NICKEL IN POWDER METALLURGY STEELS

A GUIDE TO THE USE OF
NICKEL-CONTAINING ALLOYS
Nº 11006

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Foreword

Nickel has found an important place as an alloying element in steels produced from metal powders.

The desire to attain consistent and improved mechanical properties in steel parts has led to increased use of nickel-alloyed powder metal (P/M) steel. It is the intent of this publication to summarize the current state of the art in nickel-alloyed ferrous powder compacts and to indicate the properties that can be achieved at various densities and with various compositions and heat treatments. Also included are a substantial number of examples of successful applications, gleaned from the literature and from discussions with powder producers and part producers. Many of these applications are in the automotive industry, and these are emphasized because of their economic implications.

No attempt has been made to provide a detailed coverage of the subject of metal powder processing, but, instead, to call attention to new developments which enhance the properties of powder metal (P/M) parts. Choice of alloy additions becomes critical in the sintering of powder metal compacts. Nickel, copper and molybdenum form oxides less readily than iron, so atmospheres which are reducing for iron will also be reducing for these alloying elements, thus assuring their effectiveness. Manganese, silicon, chromium and vanadium form oxides more readily than iron, and if present in the compact may remain as oxides and detract from, rather than enhance, mechanical properties. Nickel and molybdenum are especially advantageous as alloys during heat treatment of P/M compacts, and are used in larger amounts than in wrought steels because of limitations on the use of manganese and chromium in P/M compacts.

Mechanical properties of P/M steel parts are strongly dependent on density. Nickel increases the density of sintered compacts made with elemental nickel powders. Carbon content dictates the maximum strength attainable in P/M steels, either as-sintered, or when heat-treated after sintering. Alloy additions enhance the ability to achieve high strength with useful ductility and fracture resistance. Nickel contributes most effectively to this goal. Published data on mechanical properties of (1) assintered, (2) sintered and heat-treated, and (3) sintered, forged and heat-treated P/M compacts are summarized in this publication. These data show the consistently beneficial effect of nickel at any given strength level: to increase ductility; to improve resistance to impact; and to increase fatigue life. Several examples show that forged alloyed P/M steel parts can exhibit properties superior to those produced from melted and forged steel.

Applications of nickel-alloyed P/M steels represent a wide range of structural parts, many of which are used in the automotive industry. The publication includes examples of parts used in the as-sintered condition as well as those heat-treated after sintering. P/M forgings are being used increasingly to attain high fatigue strength and resistance to impact; several examples of such parts are included.

Current materials and processing standards for alloyed P/M components are summarized in the last section, to indicate the scope of these standards. The references listed at the end of the publication will guide the reader to more detailed information on the topics presented.

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Introduction

Since their commercial introduction in the 1940s, steel parts made from powder metals have assumed a dominant role in the powder metal industry. At first, powdered iron was combined with carbon, pressed in metal dies to form a simple part shape, then the *green* compact was sintered at high temperatures in a reducing atmosphere to remove oxygen, promote carbon diffusion and to permit the clean metal particles to bond together.

The sintered compact was often used in the as-sintered condition, but it could also be re-pressed or coined to increase density and to make the dimensions more accurate. Post-sinter heat treatments were also used to achieve hardness or strength requirements of the part.

In the 1948 ASM *Metal Handbook,* the Subcommittee on Powder Metallurgy stated that "typical products include machined parts in which the mechanical properties may be somewhat inferior to those of wrought metals, but in which the necessary tolerances and shapes can be attained at reduced cost, by the elimination of machining operations.... Principal limitations of the process are those imposed by the size and shape of the part, the compacting pressure required, and the materials used.... Physical limitations are imposed by the dies required to hold the powders.... Also (there is) no lateral flow, so shapes are limited."

In a 1969 article, Carlson[1]* summarized then currently available powders and processes, and stated that "substantial penetration of the higher-strength materials market will depend upon the capability of the P/M fabricator to produce components to full or nearly full density."

In recent years, all steps of the powder metallurgy process have been examined to optimize the process and broaden the range of applications. Alloys have been introduced to increase the as-sintered properties or the response of the parts to heat treatment. More sophisticated compacting methods have been developed, including: dies with multiaxial motion to increase the uniformity of density in the compact; cold isostatic pressing (CIP) of powders under high pressures in rubber or other flexible molds; hot forging of cold-pressed powder billets in both simple and complex dies; and hot isostatic pressing (HIP) of compacts in pressure vessels at high temperatures in inert atmospheres under high pressure. Metal injection molding (MIM) is the most recent advancement in converting metal powders into useful and complex shapes. This process uses metal powder in a thermoplastic binder which can be warm extruded into a mold cavity just as in die casting. The part is extracted from the cooled mold and subjected to a *de-binding* treatment at low temperatures to remove the thermoplastic. Improvements have also been made in sintering equipment and sintering atmospheres, and subsequent processing steps which all lead to improved and more uniform properties and more accurate dimensional control.

From the standpoint of optimum mechanical properties, the fully dense powder metal parts are best, but for many components, adequate strength can be obtained at less than full density. With part requirements in mind, the designer, materials engineer and process engineer can use the information presented in this publication to decide the cost effectiveness of powder metallurgy steels in meeting those requirements. The advantages of alloying to meet part requirements and to aid processing will be included in the consideration of cost effectiveness.

Kennedy[2] recently summarized the advantages of powder metals and stated that "automotive continues to be

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*Refererences are shown as superscripts.

the largest field of use for powder metal." He also summarized the real benefits of current powder metal processing as follows:

> "Closer dimensional tolerances (are attainable) in comparison with traditional castings and forgings."

> "Static and dynamic engineering properties in many cases exceed those of traditionally manufactured parts."

> "Material savings result from net- or near-net-shape parts with minimal or no scrap losses due to machining."

> "Fully densified parts are providing significant weight reductions."

> "Machining is better understood with resultant significantly longer tool life."

> "Powders are cleaner, in greater supply and easier to handle with better physical and mechanical properties in many instances."

With the improvements in available ferrous metal powders and the advances in processing, it is evident that powder metallurgy steel has joined the ranks of engineered materials and should be considered by designers, materials engineers and process engineers for many new applications which require controlled material properties. To do this, specific data on attainable properties must be available, as well as comprehensive specifications for raw materials and processing.

This publication summarizes the current state of the art in nickel-alloyed ferrous powder compacts and indicates the properties that can be achieved at various densities and with various compositions and heat treatments. References to more detailed descriptions of processes and to current industry specifications are included. Also included are a substantial number of examples of successful applications, gleaned from the literature and from discussions with powder producers and part producers. Many of these applications are in the automotive industry, and these are emphasized because of their economic implications.

No attempt has been made to provide a thorough coverage of the subject of metal powder processing. Instead, an effort has been made to direct attention to new process developments which enhance the properties of powder metal parts.

Production of parts from metal powders

Powder metallurgy is a highly developed method of manufacturing reliable steel parts. P/M typically uses more than 97% of the starting material in the finished part, and thus is a process that conserves both materials and energy. The versatility of the process and the opportunities for cost savings are summarized in a publication of the Metal Powder Industries Federation (MPIF).[3] *Figure 1,* from that publication, summarizes the various possible steps in part production, and itemizes some of the corollary operations which can enhance the quality of the part. *Figure 2,* from a recent paper by Morioka and Takajo[4] is a diagram of the factors influencing properties of the resulting parts. The following summary of powder production techniques examines in some detail how alloys can affect favorably the processing and/or the properties of the part.
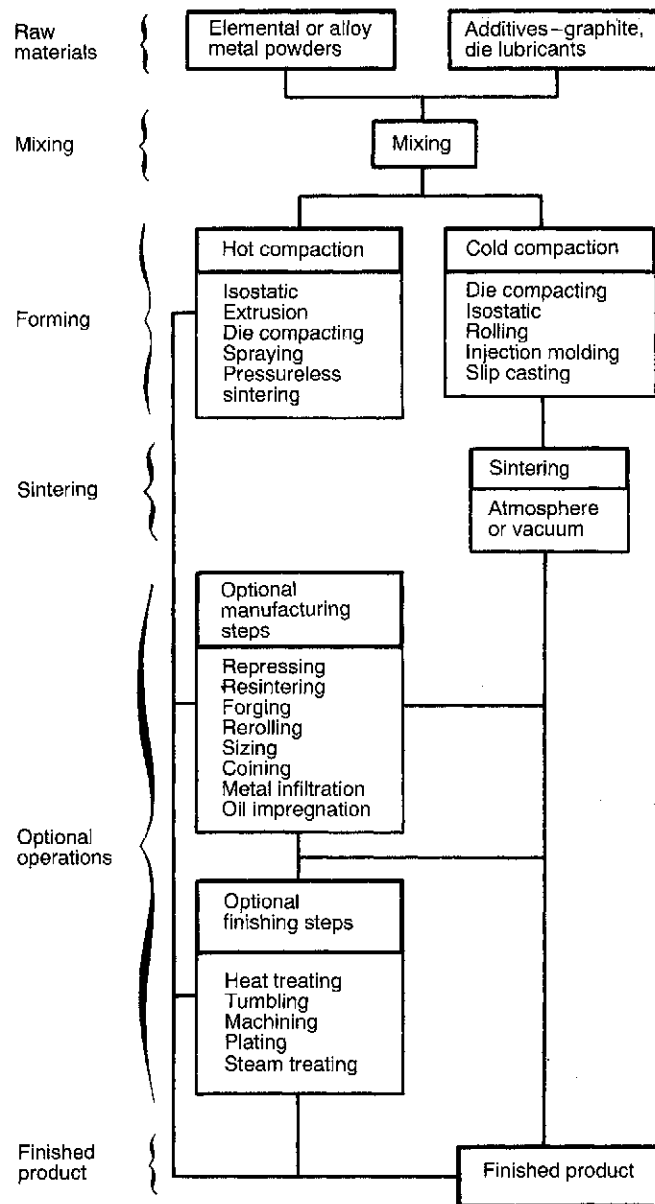
Figure 1. Powder metallury processing.
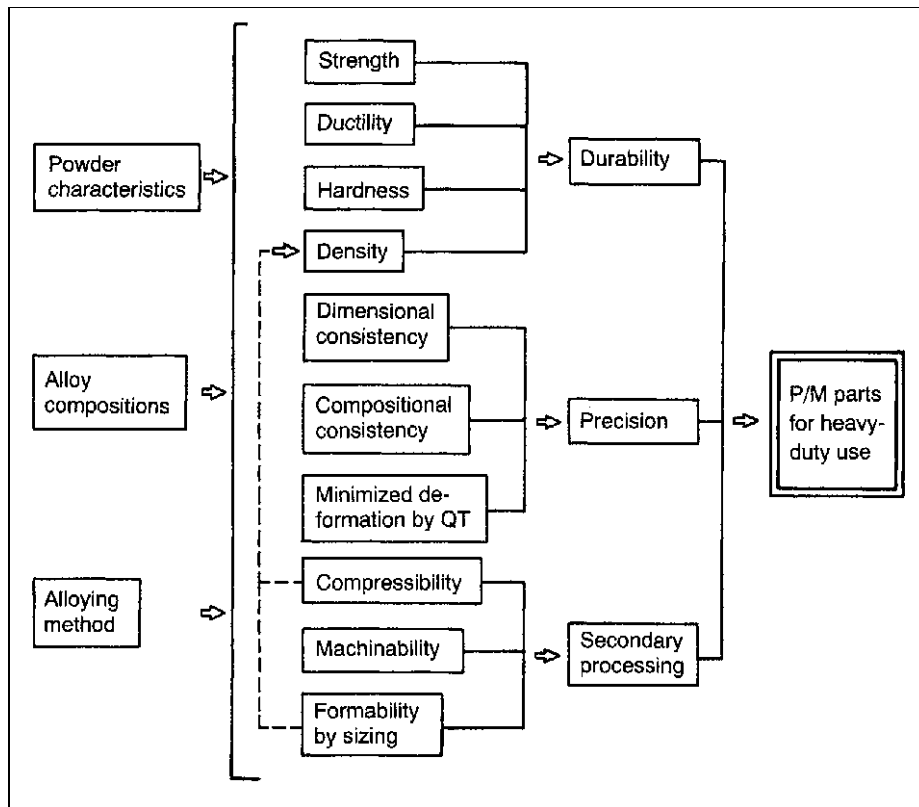
Figure 2. Factors determining the properties of powder metallurgy products.

Preparation of alloyed powders

Alloy P/M steel parts can be made from mixtures of elemental powders, from prealloyed powders, or from hybrid processing involving alloy additions to prealloyed powders of lower alloy content. Several references were found to advocate any of these approaches, but the largest production of alloyed powder is atomized from molten alloyed steel of quite low carbon content. A paper by Kawai[5] and others describes techniques to prevent slag from entering the product. The steps involved in atomizing are summarized in Lenel's[6] text. After melting and atomizing (usually with water jets), the powders are harder than desired because of the rapid cooling during atomizing. To soften them, and to reduce oxygen and carbon content, powders are annealed in a controlled atmosphere in preparation for mixing and compacting.

Compacting alloyed powders

After metal powders are mixed with lubricants, graphite and (for special cases) supplemental alloy additions, controlled amounts of the mixture are fed into a precision die and compacted, usually at room temperature. Normally, pressures in the range 30-50 tons per square inch (415 to 690 MPa) are used to achieve the desired green density. A pressing cycle for a simple part is shown schematically in *Figure 3*.

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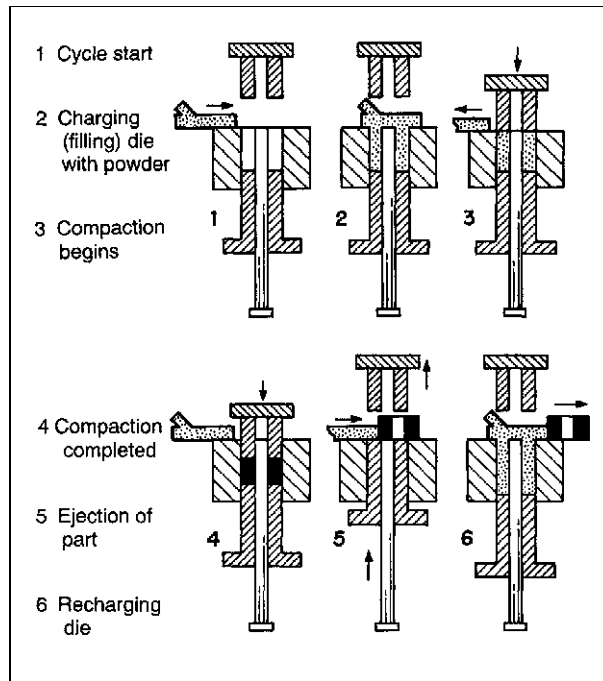
Figure 3. Pressing cycle for a simple cylindrical part, using a double-action die and core.

The components of the die set are shown in *Figure 4* for a flat spur gear; the dies are usually made from hardened steel and/or carbides. The die receives a charge of mixed powder, delivered to the cavity by a feeder shoe. Upper and lower punches compress the powder. The upper punch is withdrawn, the lower punch ejects the pressed compact, and the feeder shoe slides the piece away from the die cavity. The feeder shoe continues forward and refills the cavity with another charge of powder for the next cycle. More complex parts require multiple punches and separate actions.

The so-called green density of a part depends not only on compacting pressure, but also on the type and
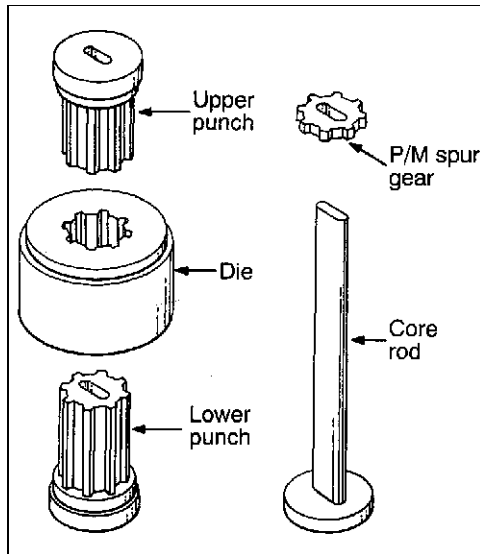
Figure 4. Typical tool set for a flat spur gear.

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composition of powder. The objective in structural P/M parts is to provide as high a density as possible, so a powder of higher compressibility enhances the mechanical properties of the part. Powder manufacturers have developed prealloyed powders having high compressibility, according to Mocarski and Hall.[7] In a later paper, Mocarski and others[8] state that single pressing generally can produce green density not greater than about 7.2g/cm^3. This compares with about 7.85g/cm^3 for fully dense wrought steel.

