, cycling between tensile and compressive stress, lateral flow during forging does not affect the fatigue limit.

Heat treatment of powder forged parts is similar to that of wrought steel. For ferrous forgings, conventional quench and temper cycles can be used to heat treat parts. Figure 22 shows that tensile and yield strengths are comparable for 4640 bar stock and 4640 powder-forged material heat treated to the same hardness. Owing to the finer grain size of powder-forged parts, however, hardenability is slightly reduced.

6. Relationship Between Microstructure, Microchemistry, and Properties

Sintered steels are heterogeneous in microstructure, and as shown by Lindskog and Skoglund,[17] the heterogeneity gives superior strength compared to homogeneous steels made from prealloyed powder. To compare the relationship of properties to porosity, microstructure, and microchemistry, Faulkner and Burr[18] conducted experiments on compacted and sintered samples of 5Ni-0.5Mo-0.5C steel made from elemental powders. These samples were machined to produce tensile specimens, elongation was determined, and metallographic examination was conducted.

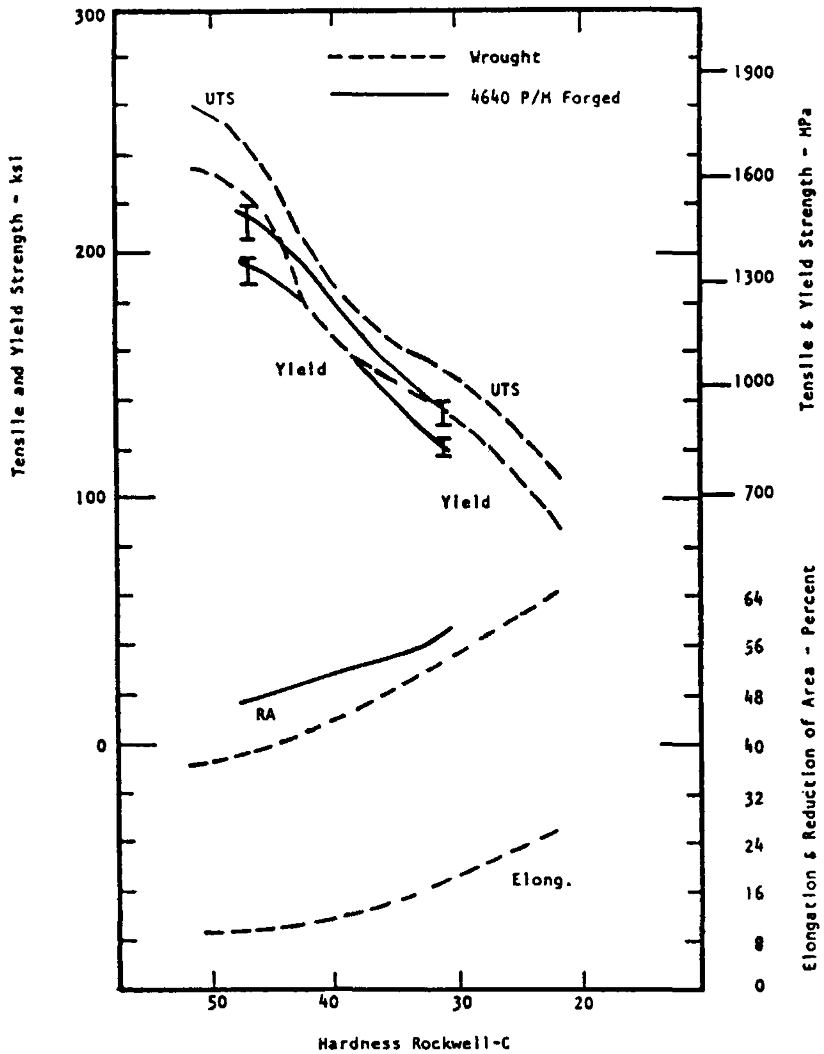

Fig. 22 Tensile properties of P/M forged 4640 and typical properties of wrought 4640.[16]

The density was found to increase with sintering temperature and time and an optimum time was required to produce maximum strength. The microstructure was characterized by spheroids of high nickel martensite, acicular martensite or bainite, and a pearlite-ferrite mixture. Even on closer examination, the central regions were not observed to contain martensitic phase structure. It was therefore concluded that martensite may exist in a very finely divided form. However, because its volume percentage was quite small, its influence on tensile properties was considered insignificant. Although porosity and pore geometry are contributing factors to mechanical properties, the microstructure/microchemistry and its heterogeneity could be a controlling factor in producing peak strength.

