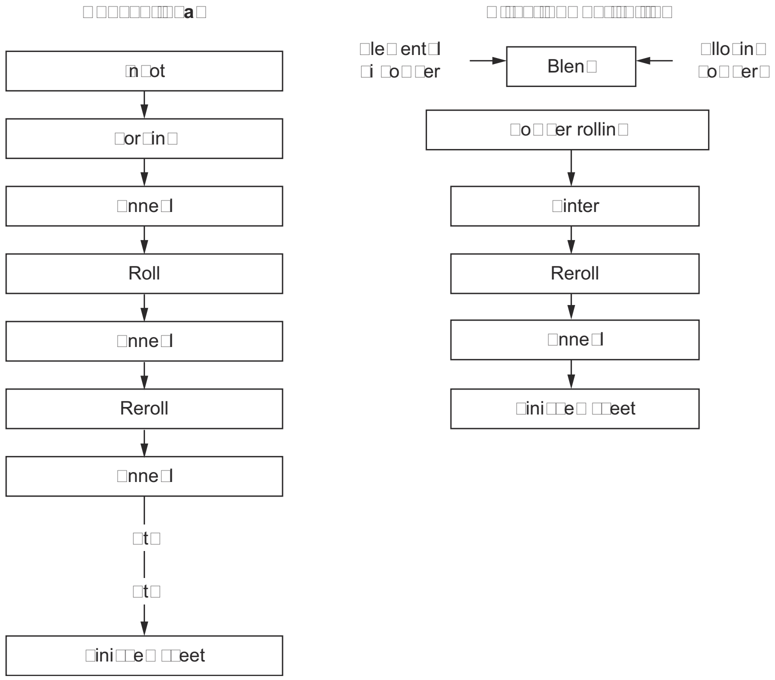

Fig. 4 Comparison of the conventional ingot-based process with the direct powder rolling process for titanium alloy sheet

In this process, the fine, irregular titanium powder or titanium alloy blend is fed from a hopper into the roll gap of the compacting rolls. It is drawn through the nip partially by friction between the powder and roll surface and partially by gravitational force. A coherent green strip is produced. Subsequent processing involves sintering to densify the rolled sheet of powder particles. This is followed up with an additional cold reduction step along with an additional sintering or annealing operation. If required, one or more temper rolling passes are given to produce the final finished product.

The direct powder rolling of titanium and titanium blended elemental powders, such as Ti-6Al-4V alloy, offers several benefits as listed below, and hence it could be the preferred manufacturing process for producing flat products of Ti and other Ti alloys (foils, sheets, plates) for various applications:

- Low capital cost compared to traditional melting, forging, etc.
- Fewer operating steps compared with melting, forging, etc.
- Availability of low cost raw materials
- Precision control of composition and ability to use high purity metals
- Applicable to composite type mixtures or immiscible components which currently cannot be produced by conventional methods
- Absence of texture and uniformity of microstructures and properties in longitudinal and transverse directions
- Adaptability and versatility, including ability to roll multilayer structures

The powder metallurgy (PM) approach to produce flat products (foil, sheet, plate) by low cost direct powder rolling process was investigated by DuPont back in the 1950s and 1960s. They produced a titanium sponge by sodium reduction process that was reduced to powder, and this powder was ideally suited for DPR process to produce sheets and to extrude green compacted billets to bar, tubing, and shapes (Ref 5, 6). Commercially pure (CP) titanium sheet and Ti-6Al-4V sheet were produced by compacting powder continuously in the nip between two rolls. Through the development of a feed hopper and an edge control system, sheet with high green strength and green density in excess of 90% of theoretical density was produced (Ref 7, 8). The green sheet was coiled and sintered off line in a continuous, inert gas, sintering furnace. Final rolling resulted in high-strength alloy foils with typical Ti-6Al-4V properties.

Imperial Clevite had been employing DPR titanium process since the late 1970s and had demonstrated capability to manufacture high strength titanium alloys (e.g. Ti-6Al-4V and Ti-6Al-2Sn-4Zr-2Mo) foil for honeycomb structures to obtain large, light-weight, high stiffness panels by the beginning of the 1980s (Ref 9).

The market for high volume applications of PM Ti-6Al-4V and other advanced titanium alloys was never tested. The major drawback was associated with the weldability issue related to PM titanium alloys, exhibiting unacceptable porosity of the finished titanium alloy strip (theoretical density of the sintered strip was in the range of 95%). The presence of chlorides (up to 0.10 wt%) trapped within the PM microstructures volatilized rapidly during welding and caused a buildup of salt on the tungsten welding electrodes which led to an unstable arc. It was estimated that satisfactory weldability would be reached at a chloride level of 0.005 wt% or less. It was judged to be impractical to achieve these low chloride levels from the manufacturing and cost standpoints. Other contributing factors were the absence of a domestic high volume titanium powder producer, high cost of available titanium powders, competition with other proven and well-established technologies, and lack of clear guidelines in planning and execution of development projects.

Technology has advanced significantly since DuPont's and Imperial Clevite's work. A new method for production of low cost and extra low chlorine content titanium powder has been recently developed by ADMA Products, Inc. (Ref 10, 11). Other processes are being developed to produce titanium powder rather than sponge or other forms of titanium; they are outlined in Ref 12. ADMA Products, Inc. has developed a process for direct powder rolling of titanium alloy into both fully dense and porous flat products (foil, sheet, plate) (Ref 13, 14). Figure 5 shows a schematic of room temperature direct powder rolling process used by ADMA Products, Inc.

Various thicknesses (1.27–6.35 mm, or 0.05–0.25 in.) and densities (50–99+%) of CP titanium, Ti-6Al-4V, Ti-Al and other Ti alloy strips and Ti-6Al-4V reinforced composite have been produced by direct powder rolling at ADMA Products, Inc. (Fig. 6). To produce the near-full theoretical density foils, sheets and plates, the green density achieved in the direct powder rolling process should be in excess of 60% of theoretical full density. The microstructure of sintered to near-full density DPR Ti6Al-4V sheet is shown in Fig. 7.

Ti-6Al-4V blend has been rolled to 318 mm (12.5 in.) wide strips of the various thicknesses (0.635–2.5 mm, or 0.025–0.100 in., thick) and green densities in the range of 50% to 90% of theoretical density. The strips were sintered in vacuum furnace, and the resulting microstructures are shown in Fig. 7. The microstructures are typically Widmanstätten (basket viewed type) mixed with equiaxed elements, which should provide good combination of mechanical properties.

Titanium metal matrix composites (TMMC) and multilayer composite strips can also be produced by the direct powder rolling process. All previously practiced processes for manufacturing dense titanium matrix composites from Ti-alloy matrix and reinforcing powders have shown considerable drawbacks. The resulting products have been unsatisfactory in terms of density, strength, and ductility, as well as cost. The products lacked in their resistance to internal oxidation due to presence of interconnected porosity. This led to rapid oxidation of the reactive titanium powder to a substantial depth during hot consolidation (HIPing, hot pressing).

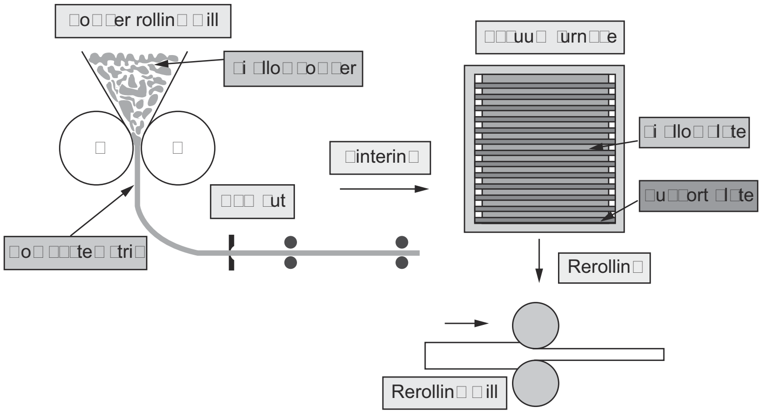

Fig. 5 Schematic of room temperature direct powder rolling. Courtesy ADMA Products, Inc.

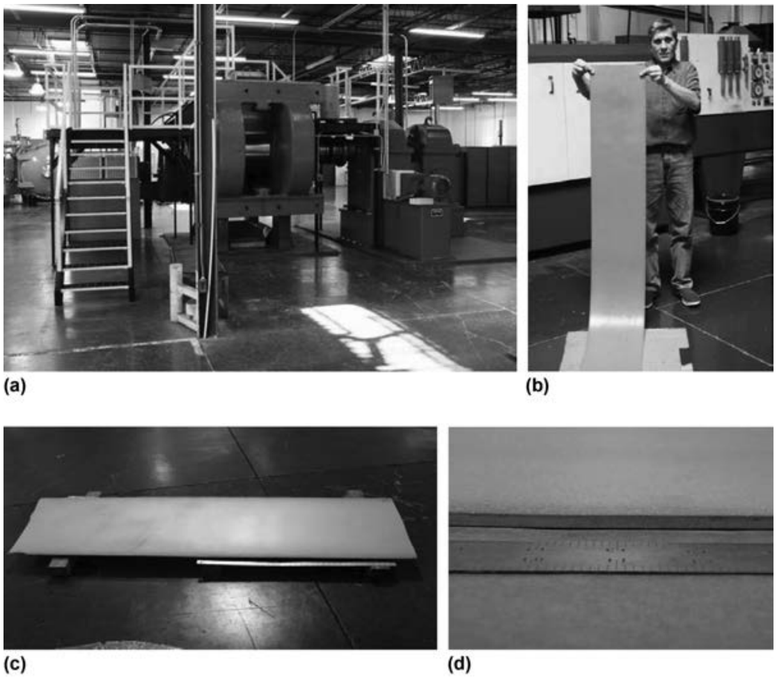

Fig. 6 (a) Direct powder rolling mill, (b) 0.25 mm (0.010 in.) thick porous Ti strip, (c) and (d) 6.35 mm (0.25 in.) thick Ti-6Al-4V direct powder rolled plate. Courtesy ADMA Products, Inc.