One recent development described by Morioka[4], is a composite-type powder of higher nickel content that develops quite a high green density due to its good compressibility (see *Figure 5*). The processing of Sigmaloy 415 S powder, that contains 4.3% Ni, 1.6% Cu and 0.5% Mo, is described in the reference, and combines partial diffusion of alloys into pure iron powder during annealing after mixing, but before compacting, thus taking advantage of the good compressibility of pure iron powder while introducing alloying elements to provide strength in the sintered compact.

	Chemical composition,%										
	C	Si	Mn	P	S	Ni	Cu	Mo	Cr	N	O
4600 ES	0.001	0.01	0.08	0.017	0.007	1.12	0.42	0.23	-	0.001	0.09
4600 AS	0.003	0.01	0.08	0.009	0.004	1.45	0.53	0.47	-	0.001	0.12
Sigmaloy 415S	0.004	0.01	0.05	0.005	0.005	4.31	1.60	0.48	-	0.001	0.11

Figure 5.   Compressibility of various alloyed-steel powders.

Sintering of alloyed powder compacts

In the typical sintering step, the green compact, placed on a wide-mesh endless belt, moves slowly through a controlled atmosphere furnace, where the parts are heated to below the melting point of the base material, held at temperature, and then cooled slowly. Sintering produces a metallurgical bond between the powder particles, and also promotes homogeneity by diffusion of alloys. Sintering also increases the density of the compact. This is especially true for nickel-alloyed powders. According to Engstrom and Allroth[9] nickel promotes shrinkage during sintering and is one of the reasons for choosing nickel as the principal alloying element in P/M steel.

A typical sequence for sintering steel is shown in *Figure 6*; it is a schematic illustration of the zones of a sintering furnace, their temperatures, and compositions and functions of the atmospheres, as described in the Powder Metallurgy volume of the *Metals Handbook*[10]. In the low-temperature zone in which lubricant is removed, a slightly oxidizing atmosphere not only burns out the lubricant, but also prevents sooting which would interfere with bonding at the higher temperatures. In the preheat zone, with temperatures in the range 1200 to 1900°F (650 to 1040°C), surface oxides on the metal particles are removed. It is at this sintering stage

	Preheating zone		Slow cooling zone	
Delubing zone		Hot zone		Water-cooling zone

Atmosphere functions

• Convey heat quickly and uniformly • Burn and sweep out lubricants to front exit	• Reduce surface oxides • Carbon diffusion	• Copper melting, coating or infiltrating • Bonding • Carbon control	• Carbon control • Cooling rate control	• Cooling • Prevent oxidation or controlled light oxidation

Atmosphere compositions

• Lightly oxidizing	• Highly reducing • Neutral to carbon	• Reducing • Neutral to carbon preferred	• Reducing • Neutral to carbon preferred	• Slightly reducing or neutral or slightly oxidizing

Temperature range, steel

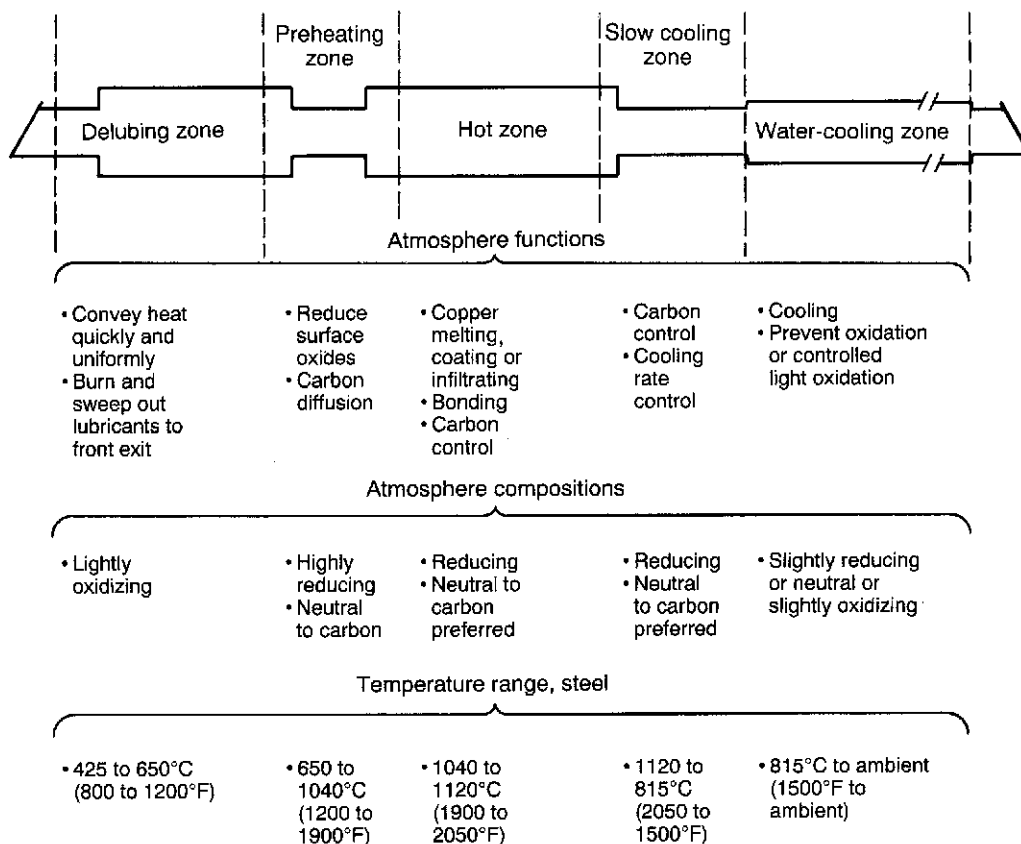|				
• 425 to 650°C (800 to 1200°F)	• 650 to 1040°C (1200 to 1900°F)	• 1040 to 1120°C (1900 to 2050°F)	• 1120 to 815°C (2050 to 1500°F)	• 815°C to ambient (1500°F to ambient)

Figure 6. Scheme of typical furnace for sintering steel, and description of functions.
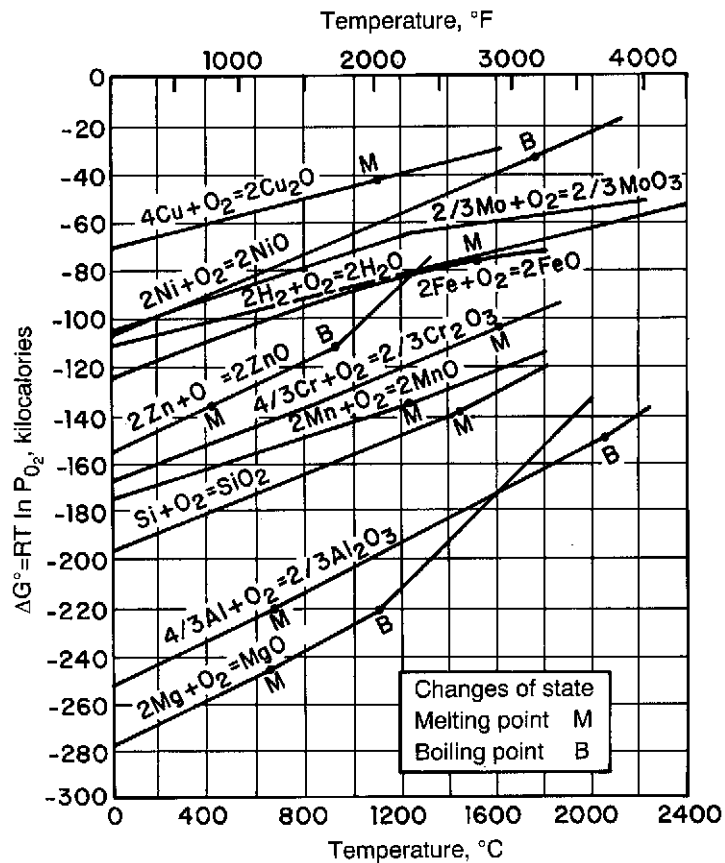
Figure 7. Standard free energy of formation of metal oxides.

that the choice of alloying elements becomes critical. With currently used temperatures and atmospheres, oxides of nickel, copper and molybdenum are more readily reduced than oxides of iron, as indicated in the free-energy diagram, *Figure 7,* from Lenel's text.[6] In this diagram, smaller negative values of free energy reverse the reaction shown above each line; larger negative values promote the reaction. Thus atmospheres that reduce iron oxide to iron will also reduce nickel, copper and molybdenum oxides to their respective metals. For example, at 1000°C (1830°F), atmospheres with free energy values in the range -40 to -90 kilocalories will reduce Cu_2O, NiO, MoO_3 and FeO, but will not reduce Cr_2O_3, MnO or SiO_2. Returning *to Figure 6,* most of the sintering occurs in the hot zone, in which temperatures may range from 1900 to 2050°F (1040 to 1120°C). Sintering is followed by slow cooling to about 1500°F (815°C), then faster cooling is permitted.

Types of atmospheres and their control are quite thoroughly discussed in the *Metals Handbook*[10] and in the chapter on sintering practice in Lenel's text.[6] Diffusion of carbon and alloying elements into the austenite occurs in the hot zone. X-ray microprobe analysis can be used to determine the degree of homogeneity, it can aid in defining the length of sintering time required. Use of

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prealloyed powders can reduce the hot zone sintering time since there is no requirement for alloy homogenization by diffusion; carbon diffusion is quite rapid.

Post-sintering operations

Parts that are produced by single pressing and sintering may require some additional operations after sintering to achieve the desired size tolerances and mechanical properties. Operations include coining, sizing and heat treatment. There are, of course, more complex operations which can be used to increase density and thus increase mechanical properties.

Coining and sizing

Coining a P/M part may increase density, at least near the surface, and improve strength and hardness. Sizing, on the other hand, primarily ensures dimensional accuracy with little increase in density or strength. These steps are accomplished with special sets of tools, and pressed and sintered parts are fed to a specialized press for the purpose.

Cold forging

A post-sintering operation which can significantly increase density has been developed by Pennsylvania Pressed Metals and has been reported by Pease.[11] In this process, sintered preforms of low-alloy steel are lubricated and cold forged in a 75-ton (665kN) press, using both forward and backward extrusion as part of the operation. A density of 7.8g/cm^3 is achieved. The process is best applied to runs of at least 25,000 pieces. Technical keys to the success of the process include proper design and maintenance of at least some compressive stresses at all times during the operation. *Figure 8* shows a bearing race preform (A) in place in the forging die, and the final part (B) after the cold forging operation.
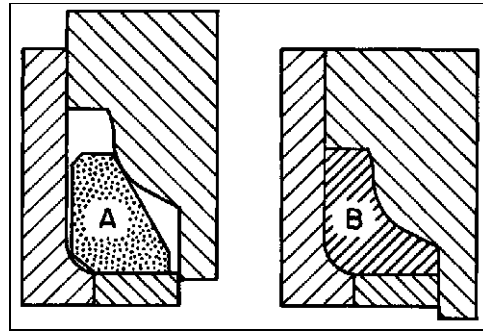

Figure 8. Cross-section of sintered preform (A) and cold-forged ball bearing race (B).

Heat treatment

Alloyed P/M steel parts are usually heat treated to optimize mechanical properties. Such heat treatments can include carburizing and hardening low-carbon parts or fully hardening parts of medium- and high-carbon content. For parts with density of 7.2g/cm^3, conventional furnaces and heat-treating procedures can be used. Molten salt should not be used, and quenching media should be oil or air, not water or brine, to avoid corrosion of the heat-treated parts.

Hardness of P/M parts is not the same as for fully dense wrought steel, so conversion charts must be developed for purposes of quality control. It is not possible to prepare standard charts; but conventional and microhardness readings should be obtained in critical locations of parts of the same design, composition and density, as a basis for empirical charts.

Hardenability

Depth of hardening, or hardenability, of P/M parts with at least 7.2g/cm^3 density is about the same as for wrought steels, and depends on carbon and alloy content. For carburized parts, it should be noted that the effects of alloys differ in the carburized case from those in the core.

As noted above, silicon, manganese and chromium are minimized in P/M alloy steels because of the tendency of these elements to oxidize in the atomizing or reduction steps as well as in conventional sintering. Therefore, most alloyed P/M steels depend on nickel, copper and molybdenum to provide required hardenability. Studies have been made of the hardenability of compositions suitable for P/M application, and include the work of Smith and Pathak[12] and Eldis, Diesburg and Smith.[13]

In the study by Smith and Pathak, data were obtained using experimental wrought steels of compositions suited to powder processing. A matrix of compositions included the following carbon and alloy levels:

Carbon	0.2 and 0.4%
Manganese	0, 0.4 and 0.8%
Nickel	0, 0.4 and 0.8%
Copper	0, 0.4 and 0.8%
Molybdenum	0, 0.25, 0.5 and 0.75%

A complete matrix was not used, since certain combinations would not be practical. The steels all contained 0.24/0.52% Si and the *zero* level of manganese was 0.04/0.08%. As expected, manganese and molybdenum provided the maximum hardenability effects, nickel provided a smaller but increasing hardenability effect with increasing nickel content, and copper provided an effect similar to that of nickel up to about 0.4%, beyond which it provided no increase in hardenability.

In the study by Eldis et al[13], experimental water-atomized alloy powders were blended with graphite, isostatically compacted into forging preforms, sintered, and then hot forged in a closed die to achieve full density. Subsize Jominy end-quench bars 0.75 in. (19mm) in diameter were prepared for 0.2 and 0.4% carbon steels having the following nominal alloy contents:

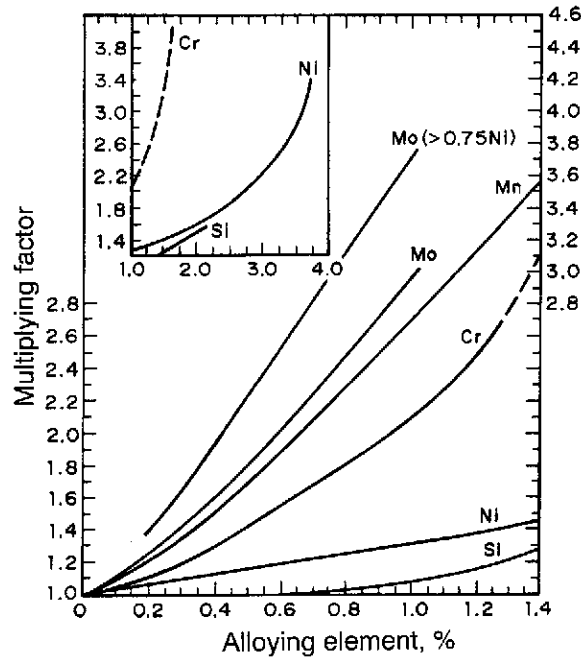(A) 0.3% Mn-0.9% Ni-0.7% Mo,
(B) 0.3% Mn-1.0% Ni-1.0% Mo; and

Figure 9. Hardenability mulitiplying factors for alloying elements in steels containing carbon in the range 0.13 to 0.28%.

(C) 0.001% Mn-1.0% Ni-1.0% Mo. These steels were compared to hot-forged commercial *4600 type* P/M steel containing 0.12% Mn, 1.8% Ni and 0.6% Mo, made to the 0.2% carbon level only. Steel A provided virtually the same hardenability as the P/M *4600* steel. A higher level of hardenability was achieved with Steel B, designed to be equivalent in hardenablility to conventional wrought SAE 8800 steels. The manganese-free Steel C was much lower in hardenability in comparison to Steels B and SAE 8800.

Experience has shown that manganese up to 0.3% can be used in prealloyed powders to aid heat treatment response without causing oxidation problems. Although other hardenability data for P/M steels are lacking, one can be guided by available data and calculation methods for wrought steels of low manganese content. As indicated in *Figure 9* such data show a synergistic effect of nickel in combination with molybdenum, especially at the low carbon contents characteristic of steels to be carburized and hardened.[14] The contribution of nickel, molybdenum and copper to hardenability and ease of heat treatment explains the use of *4600* type steels and steels of higher alloy content for structural P/M parts of medium and high density.

Other consolidation methods

Methods for consolidating alloy steel powders to achieve density levels higher than can be obtained by conventional pressing and sintering include double pressing and double sintering, hot forging, cold isostatic pressing, hot isostatic pressing, and metal injection molding. These techniques, with the possible exception of double pressing and sintering, require additional tooling and more sophisticated equipment, but the higher densities achieved make it possible to approach or exceed the mechanical properties of wrought steels.