It was suggested that, as the carbon of the bainite/pearlite region decreases, the austenite from which they form moves from a hypereutectoid to a eutectoid composition, at which point hardenability is at its maximum, *i.e*, bainite transformation is maximized and is responsible for the increasing strength. Apart from the contribution of carbon and the hard phase of bainite and martensite, the nickel content also influences microstructure as:

- Initial heterogeneity caused by nickel segregation was followed by carbon segregation
- Responsible for the presence of martensite
- Its effect on the eutectoid carbon level of regions that transform to bainite and/or pearlite
- TTT curve being pushed further to the right at higher modal levels, with a result that for a given carbon content and cooling rate, more bainite is formed
- It is also supposed that a decreasing level of martensite with increased sintering time improves ductility. The strength peak is supposed to occur when nickel and carbon diffuse, causing the austenite to be close to the eutectoid composition, which in turn primarily transforms to bainite.

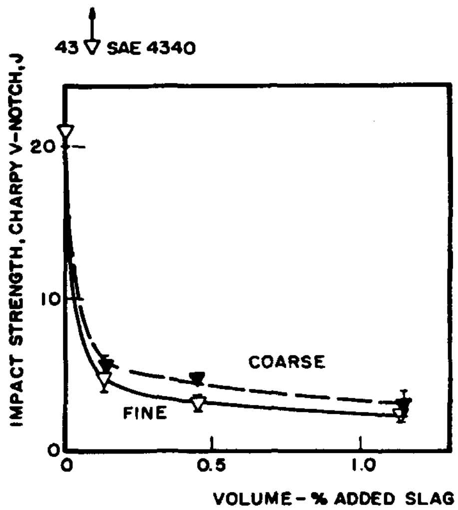

Fig. 23 Impact energy of hot repressed compacts of SAE 4340 steel heat treated to a hardness of 320 to 350 HV_5, as a function of varying volume percentages of added coarse and fine slag particles. Residual porosity less than 0.1%.[3]

7. Role of Impurities on Mechanical Properties

The inclusions in P/M forged parts may originate from slag entrapment from the melt or deterioration of melting furnace refractories, or they may be present because oxides are not completely reduced during sintering of preforms. Bockstiegel and Blande[19] studied the effects of coarse and fine inclusions that were deliberately added to increase toughness in P/M forging. Figures 23 and 24 show the relationships of impact strength with volume percentage of added slag and impact energy versus oxygen content, respectively. This behavior can be explained by the stress analysis of internal stress concentration of collapsed pores in the powder forging.

Impurity elements, when concentrated in large amounts at internal surfaces, can cause inferior bonding of the particles with resulting brittleness. Joshi *et al.*[20] investigated fracture surfaces using Auger electron spectroscopy (AES) to determine the chemistry of the fracture surface and scanning electron microscopy (SEM), along with tension and density tests, to evaluate the surface condition/weld relationships in P/M iron.

All materials tested exhibited common impurities such as sulfur, cobalt, carbon, and oxygen at the fracture surface. A typical Auger electron spectrum is shown in Fig. 25. Nitrogen and zirconium were also observed in small amounts in some samples. The SEM studies indicate fractures were more than 95% interparticle, although particle size varied from sample to sample. It was shown that only oxygen exhibits a systematic variation with density, and the presence of oxygen at interparticle interfaces has a strong influence in the sintering process and on the mechanical properties.