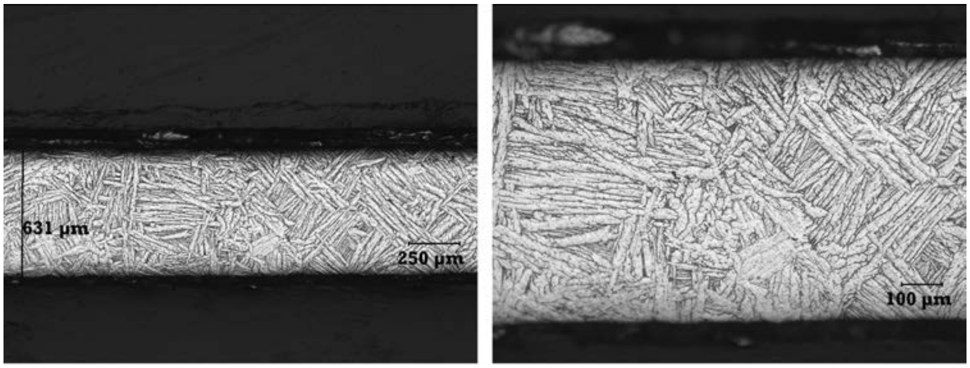

Fig. 7 Microstructures of PM direct powder rolled Ti-6Al-4V strips produced from ADMA titanium powder. UTS = 965 MPa (140 ksi), YS = 848 MPa (123 ksi), El = 12.5%

Use of cases and encapsulation did not fully protect the sintered article from rapid oxidation, and it also increased production costs. Significant differences in structural and mechanical properties between sintered material and material used for encapsulation resulted in nonuniform deformation and stress concentration in the TMMC during the hot deformation. Cracks occurred in various areas of the sintered material during the first cycles of hot deformation due to interconnected porosity and stress concentration. These cracks do not allow maintaining a reliable and reproducible manufacturing process through forging or hot rolling.

To resolve these manufacturing issues, the following requirements were considered in production of the composite materials at ADMA: a high-strength and near fully dense titanium matrix composite having less than 2% discontinuous porosity after sintering, a cost-effective method for producing such composites using blended elemental powders, and using in-situ formation of reinforced particles by co-attrition of graphite with elemental metals, blending this co-attrited powder with CP titanium and master alloy to achieve the required titanium alloy composition, room temperature consolidation and forming carbides during sintering. The major goal was to produce near-full density parts from a titanium matrix composite material that has acceptable mechanical properties without a need for further hot deformation and/or to provide a powder metallurgy technique for manufacturing near-net shape sintered titanium MMC that can be used as a final product in as-sintered conditions or after hot deformation without finishing by machining or chemical milling and to establish a continuous cost-effective process to produce fully dense flat and shaped titanium alloy matrix composite parts with controlled size tolerances from either blended elemental powders or from a combination of a prealloyed and elemental powder blend.

These requirements could be achievable by using complex carbides as additional reinforcing components in the Ti/TiC composite structure, and by providing a method through which the sintered structure has only the discontinuous porosity being close to theoretical full density, while at the same time, the composite material exhibits acceptable mechanical properties in the as-sintered conditions, and/or it is manufactured while foregoing hot deformation without any encasing, canning, or encapsulating if more complicated shapes with improved size control of the finished parts or improved properties are required.

The microstructures of BE Ti-6Al-4V composite materials manufactured from ADMA hydrogenated titanium powder by direct powder rolling and sintering are presented in Fig. 8. Homogeneous lamellar $\alpha+\beta$ microstructure with average grain size of 100–120 μm and fine TiVCrC (5–20 μm) reinforcements uniformly distributed was observed in direct powder rolled and sintered strip.

The relatively small grain size is caused by the pinning effect of particulates. EDS analysis and x-ray diffraction analysis (Fig. 9) on the polished surfaces confirmed that the TiVCrC particles were formed. Metallographic observation together with x-ray analysis confirmed that carbon diffuses into Ti-Al-V matrix and forms the carbide particles during sintering. Chromium content in precipitates does not exceed 2.0 wt%, which is consistent with previously reported results (Ref 15). The densities of sintered material were close to full theoretical density.

The roll compaction process, developed by Ametek Corporation for the commercial production of nickel alloy sheets, was used to manufacture titanium thin gage sheets from ITP titanium powder (Ref 16). Roll compaction begins with raw Ti powder fed into rolls from a hopper. The rolls compact the ductile powder into sheet. The sheet is then fed into a furnace where it is sintered. Subsequent roll and sinter operations are performed continuously until a dense, thin gage sheet is produced. Figure 10 shows a schematic of the roll compaction process.

Microstructural investigations were performed on the roll-compacted titanium and Ti-6Al-4V thin gage sheet materials. Optical microscopy revealed that the roll-compacted titanium sample had a microstructure similar to the structure shown in Fig. 11(c). Throughout the cross section, the roll-compacted sheet was virtually flaw free with a consistent microstructure. The roll-compacted Ti-6Al-4V showed a typical Widmanstätten structure with some areas of retained alpha, indicating that some oxidation might have occurred. Tensile testing results for the roll-compacted samples are shown in Table 1. Figure 12 shows the microstructures of the roll-compacted titanium and Ti-6Al-4V sheet. The mechanical properties of roll-compacted titanium sheet showed that the strengths are comparable to grade 4 titanium. However, the oxygen content of the roll-compacted titanium sample slightly exceeded the allowable limit for grade 4 and ductility suffered as a result. The mechanical properties of the roll-compacted titanium exceeded the lower limits for grade 5 Ti-6Al-4V, but the ductility was slightly lower than expected. Again, the oxygen content slightly exceeded the allowable limit for grade 5 Ti-6Al-4V. The chemical analysis of the roll-compacted materials is shown in Table 2.

The combination of direct powder rolling with hot rolling densification (HRD) was used for manufacturing the commercially pure titanium sheet at CSIRO (Fig. 11a) (Ref 17). The properties of feedstock (Ti powder) determine compaction behavior and resulting properties of green strip: morphology, flow, fill/tap density, and chemistry. The green densities of DPR titanium strips were in the range of 70-05% of theoretical (Fig. 11b). The properties of the consolidated strip (Fig. 11c) depend on the hot rolling densification process parameters: preheat temperature, dwell time, rolling speed, as well as the degree of deformation, microstructure, and chemistry.

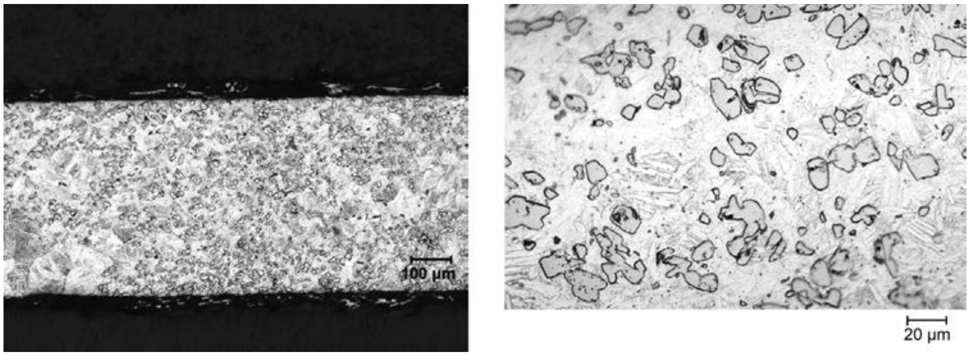

Fig. 8 Microstructure of titanium MMC strip produced by direct powder rolling plus sintering. Density is 4.25 g/cm^3.