Double pressing and sintering

A recent review by Mocarski and others[8] of methods to achieve high density noted that double pressing and double sintering can provide density levels of 7.3-7.5g/cm^3. The technique consists of conventional pressing, followed by sintering at about 1400°F (760°C), a temperature below that at which carbon diffuses readily. These relatively soft parts are repressed, then sintered at high temperatures in the range 2280-2400°F (1250-1320°C).

Powder forging

This technique has become commercially accepted as the way to achieve substantially full density in ferrous P/M parts. As shown in the schematic drawing in *Figure 10,* after conventional pressing and sintering, preforms are heated in a furnace, or by induction, then hot forged and heat-treated.[3]

Figure 11, from a report by Tsumuti and Nagare[15], compares the energy required to produce connecting rods by powder forging and conventional forging of wrought steel; only half the energy of conventional steel forging is consumed in the powder forging process. The yield of premachined forging weight to starting material weight is 70% in the case of wrought steel, and over 99% in the case of powder forging. Subsequent machining operations revise these yield figures to 45 and 80%, respectively.

In terms of cost, *Figure 12,* from the Tsumuti and Nagare report[15], shows that powder forging is more economical. Material costs are slightly lower, because powder-forged parts require much less material. Processing costs are about the same for the two methods, but machining costs are considerably less for the powder forged connecting rods.
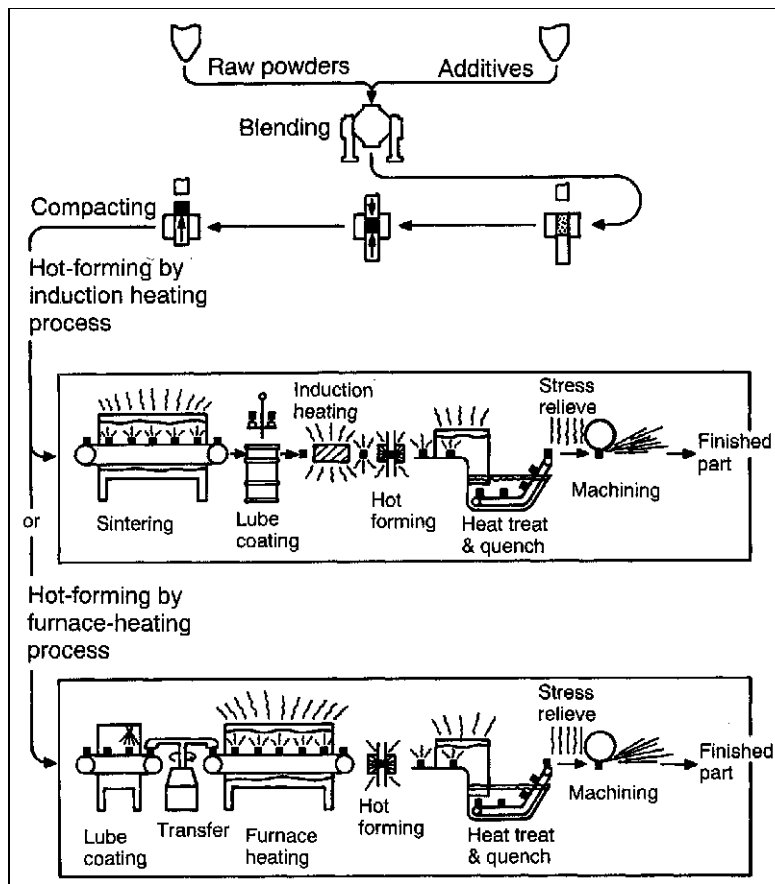
Figure 10. Hot forging process.

Cold isostatic pressing

As an alternate to conventional die pressing for the preparation of near net shapes from powder, isostatic compacting can achieve more uniform density. *Figure 13* is a simplified schematic diagram of the process, as employed for a tubular part. More complex shapes can be formed by isostatic pressing, as shown in *Figure 14*. Compaction is carried out at room temperature, usually with an elastomer for the mold and external pressures in the order of 60 ksi (415 MPa). The significant advantage is freedom from frictional forces. Isostatic pressing is followed by conventional sintering and heat treatment to attain desired properties.

Hot isostatic pressing, HIP

Isostatic compaction of steel powders can also be performed at elevated temperatures to achieve full density.[3,11] A gaseous atmosphere within the pressure vessel exerts the necessary pressure. The powder is contained in a glass or sheet metal container that can provide the exterior shape of the part. The container is evacuated, the assembly is heated to temperatures as high as 2300°F (1250°C), and pressures of the order of 15 ksi (105 MPa) are imposed. The technique is applicable to billets as large as 4 ft. (1.2m) in diameter by 9 ft. (2.7m) long.

Modifications of the HIP process are discussed by Ferguson.[16] These include
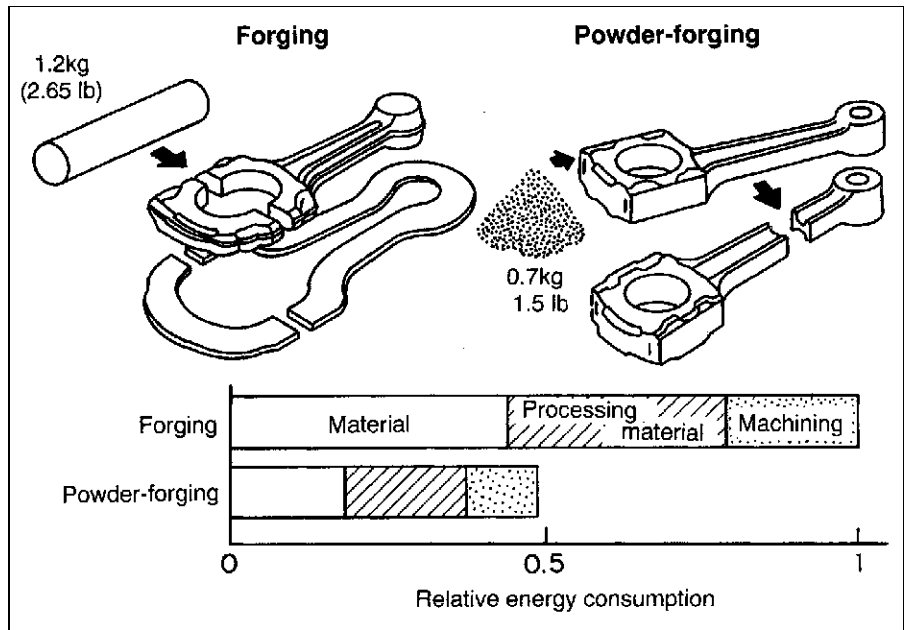
Figure 11. Comparison of P/M powder forging and forging of wrought steel, indicating relative energy consumed in the manufacture of connecting rods.

the Ceracon process, Rapid Omnidirectional Compaction, ROC, and the STAMP process. These processes combine the advantages of powder forging and hot isostatic pressing by using a die (of steel or ceramic) plus a fluid medium (or a combination of ceramic particles and an inert gas) to

Figure 12. Relative cost of production of connecting rods when forging from wrought steel, or forging from powder metal preforms.

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Figure 13. Isostatic compacting a simple cylinder.

Figure 14. Shapes formed by isostatic compacting.

achieve nearly isostatic conditions at even higher pressures than HIP. This permits the use of somewhat lower temperatures and shorter times, thus increasing the efficiency of the process.

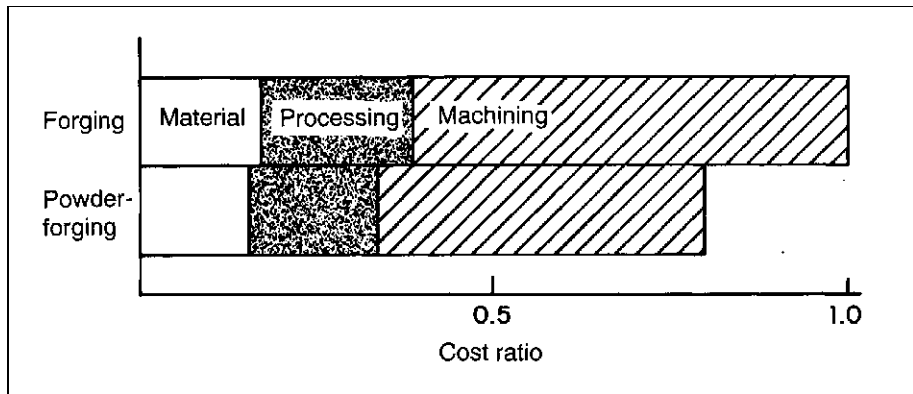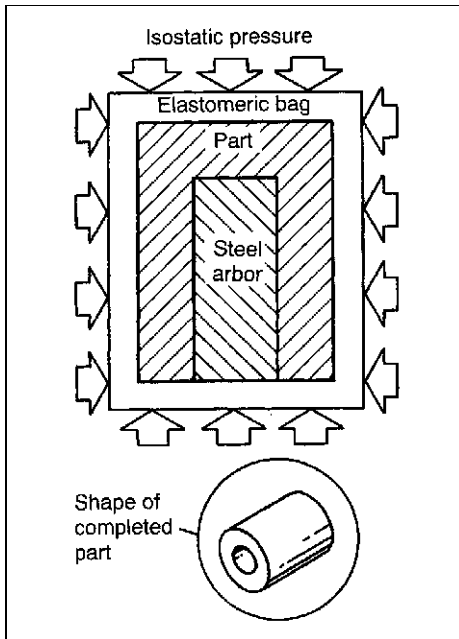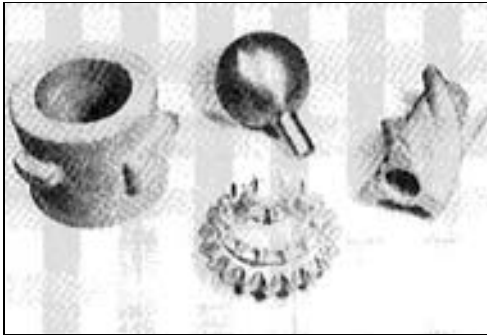**Metal injection molding, MIM**
Injection molding of metal powder/ polymer mixtures utilizes conventional plastic molding equipment, then, by carefully removing the plastic binder–

debinding–and sintering, complex shapes can be made from metal powders. The process and some parts made from alloy steel powders are described by Pease.[11] He reports density levels of 7.7g/cm^3 for alloy steel parts. Recent work at Rensselaer Polytech[17] provides data on the effect of processing variables on strength and ductility of nickel-alloyed steels produced by MIM. Currently the process is expensive, but it can be justified for the production of complex parts in stainless steels and nickel or cobalt-base alloys. Mocarski[8] suggests that the process might be used for high production parts if further developments result in lower production costs.

Summary

In the production of P/M parts, choice of alloy additions becomes critical in the sintering stage. Nickel, copper and molybdenum form oxides less readily than iron, so atmospheres which are reducing for iron will also be reducing for these alloying elements, thus assuring their solution in austenite during sintering. Manganese, silicon, chromium and vanadium form oxides more readily than iron, and if present in the compact may remain as oxides and detract from desired mechanical properties.

For the same pressing and sintering conditions, powder mixtures containing nickel provide higher density compacts. This is attributed to the fact that elemental nickel promotes shrinkage during sintering.

Nickel and molybdenum are especially advantageous as alloys during heat treatment of P/M compacts. Hardenability of P/M steels tends to be low because of the necessity to restrict manganese to small amounts and to avoid the use of chromium.

Accordingly, to obtain the required hardenability, nickel and molybdenum are added in quantities greater than those found in wrought steels intended for similar applications.

Mechanical properties of P/M steels

As stated earlier, the mechanical properties of P/M parts are, to a great extent, dependent upon the density achieved in the part. But, in addition, mechanical properties are also influenced by carbon and alloy content, and heat treatment. There are basically three conditions in which P/M parts are used:

(a) as-sintered

(b) sintered and heat-treated

(c) sintered, forged and heat-treated

In this section, an attempt has been made to demonstrate how to optimize properties in each of the above conditions. It should be evident that costs increase with processing complexity, so that one must evaluate the properties required, and select the most cost-effective approach.

The Metal Powder Industries Federation has developed standard designations for P/M compositions which are readily understood by those working in the field. The MPIF designations will be used where possible in describing P/M grades and their properties.

Effect of density on properties

The density of wrought steel is about 7.85g/cm^3, ranging from 7.84g/cm^3 for SAE 1080 steel to 7.87g/cm^3 for pure iron. P/M steel compact density ranges upward from about 6.4g/cm^3, or about 80% of theoretical density, and depends upon compacting pressure, compressibility of the powders, and whether compacts are repressed and resintered.

Density vs. as-sintered properties
For parts made from 2% Ni-0.8% C steels (MPIF FN0208), *Figure 15* indicates the effect of density on both yield

and ultimate tensile strength of as-sintered compacts. *Figure 16* shows the effect of density on percent elongation in the tensile test, and *Figure 17* provides data on impact strength for as-sintered 2% Ni steels containing 0.5 and 0.8% C. These data are from the MPIF *Design Handbook.*[3]
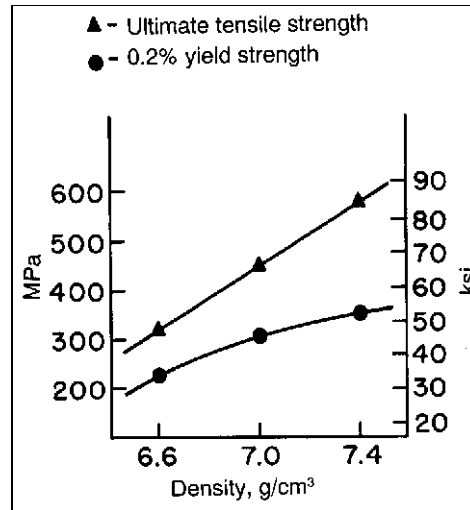

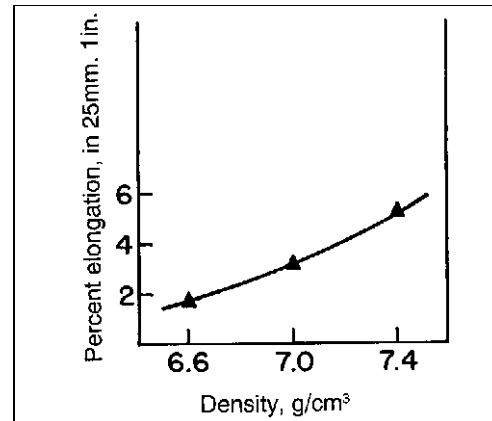**Figure 15.** Tensile and yield strength as a function of density for as-sintered 2% Ni-0.8% C steels (FN-0208).

Figure 16. Percent elongation in tensile tests as a function of density for as-sintered 2% Ni-0.8% C steels (FN-0208).
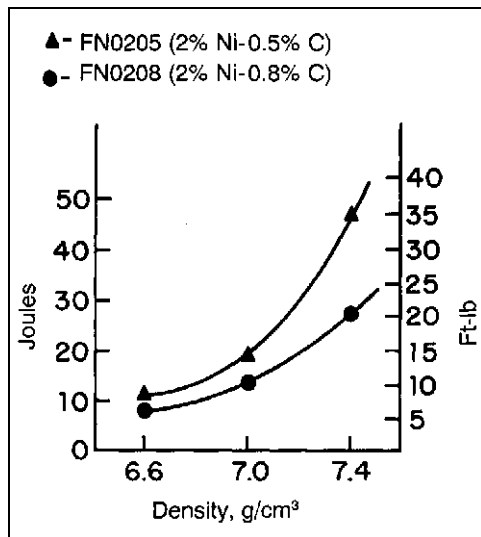
15

Figure 17. Unnotched Charpy impact energy as a function of density for as-sintered 2% Ni steels containing 0.5 and 0.8% C.

Increasing density has a marked effect; all three properties, strength, ductility and impact resistance increase with density. In the discussion of the effect of alloys on as-sintered properties, it will be shown that nickel increases density of sintered compacts made from mixtures of iron and nickel powders.

Powder processing can influence the properties obtained in as-sintered steel. Bertilsson and Carlson[18] studied two different powders with the same nominal composition Fe-1.75% Ni-0.5% Mo. One was water-atomized from a prealloyed melt to produce a homogeneous powder; the other was an elemental powder mixture of water-atomized iron powder and alloying elements as powders. The inhomogeneous mixed powder attained higher densities at the same compacting pressure, apparently due to the higher compressibility of the unalloyed iron powder. When pressed and sintered, however, tensile strength and ductility increased with density, but powder processing did not affect these properties consistently. One notable effect on strength was a consistently higher yield strength for the homogeneous powder at all density levels tested. Fracture toughness tests on sintered specimens form these two powders showed higher values with higher density, and higher fracture toughness for the homogeneous (atomized) powder, at all density levels.