In other experimental studies,[21] it has been shown that an increase in the bulk oxygen content drastically reduces the impact strength of steels. This study also indicated that the presence of sulfur, chlorine, and carbon seems to have no significant influence on impact strength. It is the impurity elements

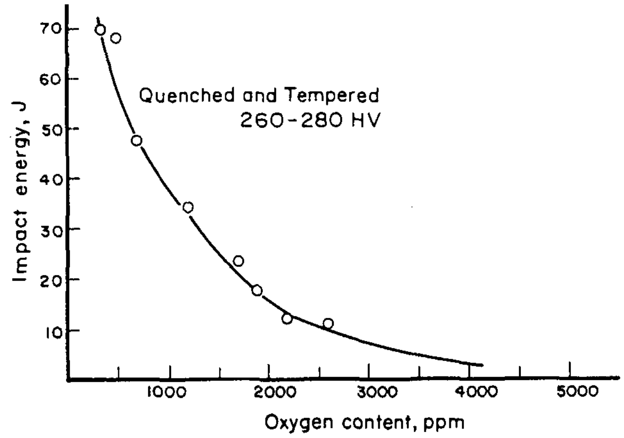

Fig. 24 Room temperature Charpy V-notch impact energy of forged alloy powder specimens (0.29% Ni, 0.62% Mo, 0.58% Mn, 0.35% Cr, 0.4% C) quenched and tempered to 260 to 280 HV as a function of residual oxygen content.[3]

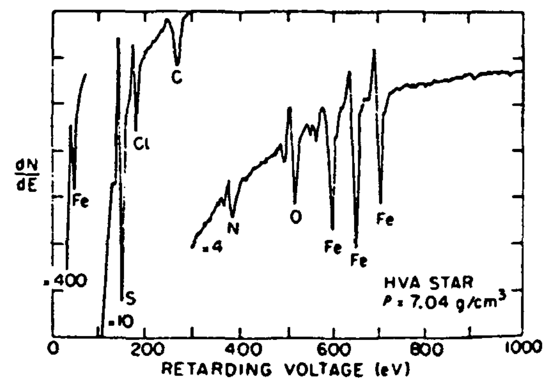

Fig. 25 Auger electron spectrum of powder metallurgy iron sample.[20]

that are localized in large concentrations at the particle interfaces that tend to be the weak links in the compacted materials.

The influence of slag particles on the mechanical properties and corrosion resistance of a P/M austenitic stainless steel was studies by Arnberg *et al.*[22] A series of type 316L stainless steels was produced by hot extrusion of nitrogen-atomized powders. A high concentration of nonmetallic inclusions was introduced in these steels by atomizing a melt with a high sulfur content, by controlled powder surface oxidation, or by mixing powder with slag particles prior to extrusion. It was found that the slag levels influenced both the impact strength and the tensile properties of the steel and that the fatigue strength decreased significantly with additions of large (~ 500 μm) exogeneous particles.

The pitting corrosion resistance is also affected by the addition of large, exogeneous slags, and the corrosion resistance measured by the Huey test decreases when some slags are present. An increased sulfur content or powder surface oxidation results in evenly distributed submicron slag particles in the ex-

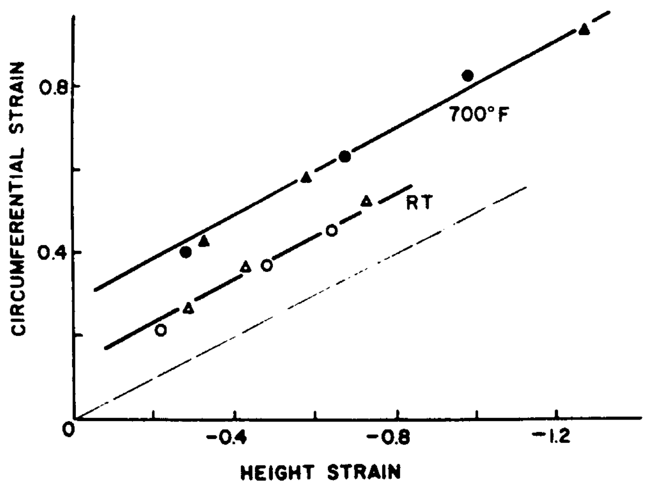

Fig. 26 Locus of surface strains at fracture during upsetting of sintered 4620 low-alloy steel powder cylinders. Induction sinter: O 2350 °F for 3 min, O 2050 °F for 3 min. Conventional sinter: 2050 °F for 1/2 hr.[2]