Intensity, imp/second

	Cr	V	Al	Ti
Particle 1	300	6500	120-180	75,000
Particle 2	1500	7500	200-250	73,000
Matrix white	10,500	14,000	350-400	78,000
Matrix gray	9000	15,000	430-450	78,000

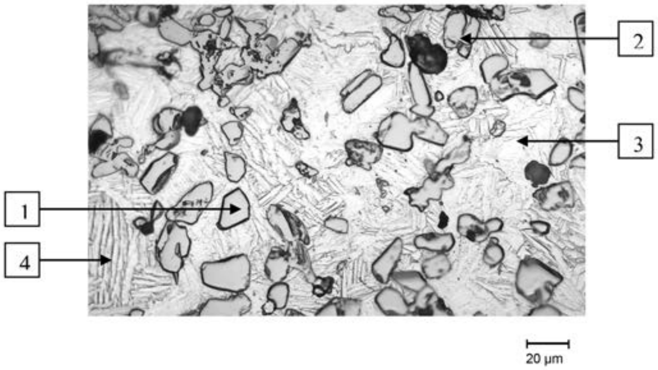

Fig. 9 X-ray diffraction analysis of titanium MMC manufactured using ADMA

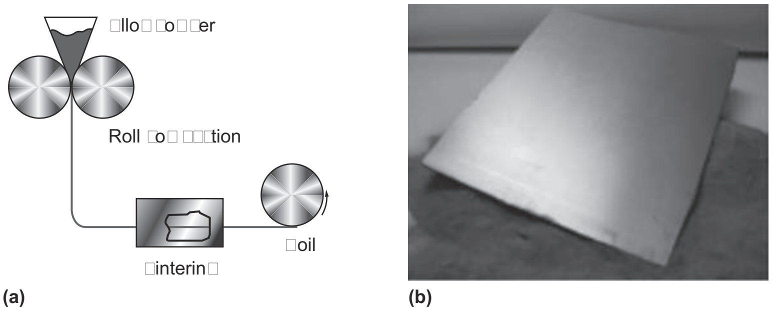

Fig. 10 (a) Schematic of Ametek roll compaction process and (b) roll-compacted sheet (Ref 16)

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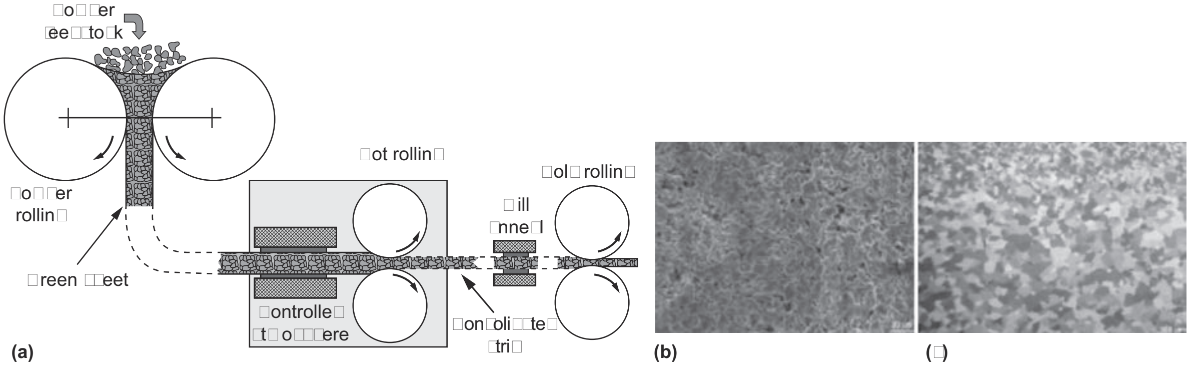

Fig. 11 CSIRO DPR/HRD process: (a) schematic, (b) microstructure of green Ti strip, and (c) consolidated strip. Source: Ref 17

Table 1 Mechanical testing results of roll-compacted Ti sheet

	Yield strength		Tensile strength		
Sample	**MPa**	**ksi**	**MPa**	**ksi**	**Elongation, %**
Ti roll compacted	529	77	656	95	9.6
CP Ti grade 4 (min values)	483	70	552	80	15.0
Ti-6Al-4V roll compacted	909	132	1,040	151	7.3
Ti-6Al-4V grade 5 (min values)	828	120	897	130	10.0

Source: Ref 16

Table 2 Chemical analysis of roll-compacted thin gage Ti sheet

Sample	O_2	N_2	C
Ti roll compacted	0.42	0.01	0.03
CP Ti grade 4 (max limit)	0.40	0.05	0.08
Ti-6Al-4V roll compacted	0.26	0.03	0.02
Ti-6Al-4V grade 5 (max limit)	0.20	0.05	0.08

Source: Ref 16

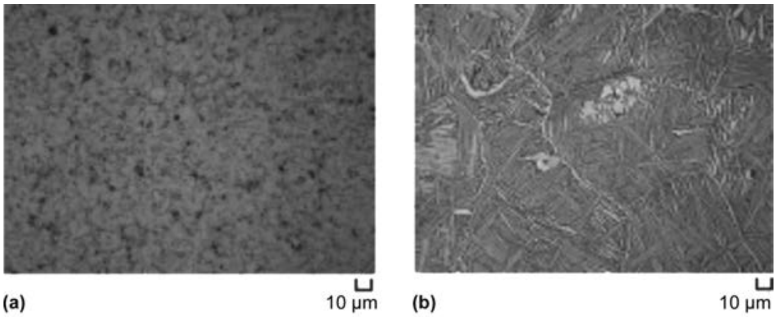

Fig. 12 The microstructure of thin gage sheet samples of (a) roll compacted titanium and (b) roll compacted Ti-6Al-4V. Source: Ref 16

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Ferrous Powder Metallurgy Materials*

Updated and revised by W. Brian James, Hoeganaes Corp., retired

FERROUS POWDER METALLURGY (PM) processing is a net or near-net-shape production technology, which generally minimizes the need for postsintering (secondary) machining operations. Ferrous PM offers a wide range of engineered materials for use in structural applications and satisfies close dimensional tolerance requirements for parts with complex geometries.

When a material is selected for an intended application, it is important that a "systems" approach, as illustrated in Fig. 1, is followed (Ref 1). Part designers should involve part fabricators, tool designers, and material engineers from the outset of an application development program. Performance targets for the part need to be defined, as well as the application environment. The part fabricator can suggest design changes that will lead to a more robust PM part, and the designer can assess the impact of the proposals on the anticipated performance of the part. It is important to determine from the outset whether the fabricator can make a net-shape part or whether postsintering machining operations will be needed. This has a major influence on the material selection for any proposed part processing sequence.

In addition, ferrous PM encompasses several production technologies other than traditional press and sinter operations. These include copper-infiltrated steels, powder-forged steels, and injection-molded steels, which are discussed in detail in separate articles in this Section. Other options are also used to increase the performance of PM parts, including additional processing (Fig. 2a) (Ref 2) and alloying (Fig. 2b) (Ref 3). This article briefly summarizes the general classification, mechanical properties, and applications of ferrous PM materials for parts production. More detailed coverage on major alloys and processing methods are discussed elsewhere in this Volume and in Ref 3 and 4.

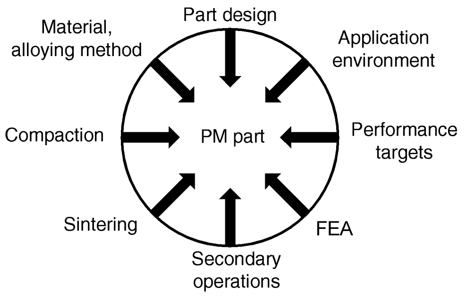

Fig. 1 Systems approach to PM part development. Source: Ref 1

Alloying Methods

Four principal ferrous PM alloy types are:

- Admixed elemental alloys
- Diffusion alloys (also known as partially alloyed materials)
- Prealloys
- Hybrid alloys

Each method is described and the benefits and disadvantages of each method are reviewed together with the effect of processing on material microstructure and properties. In general, comments made with respect to sintering relate to sintering at a temperature of 1120 °C (2050 °F) unless specified otherwise.

Admixed Elemental Powders. Alloying additions in elemental form and as ferroalloys (e.g., Fe_3P, FeMn, and FeCr) are mixed with an iron powder. This is generally the least expensive, most commonly used alloying method in ferrous PM. When the mix is pressed, the additions are not alloyed with the iron powder; therefore, admixed materials retain most of the compressibility of the base iron powder. The degree of alloying during sintering is limited by the diffusivity of alloying elements in iron at the sintering temperature. The resulting microstructures are chemically and microstructurally inhomogeneous.

Direct-reduced sponge iron and water-atomized iron powders are used as the base powder for admixed elemental materials. The density required to achieve desired mechanical properties generally dictates which type of powder is used. Sponge powders are selected typically for the density range of 6.4 g/cm^3 and lower, while atomized iron powders are used for parts with a density of 6.7 g/cm^3 and higher. Either type of powder can be used for the intermediate density range; the choice generally depends on part geometry and available compacting press tonnage.

Diffusion-Alloyed Powders. In diffusion-alloyed powders, also known as partially alloyed powders, the alloy addition or additions are metallurgically bonded to either an elemental iron powder or to a prealloyed powder base (see the section "Prealloyed Powders" for an explanation of prealloyed powders). Diffusion alloying of additions is controlled to provide adequate bonding of the additions to the base powder while limiting the extent of diffusion of the additives so they do not appreciably reduce the compressibility of the base powder.

While there is a wide range of diffusion-alloyed powders available in Europe (Ref 5), there are only two grades in widespread commercial use in North America, South America, and Canada. Both are based on a highly compressible iron powder, containing nominally 1.5 wt% Cu and 0.5 wt% Mo, and differ with respect to their nickel contents (1.75 wt% Ni and 4 wt% Ni). Parts made using diffusion-alloyed powders have a complex as-sintered microstructure consisting of areas of martensite, bainite, fine unresolved pearlite, nickel-rich ferrite containing blocky carbides, and dispersed nickel-rich areas (Fig. 3). This complex microstructure provides a combination of good tensile strength, tensile ductility, and excellent impact energy.

Prealloyed Powders. Prealloyed, low-alloy steel powders are particularly useful in the manufacture of PM parts designed for use in high-performance applications. Combinations of molybdenum, manganese, and nickel are added to molten iron during the steelmaking process to produce a chemically uniform powder. Practices are followed during melting and atomization to ensure production of powders with nonmetallic inclusion content suitable for the most stringent requirements. The reactivity of

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* Revised from W.B. James and G.T. West, Ferrous Powder Metallurgy Materials, *Powder Metal Technologies and Applications*, Vol 7, *ASM Handbook*, ASM International, 1998, p 751–768.