Similar improvements in properties with increased sintered density were also observed by O'Brien.[19] Increases in density resulted in improved tensile properties and fatigue strength with all processing methods used.

Density vs. sintered and heat treated properties

Figure 18 shows tensile and endurance limit data reported by Lenel[6] for P/M *4640* steel (nominally 0.4% C-2% Ni-0.3% Mo), after double pressing and sintering to achieve a range of density values, then heat-treating to attain higher strength. Comparing the data in *Figure 18* with those in *Figures 15* and *16*, note that the strengths are considerably higher than in the as-sintered condition; elongation values are lower, as expected.

Density vs. sintered, forged and heat treated properties

The objective of forging P/M billets, of course, is to achieve nearly full density in the final part. For this reason, limited data are available on the effect of less than full density on properties of sintered, forged and heat-treated specimens. Hendrickson and others[20] did investigate forging techniques, and reported the effect of forged density on ductility, as measured by reduction in area in the tensile test, for specimens heat-treated to tensile strengths in the range 245 to 260 ksi (1700 to 1800 MPa). The results are shown in *Figure 19*. It is evident that quite high ductility can be achieved, but only at substantially full density.

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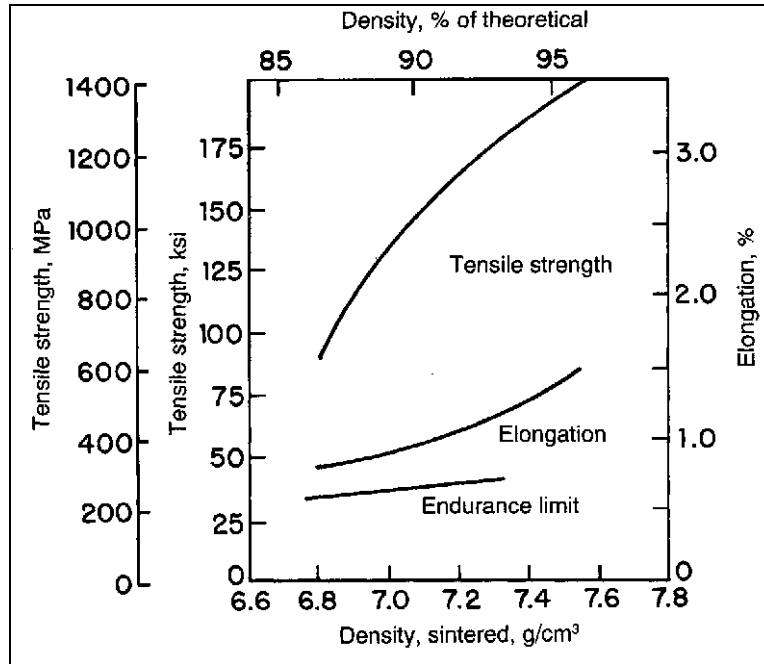**Figure 18.** Tensile properties and endurance limit as a function of density for sintered and heat-treated 0.4% C-2% Ni-0.3% Mo steels. Highest density achieved by repressing and sintering before heat treatment.
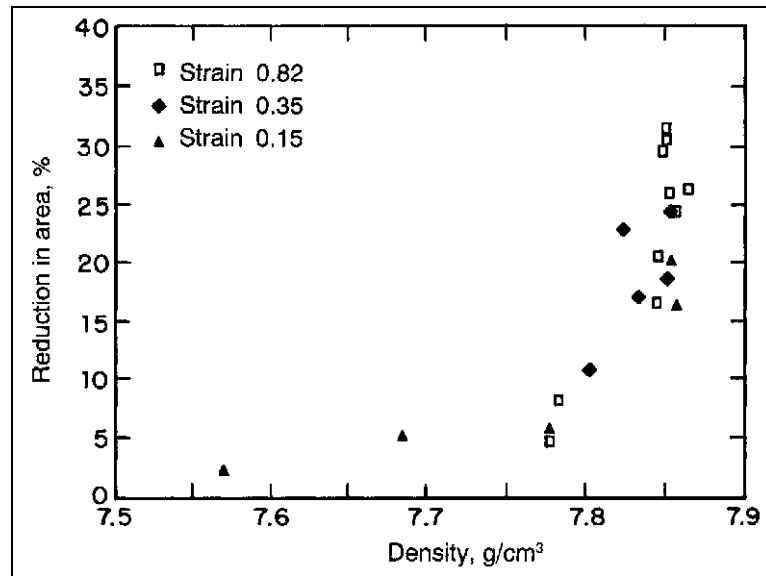

Figure 19. Reduction in area in the tensile test for sintered, forged and heat-treated P/M *4650-60* steels as a function of density, achieved by forging, using three levels of forging height strain.

Effect of carbon content on properties

Carbon in iron-base alloys provides the opportunity to achieve strength by transformation of austenite. This is true for P/M steels as well as wrought steels. Carbon dissolves in austenite on heating, and the subsequent transformation of austenite to ferrite-carbide aggregates results in varying strength levels upon cooling from the austenitizing temperature. Porosity in sintered P/M steels influences the properties attainable after heat treatment, and, as indicated above, properties depend on the processing conditions.

Carbon content vs. as-sintered properties

Sintering is accomplished at high austenitizing temperatures, providing ample opportunity to dissolve carbon in austenite. Transformation strengthening occurs when the sintered compact is cooled from the sintering temperature. As would be expected, increasing carbon content of sintered steels increases strength, but decreases ductility and toughness. The effects are shown in *Figure 20,* from Lenel's text.[6] The increase in strength with increase in carbon content is more evident at higher density levels, but is generally proportional to density. Elongation and resistance to impact decrease with increase in carbon content, but are always higher at higher density levels.

Note also in *Figure 20* (b) the classification of density levels recognized by the Metal Powder Industries Federation: R ranges from 6.4 to 6.8g/cm^3; S ranges from 6.8 to 7.2g/cm^3; and T ranges from 7.2 to 7.6g/cm.^{3} The T density level is achieved by double pressing and sintering, and even S level may require double pressing and sintering.

Carbon content vs. heat treated properties

The effect of carbon content on the properties of heat-treated P/M parts is shown in the next section, as part of a discussion of alloy and carbon effects for both low- and high-density parts.

Effect of alloy content on properties

Alloying is especially important in P/M steels because most are made with low silicon and manganese contents to minimize oxidation during sintering. To control microstructure as-sintered, or in response to heat treatment, alloying elements such as nickel, copper and molybdenum are added in preference to chromium and vanadium; the latter two elements readily form oxides. This section first presents typical properties for standard P/M steels, as given in MPIF Standard 35[21], for some carbon and low alloy steels, then cites data from recent P/M alloy steel developments.

Alloys vs. as-sintered properties

Typical tensile properties, transverse rupture strength, Charpy unnotched impact strength, and fatigue limit are given in *Table I* for P/M steels at density values in the range 6.9 to 7.0g/cm^3, and, where available, for a higher density of 7.4g/cm^3. Included in the table are data for carbon contents of nominally 0.5 and 0.8%. The steel designations correspond to MPIF grades; nominal compositions are given. The data in the table . show that adding nickel can increase strength, ductility and impact energy at the same density and combined carbon content.
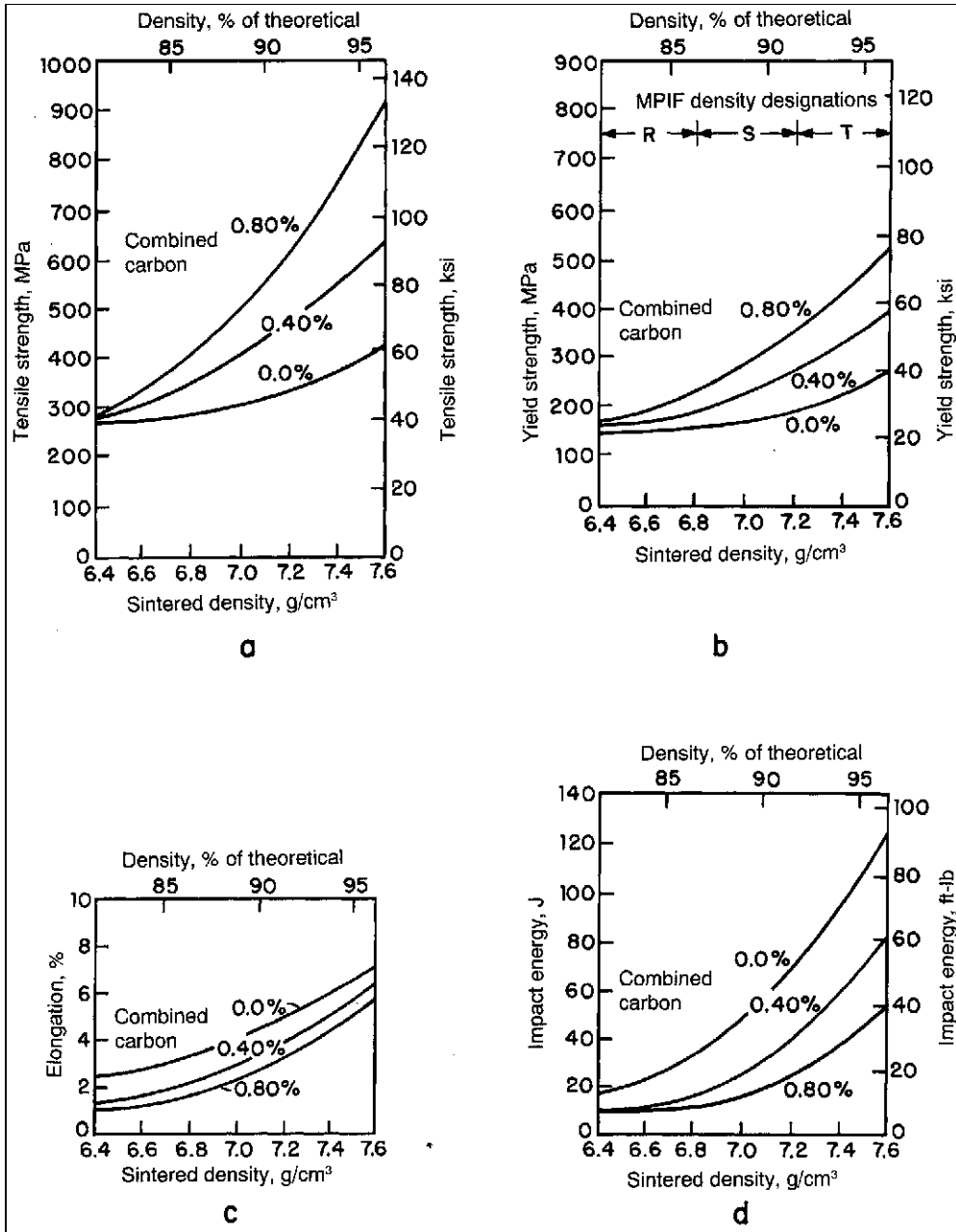
Figure 20. Tensile and impact properties as a function of density for sintered 4% Ni steel of various carbon contents.

Table I
Effect of alloying on mechanical properties of as-sintered P/M steels

MPIF material designation*	Density g/cm³	Tensile properties			Mod. x10⁶ psi (GPa)	Transverse rupture strength[a] ksi (MPa)	Impact energy[b] ft-lb (J)	Fatigue limit[c] ksi (MPa)
		UTS ksi (MPa)	0.2 YS ksi (MPa)	Elong. %				
F-0005-25 (0 Ni-0.5 C)	6.9	38 (260)	28 (195)	1.5	18.0 (125)	76 (525)	5 (7)	14 (95)
F-0008-35 (0 Ni-0.8 C)	7.0	57 (395)	40 (275)	1.0	19.0 (130)	100 (690)	5 (7)	22 (150)
FN-0205-25 (2 Ni-0.5 C)	6.9	50 (345)	30 (205)	2.5	18.5 (125)	100 (690)	12 (16)	19 (130)
FN-0205-35 (2 Ni-0.5 C)	7.4	70 (480)	40 (275)	5.5	24.0 (165)	150 (1035)	34 (46)	27 (185)
FN-0208-35 (2 Ni-0.8 C)	6.9	55 (380)	40 (275)	1.5	18.5 (125)	105 (725)	8 (11)	21 (145)
FN-0208-50 (2 Ni-0.8 C)	7.4	90 (620)	55 (380)	3.0	24.0 (165)	170 (1170)	21 (28)	34 (235)
FN-0405-35 (4 Ni-0.5 C)	7.0	60 (415)	40 (275)	3.0	19.5 (135)	120 (825)	14.5 (20)	23 (160)
FN-0405-45 (4 Ni-0.5 C)	7.4	90 (620)	50 (345)	4.5	24.0 (165)	175 (1205)	33.5 (45)	34 (235)
FN-0408-45 (4 Ni-0.8 C)	6.9	65 (450)	50 (345)	1.0	18.5 (125)	115 (790)	7.5 (10)	25 (170)

Footnotes to Table I:

F-000X-YY = Carbon steels, containing nominally 0.X% C, with minimum 0.2% offset yield strength of YY ksi (YY>6.895=MPa).

FN-020X-YY = Nickel steels, containing nominally 2% Ni and 0.X% C, with minimum 0.2% offset yield strength of YY ksi (YY>6.895=MPa).

FN-040X-YY = Nickel steels, containing nominally 4% Ni and 0.X% C, with minimum 0.2% offset yield strength of YY ksi (YY>6.895=MPa).

*F Steels may contain up to 2% other elements added for specific purposes.
*FN Steels may also contain 2.5% Cu max.
UTS = Ultimate tensile strength; Mod. = Modulus of elasticity in tensile test.

[a]Transverse rupture strength determined as in MPIF Standard 41.
[b]Unnotched Charpy impact energy determined as in MPIF Standard 40.
[c]Fatigue limit determined using R.R. Moore specimens as rotating beams.

Engstrom and Allroth[9] developed as-sintered P/M compositions that showed enhanced ductility. They used high compressibility pure iron powder, and blended it with graphite, nickel and molybdenum powders to obtain compositions in the range 6 to 12% Ni, 0.5 to 1.0% Mo and 0.3 to 0.8% C. As might be expected in as-sintered compacts with alloy contents this high, the microstructure was heterogeneous, comprising austenite, martensite and bainite in high-alloy regions, and coarse and fine pearlite in the low-alloy regions. Their objective was to obtain as-sintered tensile strength greater than 950 MPa (140 ksi), and greater than 4% elongation with sintered densities greater than 7.3g/cm^3. They observed that nickel additions resulted in shrinkage during sintering which enhanced sintered density. The density data, summarized in *Figure 21,* showed that compacts with at least 6% Ni, 0.5% Mo and 0.8% C provided sintered density above 7.3g/cm^3 after compacting at 85 ksi (590 MPa) and sintering at 2100°F (1150°C) for 60 minutes. Density increased with increasing nickel and carbon contents.

Tensile strengths for various alloy combinations investigated by Engstrom and Allroth[9] are shown in *Figure 22,* and elongation values in the tensile test are shown in *Figure 23.* The somewhat lower tensile strength but higher elongation of the high nickel compacts is attributable to larger amounts of austenite. These data show that the project goals were met with as-sintered steels containing 0.5% C, 8 or 10% Ni, and 0.5 or 1.0% Mo.

Engstrom and Allroth[9] also tested two of the alloys in bending fatigue. The results, shown in *Figure 24,* indicate fatigue limits in the range 270 to 290 MPa (39 to 42 ksi) for as-sintered alloys containing 0.5% C and either 8% Ni with 1 % Mo or 10% Ni with 0.5% Mo.

One of the as-sintered P/M steels was also tested with notched specimens in axial loading. The results are shown in *Figure 25;* curves for 10, 50 and 90% probability of failure were statistically determined, and indicate a 50% probability of failure (in 2 x 10^6 cycles) with notched specimens in fatigue at a stress of 180 MPa (26 ksi). The investigators stated that the notch effect is comparable to that observed in wrought steels.

The Fe-8% Ni-1 % Mo powder described above was developed as a commercial grade, Distaloy AG, and tensile properties of as-sintered compacts of this composition were compared by Tengzelius[22] with compacts made from Fe-4% Ni-1.5% Cu-0.5% Mo powder, Distaloy AE, and with Fe-2.5% Cu powder. In this study, nickel, molybdenum, and/or copper were diffusion-bonded to the iron powder, then mixed with graphite so that the sintered compacts would contain 0.5% C for the 8Ni-1 Mo grade or 0.6% C for the 4 Ni and the 2.5 Cu grades. Density variations were obtained by varying compacting pressures. Sintering was accomplished in an atmosphere of dissociated ammonia; compacts were held at 2100°F (1150°C) for 60 minutes.

