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Recent trends in iron powder for powder metallurgy, especially the consumption of iron powder in Japan, manufacturing equipment and capacity of iron powder manufacturers in the world, and progress in powder metallurgy technology and iron powder manufacturing techniques in the past forty years, are outlined. The newly developed KIP (Kawasaki Steel iron powder) products, particularly high compressibility atomized iron powder, good compatibility atomized iron powder, segregation-free iron powder which prevents the segregation of graphite powder, and low alloy steel powders for high strength sintered parts, are introduced. The recent level of strength obtainable with high strength sintered materials, and atomization techniques and mechanisms, are also described herein.

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1 Introduction

Kawasaki Steel Corp. began to produce and market iron powders following the introduction of an integrated manufacturing process for reduced iron powder at Chiba Works in 1966. Kawasaki Steel then proceeded to develop a wide range of iron powder manufacturing technologies, and constructed and expanded its manufacturing facilities with the aim of producing and stably supplying iron powders of outstanding quality. In 1978, the company installed new production equipment for atomized iron powder, establishing its position as a total iron powder maker with both reduced and atomized iron powder capabilities.

This report presents an outline of market trends in iron powders for powder metallurgy applications in Japan and worldwide, and includes an introduction to Kawasaki Steel's iron powder products.

2 Market for Iron Powder for Powder Metallurgy

2.1 Demand of Iron Powder

The volume of iron powder shipments is shown in **Fig. 1**.[1] For more than the past ten years, iron powder demand has shown an average growth rate of approximately 10%. Although the oil shock of 1982 and the recession caused by the sharp appreciation of the yen in 1985 represented temporary setbacks, growth was particularly strong in 1986 and thereafter. In 1990, iron powder shipments for powder metallurgy alone exceeded an annual amount of 100 000 t, but stalled in 1991 as a result of stagnation in the auto industry.

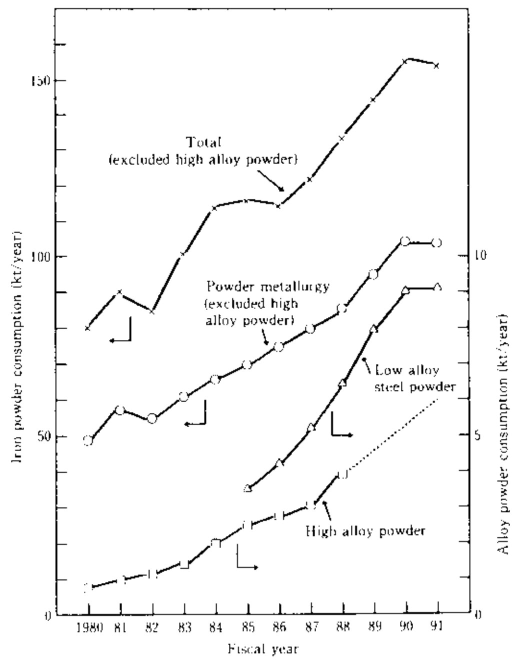

Fig. 1 Consumption of iron and alloy steel powder in Japan[1-3)]

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The ratio of iron powder for powder metallurgy to total iron powder demand is high. Among powder metallurgy applications, the percentage used in machine parts is overwhelming, at approximately 90%. Within the major demand sector of machine parts, automobiles and other transport equipment hold a share of more than 80%.

The growth of demand for low alloy steel powders and high alloy powders is shown in Fig. 1, together with that of iron powder. The figure for low alloy steel powder is an estimate by Kawasaki Steel, but since this product went on the market nearly ten years ago, consumption has grown to almost 1 000 t/month. This volume breaks down into approximately 80%Ni-Cu-Mo partially alloyed steel powders, with the remainder comprising mainly Ni-Mo pre-alloyed steel powders and vacuum-reduced Cr-alloyed steel powders. The most important high alloy powders are stainless steel powders and high speed steel powders. High alloy powders also include the super alloys, which have shown marked growth.[2,3] It should be noted that the data for iron powder shipments includes low alloy steel powders, but does not include high alloy powders.