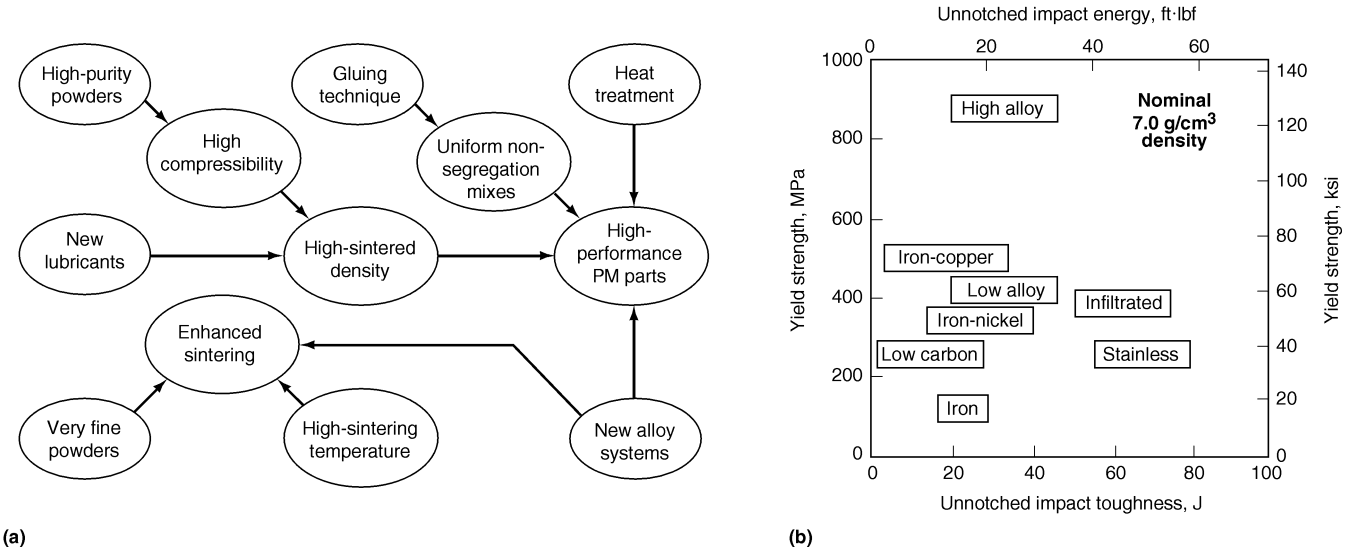

Fig. 2 General methods to achieve high-performance PM steels. (a) Processing options. (b) Higher alloying to improve strength and toughness. Source Ref 2 and 3

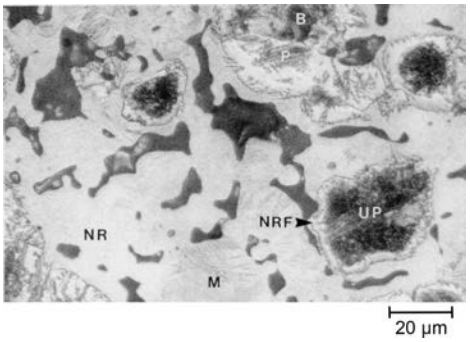

Fig. 3 As-sintered microstructure of a part made of a diffusion-alloyed powder FD-0405: B, bainite; P, pearlite; UP, unresolved pearlite; NR, nickel-rich region; NRF, nickel-rich ferrite; M, martensite

carbon, in the form of graphite, with prealloyed powders is excellent, enabling close control of combined carbon content during sintering.

These powders are used in a wide range of applications. Varying performance requirements are satisfied through a combination of alloy selection, carbon additions, and processing conditions. In general, the compressibility of prealloyed powders is lower than that of admixed and diffusion-alloyed powders. However, prealloyed powders, in which molybdenum is the principal alloy addition, have compressibilities comparable to those of iron powders (Ref 1).

Hardenability of prealloyed materials is controlled by the amount and type of alloying used and can be tailored to fit specific applications. Prealloyed materials have homogeneous microstructures with uniform apparent hardness. Unlike elemental admixed, diffusion-alloyed, and some hybrid alloys, alloying is not primarily dependent on diffusion processes. Nevertheless, just as with elemental admixed, diffusion-alloyed, and hybrid alloys (discussed later), higher sintering temperatures (>1120 °C, or 2050 °F) and longer sintering times (greater than 20 min at temperature) influence the number, size, and shape of pores present in the microstructure. Pore coalescence occurs with increasing sintering temperature and time; large pores grow at the expense of smaller pores. Increased time and temperature also lead to reduced irregularity of pore shape.

Certain applications require supplemental alloy additions via admixing to enhance hardenability and mechanical properties of the material. Such materials are termed hybrid alloys.

Hybrid-Alloy Powders. Hybrid alloys consist of either prealloyed or diffusion-alloyed base powders to which elemental or ferroalloy additions are made to achieve the desired chemical composition. The practice of making nickel and copper additions to prealloyed powders has become widespread since the introduction of highly compressible, prealloyed powders with molybdenum as the principal alloy addition (Ref 1, 6). These powders are also particularly suitable for the addition of high-carbon ferroalloys to produce chrome-molybdenum, manganese-molybdenum, and chrome-molybdenum-manganese steels (Ref 7). Elemental nickel additions are made to diffusion-alloyed powders to provide even greater impact properties (Ref 8, 9). Compressibility and hardenability of hybrid-alloy materials depend primarily on the compressibility and hardenability of the base powder used. Hybrid materials generally have an inhomogeneous microstructure with nonuniform apparent hardness. Higher sintering temperatures and longer sintering times lead to greater diffusion of alloy additions and to more homogeneous microstructures.

Ferrous Powder Materials

Material code designations for ferrous PM materials are found in Metal Powder Industries Federation (MPIF) Standard 35, Materials Standards for PM Structural Parts. Similar designations have been adopted by ASTM, and are summarized in specification B783, "Standard Specification for Materials for Ferrous Powder Metallurgy (PM) Structural Parts" (Ref 10). These standards are subject to periodic review, and users are cautioned to refer to the latest edition. Prefixes used for ferrous material designations are:

- F, iron
- FC, iron-copper and copper steel
- FN, iron-nickel and nickel steel
- FD, diffusion-alloyed steel (partially alloyed)
- FL, prealloyed ferrous material, except stainless steel
- FLD, diffusion-alloyed steel based on a prealloyed powder
- FX, copper-infiltrated iron and steel
- SS, stainless steel (prealloyed)

Figure 4 provides examples of material designations. The designation FN-0205-35 (Fig. 4a) refers to a nickel steel with nominally 2 wt% Ni, 0.3 to 0.6 wt% combined carbon, and a guaranteed minimum 0.2% offset yield strength of 240 MPa (35 ksi). The FN prefix designates an admixed nickel steel, and the 02 following the prefix indicates that there is nominally 2 wt% of the major alloy addition (nickel). The 05 refers to the combined carbon content of the material. Code designations for various combined carbon contents are:

Combined carbon range, wt%	Code designation
0–0.3	00
0.3–0.6	05(a) (b)
0.6–0.9	08

(a) The 05 designation for the FL materials (prealloyed) refers to 0.4 to 0.7 wt% combined carbon. (b) The 05 designation for FLC-4805 refers to 0.5 to 0.7 wt% combined carbon.

The designation FL-4405-175HT in Fig. 4(b) refers to a quench-hardened and tempered prealloyed steel with a combined carbon content of 0.4 to 0.7 wt% and a guaranteed minimum ultimate tensile strength of 1210 MPa (175 ksi).

For as-sintered materials, the material designation suffix refers to the guaranteed minimum 0.2% offset yield strength in ksi. For example, FC-0208-50 refers to an admixed copper steel with nominally 2 wt% Cu, a combined carbon content of 0.6 to 0.9 wt%, and a guaranteed minimum 0.2% offset yield strength of 340 MPa (50 ksi).

For heat-treated materials, the material designation suffix refers to the guaranteed minimum ultimate tensile strength in ksi. For example, FN-0205-130HT refers to elementally admixed nickel steel with nominally 2 wt% nickel, a combined carbon content of 0.3 to 0.6 wt%, and a guaranteed minimum ultimate tensile strength of 900 MPa (130 ksi).

Admixed Elemental Powders

Elemental admixed materials are used throughout the ferrous PM industry. They contain sufficient graphite to provide the desired carbon content after sintering because the typical base powders used are essentially carbon free. Base powders have low carbon contents because carbon forms an interstitial solid solution with iron and significantly reduces the compressibility of the powder. In addition to graphite, mixes contain a lubricant that aids particle rearrangement during the initial stages of compaction. However, the principal purpose of lubricant is to reduce friction between powder particles and compaction tooling members (die wall, core rods, and punches) and make ejection of the compacted part easier. Lubricant additions vary from 0.5 wt% to sometimes >1 wt%, depending on the part geometry, part density, and the surface area of the compact at the die-wall and core rod interfaces. Lubricant additions of 0.75 wt% are common. Lubricants are generally metallic stearates (e.g., zinc stearate) and ethylene bisstearamides. The use of zinc stearate is decreasing due to environmental concerns related to products released to the atmosphere following delubrication. Lubricants are white solids with pycnometric densities of ~1 g/cm^3. Typical additions are about 0.75 wt%, but due to their low density relative to that of iron, they occupy ~5.5 vol% in the mixture. This is particularly significant when parts are compacted at high pressures (Ref 11–13).