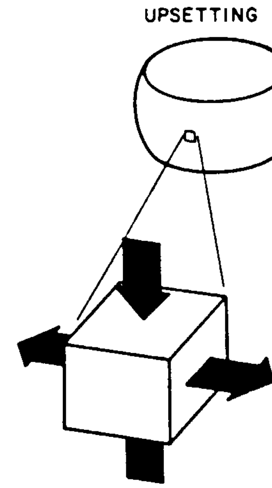

Fig. 27 Circumferential tensile stress and axial compressive stress at the bulge surface of cylinders compressed axially with high contact friction.[2]

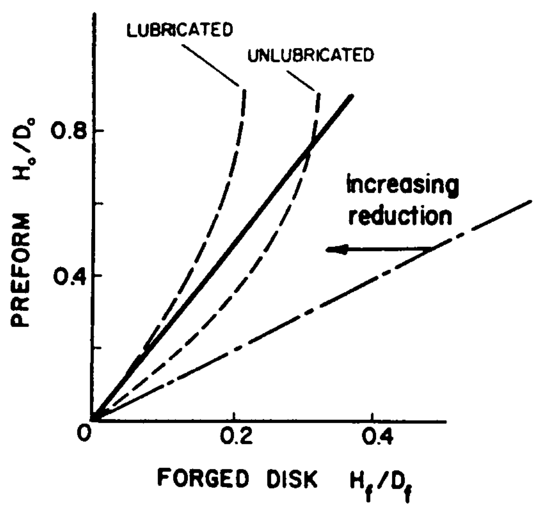

Fig. 28 Design curves for disk forging to achieve maximum mechanical properties (left of solid line) without causing fracture during forming (right of dashed line).[2]

truded alloys. Subsequent cold work breaks up and redistributes the slag significantly. Fatigue strength decreases significantly with large slags due to crack initiation at the particles. Pitting corrosion resistance is affected mainly by slag chemistry and size due to cracks and cavities at the particles where solution is trapped locally. Chemical attack on large furnace-type slags cause severe weight loss in the Huey test.

8. Effect of Flow on Fracture During Forging

Fracture during plastic deformation of fully dense materials that are ductile initiates by void formation at inclusions or other inhomogeneities in the metal matrix. The pre-existence of voids in materials, as in P/M, eliminates the need for void initiation, and only coalescence of voids is necessary. Thus, the presence of voids and inclusions decreases ductility of sintered powder materials. Kuhn and Lawley (Ref 2, Chapter 4) present a study of fracture in powder metal parts. They describe the upset test and point out that increasing the aspect ratio of the cylinder (height/diameter) increases the deformation to fracture. They also explain the anomaly that deformation to fracture is essentially independent of initial porosity of the material. The increase in initial porosity, although decreases the ability to withstand the tensile stresses to fracture, also decreases the Poisson ratio, resulting in less bulge and therefore less tensile stresses.

9. Fracture Mechanisms in Forging of Sintered Preforms

A locus of surface strains at fracture during upsetting (forming limit diagram) for 4620 steel alloy (Fig. 26), by measuring the axial and circumferential strain of the bulge surface (Fig. 27) is considered as fracture criteria for the evaluation of the deformation to fracture in more complex deformation processes. This concept is an extension of the forming limit diagram concept, which is popular in sheet metal forming. The progressing deformation strain paths in the potential fracture regions of the process under consideration are first determined through plasticity analysis or measurements on a model material. These strain paths are then compared with the fracture locus of the material. If the strain path crosses the fracture locus before the deformation process is complete, fracture is likely. The above discussed locus of fracture strain are for free surface fracture.