In comparison with other methods, powder metallurgy products manufactured from iron powder offer a combination of features unique to powder metallurgy, including not only economic advantages, but also superior heat and wear resistance, less noise during sliding, and the potential for weight reduction, which are reflected in the remarkable growth in demand to date. In the future, increasing demand for various types of alloy steel powders is expected as users strive to meet the requirements of higher product quality and higher strength in sintered machine parts.

2.2 Recent Trends among Iron Powder Makers

Table 1 shows the history of powder metallurgy and iron powder over the last 40 years, together with recent trends. The construction of iron powder manufacturing plants at Kawasaki Steel is also shown in the table. Emerging as a viable industry around 1950, powder metallurgy first centered on small parts such as shock absorbers in the 1950s, with virtually all the material used being reduced iron powder, which offers excellent compactibility. The production of larger parts dates from the years 1960-1970, when atomized iron powders also began to appear. With the shift to high strength parts and high function materials in recent years, makers have begun to develop various types of alloy steel powders and segregation-free iron powders to prevent the segregation of the graphite and lubricants generally mixed with the material iron powder.

As previously mentioned, in 1966 Kawasaki Steel constructed an integrated production and processing line from the the primary reduction furnace (tunnel kiln) through finishing reduction, and began to produce and sell iron powders. In 1978, the company constructed and thereafter continued to upgrade the various equipment which Kawasaki Steel itself had developed for manufacturing atomized iron powder. No. 7 finish reduction furnace (3 000 t/month) was constructed in

Table 1 History of powder metallurgy and Kawasaki Steel iron powder (KIP)

Year	1950~	1960~	1970~	1980~	1990~
The trend of PM parts	Small size (Compactibility)	Large size (Compressibility)	Composite Joining For exhaust gas	High strength High density	Functional High precision
Strength level	Cast iron	High strength cast iron	—	Carbon steel	Carbon steel Special steel
Example of PM parts	Shock absorber Ball joint Door striking Bearing	Timing belt pulley Synchronized hub Sprocket Clutch plate	Valve guide Valve seat Rocker arm Tappet	Power steering pump (cam ring, rotor) Connecting rod Clutch race	Planetary gear carrier Camshaft cam Cylinder High strength gear
The trend of iron powder	Reduced (sponge) iron powder		Atomized iron powder, Alloy steel powder Partially alloyed powder, No segregation powder		
Kawasaki Steel iron powder (equipment)	—	1966 Reduced Iron Powder Plant (500 t/month)	1972 No. 2 tunnel kiln (1300 t/month) 1978 Atomized Iron Powder Plant (2000 t/month)	1984 Vac. de-oxidation furnace 1986 No. 7 finish-reduction furnace (3750 t/month) 1989 No segregation iron powder (1000 t/month)	1991 No. 2 Vacuum de-oxidation (200 t/month)

Table 2 Iron powder manufacturers in the world[4)]