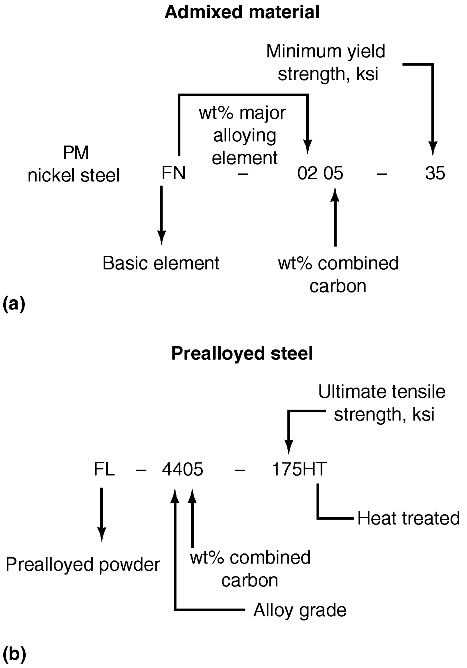

Fig. 4 Examples of ferrous PM material designations. (a) FN-0205-35 and (b) FL-4405-175HT

Because various powders that comprise elemental admixed alloys have different particle sizes and densities, admixed alloys are particularly susceptible to dusting and segregation during handling and transfer to the die cavity. Numerous opportunities exist during the PM process for dusting and segregation to occur (Ref 14). Compositional variations that result from these demixing phenomena cause inconsistencies in green and sintered properties of PM parts. The tendency for mixes to dust and segregate is reduced significantly through the use of binder-treated premixes (Ref 15–18). In addition to reducing dusting and segregation, binder-treated premixes improve powder flow and die-filling characteristics during part manufacturing, which results in more consistent part sectional densities and improved control of part mass. Improved flow and die-fill uniformity result in reduced press cycle times and more consistency throughout the entire part manufacturing process.

Improved retention of alloy additions provides an economic advantage in terms of reduced amounts of green scrap, enhanced alloy efficiency, and a more pleasant, easier to maintain work environment. Plant cleanliness is dramatically improved, and the amount of respirable dust in the immediate vicinity of the compaction press is reduced by an order of magnitude (Fig. 5) (Ref 1). Binder-treated premixes are produced using a proprietary mixing process that utilizes patented binders (Ref 15–18).

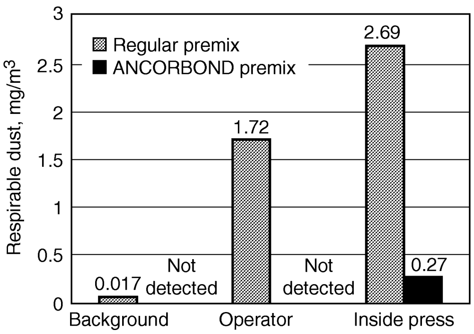

Fig. 5 Respirable dust in the work area of a plant for manufacturing PM parts Source: Ref 1

Iron and Carbon Steels. Table 1 summarizes the chemical compositions of the iron and carbon steels listed in MPIF Standard 35 – Materials Standards for PM Structural Parts.

Unalloyed iron (F-0000) materials are used in lightly loaded structural applications and for structural parts requiring self-lubrication where strength is not critical. The combined carbon content of these materials can be from 0 to 0.3 wt%. Iron parts that are essentially carbon free are often used (particularly at higher part densities) for their soft magnetic properties (Ref 19–21). In this case, they are given the designation FF-0000. The last two digits (00) relate to the combined carbon content, which, for soft-magnetic materials such as this, is from 0.00 to 0.03 wt%, as carbon is particularly detrimental to soft-magnetic performance.

PM carbon steels with 0.3 to 0.6 wt% combined carbon (F-0005) have moderate strength and apparent hardness. They are used in applications where such properties combined with machinability are desired.

Higher carbon PM steels (F-0008) have moderately higher strength compared with F-0005 materials, but are more difficult to machine. In the as-sintered condition, carbon steels have a ferrite/pearlite microstructure (Fig. 6). Both F-0005 and F-0008 steels can be heat treated to increase tensile strength, improve apparent

Table 1 Chemical composition of iron and carbon steels

	Chemical composition, wt%		
Material designation	Fe	C	Other elements
F-0000	Balance	0.0	min
		0.3	max
F-0005	Balance	0.3	min
		0.6	max
F-0008	Balance	0.6	min
		0.9	max

Other elements: Total by difference equals 2.0 wt% maximum, which may include other minor elements added for specific purposes. Source: MPIF Standard 35, Materials Standards for PM Structural Parts, 2012 Edition

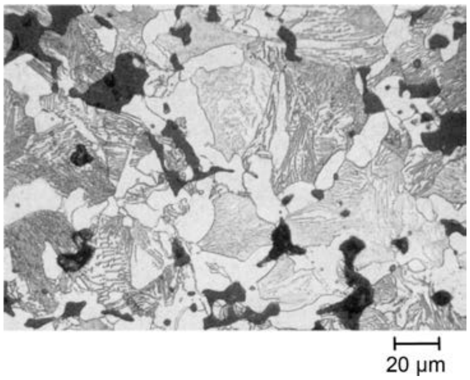

Fig. 6 Ferrite-pearlite microstructure of an as-sintered PM carbon steel (F-0005)

hardness, and enhance wear resistance. Heat treated carbon steels have a martensitic microstructure (Fig. 7). Table 2 summarizes mechanical properties of various carbon steels.

PM carbon steels often are steam treated to improve shelf life; close surface-connected porosity; and increase compressive yield strength, apparent hardness, and wear resistance. However, steam treatment significantly degrades tensile properties (Ref 22).

Iron-Copper and Copper Steels. Table 3 summarizes chemical compositions of iron-copper and copper steels listed in MPIF Standard 35 Materials Standards for PM Structural Parts.

Copper is added to increase strength, apparent hardness, and wear resistance. Copper steels (FC-0205 and FC-0208) are used in medium-strength structural applications. Copper steels with combined carbon content greater than 0.5 wt% are more difficult to machine than copper steels with lower combined carbon content. In the as-sintered condition, copper steels have a ferrite-pearlite microstructure. FC-0208 material shown in Fig. 8 is almost of the eutectoid composition, and is mostly pearlitic.

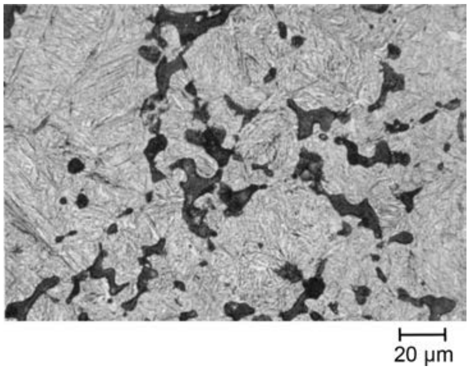

Fig. 7 Tempered martensitic microstructure of a quench-hardened and tempered PM carbon steel (F-0008)

Copper steels can be heat treated to increase strength, apparent hardness, and wear resistance. Table 4 summarizes mechanical properties of various copper steels.

Heat-treated copper steels have martensitic microstructures (Fig. 9). Higher copper contents are used for increased wear resistance when heat treatment is not practical.

Copper melts at 1083 °C (1981 °F), leaving a pore at the site of a prior copper powder particle. Admixed copper powders typically are −270 mesh (−53 μm). This is considerably coarser than the size of admixed nickel powders (8 μm), and the pore structure of copper steels is considerably different from that of admixed nickel steels (Fig. 10) (Ref 23). Sintered copper steels with 2 wt% Cu generally show little or no undissolved copper. At higher percentages, the copper is observed as a separate phase. The form of the copper phase indicates whether the material was heated to a temperature in excess of 1083 °C (1981 °F) (Fig. 11). When copper has precipitated from solid solution, there is a considerable difference in the shape and distribution of the copper. The copper is no longer in the form of discrete particles; typically, it follows grain boundary contours and fills small pores (Fig. 12).

Table 3 Chemical composition of iron-copper and copper steels

	Chemical composition, wt%			
Material designation	Fe	Cu	C	Other elements
FC-0200	Balance	1.5	0.0	min
		3.9	0.3	max
FC-0205	Balance	1.5	0.3	min
		3.9	0.6	max
FC-0208	Balance	1.5	0.6	min
		3.9	0.9	max
FC-0505	Balance	4.0	0.3	min
		6.0	0.6	max
FC-0508	Balance	4.0	0.6	min
		6.0	0.9	max
FC-0808	Balance	7.0	0.6	min
		9.0	0.9	max
FC-1000	Balance	9.0	0.0	min
		11.0	0.3	max

Other elements: Total by difference equals 2.0 wt% maximum, which may include other minor elements added for specific purposes. Source: MPIF Standard 35, Materials Standards for PM Structural Parts, 2012 Edition.

Iron-Nickel and Nickel Steels. Table 5 lists the chemical compositions of iron-nickel and nickel steels listed in MPIF Standard 35 Materials Standards for PM Structural Parts.