Tensile strengths as a function of density for the three alloys tested by Tengzelius[22] are shown in *Figure 26.* The tensile strength of each grade increased with density, as would be expected. Note, however, that the strength of the 8Ni-1 Mo-0.5C P/M steel is substantially higher than the other grades, and increases more rapidly with increasing density.

In the work cited above, nickel has contributed to strengthening in two ways – by increasing sintered density at the same compacting pressure, and by modifying the as-sintered microstructure. The microstructure was a mixture of: (1) fine pearlite in the areas having the lowest nickel and molybdenum content but high carbon content; (2) austenite in the areas highest in nickel and lowest in carbon; and (3) martensite and bainite in the areas of intermediate alloy content. The carbon and alloy contents were
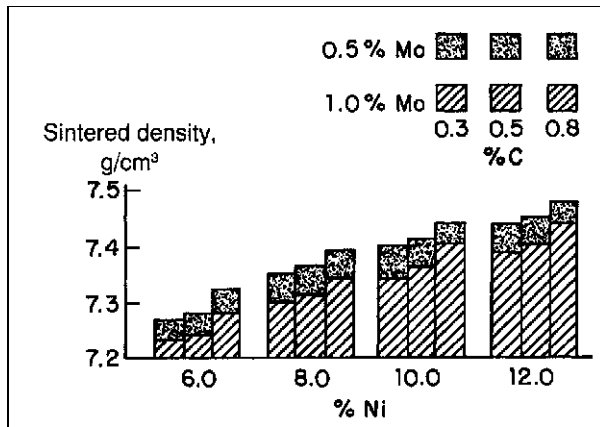
Figure 21.   Sintered density obtained for various Fe-Ni-Mo-C alloys.
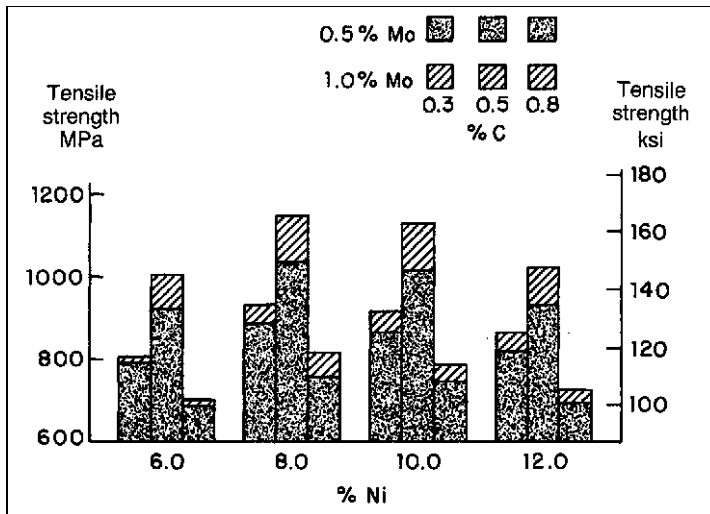
Figure 22.   Tensile strength for various as-sintered Fe-Ni-Mo-C alloys.
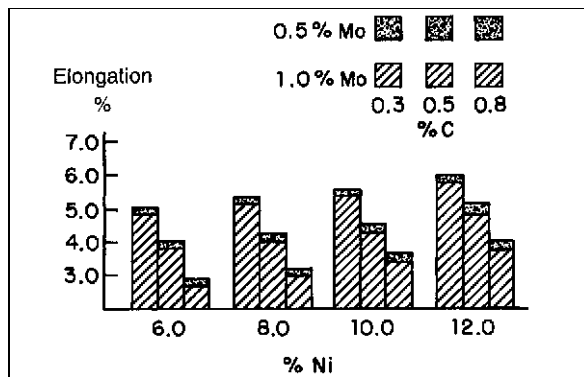
Figure 23.   Percent elongation in the tensile test for various
as-sintered Fe-Ni-Mo-C alloys.
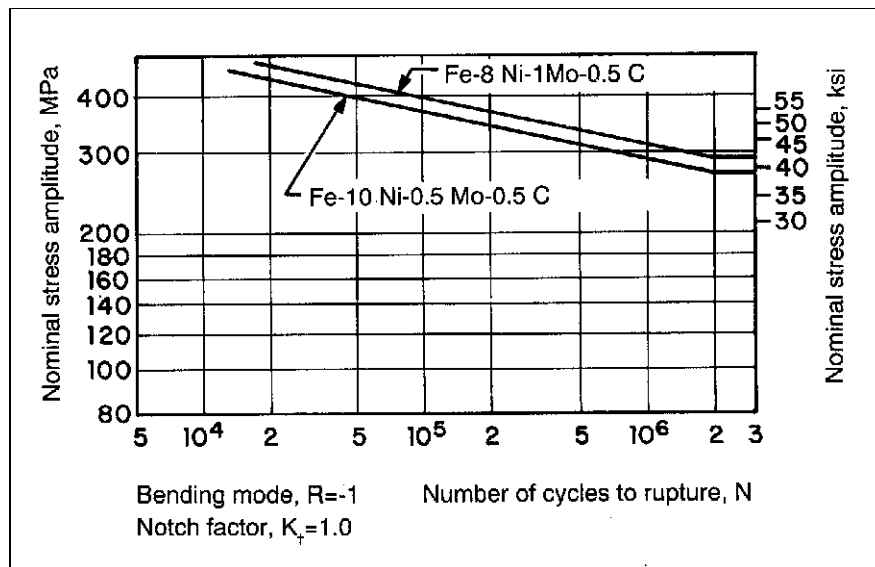
Figure 24. Bending fatigue (S-N) curves for two as-sintered Fe-Ni-Mo-C alloys tested in the unnotched condition.
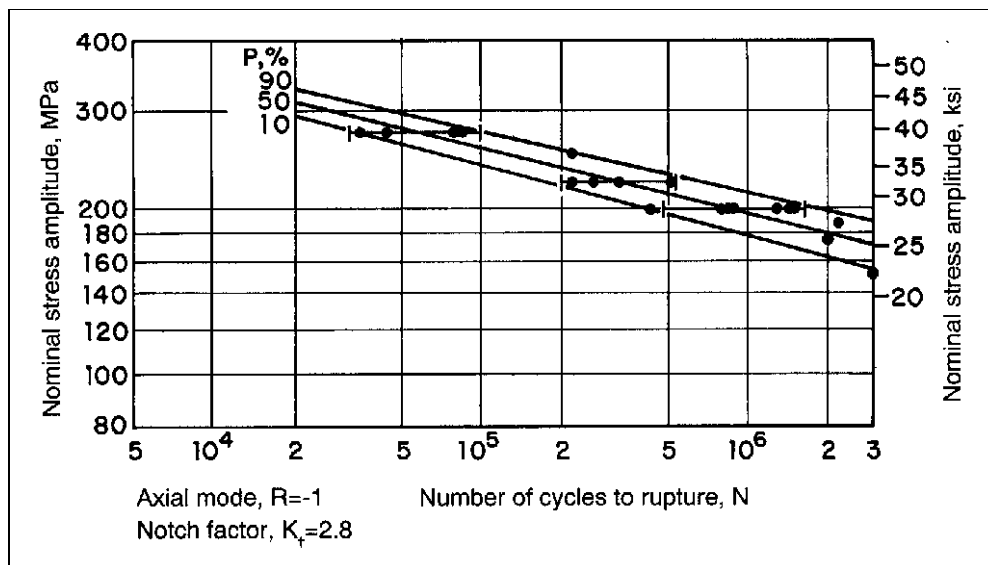
Figure 25. Axial fatigue curves for as-sintered and notched specimens of a Fe-8 Ni-1.0 Mo-0.5 C alloy. The 10, 50, and 90% failure probability lines were statistically determined from the data.

23
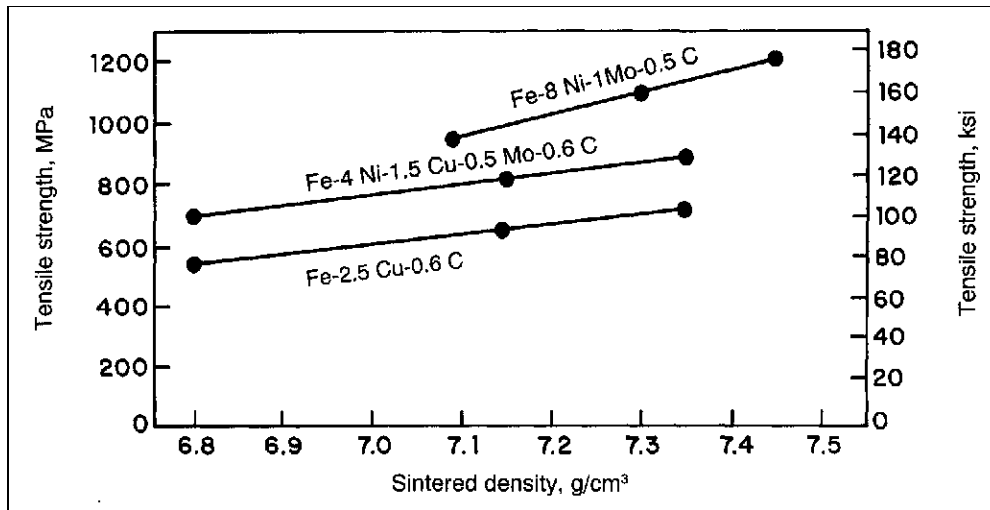
Figure 26. Tensile strength of as-sintered P/M steels as a function of density. Variations in compacting pressures resulted in a range of density values for each grade. Compacts were sintered 60 minutes at 2100°F (1150°C).

defined using lineal microprobe analysis.

Similar observations were made by Lindqvist[23] in a study of the effect of alloy and processing variables on as-sintered tensile and fatigue properties. He compared the properties of iron-base compacts of the following alloy contents:

1.75% Ni-1.5% Cu-0.5% Mo,

4.0% Ni- 1.5% Cu-0.5% Mo, and

8.0% Ni-1.0% Mo.

Alloying was achieved by premixing and diffusion annealing, as described.[23] Graphite was added to achieve a combined carbon content of 0.5% after sintering at 2050°F (1120°C). Reverse bending fatigue strength of the 8 Ni-1 Mo compact was the highest reported, 43 ksi (300 MPa) at a sintered density of 7.3g/cm³. The 4 Ni-1. 5 Cu-0.5 Mo compact exhibited a sintered density of 7.5g/cm³ and a fatigue strength of 41 ksi (280 MPa).

Alloys vs. sintered and heat-treated properties

Table II contains typical data for the same steel grades as in *Table I,* but after heat treatment that usually consists of quenching and tempering to achieve the minimum tensile strength corresponding to the grade designation. Data for two low-alloy heat-treatable grades are also included in *Table II.* Reference 21 points out that yield strength in heat-treated P/M steels is the same as the tensile strength; the lack of significant elongation in the tensile test affirms this.

It is evident by comparing the data presented in *Table I* and *II* that heat treatment increases strength (tensile, transverse rupture, and fatigue strength) but decreases ductility and toughness. Nickel additions increase strength in both the as-sintered and heat-treated condition, but also provide improved impact resistance for the same strength. The effect of density on properties is also evident from the tabular data; increasing density from 7.0 to 7.4 improves properties significantly.

Table II
Effect of alloying on mechanical properties of sintered and heat-treated P/M steels

MPIF material designation*	Density g/cm³	UTS ksi (MPa)	Tensile properties Elong. %	Mod. x10⁶ psi (GPa)	Transverse rupture strength ksi (MPa)	Impact energy ft-lb (J)	Fatigue limit ksi (MPa)
F-0005-70HT (0 Ni-0.5 C)	7.0	80 (550)	<0.5	19.0 (130)	140 (965)	4.0 (5)	30 (205)
F-0008-75HT (0 Ni-0.8 C)	6.9	85 (585)	<0.5	18.0 (125)	130 (895)	4.5 (6)	32 (220)
FN-0205-105HT (2 Ni-0.5 C)	6.9	120 (825)	<0.5	18.5 (125)	160 (1105)	4.5 (6)	46 (315)
FN-0205-180HT (2 Ni-0.5 C)	7.4	185 (1275)	<0.5	24.0 (165)	250 (1725)	9.5 (13)	70 (480)
FN-0208-130HT (2 Ni-0.8 C)	7.0	145 (1000)	<0.5	19.5 (135)	185 (1275)	5.5 (7.5)	55 (380)
FN-0208-180HT (2 Ni-0.8 C)	7.4	195 (1345)	<0.5	24.0 (165)	250 (1725)	8.0 (11)	74 (510)
FN-0405-130HT (4 Ni-0.5 C)	7.0	135 (930)	<0.5	19.5 (135)	200 (1380)	6.5 (9)	61 (420)
FN-0405-180HT (4 Ni-0.5 C)	7.4	185 (1275)	<0.5	24.0 (165)	280 (1930)	13.0 (17.5)	70 (480)
FL-4205-120HT (0.5 Ni-0.7 Mo-0.5 C)	7.0	130 (895)	<0.5	22.0 (150)	185 (1275)	4.0 (5.5)	49 (340)
FL-4605-120HT (1.8 Ni-0.6 Mo-0.5 C)	6.95	130 (895)	<0.5	20.0 (140)	195 (1345)	6.0 (8)	49 (340)

[Please see notes in *Table I* regarding test methods]

F-000X-ZZHT	=	Carbon steels, containing nominally 0.X% C, heat-treated to a minimum ultimate tensile strength of ZZ ksi (ZZ >6.895=MPa).
FN-020X-ZZHT	=	Nickel steels, containing nominally 2% Ni and 0.X% C, heat-treated to a minimum ultimate tensile strength of ZZ ksi (ZZ >6.895=MPa).
FN-040X-ZZHT	=	Nickel steels, containing nominally 4% Ni and 0.X% C, heat-treated to a minimum ultimate tensile strength of ZZ ksi (ZZ >6.895=MPa).
FL-4205-120HT	=	Low-alloy steel containing nominally 0.5% Ni, 0.7% Mo and 0.5% C, heat-treated to a minimum ultimate tensile strength of 120 ksi (825 MPa).
FL-4605-120HT	=	Low-alloy steel containing nominally 1.8% Ni, 0.6% Mo and 0.5% C, heat-treated to a minimum ultimate tensile strength of 120 ksi (825 MPa).

*F and FL Steels may contain up to 2% other elements added for specific purposes.
*FN Steels may also contain 2.5% Cu max.

Ogura and others[24] achieved good tensile and impact properties in heat-treated P/M steel by using composite-type powders (a mix of prealloyed low alloy powder for good compressibility plus further alloy additions). Best results were obtained with compacts containing 2 to 4% Ni, 1.5% Cu and 0.5% Mo made by pressing at 100 ksi (690 MPa), then sintering at 2280°F (1250°C) in dissociated ammonia. Sintered densities of 7.2g/cm³ were attained. The compacts were then carburized at 1650°F (900°C), oil quenched and tempered at 355°F (180°C). Tensile strengths are shown in *Figure 27,* and impact energy values are shown in *Figure 28,* as a function of nickel content. The benefit of increasing nickel content is evident from these data. The authors determined retained austenite contents at the surface of the carburized compacts, and showed values ranging from 22 to 25% austenite.

Figure 27. Tensile strength of sintered and heat-treated (carburized and hardened) compacts made from composite-type alloy steel powders. The compacts contained 2 to 4% Ni, 1.5% Cu and 0.5% Mo.

Alloys vs. forged and heat treated properties

Many references have shown that hot-forging P/M steel compacts to full density can result in attaining mechanical properties comparable to wrought steel. What may be more significant is the evidence that hot-forged powder compacts can provide properties that *exceed* those attainable in steel produced by conventional melting and forging.