Country	Manufacturers	Process[a)]	Capacity (t/year)	Equipment (start-up)	New products
U.S.A.	Hoeganaes Crop. (Riverton)	OR	70 000	—	High strength: Distaloy 4600A, 4800A
		WA	70 000	EF 30, 45 t	High strength: Ancorsteel 85 HP
	(Gallatin)	WA	48 000	EF 60 t (1981)	High hardness: ASTALOY Mo
	(Milton)	Pre-mix	36 000	(1988, 11)	No segregation: Ancor Bond
	Pyron (Niagara Falls)	MR	20 000	—	Compactibility: Pyron D-63
		WA	22 000	—	Compressibility: Pyronized 2067
	Kobelco Metal Powders (Seymour)	WA	24 000	EF 20 t (1989, 7)	Low inclusions: 300ME Compressibility: 300MC
Canada	Quebec Metal Powders Ltd. (Tracy, Sorel)	WA	37 000	—	Powder forging: 1001 PF
		WA	56 000	56MT Converter (1987, 12)	Compressibility: 1001 HP
	Domfer Metal Powders Ltd. (Montreal)	WA	25 000	H.F.F. 14 t	Machinability: MP37 & 36S
Sweden	Höganäs (Höganäs)	OR	160 000	Tunnel kiln × 3	—
	(Bohus)	WA	36 000	For Distaloy (1990)	High strength: Distaloy AE & AG
	(Halmstad)	WA	200 000	(1992)	Compressibility: ABC100·30
		Pre-mix	48 000		No segregation: STAR-MIX
CIS	Krasnij-Sulin	WA	80 000	EF 25 t × 2 (1986)	—
Germany	Mannesmann Demag (Möchengladbach)	WA	35 000	—	Compactibility: WPL-X 200
China	Wuhan Iron & Steel (Hubei)	MR	10 000	—	—
	Anshan Iron & Steel (Liaoning)	WA	12 000	— (1986)	—
Japan	Kawasaki Steel Corp. (Chiba)	MR	30 000	No. 2 Vac. R.F. 2400 t/year	No segregation: KIP Clean Mix
		WA	54 000	No. 7 F.R.F. 45000 t/year	High strength: KIP SIGMALOY
	Kobe Steel, Ltd. (Takasago)	WA	72 000	EF 30 t (1992)	Compressibilty: Atomel 300 NH No segregation: Atomel Seguresu
	Dowa Mining Co. Ltd. (Okayama)	OR	31 000	Tunnel kiln × 2	Compactibility: DNC
	Powdertech Co. Ltd. (Chiba)	OR	12 000	Tunnel kiln × 1	Compactibility: TNC

a) OR: Ore reduced MR: Millscale reduced WA: Water atomization

1986. Responding to the trend toward higher strength and higher product quality in recent years, Kawasaki Steel has also constructed production lines for vacuum reduced steel powder, and for KIP Clean Mix which is a segregation-free iron powder.

Table 2 shows the recent trends among the world's major iron powder manufacturers.[4)] Production methods, equipment capacity, and recently announced new products are also shown in the table. Particularly noteworthy are the new water-atomization iron powder plant put into service by Höganäs in Sweden (1992; capacity, 200 000 t/year), and in Japan, the upgrade of equipment at Kawasaki Steel and Kobe Steel's new water atomization iron powder plant (1992; capacity, 72 000 t/year).

Other notable points in the table are the construction by a number of companies over the last several years of production lines for segregation-free iron powders and for partially alloyed steel powders for use in high strength parts. If the production capacities of the iron powder makers shown in the table are totaled by method, the capacity is 751 000 t/year for atomized iron powder and 333 000 t/year for reduced iron powder. In the past, actual shipments of reduced iron powder were overwhelming greater, but with growing demand for atomized iron powder in recent years, the consumption of atomized iron powder now accounts for 50% of the total, including in Japan.

3 Manufacturing Processes for Iron Powder for Powder Metallurgy

3.1 Manufacturing Process for Atomized Iron Powder

This section mainly surveys the literature published in the past several years on manufacturing processes for atomized iron powder, which has recently been a subject of considerable interest. The reader is invited to see the discussion by the author[5)] and others of the fundamental manufacturing processes for iron powder for powder metallurgy.

Table 3 summarizes the manufacturing processes for atomized iron powder discussed publicly in recent years, and refers the reader to the literature related to the technologies listed in the table.[5-35)] Water atomization is widely used as an industrial process. In this method, molten metal is allowed to flow out through a small-opening nozzle at the bottom of the tundish, and a water jet is blown against the stream of molten material to produce powder. When the water pressure produced by the high pressure pump exceeds 50 MPa, the method is termed high pressure water atomization, and is appropriate for manufacturing fine powders of approximately 10 μm and under in diameter.