Typical admixed nickel additions in PM nickel steels range from 2 to 4 wt%. Nickel does not diffuse very rapidly in iron, nor does iron diffuse very rapidly in nickel at the typical sintering temperature of 1120 °C (2050 °F). The sintered microstructure of these materials contains nickel-rich regions that improve toughness

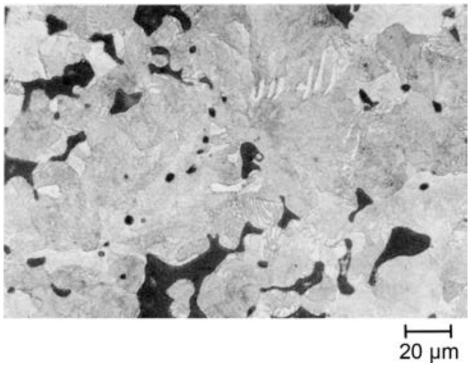

Fig. 8 Ferrite-pearlite microstructure of an as-sintered PM copper steel (FC-0208)

Table 2 Mechanical properties of iron and carbon steels

Minimum values			Typical values											
			Tensile properties			Elastic constants					Rockwell hardness			
Material designation code	Minimum strength, ksi Yield	Minimum strength, ksi Ultimate	Ultimate strength, ksi	Yield strength (0.2%), ksi	Elongation in 1 in. %	Young's modulus, 10^6 psi	Poisson's ratio	Unnotched Charpy impact energy, ft · lbf	Transverse rupture strength, ksi	Compressive yield strength (0.1%), ksi	Macro (apparent)	Micro (converted)	Fatigue limit (90% survival), ksi	Density, g/cm^3
F-0000-10	10	· · ·	18	13	1	15.0	0.25	3	36	16	40 HRF	N/D	7	6.1
F-0000-15	15	· · ·	25	18	2	17.5	0.25	6	50	18	60 HRF	N/D	10	6.7
F-0000-20	20	· · ·	38	25	7	23.5	0.28	35	95	19	80 HRF	N/D	14	7.3
F-0005-15	15	· · ·	24	18	<1	15.0	0.25	3	48	18	25 HRB	N/D	9	6.1
F-0005-20	20	· · ·	32	23	1	16.5	0.25	4	64	23	40 HRB	N/D	12	6.6
F-0005-25	25	· · ·	38	28	1	19.5	0.27	5	76	28	55 HRB	N/D	15	6.9
F-0005-50HT	· · ·	50	60	(a)	<1	16.5	0.25	3	105	43	20 HRC	58 HRC	23	6.6
F-0005-60HT	· · ·	60	70	(a)	<1	18.5	0.27	3.5	120	52	22 HRC	58 HRC	27	6.8
F-0005-70HT	· · ·	70	80	(a)	<1	20.5	0.27	4	140	61	25 HRC	58 HRC	32	7.0
F-0008-20	20	· · ·	29	25	<1	12.5	0.25	2.5	51	28	35 HRB	N/D	11	5.8
F-0008-25	25	· · ·	35	30	<1	16.0	0.25	3	61	31	50 HRB	N/D	14	6.2
F-0008-30	30	· · ·	42	35	<1	16.5	0.25	4	74	31	60 HRB	N/D	17	6.6
F-0008-35	35	· · ·	57	40	1	20.5	0.27	5	100	36	70 HRB	N/D	25	7.0
F-0008-55HT	· · ·	55	65	(a)	<1	16.5	0.25	3	100	70	22 HRC	60 HRC	26	6.3
F-0008-65HT	· · ·	65	75	(a)	<1	16.5	0.25	4	115	80	28 HRC	60 HRC	30	6.6
F-0008-75HT	· · ·	75	85	(a)	<1	19.5	0.27	4.5	130	90	32 HRC	60 HRC	34	6.9
F-0008-85HT	· · ·	85	95	(a)	<1	21.5	0.27	5	145	100	35 HRC	60 HRC	38	7.1

HT, heat treated; N/D, not determined for the purposes of this standard. Suffix numbers represent minimum strength values in ksi (10^3 psi); yield in the as-sintered condition and ultimate in the heat-treated condition. Mechanical property data derived from laboratory prepared test specimens sintered under commercial manufacturing conditions. Tempering temperature for heat-treated materials: 180 °C (350 °F). (a) Yield and ultimate tensile strength are approximately the same for heat-treated materials. Source: MPIF Standard 35, Materials Standards for PM Structural Parts, 2012 Edition.

Table 4 Mechanical properties of various iron-copper and copper steels

Minimum values			Typical values											
	Minimum strength, ksi		Tensile properties			Elastic constants					Rockwell hardness			
Material designation code	Yield	Ultimate	Ultimate strength, ksi	Yield strength (0.2%), ksi	Elongation in 1 in. %	Young's modulus, 10^6 psi	Poisson's ratio	Unnotched Charpy impact energy, ft · lbf	Transverse rupture strength, ksi	Compressive yield strength (0.1%), ksi	Macro (apparent)	Micro (converted)	Fatigue limit (90% survival), ksi	Density g/cm^3
FC-0200-15	15	···	25	20	1	14.0	0.25	4.5	45	18	60 HRF	N/D	10	6.0
FC-0200-18	18	···	28	23	1	16.5	0.25	5	51	21	65 HRF	N/D	11	6.3
FC-0200-21	21	···	31	26	1	16.5	0.25	5.5	56	23	26 HRB	N/D	12	6.6
FC-0200-24	24	···	34	29	2	19.5	0.27	6	63	26	36 HRB	N/D	13	6.9
FC-0205-30	30	···	35	35	<1	14.0	0.25	<2	60	35	37 HRB	N/D	13	6.0
FC-0205-35	35	···	40	40	<1	16.5	0.25	3	75	40	48 HRB	N/D	15	6.3
FC-0205-40	40	···	50	45	<1	17.5	0.25	5	95	45	60 HRB	N/D	21	6.7
FC-0205-45	45	···	60	50	<1	21.5	0.27	8	115	50	72 HRB	N/D	31	7.1
FC-0205-60HT	···	60	70	(a)	<1	16.0	0.25	2.5	95	57	99 HRB	58 HRC	27	6.2
FC-0205-70HT	···	70	80	(a)	<1	15.5	0.25	3.5	110	71	25 HRC	58 HRC	30	6.5
FC-0205-80HT	···	80	90	(a)	<1	18.5	0.27	4.5	120	86	31 HRC	58 HRC	34	6.8
FC-0205-90HT	···	90	100	(a)	<1	20.5	0.27	5.5	135	95	36 HRC	58 HRC	38	7.0
FC-0208-30	30	···	35	35	<1	12.5	0.25	<2	60	40	50 HRB	N/D	13	5.8
FC-0208-40	40	···	50	45	<1	16.5	0.25	2	90	45	61 HRB	N/D	17	6.3
FC-0208-50	50	···	60	55	<1	17.5	0.25	5	125	50	73 HRB	N/D	23	6.7
FC-0208-60	60	···	75	65	<1	22.5	0.28	7	155	55	84 HRB	N/D	33	7.2
FC-0208-50HT	···	50	65	(a)	<1	15.0	0.25	2.5	95	58	20 HRC	60 HRC	25	6.1
FC-0208-65HT	···	65	75	(a)	<1	17.5	0.27	3.5	110	72	27 HRC	60 HRC	30	6.4
FC-0208-80HT	···	80	90	(a)	<1	18.5	0.27	4.5	130	91	35 HRC	60 HRC	35	6.8
FC-0208-95HT	···	95	105	(a)	<1	21.5	0.27	5.5	150	105	43 HRC	60 HRC	40	7.1
FC-0505-30	30	···	44	36	<1	12.5	0.25	3	77	50	51 HRB	N/D	17	5.8
FC-0505-40	40	···	58	47	<1	16.5	0.25	4.5	102	54	62 HRB	N/D	22	6.3
FC-0505-50	50	···	71	56	<1	17.5	0.25	5	124	58	72 HRB	N/D	27	6.7
FC-0508-40	40	···	58	50	<1	13.0	0.25	3	100	58	60 HRB	N/D	22	5.9
FC-0508-50	50	···	68	60	<1	16.5	0.25	3.5	120	63	68 HRB	N/D	26	6.3
FC-0508-60	60	···	82	70	<1	18.5	0.27	4.5	145	68	80 HRB	N/D	31	6.8
FC-0808-45	45	···	55	50	<1	14.0	0.27	3	85	62	65 HRB	N/D	21	6.0
FC-1000-20	20	···	30	26	<1	14.0	0.27	3.5	53	33	60 HRF	N/D	11	6.0

HT, heat treated; N/D, not determined for the purposes of this standard. Suffix numbers represent minimum strength values in 10^3 psi; yield in the as-sintered condition and ultimate in the heat-treated condition. Mechanical property data derived from laboratory prepared test specimens sintered under commercial manufacturing conditions. Tempering temperature for heat-treated materials: 180 °C (350 °F). (a) Yield and ultimate tensile strength are approximately the same for heat-treated materials. Source: MPIF Standard 35, Materials Standards for PM Structural Parts, 2012 Edition.