Work by Adams and Glover[25], reported in 1977, showed that powder-forged cups for tapered roller bearings exhibited considerably longer rolling contact fatigue life than cups forged from conventional ingot steel, as shown in *Figure 29,* in terms of L_{10} life, the statistically-determined probability that only 10% of parts would fail at the tested stress level. Powder forging also increased the L_{10} life of bearing cones, another critical part, by a factor of three. The improvement in life was
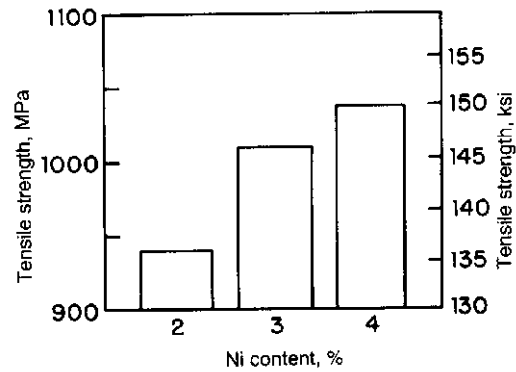
Figure 28. Unnotched Charpy impact values of sintered and heat-treated (carburized and hardened) compacts made from composite-type alloy steel powders. The compacts contained 2 to 4% Ni, 1.5% Cu and 0.5% Mo.
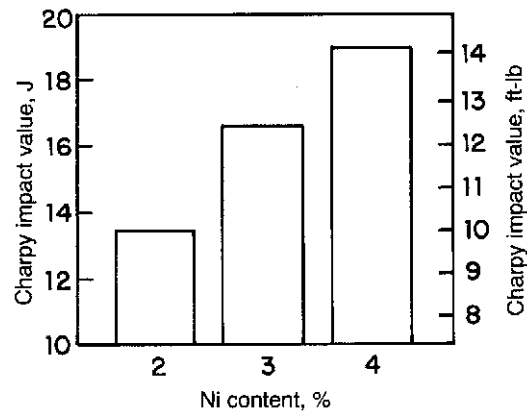
attributed to a more uniform dispersion of nonmetallic inclusions, making them less likely to create sites of stress concentration and pitting.
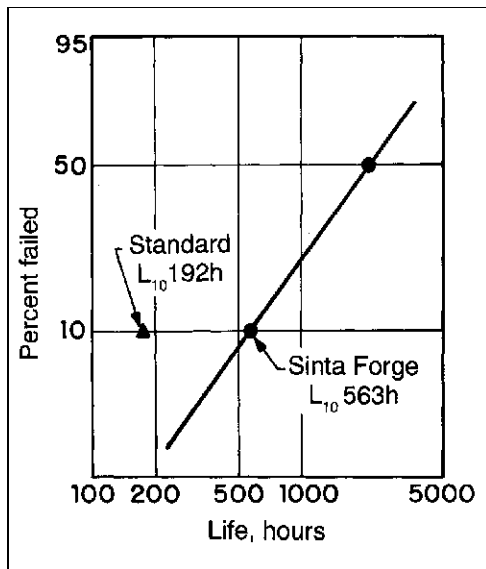
Figure 29. Typical Weibull plot of fatigue data for forged P/M *4625* bearing cups compared with data from cups forged from standard ingot steel of similar composition. Both cups were carburized and hardened.

Figure 30. Fatigue performance of connecting rods made from powder forged 1.8% Ni-0.5% Mo steel, compared with drop-forged steel connecting rods. Both connecting rods were carburized and hardened.

James[26] reported on improved fatigue performance of connecting rods for Porsche engines when made from powder forgings. When powder forgings were made under well-controlled conditions from prealloyed powders of controlled cleanliness containing nominally 1.8% Ni and 0.5% Mo, then carburized and hardened, fatigue properties of the powder-forged connecting rods exceeded those of rods produced from drop-forged wrought steel, as shown in *Figure 30*. An important part of the development was control of nonmetallic inclusions, not dissimilar to the bearing development described above. The author describes quality assurance techniques developed.

Effect of powder processing on properties

Burr[77] reported a comparison between steel compacts prepared from prealloyed, premixed elemental, and mixtures of prealloyed and elemental–*hybrid*–powders. He used elemental atomized iron powder with pure nickel powder, ferromanganese and ferromolybdenum, as well as two atomized steel powders: *4620* (containing 1.9% Ni, 0.1% Mn and 0.5% Mo) and a low-alloy steel (containing 0.4% Ni, 0.4% Mn and 0.5% Mo). The *hybrid* steels were mixtures of prealloyed powders and elemental powders, and provided an intermediate alloy content of 0.93% Ni, with nominally 0.5% C and 0.5% Mo. Compacts were pressed, presin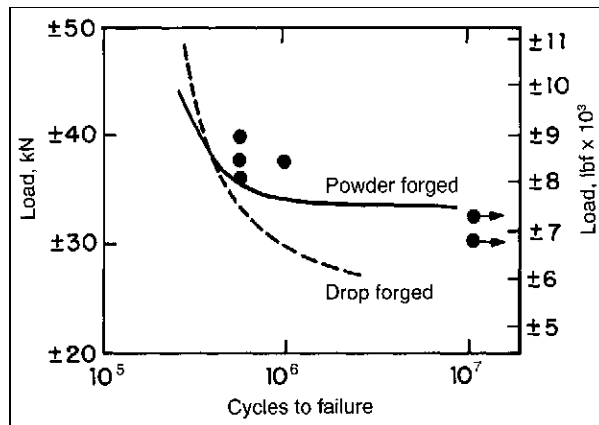tered at 1470°F (800°C) repressed and resintered at 2050°F (1120°C) to achieve the desired sintered density. Densities ranged from 7.25 for the *hybrid* and prealloyed powder compacts to 7.45g/cm^3 for the compacts made from elemental powder.

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The effect of powder processing and nickel content on ultimate tensile strength of heat-treated compacts is shown in *Figure 31*, as a function of tempering temperature after oil quenching from 1650°F (900°C). Note the general trend toward higher strengths with higher nickel content. But also note that the elemental powder compacts exhibit higher strengths except for specimens tempered at 1020°F (550°C). Some additional data are given in *Table III*.

In *Table III*, the data by Burr[27] for as-sintered compacts as well as heat-treated compacts are included, but only the data for 300°F (150°C) temper, for simplicity. Note the low elongation values and lack of measurable yield strength for some of the heat-treated P/M steels. Heterogeneity in the microstructure of heat-treated P/M steels made from elemental powders may explain the measurable elongation and higher tensile strength values shown in *Table III*.

Morioka and Takajo[4] reported good tensile and impact properties for double-pressed, double-sintered and heat-treated compacts made from two types of alloy steel powders. They achieved 7.40 to 7.47g/cm^3 sintered density by pressing at 100 ksi (690 MPa), first sintering at 1560°F (850°C), then repressing and sintering at 2280°F (1250°C). Graphite was added to the alloy steel powders to obtain 0.3 and 0.6% C after sintering. Tensile strength and impact energy values are given in *Table IV* for two of the powders.

Kawai and others[5] reported significantly improved rolling contact fatigue properties for powder-forged bearings processed from *clean 4600* powder and vacuum sintering. The properties were equal to those obtained from vacuum-degassed steels that were cast and conventionally forged and heat-treated. Powder-processed parts had the additional advantage of exhibiting the same
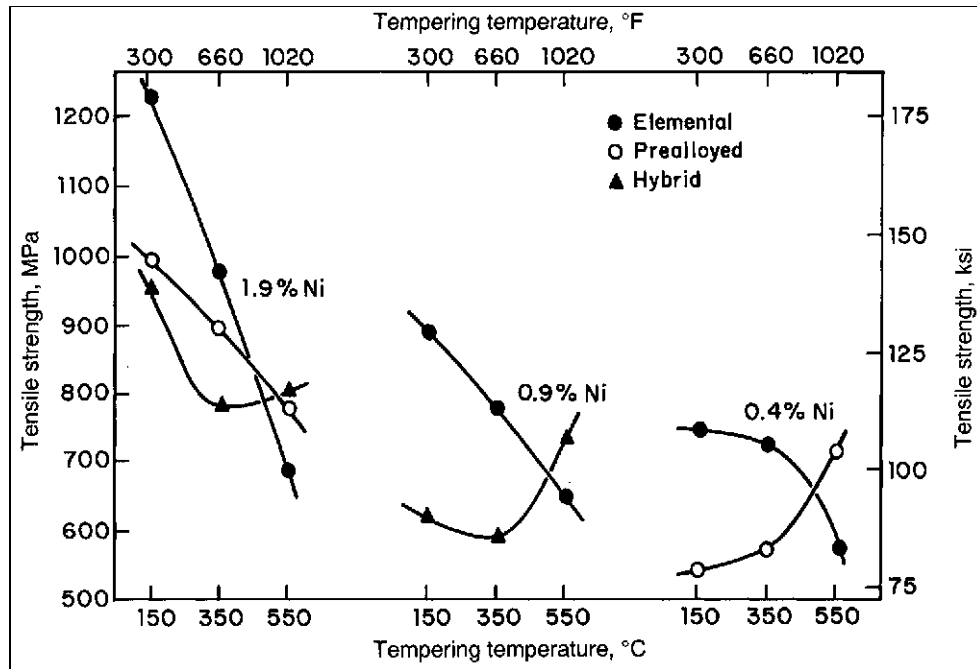
Figure 31. Tensile strength as a function of tempering temperature for heat-treated P/M steels made from elemental, prealloyed and hybrid powders, containing various nickel contents.

Table III
Properties of P/M steels with different powder processing

Alloy	Material* Type	% Ni	Density g/cm^3	Tensile Properties UTS ksi (MPa)	0.2 YS ksi (MPa)	Elong. %	Impact energy ft-lb (J)
				As-sintered			
1	P	1.9	7.25	73 (505)	58 (400)	2	12.5 (17)
2	H	1.9	7.25	81 (560)	62 (425)	2	12 (16)
3	E	1.9	7.45	71 (490)	38 (260)	8	20 (27)
4	H	0.9	7.25	71 (490)	55 (380)	2	14 (19)
5	E	0.9	7.45	59 (405)	32 (220)	5	17.5 (24)
6	P	0.4	7.25	59 (405)	52 (360)	1.5	12.5 (17)
7	E	0.4	7.45	55 (380)	35 (240)	4.5	24 (33)
				Heat treated (1650 ºF [900 ºC]) O.Q. + 300 ºF [150 ºC])			
1	P	1.9	7.25	143 (985)	141 (970)	<0.5	11 (15)
2	H	1.9	7.25	138 (950)	–	<0.5	12 (16)
3	E	1.9	7.45	178 (1225)	141 (970)	1	20 (27)
4	H	0.9	7.25	90 (620)	–	<0.5	9.5 (13)
5	E	0.9	7.45	129 (890)	–	0.5	16 (22)
6	P	0.4	7.25	78 (540)	–	<0.5	12.5 (17)
7	E	0.4	7.45	107 (735)	91 (625)	0.5	18 (25)

* Each alloy contained nominally 0.5% C, 0.5% Mo and 0.1 or 0.4% Mn.

E = Elemental powders;   P = Prealloyed powders;   H = hybrid
UTS = Ultimate tensile strength; 0.2% YS = 0.2% offset yield strength or proof stress

Table IV
Properties of double-pressed, double-sintered and heat-treated compacts
of two alloy powders

Alloy type	Added graphite, %	Density, g/cm³	Tensile strength ksi	(MPa)	Impact energy ft-lb	(J)
4600ES	0.3	7.47	155	(1070)	31	(42)
	0.6	7.44	196	(1350)	27	(36)
Sigmaloy 415S	0.6	7.40	194	(1340)	31	(42)

Compacts were prepared as described in the text, then heat-treated by oil quenching form 1600°F (870°C) and tempering at 355°F (180°C).

4600ES powder contains nominally 1% Ni, 0.3% Cu and 0.2% Mo, and is annealed in pure hydrogen to improve compressibility.

Sigmaloy 415S powder contains nominally 4% Ni, 1.5% Cu and 0.5% Mo, and is prepared by mixing water-atomized pure iron powder with elemental alloy powders, then annealing the mixed powders in a reducing atmosphere to diffusion bond the alloy particles to the iron particles.

properties when tested in the transverse as in the longitudinal direction.

A comparison by Townsend[28] of surface fatigue characteristics of hot-forged P/M gears included evaluation of gears machined from 4620 and 4640 P/M steels, and SAE 4340 and 9310 ingot steels. Forged gear blanks were machined, then carburized and hardened. He noted the presence of some porosity in gear tooth tips, and some "foreign material" present in the P/M gear teeth. Fatigue performance of finish-ground P/M 4620 gears was about 70% of that exhibited by standard SAE 9310 ingot steel gears and slightly better than that of the 4340 ingot steel. Close control of raw materials and the powder-forging process was needed to attain the best results with P/M parts.

Zhang and others[17] recently compared tensile properties of metal injection molded (MIM) Fe-Ni-C alloys with similar alloys produced by conventional pressing and sintering (P/M). Focussing on the Fe-2% Ni alloy, they concluded that processing conditions and carbon control were critical to successful control of mechanical properties. Thermal debinding in the MIM process should be performed at about 930°F (500°C). Sintering at 2190°F (1200°C) in a hydrogen atmosphere provided high density and excellent ductility, but only moderate strength. Subsequent heat treatment provided the usual increase in strength but decreased ductility. The best properties reported for MIM processing[17] are given in *Table V.*

Structure/property relationships

It should be pointed out that P/M products, except those produced by powder forging, usually exhibit a mixed microstructure as-sintered and even after heat treatment. Prealloyed powders can exhibit variations in carbon content, and premixed and *hybrid* powders exhibit variations in alloy content as well. Thus it is difficult to use traditional physical metallurgy principles in relating mechanical properties to structure.

Table V
Tensile properties of metal injection molded, MIM, parts

Composition Ni	% C	Condition	Density, g/cm^3	Tensile strength ksi	(MPa)	Elongation %
0	0.2	Sintered	7.6	55	(380)	23
2	0.5	Sintered	7.4	65	(450)	20
2	0.5	Heat treated	7.4	180	(1230)	1
8	1.0	Heat treated	7.6	200	(1385)	5

Some studies have been made to establish structure/property relationships in P/M parts. One is the work of Bertilsson and Carlson cited previously.[18] They concluded that homogeneous compacts generally exhibited better mechanical properties than heterogeneous compacts. In this work, the homogeneous compacts were made from prealloyed, water-atomized iron powder containing 1.75% Ni and 0.5% Mo while the heterogeneous compacts had the same average composition but were produced from mixtures of water-atomized iron powder, with alloying elements mixed in and partially diffused during sintering.

As-sintered compacts of the homogeneous alloy comprised essentially coarse pearlite with irregular cementite morphology, while the heterogeneous alloy exhibited ferrite and some martensite in addition to pearlite.[18] Nevertheless, tensile and impact properties were improved more by increasing density than by increasing homogeneity. Fracture toughness also increased with density, but the homogeneous material was slightly tougher. The homogeneous material exhibited slightly better fatigue properties.

Summary

Mechanical properties of P/M steels are strongly dependent on density. Nickel increases the density of sintered compacts made using elemental nickel powders.

Carbon content dictates the strength level attainable in P/M steels. As-sintered compacts can achieve high strength if cooled from the sintering temperature at a rate rapid enough to result in the formation of fine pearlite, bainite or martensite. Alloy additions increase this opportunity.

Alloy additions to P/M steels are especially important, and must be made selectively to minimize oxidation during sintering. The elements nickel, copper and molybdenum are used to provide hardenability, rather than the readily oxidizable elements manganese, silicon, chromium and vanadium. As in wrought steels, nickel enhances the hardenability effect of molybdenum, especially at low carbon levels. Available data show the consistently beneficial effect of nickel at any given strength level: to increase ductility; to improve resistance to impact; and to increase fatigue life.

Alloyed P/M steel parts forged to full density exhibit properties equal to those made from cast and forged steel. Several examples show that alloyed P/M steels can exhibit properties superior to those of cast and forged steels.

Improvements in powder processing have resulted in improved mechanical properties of P/M steel parts, thus increasing the cost-effectiveness of P/M processing.

Applications of P/M nickel steels

Growth in the use of P/M alloyed steel has been dramatic in the high-volume production of components in the automotive, machine tool and farm equipment industries. In 1974, Feir[29] stated that "the past decade has seen a tremendous growth in the use of structural parts in the power tool industry." He then stated that "most engineers use the nickel alloys (steels) in applications where high impact loads are encountered," and described several such parts in portable drills, hedge trimmers and impact screw drivers.

In 1980 over half of P/M parts produced were in the automotive industry, according to Lenel.[6] He noted that more and more parts are now "designed as P/M structural parts." The 1984 *Metals Handbook*[10] cited 116 typical parts in automobiles, and stated that such parts were "dominated by iron-based powders." The *Metals Handbook* also provides examples of applications of P/M steels in farm equipment, business machines, military vehicles and ordnance applications.

In 1987, Mocarski and Hall[7] reviewed automotive applications, noting that the progress in the decade 1977-1987 in applying the relatively new P/M technology to mass production was due in great part to improvements in powder production technology, and to improvements in component fabrication technology. In 1989, these same authors[8] updated their review of applications in automotive applications.