In the gas atomizing method, gas is used as the atomizing medium instead of water. The oxygen content of the product is lower in gas atomizing than in the water atomizing method, but the grain morphology trends to be spherical because cooling is slower in gas atomizing. Various processes can be categorized as subsonic or supersonic depending on the velocity of the gas jet, and as the free-fall type, in which the molten metal is allowed to fall freely from the tundish, and the confined type, in which the flow of metal is controlled. In the confined type, the internal pressure in the nozzle is negative relative to the peripheral atmosphere formed by the gas jet, creating a suction effect which results in a forced downward motion of the molten metal stream and makes it possible to obtain powders with a finer particle size.[14)]

Processes using liquefied gases such as Ar or N_2 are categorized as liquid gas atomizing methods. The aims of liquid gas atomizing are to produce high-purity iron powders and accelerate the rate of cooling. The formed powder is recovered by volatilizing the liquid gas.[20,21)]

In oil atomization, oil is used as the atomizing medium. This method avoids the problems of the water and gas atomizing methods, and makes it possible to obtain powders with good compactibility, which provide simultaneously both irregular morphologies and low oxygen contents.[22,23)]

The vacuum atomization method is used to obtain

Table 3 Manufacturing processes for atomized powders (by recently published literature)

Process	Content	Powder	Reference
Water atomization	Pressure ≑ 5 ~ 20 MPa	Relatively irregular in shape High surface oxygen contents	5~7)
High pressure water atomization	Pressure: 50 ~ 100 MPa	Fine particle size <10 μm	8~10)
Gas atomization (N_2, Ar or air) (liquid inert gas)	Pressure ≑ 1 ~ 5 MPa Free-fall type, confined type	Spherical Low surface oxygen contents High purity	11~19) 20, 21)
Oil atomization	Using of oil in place of water or gas	Relatively irregular	22, 23)
Vacuum atomization	Molten metal supersaturated with gas under pressure is suddenly exposed to vacuum	Spherical High purity, clean	24, 25)
Ultrasonic atomization	Impinging of wave ($6 \sim 12 \times 10^4$ cps) on the liquid metal stream	Spherical Narrow size range	26, 27)
Electromagnetic atomization	Impinging of magnetic field on molten metal in using plasma arc discharge	For high melting point metals High purity	28~30)
Rotating electrode process (REP or PREP)	The end of a metal bar is rotated about its longitudial axis, melted and centrifugally ejected	Spherical High purity, ultra clean	31~33)
Rotating disk atomization (centrifugal atomization)	Impinging of a molten metal stream onto the surface of a rapidly spinning disk	Spherical, flake High purity	34, 35)

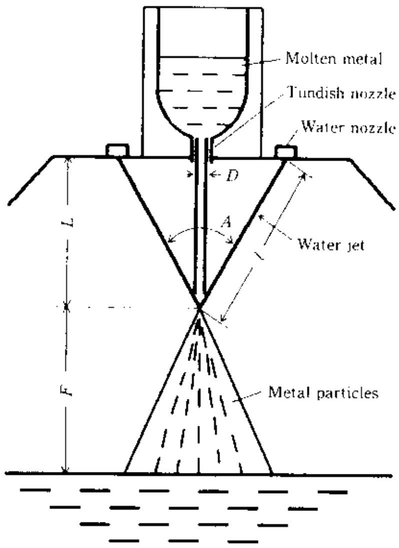
powders with low oxygen contents. In this process, metals melted under a vacuum are directly atomized in the vacuum tank,[24] where the supersaturated gas present in solid solution in the molten metal expands in the vacuum, promoting finer particle formation. In addition, a suction pipe has been used. This device is equal in length to the distance from the tip of the molten metal nozzle to a point directly above the grain formation region in the jet, and is intended to reduce the pressure and stabilize the jet.[25] Because cooling is slow, the particle shape tends to be spherical.