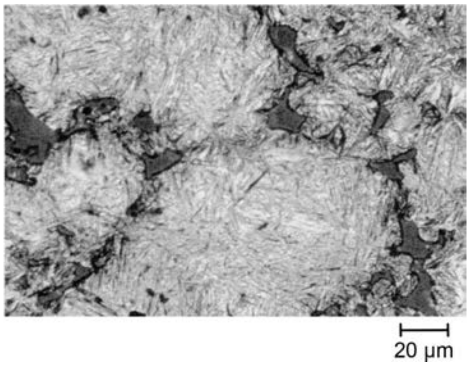

Fig. 9 Tempered martensitic microstructure of a quench-hardened and tempered PM copper steel (FC-0208)

significantly, particularly in the heat-treated condition (Fig. 13). PM nickel steels are used mainly for heat-treatable structural parts that need a combination of strength, wear resistance, and good impact toughness. Table 6 summarizes the mechanical properties of various nickel steels.

Copper-Infiltrated Iron and Steel

Table 7 summarizes the chemical composition limits of the copper-infiltrated irons and

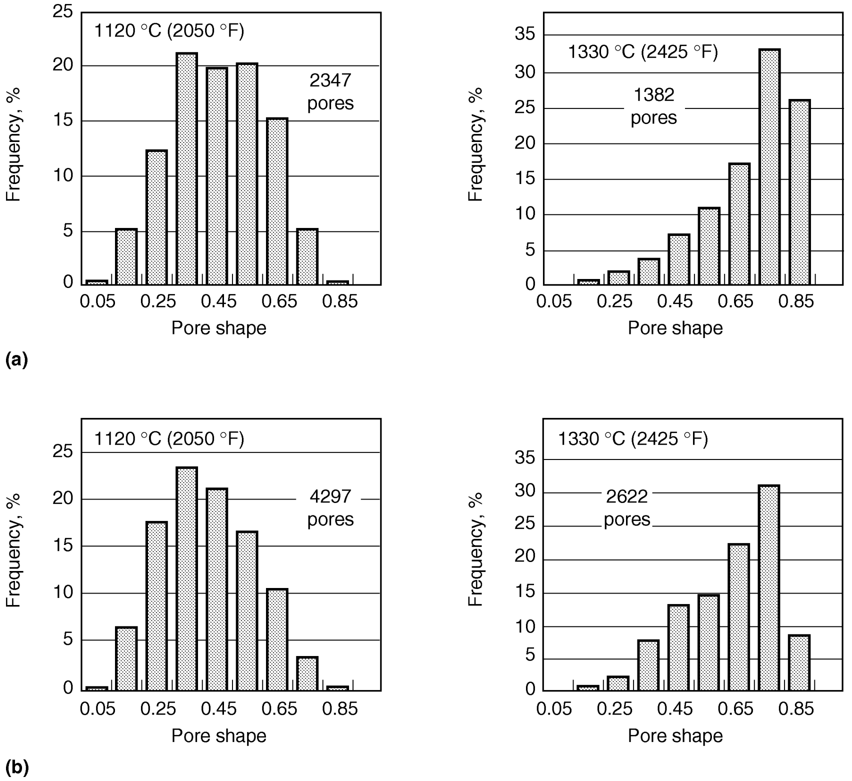

Fig. 10 Shape and size of porosity in PM copper (FC-0208) and nickel (FN-0208) steels. Pore shape = 4nA/p2 (for a circulare pore = 1). Source: Ref 23

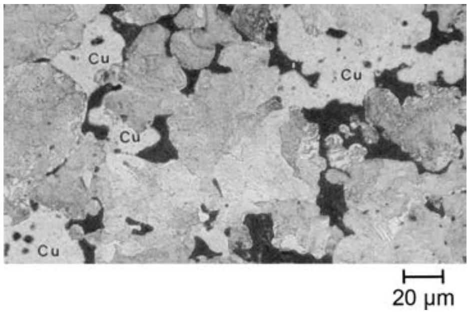

Fig. 11 Free copper in a PM copper steel (FC-0508) that has not reached a temperature of 1080 °C (1980 °F) during sintering

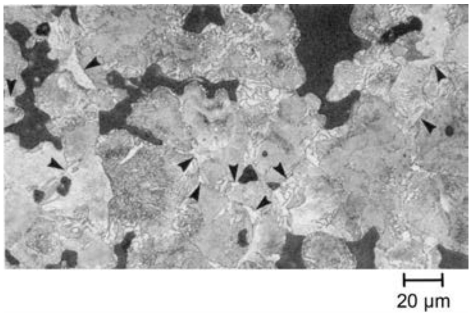

Fig. 12 Free copper (see arrows) that precipitated from solution in a PM copper steel (FC-0508)

Table 5 Chemical composition of iron-nickel and nickel steels

Material designation	Chemical composition, wt%				
	Fe	Ni	C	Cu	Element
FN-0200	Balance	1.0	0.0	0.0	min
		3.0	0.3	2.5	max
FN-0205	Balance	1.0	0.3	0.0	min
		3.0	0.6	2.5	max
FN-0208	Balance	1.0	0.6	0.0	min
		3.0	0.9	2.5	max
FN-0405	Balance	3.0	0.3	0.0	min
		5.5	0.6	2.0	max
FN-0408	Balance	3.0	0.6	0.0	min
		5.5	0.9	2.0	max

Other elements: Total by difference equals 2.0 wt% maximum, which may include other minor elements added for special purposes. Source: MPIF Standard 35, Materials Standards for PM Structural Parts, 2012 Edition.

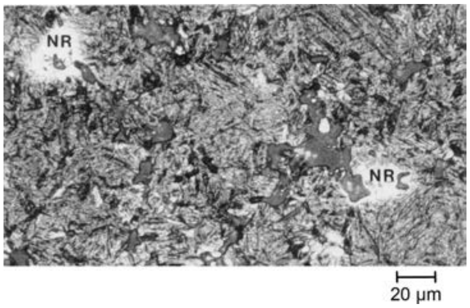

Fig. 13 Nickel-rich regions (NR) in a tempered martensitic structure of a quench-hardened and tempered PM nickel steel (FN-0208)

steels listed in MPIF Standard 35 Materials Standards for PM Structural Parts.

Infiltration is the process of filling surface-connected pores of a PM part with an alloy of lower melting point than the base material. The lower melting point alloy is drawn into the pores by capillary force (Fig. 14). Infiltrants are generally alloys of copper with iron, zinc, and manganese (Ref 24). Infiltrant slugs can be placed on top of the PM compact, beneath the compact, or both on top and beneath. The mass of the infiltrant slug is calculated to fill the surface-connected, interconnected pore volume of the compact. The infiltration process can be either a single step or double step. In the single-step process, parts are infiltrated at the same time as they are sintered. It is extremely important for the green compact to be delubricated properly prior to reaching the high heat zone of the sintering furnace. Improper delubrication leads to problems with infiltration. In double-step infiltration, parts are sintered and cooled to room temperature under a protective atmosphere. Infiltrant slugs are then positioned, and the parts are subjected to a second sintering operation during which infiltration of interconnected porosity occurs. Some parts have selected areas infiltrated to enhance properties in critical areas; a process known as selective infiltration.

Infiltration leads to higher, more uniform densities, which, in turn, results in enhanced mechanical properties. Filling surface-connected porosity makes parts pressure tight for use in medium-pressure hydraulic applications. Infiltrated parts have improved machinability and better electrical and thermal conductivity, and they can be plated. Infiltration can also be used as a joining process to make multicomponent PM assemblies during the sintering process.

Copper-infiltrated parts are used in the as-infiltrated condition or are heat treated to improve strength, apparent hardness, and wear resistance. Table 8 summarizes mechanical properties of various copper-infiltrated irons and steels. More information is contained in the article "Copper-Infiltrated Steels" in this Volume.

Phosphorus irons are admixed alloys made by adding fine (<20 µm and preferably close to 10 µm) ferrophosphorus particles to high compressibility iron powders (Ref 25–27). These alloys exhibit a good combination of tensile strength, ductility, and impact absorption energy. However, they are primarily used for parts requiring superior soft electromagnetic performance. Compared with parts made using pure, high-compressibility iron powders, those made using phosphorus irons have higher resistivity, permeability, and induction and reduced coercive field strength. The presence of phosphorus also decreases the susceptibility of a PM part to nitrogen aging (Ref 21). Typical soft-magnetic properties and mechanical properties of phosphorus irons with two levels of phosphorus (0.45 and 0.80 wt%), sintered under various conditions, are summarized in Table 9 from ASTM A839, "Standard Specification for Iron-Phosphorus Powder Metallurgy Parts for Soft Magnetic Applications." Typical applications for parts made using phosphorus irons include antilock brake sensors, magnetic solenoids, and plungers. More information on typical applications is found in the article "Magnetic Materials and Properties for Powder Metallurgy Part Applications" in this Volume.

Diffusion-Alloyed (Partially Alloyed) Powders

Table 10 summarizes chemical compositions for various diffusion-alloyed (partially alloyed) steels listed in MPIF Standard 35 Materials Standards for PM Structural Parts. Some of these materials (FD) are based on a highly compressible iron powder to which alloy additions are diffusion alloyed. Others (FLD) are based on a prealloyed (1.5 wt% Mo) powder to which alloy additions are diffusion alloyed. While dusting and segregation tendencies of alloy additions are reduced through diffusion alloying, diffusion-alloyed materials typically contain sufficient admixed graphite to provide the desired combined carbon content during sintering and lubricant to facilitate compaction. These additives are susceptible to dusting and segregation and, therefore, mixes of diffusion-alloyed powders are improved by binder treatment. The complex microstructures of these materials (Fig. 3) lead to a good combination of tensile strength, ductility, and toughness. Diffusion-alloyed materials are heat treated to improve strength, apparent hardness, and wear resistance. Table 11 summarizes mechanical properties of various diffusion-alloyed materials.