Projections of P/M steel applications into the 1990s was given in an article by Kennedy[2]. White[30] called attention to the increasing internationalization of powder metallurgy production and application.

As-sintered P/M nickel steel applications

Figure 32 represents a good application in which a P/M nickel steel was used in the as-sintered condition.[31a] The caption provides details given in the reference.

Mocarski and others[8] cite many automotive applications for as-sintered nickel alloy steels, including a crankshaft sprocket, a valve lifter guide, a transmission chain sprocket, a clutch pressure plate, a tilt steering wheel ratchet lever, bearing preload adjusters, a differential case, planetary pinions for a starter, and a cylinder and rotor for an air conditioning compressor. These parts ranged in density from 6.8 to $7.49/cm^3$, and in weight from 0.3 ounce (9g) to 3 pounds (1362g). The higher density parts were achieved by double pressing and double sintering.

Sintered and heat-treated P/M nickel steel applications

Figure 33 illustrates a heat-treated P/M nickel steel part for a computer.[31b] The caption provides details given in the reference.

Mocarski and others[8] cite many heat-treated P/M nickel steel automotive parts, including a balance shaft component (two parts brazed together and heat treated), a plate retainer for camshaft (induction hardened), a crankshaft sprocket (heat-treated to 50 HRC), a fuel injection pump part (carburized and quenched), a manual transmission detent lever (sintered at high temperature and heat-treated for strength and wear resistance), a tilt steering wheel ratchet lever (this part is heat-treated), a passive restraint pawl (heat-treated to
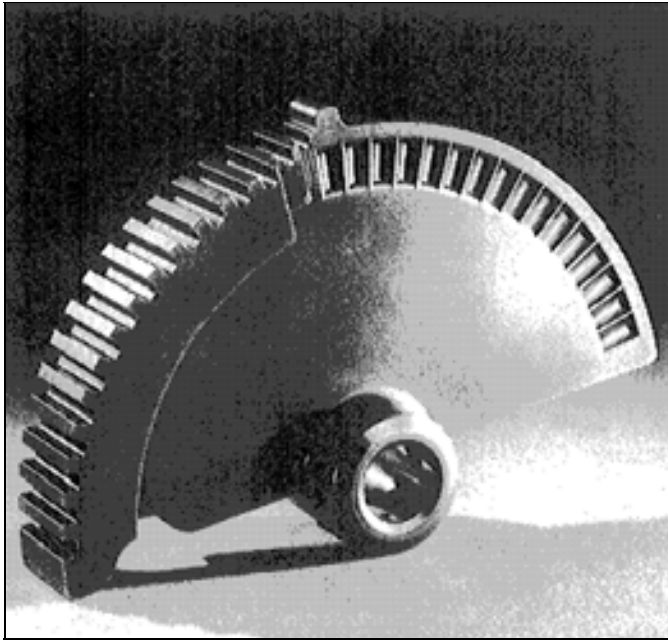
Figure 32. As-sintered P/M nickel steel sector gear which replaced an investment casting.[31a] "The part was made by Burgess-Norton Manufacturing Co., Geneva, IL, for John Deere Component Works, Waterloo, IA. It controls the hydraulic valve of a 15-speed transmission used in row-crop tractors.

"The part's density is 6.8g/cm^3 in the gear area and 6.4g/cm^3 in the detent area. Minimum hardness in the detent area is 26 HRC. The position of the teeth to the I. D. and the detent must be held to 0.010 in. (0.25mm).

"Formerly an investment casting, the P/M sector gear provides good wear properties, closer tolerances and very favorable cost savings. Secondary operations include the drilling of a hole, milling of the step and grinding the I. D."

Figure 33. Computer platen adjust handle made from heat-treated P/M nickel steel FN 0408-45HT (containing 0.6-0.9% C, 3-5.5% Ni, 2% Cu max.).[31b] "The handle is used to adjust the main high-speed printer platen in an office computer. The multilevel steel part was made by Pacific Sintered Metals Company, Los Angeles, CA, for Hewlett-Packard Co., Boise Division, Boise, ID.

"Powder metallurgy replaced an investment casting, resulting in a 40% saving. The part is heat-treated to 35-42 HRC and offers close tolerances, ±0.002 in. (0.05mm) on the I. D. of the hub. Secondary operations include drilling, tapping, pressing a screw-machined pin into the handle, and a black oxide coating."

100 ksi [690 MPa] min. tensile strength), a transfer case driven sprocket (heat-treated to 58 HRC), a differential gear clutch ring (heat-treated to 44 HRC), a pinion gear for a door window (vacuum heat-treated), and parts for an electric remote side view mirror (carburized and quenched). Parts ranged in density from 6.6 to 7.4g/cm^3, and weighed from 0.3 ounces to 4.5 pounds (8g to 2kg).

Several business machine applications for heat-treated P/M nickel steels were cited in the *Metals Handbook.*[10] These included transfer gears (heat treated to 80 ksi [550 MPa] min. yield strength), Geneva pinions (double pressed and double sintered to 7.45g/cm^3 density, then carbonitrided), hammer guides (case hardened), and drive gears (6.8-7.0g/cm^3 density, carburized and induction hardened).

Feir[29] cited some heat-treated P/M nickel steel parts for portable power tools, which included a counterweight for a jig saw (6.9g/cm^3 density, heat-treated to 15-25 HRC) and parts for an impact screw driver (7.2g/cm^3 min. density, carburized and heat-treated to 50-55 HRC).

The MPIF *Design Guidebook*[13] shows an automotive transmission lever of complex shape from P/M nickel steel, heat-treated to a minimum yield strength of 70 ksi (485 MPa). The fully finished part cost only 30% of the next best manufacturing method, a machined investment casting.

McGee and Ward[32], in 1977, cited advances in P/M gear applications, described details of processing steps employed, and provided several examples of gears made from heat-treated P/M nickel steels. These included: racks of 0.7% C-2% Ni steel pressed and sintered to 7.0g/cm^3, then oil quenched and tempered to 40 HRC; spur gears of the same composition pressed and sintered to a density of 7.0 to 7.6g/cm^3, then heat-treated to 42 to 44 HRC; a spiral face gear of 0.8% C-2% Ni steel, pressed and sintered to 6.8g/cm^3, then

heat-treated to 35 HRC; and a spiral bevel gear of 0.8% C-2% Ni-0.5% Mo steel, pressed and sintered to 7.2g/cm^3, then heat-treated to 42 HRC. All these gears involved forming the teeth in the die, thus significantly reducing machining costs.

A somewhat later article by McGee[33] on P/M gearing emphasized both the economic and technical advantages of this fabrication approach. He cited as one example a main drive gear in a high-torque hydrostatic transmission, weighing 7.85 pounds (3.56kg), made from 0.45% C-2% Ni-0.5% Mo steel, pressed and sintered to a density of 7.2g/cm^3, then hardened and tempered to a tensile strength of 140 ksi (965 MPa).

Powder-forged and other fully dense P/M nickel steel applications

Parts forged to full density from steel powder compacts have found many applications in recent years. One of the early applications was in cups and races for automotive ball and roller bearings[25], in which P/M *4625* steel was carburized and heat-treated after forging to final shape. The following paragraphs will cite several somewhat more complex parts made by the powder forging process, and other processes which develop full density.

Figure 34 is a good example of a fully-dense P/M forging for an automotive transmission.[31a] The caption provides details.

Figures 35 and *36* show three automotive parts made by Federal-Mogul from P/M *4600* type powders using their SintaForge process. The process was developed as a result of success in producing the bearing components whose excellent fatigue properties were described earlier.[25]

Lenel[6] discussed present and potential applications for powder forgings. He
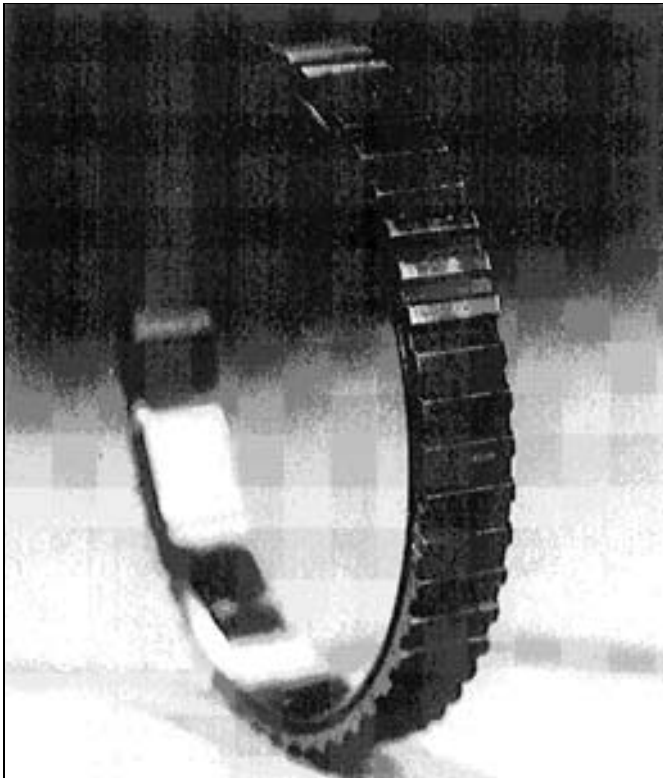
Figure 34. Forged P/M transmission race for Ford Sable and Taurus.[31a] "The high-strength part was made (from P/M *4600* steel) by the Powder Metal Products Division of Imperial Clevite, Inc., Salem, IN, for the Transmission and Chassis Division of Ford Motor Company, Dearborn, MI.

"The race is used in a spragtype clutch system.... This clutch system requires tight tolerances because of a sensitivity of total clutch assembly clearances. The race is forged to a density of 7.82g/cm^3 and has a hardness range in the inner diameter of 58-62 HRC. The race was designed as a P/M forging for improved fatigue and impact properties.

"Minimum tensile and yield properties are: 138 ksi (950 MPa) and 108 ksi (745 MPa). Through a new process developed by Imperial Clevite, the carbon levels throughout the part are varied to provide different hardnesses; 50 HRC minimum at 0.05 in. (1.3mm) depth and 45 HRC maximum at 0.11 in. (2.8mm) depth."

included several examples made from *4600* steel powders, such as transmission parts, antifriction bearings, and gears.

In a 1989 SAE paper [8] Mocarski and others cited "real progress in P/M forging" demonstrated by several clutch parts and a cam stator, made from a "modified *4600* grade" containing 0.25% C, 2% Ni, and 0.5% Mo; the hot-formed clutch parts were *sintercarburized* (combining sintering and carburizing, then presumably quenched) and the cam stator was sintered, hot-formed, machined, carburized and quenched.

The *Metals Handbook*[10] cites, as examples of automotive powder forgings, a 1.1 pound (500g) automatic transmission roller made from an iron-nickel-molybdenum alloy, and a 1.42 pound (645g) connecting rod. Several military equipment components were also cited.

McGee and Ward[32] discuss the use of P/M-forged spur bevel gears which present special problems in tool design. They then cite a truck transmission gear made from P/M forged *4620* steel, carburized to 0.050 in. (1.3mm) case depth then heat-treated to achieve a surface hardness of 58 HRC.

Toyota's application of powder forging to automotive parts has been discussed by Tsumuti and Nagara.[15] The specific application to a connecting rod was described earlier; other applications for nickel steels include ring-shaped parts for automatic transmissions that provide a significant cost benefit.

A 1989 editorial[34] presented prize-winning P/M applications that included a fully dense clutch collar for a heavy-duty truck, made from *4638* steel, pressed and sintered, and then further processed by a continuous hot forge/quench/draw operation to achieve a 57 HRC minimum surface hardness.
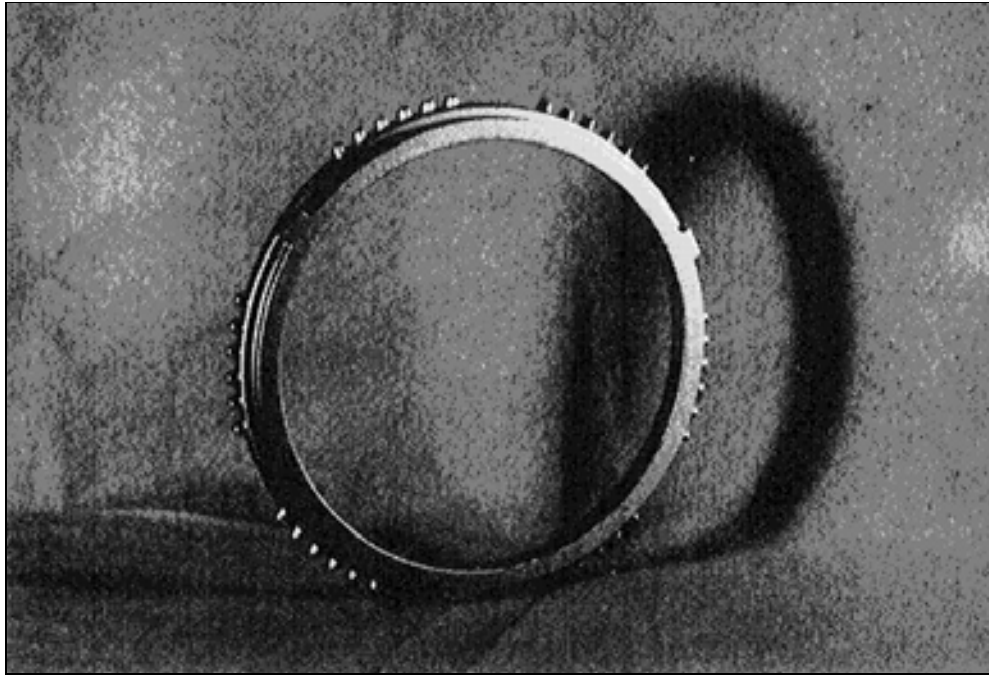
Figure 35. A sychronized blocker ring, made from forged P/M *4600* steel, carburized and air-cooled to 28 HRC max. The part was made by Federal-Mogul using its SintaForge process. Photograph courtesy of Federal-Mogul Corporation.

Figure 36. Reverse clutch cam, *left*, and converter clutch race, *right*, made by Federal-Mogul using its SintaForge process. The cam was forged from P/M *4625* steel carburized and hardened to 58 HRC min. The race was forged from P/M *4665* steel hardened to 58 HRC min. Photograph courtesy of Federal-Mogul Corporation.

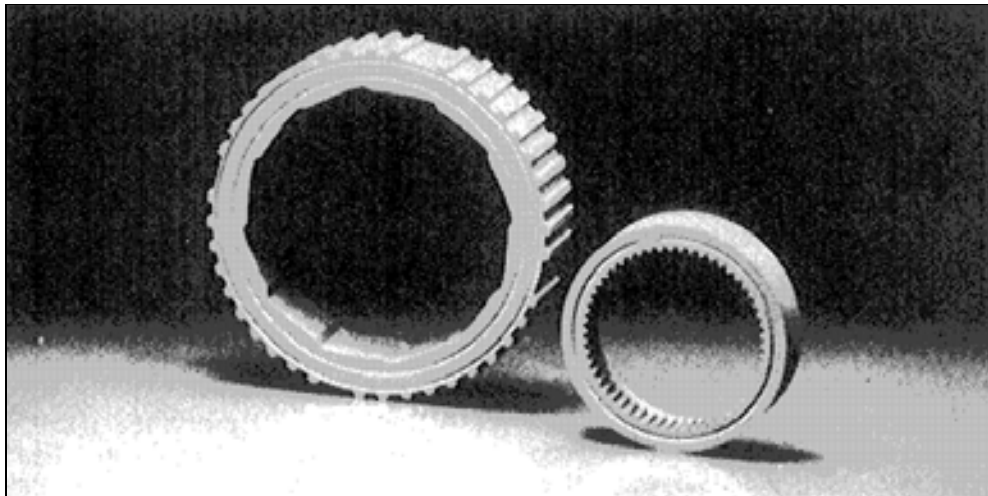Another prizewinner was a differential case made from *4620* steel, hot forged, carburized,air-cooled and then induction hardened. The clutch collar weighs 2.6 pounds (1.2kg) and the differential case weighs 4.5 pounds (2kg).