Various means have been used to improve powder forming efficiency during atomizing. Inducing ultrasonic waves during atomization in order to promote the formation of finer particles in the molten metal is termed ultrasonic atomization. In one atomizing method which has been reported, sound waves emitted by a stripe mode vibration plate are made to converge using a reflector plate. Waves form on the liquid surface, and the cavitation is subjected to compressive destruction, forming the powder.[26,27] In the electromagnetic atomization method, magnetic force is used to promote powder formation. A magnetic field is impressed in the vertical direction relative to an arc current generated between electrodes, producing magnetism in the molten metal and promoting the scattering of liquid droplets.[28-30] The rotating electrode process (REP or PREP) features an anodic rotating consumable electrode (anode) composed of the material to be pulverized. The anodic electrode is positioned relative to a stationary cathodic electrode and rotated at high speed to produce powder.

In addition to these methods, mechanical means of pulverizing the molten metal have been tested. In one method, the molten metal is atomized by the impact of striking a rapidly rotating disk or plate attached to a disk (rotational speed, 3 000–10 000 rpm).[34] It is claimed that the processes of molten metal solidification and pulverization can be clearly distinguished with this method.[35]

3.2 Effect of Parameters in Atomization Iron Powder Production

A simplified model of the water atomization process is shown in **Fig. 2** The effect of respective manufacturing parameters on the properties of atomized iron powders is shown in **Fig. 3**, which also refers the reader to the relevant literature on the parameter in question.[36-67] This discussion also includes an example of gas atomization. Although the details for each parameter are omitted here, the major factors governing particle size (fineness) are the pressure of the atomizing medium, the spray angle, the composition of the molten steel, and the atomizing temperature, while the



Water nozzle	Molten metal
A : Apex angle	D : Metal stream diameter
l : Water jet length	L : Molten metal stream length
d : Water jet diameter	F : Flight path

Fig. 2 Configuration of water atomization[7]

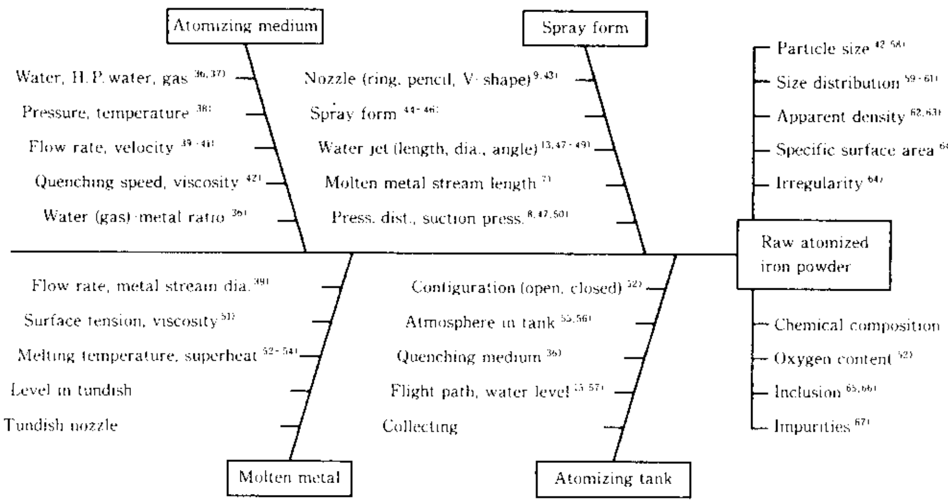


Fig. 3 Effect of water atomization parameters on powder properties

main factors affecting particle shape are pressure, flow rate, and the ratio of the atomizing medium to the molten steel. Nozzle configuration, which is to say, the spray form, is also an important factor. A detailed comparison was made of the cone type (annular concentric jet) and V-type (V-shaped jet), which are commonly used in industry.[9] In one example of the gas atomization method, the gas jet is revolved, generating powerful suction inside the jet and promoting the formation of finer grained powder.[13] As conditions related to the molten material, the flow rate, composition (viscosity, surface tension), and temperature are significant factors. The physical properties of the molten metal are also of major importance, with superheat (160–470°C) being effective in reducing the particle diameter and obtaining spherical particles.[52-54]

Finally, the atmospheric pressure was measured in the vicinity of the atomizing section, and sensors which function on-line during atomizing have been introduced and developed.[68] These trials are expected to contribute to improved product quality in the future.