Prealloyed Powders

Table 12 summarizes chemical compositions of various prealloyed, low-alloy steels listed in MPIF Standard 35 Materials Standards for PM Structural Parts, and mechanical properties of materials made using prealloyed powders are summarized in Table 13. Prealloyed powders are generally used for parts that require heat treatment. The hardenability of the prealloyed materials is controlled by the amount and type of alloying used. Nickel-molybdenum prealloyed powders have lower compressibility than prealloyed powders that use molybdenum alone as the principal alloying agent (Fig. 15). Parts made using prealloyed powders have a homogeneous microstructure, are chemically homogeneous, and have a uniform apparent hardness. In the as-sintered condition, carbides that form are not lamellar in nature (compare Fig. 16 with Fig. 6). In the as-sintered condition, prealloyed materials are identified by this characteristic carbide morphology. In the heat-treated condition, parts made using prealloyed powders exhibit a uniform tempered martensitic microstructure (Fig. 17). Prealloyed powders that use chromium as the

Table 6 Mechanical properties of various iron-nickel and nickel steels

Minimum values			Typical values											
	Minimum strength, ksi		Tensile properties			Elastic constants					Rockwell hardness			
Material designation code	Yield	Ultimate	Ultimate strength, ksi	Yield strength (0.2%), ksi	Elongation in 1 in. %	Young's modulus, 10^6 psi	Poisson's ratio	Unnotched Charpy impact energy, ft · lbf	Transverse rupture strength, ksi	Compressive yield strength (0.1%), ksi	Macro (apparent)	Micro (converted)	Fatigue limit (90% survival), ksi	Density, g/cm^3
FN-0200-15	15	···	25	17	3	16.5	0.25	10	50	16	55 HRF	N/D	10	6.6
FN-0200-20	20	···	35	25	5	20.5	0.27	20	80	18	75 HRF	N/D	13	7.0
FN-0200-25	25	···	40	30	10	23.5	0.28	50	105	20	80 HRF	N/D	15	7.3
FN-0205-20	20	···	40	25	1	16.5	0.25	6	65	25	44 HRB	N/D	14	6.6
FN-0205-25	25	···	50	30	2	19.5	0.27	12	100	30	59 HRB	N/D	18	6.9
FN-0205-30	30	···	60	35	4	22.5	0.28	21	125	35	69 HRB	N/D	22	7.2
FN-0205-35	35	···	70	40	5	24.5	0.28	34	150	40	78 HRB	N/D	26	7.4
FN-0205-80HT	···	80	90	(a)	<1	16.5	0.25	3.5	120	60	23 HRC	55 HRC	26	6.6
FN-0205-105HT	···	105	120	(a)	<1	19.5	0.27	4.5	160	80	29 HRC	55 HRC	35	6.9
FN-0205-130HT	···	130	145	(a)	<1	21.5	0.27	6	190	100	33 HRC	55 HRC	42	7.1
FN-0205-155HT	···	155	160	(a)	<1	22.5	0.28	7	215	120	36 HRC	55 HRC	47	7.2
FN-0205-180HT	···	180	185	(a)	<1	24.5	0.28	9.5	250	140	40 HRC	55 HRC	54	7.4
FN-0208-30	30	···	45	35	1	17.5	0.25	5.5	85	35	63 HRB	N/D	16	6.7
FN-0208-35	35	···	55	40	1	19.5	0.27	8	105	40	71 HRB	N/D	20	6.9
FN-0208-40	40	···	70	45	2	21.5	0.27	11	130	45	77 HRB	N/D	25	7.1
FN-0208-45	45	···	80	50	2	23.5	0.28	16	155	50	83 HRB	N/D	28	7.3
FN-0208-50	50	···	90	55	3	24.5	0.28	21	170	55	88 HRB	N/D	32	7.4
FN-0208-80HT	···	80	90	(a)	<1	17.5	0.25	4	120	99	26 HRC	57 HRC	29	6.7
FN-0208-105HT	···	105	120	(a)	<1	19.5	0.27	4.5	150	124	31 HRC	57 HRC	38	6.9
FN-0208-130HT	···	130	145	(a)	<1	20.5	0.27	5.5	185	136	35 HRC	57 HRC	46	7.0
FN-0208-155HT	···	155	170	(a)	<1	22.5	0.28	7	220	162	39 HRC	57 HRC	54	7.2
FN-0208-180HT	···	180	195	(a)	<1	24.5	0.28	8	250	188	42 HRC	57 HRC	62	7.4
FN-0405-25	25	···	40	30	<1	15.5	0.25	4.5	65	33	49 HRB	N/D	14	6.5
FN-0405-35	35	···	60	40	3	20.5	0.27	14.5	120	40	71 HRB	N/D	22	7.0
FN-0405-45	45	···	90	50	4	24.5	0.28	33.5	175	45	84 HRB	N/D	32	7.4
FN-0405-80HT	···	80	85	(a)	<1	15.5	0.25	4	115	67	99 HRB	55 HRC	26	6.5
FN-0405-105HT	···	105	110	(a)	<1	18.5	0.27	5	145	89	25 HRC	55 HRC	34	6.8
FN-0405-130HT	···	130	135	(a)	<1	20.5	0.27	6.5	200	103	31 HRC	55 HRC	42	7.0
FN-0405-155HT	···	155	160	(a)	<1	23.5	0.28	9.5	245	124	37 HRC	55 HRC	49	7.3
FN-0405-180HT	···	180	185	(a)	<1	24.5	0.28	13	280	132	40 HRC	55 HRC	57	7.4
FN-0408-35	35	···	45	40	1	15.5	0.25	4	75	37	67 HRB	N/D	16	6.5
FN-0408-45	45	···	65	50	1	19.5	0.27	7.5	115	50	78 HRB	N/D	23	6.9
FN-0408-55	55	···	80	60	1	22.5	0.28	11	150	59	87 HRB	N/D	28	7.2

HT, heat treated; N/D, not determined for the purposes of this standard. Suffix numbers represent minimum strength values in 10^3 psi; yield in the as-sintered condition and ultimate in the heat-treated condition. Mechanical property data derived from laboratory prepared test specimens sintered under commercial manufacturing conditions. Tempering temperature for heat-treated materials: 260 °C (500 °F). (a) Yield and ultimate tensile strength are approximately the same for heat-treated materials. Source: MPIF Standard 35, Materials Standards for PM Structural Parts, 2012 Edition.

Table 7 Chemical composition of copper-infiltrated irons and steels

	Chemical composition, wt%			
Material designation	Fe	Cu	C(a)	Element
FX-1000	Balance	8.0	0.0	min
		14.9	0.3	max
FX-1005	Balance	8.0	0.3	min
		14.9	0.6	max
FX-1008	Balance	8.0	0.6	min
		14.9	0.9	max
FX-2000	Balance	15.0	0.0	min
		25.0	0.3	max
FX-2005	Balance	15.0	0.3	min
		25.0	0.6	max
FX-2008	Balance	15.0	0.6	min
		25.0	0.9	max

Other elements: Total by difference equals 2.0 wt% maximum, which may include other minor elements added for specific purposes. (a) Carbon, on basis of iron only, may be a metallographic estimate. Source: MPIF Standard 35, Materials Standards for PM Structural Parts, 2012 Edition.

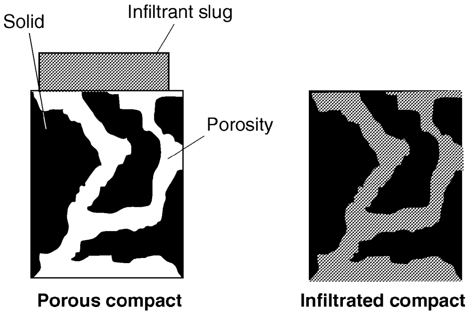

Fig. 14 Schematic of copper infiltration

primary alloy addition have been commercialized (Ref 28). While it is possible to sinter such materials at 1120 °C (2050 °F), a high quality sintering furnace is required with a low dew point and low oxygen content in the high heat zone of the furnace (Ref 29).

Hybrid-Alloy Powders

Hybrid-alloy powders consist of prealloyed or diffusion-alloyed powders to which elemental or ferroalloy additions are made to produce the desired composition. MPIF Standard 35 Materials Standards for PM Structural Parts has a section for hybrid alloys. In addition, many sinter-hardened steels are hybrid alloys. The chemical compositions of hybrid alloys referenced in MPIF Standard 35 Materials Standards for PM Structural Parts and their mechanical properties are summarized in Tables 14–17.

The compressibility of hybrid alloys depends on the compressibility of the base powder used to constitute them. While many hybrid alloys are suitable for sintering at conventional temperatures (1120 °C, or 2050 °F), the mechanical properties of parts made using these materials can often be enhanced by high temperature sintering (>1150 °C, or 2100 °F) (Ref 6, 7, 30).

Mechanical Properties of Ferrous PM Materials

Mechanical properties listed in MPIF Standard 35 Materials Standards for PM Structural Parts relate to guaranteed minimum values and typical values.

Not all commercially available ferrous PM materials are covered by current material standards. It takes time for independent testing and review before new materials are added to existing standards. Therefore, it is important that PM parts fabricators and design engineers discuss options