The Ceracon process can be used to achieve full density in complex parts such as the one shown in *Figure 37.*[31c]

In this process a preform is pressed from powders, then preheated to about 2000°F (1095°C). The preheated preform is placed in a simple preheated die cavity and is surrounded with preheated ceramic particles; the tool then transmits pressure to the part in a pseudo-isostatic manner. The figure caption gives more details for this part.
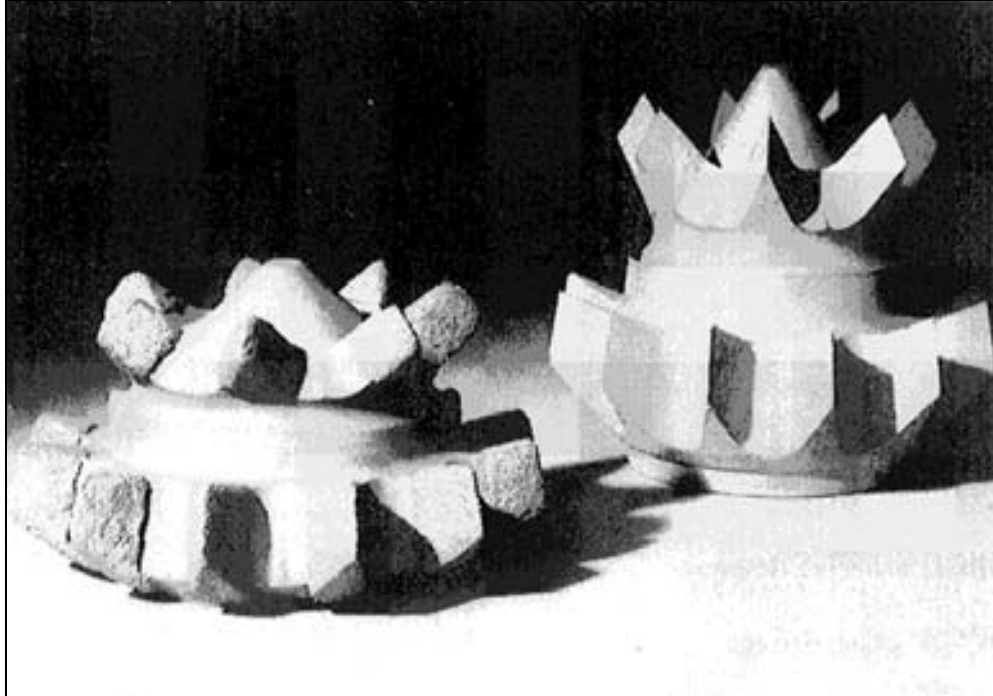

Figure 37. P/M-nickel steel roller cone drill bit hot-formed to full density, *left*; preform, *right*[31c]: This drill bit "is used in a downhole cutter for oil well drilling. Ceracon Inc., Sacramento, CA, made the part for Reed Tool Company, Houston, TX.

"Made by Ceracon's pseudo-isostatic process, the final density is 7.86g/cm^3. The 10.5 pound (4.75kg) part is austenitized, quenched and tempered, and has an ultimate tensile strength of 168 ksi (1160 MPa), a yield strength of 158 ksi (1090 MPa), an elongation of 13% and a Charpy impact strength of 17 ft-Ib (23 J).

"The bit was produced to a net shape that eliminates the need for conventional forging and machining. During the Ceracon process, the preform undergoes a 35% axial compression and a 7% lateral expansion. Secondary machining is limited to finishing the bore I.D. for a bearing.

"A tungsten carbide coating is applied to the preform during final consolidation to full density, creating an integrally-bonded hard coating on the bit. P/M offered an overall cost saving 50% of the cost of conventional forging and machining the cone.

"The Ceracon process works as follows: an 80% dense preform (isostatically or conventionally compacted) is preheated to approximately 2000°F (1095°C). The preform is then placed in a die cavity containing preheated pressure-transmitting media (graphite-type grain). A ram applies pressure to the media, which consolidates the preform to full density."

Materials and processing standards for P/M structural parts

When considering a P/M steel part for application as a structural member, it is best to take advantage of the latest techniques in a rapidly growing industry. Whether purchasing a part from a supplier, or planning to produce the part in-house, the specification and use of standard materials and standard test techniques are essential to assure consistent high quality.

The Metal Powder Industries Federation has developed material and test specifications, and has published important information to be used in specifying parts, in its P/M *Design Guidebook* [3]. The American Society for Testing and Materials [36] is also involved in such standardization, as is the Society of Automotive Engineers [37] and the International Organization for Standardization [38]. In addition, manufacturers of metal powders have specifications for their products that can be used pending development of standards by one of the organizations mentioned above. In the following paragraphs, some available specifications are reviewed.

MPIF standards

MPIF Standard 35, *Materials standards for PIM structural parts,* contains an introductory section defining the terms used in specifying both composition and properties of parts made from powders. [21] The standard includes sections on iron and carbon steel, iron-nickel and nickel steel, and low-alloy steel, in which the material characteristics, typical applications and microstructure are described. Then typical mechanical properties are listed in tabular form (excerpts from these tables are included in the section on *Mechanical properties* in this publication; the material designations being defined there).

Material characteristics and microstructure of each of the above-mentioned types are described in the following paragraphs.

Iron and carbon steel

These materials are manufactured by pressing and sintering iron powder with or without graphite additions to introduce carbon. When the final density is to be $7.0g/cm^3$ or more, it may be reached by pressing and presintering, repressing and sintering. Microstructure of the sintered compact consists of ferrite and pearlite, and the percent ferrite correlates with the carbon content.

Iron-nickel and nickel steel

These materials are manufactured from admixtures of elemental iron powder, elemental nickel powder and graphite powder (carbon), if required. Nickel additions are typically in the range 1 to 4%. Unlike carbon, complete diffusion of nickel into the iron matrix is not attained with normal commercial sintering cycles. The heterogeneous metallurgical structure developed contains nickel-rich phases that can impart significant improvements in toughness, tensile properties and hardenability. When the final density is to be $7.0g/cm^3$ or more, these materials may be manufactured by pressing, presintering, repressing and sintering. As-sintered nickel steels show light-colored, austenitic nickel-rich islands with needles of martensite or bainite around their edges.

In the heat-treated condition, the nickel-rich islands are austenite with martensitic needles at the peripheries (viewed at 1000X). This heterogeneous structure is normal and comprises

65 to 100% of the matrix, depending on quenching rate, the balance being fine pearlite.

Low-alloy steel

These materials are manufactured from prealloyed low-alloy steel powders using nickel, molybdenum and small amounts of manganese as the major alloying elements. Graphite powder (carbon) is admixed with the prealloyed steel powder to provide the necessary level of carbon in the final material. Prealloyed steel is normally selected for larger components or where a homogeneous microstructure is desirable. When density is to be 7.0g/cm^3 or more, these materials may be manufactured by pressing, presintering, repressing and sintering. Low-alloy P/M steels are typically used in the heat-treated condition to provide high strength and wear resistance. Current grades are:

FL-4205, containing 0.4/0.7% C, 0.35/0.55% Ni and 0.50/0.85% Mo.

FL-4605, containing 0.4/0.7% C, 1.70/2.00% Ni and 0.40/0.80% Mo.

Another publication of the MPIF, *Standard Test Methods for Metal Powders and Powder Metallurgy Products,* [35] contains a large group of important test techniques, including: Tension test specimens for pressed and sintered metal powders (#10), Determination of density of compacted or sintered metal powder products (#42), Determination of impact strength of sintered metal powder specimens (#40), Determination of hardness of sintered metal powder products (#43) and Determination of carburized case hardness and case depth (#37), among others.

ASTM standards

ASTM specification B783 defines ferrous P/M structural materials and adopts the material designation system in MPIF Standard 35. The ASTM specification includes acceptable chemical composition ranges for each grade, minimum yield strength for parts in the as-sintered condition and minimum ultimate tensile strength for parts in the heat-treated condition. Properties are based on specimens prepared either directly from the part or from specially prepared test bars, as agreed upon between the purchaser and the supplier. The grades, minimum properties and typical values are the same as in MPIF Standard 35, summarized earlier in *Tables I* and *II.*

Standards for forged P/M steels have been developed by ASTM[36.] These specifications include: B 790, Test method for unalloyed iron contamination of low-alloy powder-forged steel parts; B 796, Test method for nonmetallic inclusion level of low-alloy powder-forged steel parts; and B 797, Test methods for surface finger oxide penetration depth and the presence of interparticle oxide networks in low-alloy powder-forged steel parts.

ASTM standards are available for powder density (B212, B417, B703), powder flow rate (B213), green strength of compacts (B312), sampling lots of powders (B214), transverse rupture strength of sintered P/M specimens (B528), dimensional change of P/M compacts during sintering (B610), and sintered density and interconnected porosity (B328).

Society of Automotive Engineers

The current SAE Standard J471 specifies chemical composition, physical and mechanical properties of sintered ferrous P/M parts, both for bearings and for mechanical components. The Standard includes tolerances and defines methods of testing for specialized properties, such as crushing strength and density.

International Organization for Standardization

This organization has issued ISO 5755, *Specifications for sintered-metal materials.* Part 3 covers sintered alloy steels used for structural parts with densities in the range 6.4 to 7.0g/cm^3 (85 to 90% relative density). These ISO P/M steels are alloyed with a minimum of 1 % Ni, with some grades specifying a minimum of 3% Ni. Copper is present as a minimum of 1% except in two grades in which a maximum of 0.8% Cu is specified. One series specifies 0.3 to 0.7% Mo. Minimum density, minimum tensile strength and minimum hardness are specified, and approximate values of yield strength and elongation are given for information purposes. All values are for as-sintered test pieces; no standards are set nor data given for these materials in the heat-treated condition.

Other ISO standards for P/M steels include test methods for powders and P/M products. Tests on powders include tap density (3953), apparent density (3923, 4498), particle size (4497), flowability (4490), compressibility (3927) and oxygen content (4491, 4493).

For P/M compacts, ISO standards include determination of dimensional changes associated with compacting and sintering (4492), preparation of tensile test pieces (2740), determination of Young's modulus (3312), tensile testing (6892), preparation of fatigue-test pieces (3928), and determination of effective case depth of carburized or carbonitrided and hardened P/M compacts (4507).

Other proposed standards

The U.S. Army's Armament, Munitions and Chemical Command is in the process of approving a Military Specification, *Forgings, prealloyed steel powder, P/F 4620, P/F 4640 and P/F4660.* According to Mocarski and others[8], this draft contains requirements regarding chemical composition, density, mechanical properties, physical properties and microstructure; it also stipulates quality assurance provisions and quality conformance testing.

Powder producers also have published typical data for their powders and properties of P/M steel parts produced from them. Such data sheets are available from the producers.

References

1. E. E. Carlson, "New high strength ferrous P/M materials", *Progress in Powder Metallurgy, V.* 25, 1969, p. 63.

2. M. D. Kennedy, "Increased use of powder metals in the '90s", *Industrial Heating,* April, 1989, p. 50.

3. *Powder metallurgy design guidebook,* Publication GP-12-74 Metal Powder Industries Federation, Princeton, NJ 08540, 1974 and later edition, 1980. See also *Powder metallurgy design manual,* 1989.

4. Y. Morioka and S. Takajo, "Recent developments in low-alloy steel powder", *Modern developments in powder metallurgy, V.* 21, 1988, p. 521.

5. N. Kawai, K. Notomi and S. Furuta, "Rolling contact fatigue property of powder forged parts", *Metal Powder Reports, V.* 42, N° 11, 1987, p. 798.

6. F. V. Lenel, *Powder Metallurgy – Principles and Applications,* Metal Powder Industries Federation.

7. S Mocarski and D. W. Hall, "P/M parts for automotive applications", *Metal Powder Reports, V.* 42, N° 11, 1987, p. 754.

8. S. Mocarski, D. W. Hall, J. Khanuja and S. K. Suh, "Powder metal parts for automotive applications – Part III," SAE Technical paper 890409, SAE International, Warrendale PA 15096, 1989.

9. U. Engstrom and S. Allroth, "A Newly-developed sintered high-strength material", *Horizons in Powder Metallurgy, Part II,* July, 1986, p. 1039, Verlag Schmid, D-7800 Freiburg, Germany.

10. Powder Metallurgy, Metals Handbook, Ninth Edition, V. 7, ASM International, Metals Park, OH 44073.

11. L. F. Pease, "An assessment of powder metallurgy today and its future potential", SAE Technical paper 831042, 1983.

12. Y. E. Smith and R. Pathak. "New hardenability data for application in low-alloy ferrous powder forging", *Progress in Powder Metallurgy, V.* 28, 1972, Metal Powder Industries Federation.

13. G. T. Eldis, D. E. Diesburg and Y. E. Smith, "High-hardenability ferrous powders for P/M forgings", *Progress in Powder Metallurgy, V.* 33, 1977, p. 67.

14. *Modern carburized nickel alloy steels,* NiDI Reference Book Series, 11005, Nickel Development Institute, Toronto, Ontario, Canada M5C 2E3

15. C. Tsumuti and I. Nagare, "Application of powder forging to automotive parts", *Metal Powder Reports, V.* 39, N° 11, 1984, p. 629.

16. B. L. Ferguson, "Emerging alternatives to hot isostatic pressing", *Carbide and Tool Journal,* May/June 1986, p. 17.

17. H. Zhang, R. M. German, K. F. Hens and D. Lee, "Processing effects on the mechanical properties of and injection-molded Fe-2% Ni alloy", *Industrial Heating,* Feb. 1990, pp. 33-38.

18. I. Bertilsson and B. Karlsson, "Dynamic properties of sintered steel", *Powder Metallurgy, V.* 30, N° 3, 1987, p. 183.

19. R. C. O'Brien, "Fatigue properties of P/M materials", SAE Technical paper 880165, 1988.

20. A. A. Hendrickson, P. M. Machmeier and D. W. Smith, "Effects of processing variables on the mechanical properties of P/M-forged and Heat-Treated 4650-60 steels", *Horizons of powder metallurgy– Part 1,* July 1986, p. 453, Verlag Schmid.

21. *Materials standards for P/M structural parts,* MPIF Standard 35, 1990-1991 edition, Metal Powder Industries Federation.

22. J. Tengzelius, "A new powder for high-strength applications", *La Revue de Metallurgie*– CIT*,* Dec. 1988, p. 1007.

23. B. Linqvist, "Influence of microstructure and porosity on fatigue properties of sintered steels", *Modern Developments in Powder Metallurgy,* V. 21, 1988, p. 67.

24. K. Ogura, T. Abe, Y. Makiishi, S. Takajo, T. Minegishi and E. Hatsugai, "Properties of high-compressibility composite-type alloy steel powders – KIP Sigmalloy," *Metal Powder Reports,* V. 43, $N^{\underline{o}}$ 11, 1988, p. 738.

25. J. S. Adams and D. Glover, "Improved bearings at lower cost via powder metallurgy", *Metal Progress,* Aug. 1977, p. 39.

26. W. B. James, "Quality assurance procedures for powder-forged materials", SAE paper $N^{\underline{o}}$ 830364, SAE transactions, 1983, p. 37.

27. D. J. Burr, "Prealloyed, premixed, and hybrid sintered steels", *International Journal of Powder Metallurgy & Powder Technology,* V. 13, $N^{\underline{o}}$ 2, Apr. 1977, p. 121.

28. D. P. Townsend, "Surface fatigue and failure characteristics of hot-forged powder metal 4620, 4640 and machined AISI 4340 steel spur gears", NASA technical memorandum 87330. 1986.

29. M. Feir, "Structural P/M parts in power tools", *International Journal of Powder Metallurgy & Powder Technology,* V*. 10,* N°- 1, 1974, p. 43.

30. D. G. White, "Growing internationalization of powder metallurgy", *Industrial Heating,* April, 1989, p. 62.

31.(a-c). P. K. Johnson. "Award-winning parts show broad spectrum of P/M applications", *International Journal of Powder Metallurgy, (a)* Vol. 22, $N^{\underline{o}}$ 4, 1986, (b) Vol. 24, $N^{\underline{o}}$ 3, 1988, (c) Vol. 25, $N^{\underline{o}}$ 3, 1989.

32. S. W. McGee and N. L. Ward, "Advances in P/M gear capabilities", *Progress in Powder Metallurgy, V.* 33, 1977, p. 123.

33. S. W. McGee, "Design of P/M gears", SAE paper 830295, in SAE SP-535, 1983, p. 11.

34. "Advanced P/M applications acknowledged at 1989 powder metallurgy conference", editorial in *Industrial Heating,* Aug. 1989, p. 32.

35. *Standard test methods for metal powders and powder metallurgy products, 1985-1986 edition,* Metal Powder Industries Federation.

36. *Annual Books of Standards,* American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103.

37. *Annual Handbook,* Volume 1, Materials, Society of Automotive Engineers (SAE International), 400 Commonwealth Drive, Warrendale, PA 15096.

38. International Organization for Standardization, 1 rue de Varembé, Genève, Switzerland.