3.3 Mechanism of Powder Formation

Because of the volume of literature on the mechanism of powder formation in the atomizing method, the present discussion will be limited to recent trends. A typical example is shown schematically in **Fig. 4**.[6,69] As previously mentioned, water nozzles are of the confined type and free fall type. Ligaments and other types of molten metal fragments first scatter. In one concept, an actuator is positively applied before the molten metal comes into contact with the atomizing medium, producing uniformly dispersed particles.[70] Although the molten metal separates out in different forms depending on the atomizing conditions, particles form into spherical, irregular, and fragmented spherical particles in the primary atomization process. Particle formation takes place during the secondary atomization process. In the final step, the final shape of the powder particles is determined by impact between particles and the walls of the recovery vessel, by impact between particles and/or by coalescence. Formerly, particle size and shape were controlled only by the conditions applied in the first part of the atomizing process, but more recently, it has become possible to control the degree of coalescence which is conducted during the latter part of the manufacturing process. Although also differing with atomizing conditions, the relative proportion of primary particles which collide to form secondary particles is approximately 1/3 of the total, which is a high proportion. The reader should note that Fig. 4 shows the atomizing process in five stages, but in some cases, it is represented in three steps, viz. stage 2, stage 3 (which includes stages 4), and stage 5.

Three-dimensional morphological analyses of formed particles have recently been conducted. Particle morphology and morphological distribution and dispersion con-

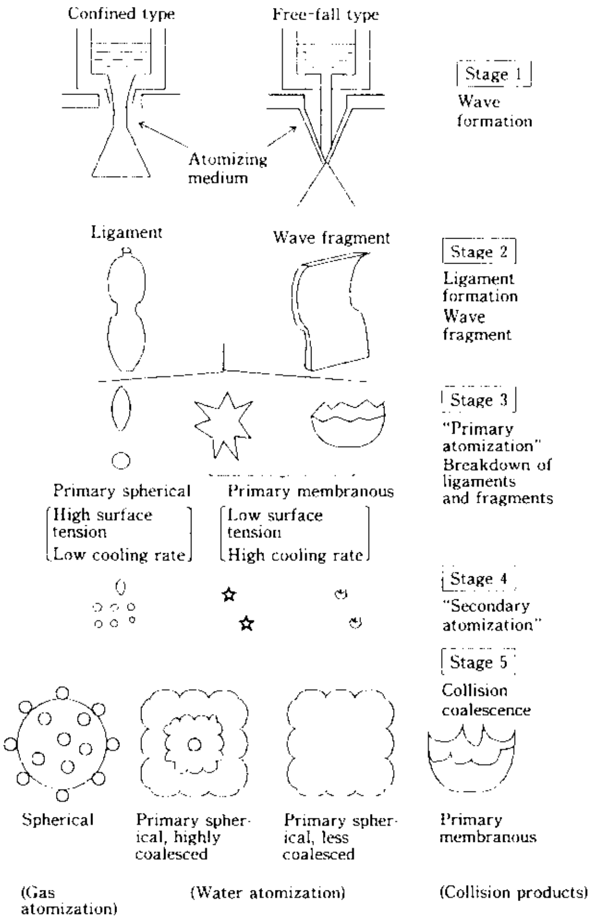


Fig. 4 Schematic illustration of particle formation stages during atomization[6]

ditions have been quantified,[62] and size/shape variation charts have been prepared by statistical processing.[71] In addition, three-dimensional images of atomized iron powder particles have been constructed from the images obtained using a scanning electron microscope and image processing equipment.[71] Elucidation of the mechanism of powder formation and the morphological analysis of formed particles are absolutely essential for a high product quality and high precision iron powder manufacturing in the future.