An example of a methodology of preform design for a disk forging to provide sufficient metal flow to achieve maximum properties, but less than that at which fracture occurs, follows. Given a disk diameter and height, fracture in upsetting can be avoided if the expanding free surface of the cylinder reaches

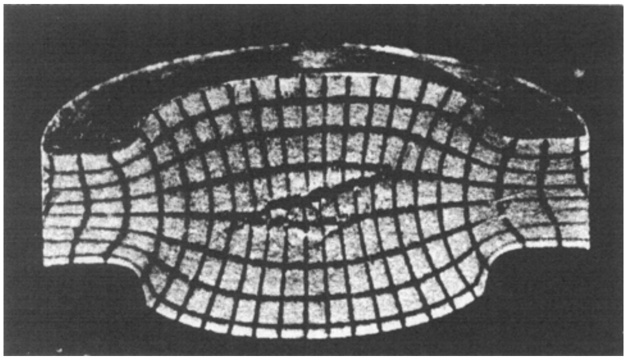

Fig. 29 Central burst in a forged part consisting of two opposed hubs. Grid lines placed on midplane prior to deformation to permit measurement of internal strains.[2]

the die sidewalls before the reduction at fracture is reached. The preform's aspect ratio versus forged disk aspect ratio is plotted, as shown in Fig. 28, and for a given preform aspect ratio, the forged disk aspect ratio must be to the left of the solid line to achieve maximum properties of 50% reduction. Also the forged disk aspect ratio must be to the right of the dashed line to avoid fracture.

Figure 29 shows internal fracture occurring in a part. This is caused by opposed axial flow from the center toward each hub, and the magnitude of the resultant tension at the center depends on the aspect ratio of the preform. Forming limits due to surface cracks, buckling, and central burst are shown in Fig. 30. Preform design for powder forging involves achieving a delicate balance of sufficient deformation for maximum densification and mechanical properties and yet preventing deformation leading to failure.

10. Conclusions

In forging powder metal parts, residual porosity, homogeneity of densification, extent of densification, microstructure, microchemistry, surface oxidation, impurities, extent of flow, fracture-causing mechanisms, tooling configurations, and friction are some of the key factors that must be understood and controlled to produce powder forgings of required strength and mechanical properties. In this article, the various studies of the influence of the above-mentioned parameters on part properties and the concept of forming limit diagrams to limit fracture have been presented.

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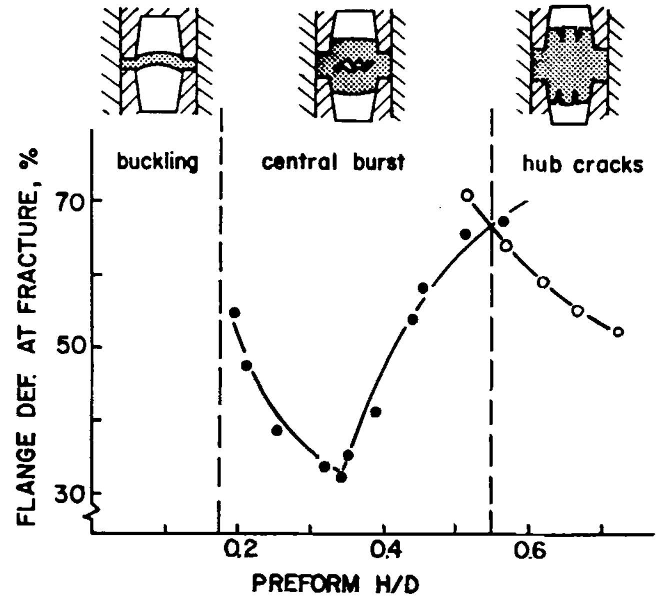

Fig. 30 Limiting deformations for buckling, central burst, and hub cracking in double hub extension of sintered 601 AB aluminum alloy powder.[2]

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