4 Iron Powder and Alloy Steel Powders for Powder Metallurgy

4.1 Pure Iron Powder

4.1.1 High compressibility iron powder

The compressibility of and historic trends in various iron powders sold commercially by Höganäs[72] and Kawasaki Steel are shown in **Fig. 5**, which indicates that, in the reduced iron powders MH 100 · 24 and NC 100 · 24, and SC 100 · 26 for high density applications, a marked improvement in compressibility has been achieved by the elimination of inclusions and

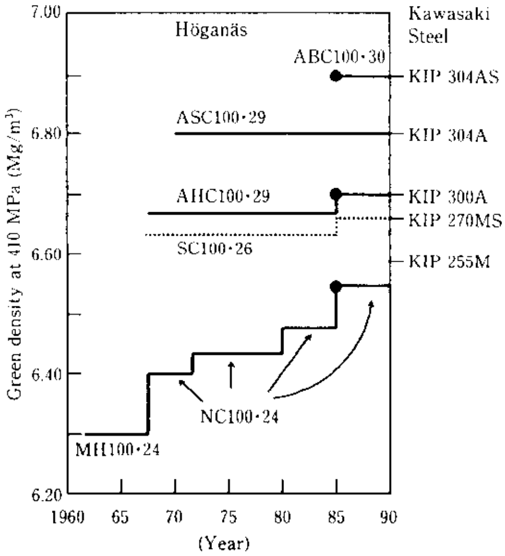


Fig. 5 Progress in compressibility[74]

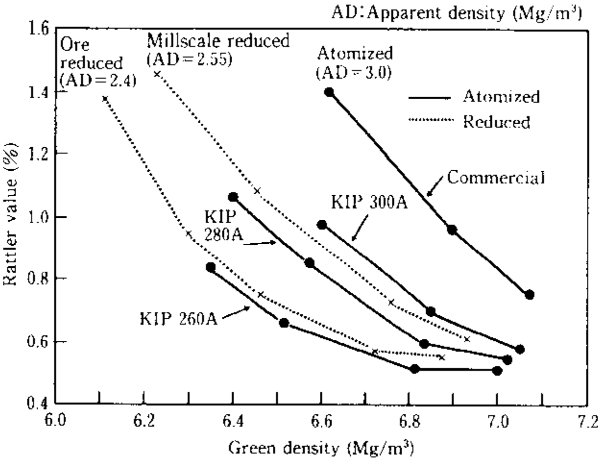


Fig. 6 Compactibility of KIP atomized iron powder by Rattler testing

Table 4 Chemical composition of high compressibility iron powder[73,74]

(wt %)

Chemical composition	High compressibility iron powder		Conventional
	KIP 304AS	ATOMET 1001 HP	KIP 300A
C	0.001	0.004	0.002
Si	0.01	0.003	0.02
Mn	0.03	0.015	0.08
P	0.003	0.01	0.017
S	0.003	0.004	0.015
O	0.08	0.06	0.133
N	0.0008	—	0.0021

impurities. On the other hand, even in atomized iron powders, compressibility can be enhanced by reducing the level of inclusions, securing higher purity, and controlling powder characteristics. In fact, Höganäs' ABC 100 · 30 and Kawasaki Steel's KIP 304AS offer the highest compressibility available in any iron powder worldwide.

Examples of the chemical composition of Kawasaki Steel's high compressibility iron powder 304AS and Quebec's high compressibility iron powder ATOMET 1001HP are shown in **Table 4**.[73,74] In comparison with Kawasaki Steel's conventional product of 300A, efforts have been made to reduce the levels of Mn, P, S, O, and N, and the particle morphology and particle size distribution have been adjusted for high compressibility. A green density value of 7.24 Mg/m^3 is obtained at a compacting pressure of 690 MPa. This value is approximately 0.1 Mg/m^3 higher than that with conventional the 300 A.[73] The effect of each type of impurity contained in the iron powder has also been confirmed.[67,75]

4.1.2 Medium/low apparent density iron powders

Atomized iron powders produced using an aqueous atomizing medium tend to show a spherical particle morphology, and products with a high apparent density on the order of 3.0 Mg/m^3 are common. However, recent progress in iron powder-manufacturing technology has made it possible to produce atomized iron powders which have medium and low apparent densities and offer satisfactory compactibility.

The compactibility of Kawasaki Steel's atomized iron powders and other commercially available products is shown in **Fig. 6**. The Rattler test measures a type of wear which is sometimes called edge stability. Lower Rattler values indicate better compactibility. It may be stated as a general rule that cracking will not occur if the Rattler value is 1% or under. Kawasaki Steel's atomized iron powders are markedly superior to earlier products in terms of compactibility, with the iron powders of medium apparent density (280A, 2.8 Mg/m^3; 260A, 2.6 Mg/m^3) showing compactibility values equivalent to those of reduced iron powders. Development of an atomized iron powder with a low apparent density on the order of 2.4 Mg/m^3 is also to be expected.

4.2 Segregation-Free Iron Powders

Although graphite, lubricants, and alloying elements are commonly mixed with iron powders, graphite and lubricants have a lower specific gravity than iron and tend to segregate in such mixtures. For this reason, segregation-free iron powders in which the graphite and lubricant adhere to the surface of the iron powder particles have recently been developed,[76-78] using the principle shown schematically in **Fig. 7**. (The segregation-free iron powders marketed by respective makers have already been listed in Table 1.) In addition to excellent flowability (23 s/50 g; conventional powder, 33 s/50 g), this type of powder possesses other outstand-

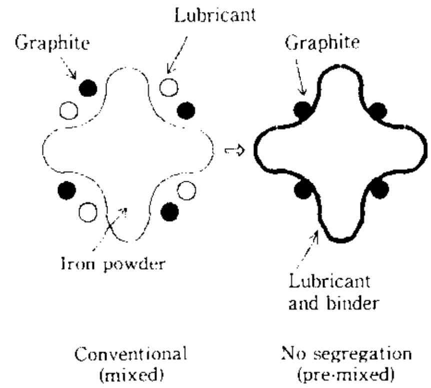


Fig. 7 Schematic illustration of segregation-free powder

ing characteristics such as low dust generation (1/10 of the level in conventional powders) and minimal segregation of graphite. Accordingly, variations in the C content of sintered compacts have sharply decreased, and variations in dimensional changes have been reduced to approximately half the previous level. Following these improvements, actual published data on the manufacture of sintered parts has confirmed a major decrease in the variations in C seen in conventional mixed powders during discharge from the hopper.[79]

4.3 Low Alloy Steel Powders

4.3.1 Ni-Mo low alloy steel powders (hydrogen reduction)

If categorized broadly by production method, low alloy steel powders at present comprise: (1) completely alloyed (pre-alloyed) steel powders, which are produced by hydrogen reduction and are completely alloyed; (2) pre-alloyed steel powders produced by vacuum reductions, which are also completely alloyed; and (3) partially alloyed steel powders, in which fine powders of alloying elements are diffusion alloyed onto the surface of the iron powder particles.[80] **Table 5** shows representative low alloy steel powders sold by Kawasaki Steel, along with their chemical composition.

To begin with the low alloy steel powders produced by hydrogen reduction, 2Ni-0.5Mo steel powders of the AISI 4600 type have a long history. Kawasaki Steel's 4600A is a 1.5Ni-0.5Cu-0.5Mo product. The company also produces a 1Ni-0.5Cu-0.3Mo steel powder which is excellent in repressing performance.[81] Because the atomized powder is subjected to reduction treatment in a hydrogen atmosphere, this type of powder is limited to those which contain such alloying elements as Ni, Cu, and Mo, whose oxides are readily reduced in hydrogen.

4.3.2 Cr-Mn low alloy steel powder (vacuum reduction)

Because oxides of Cr and Mn are difficult to reduce in hydrogen, low alloy steel powders containing these elements are produced by reducing the raw powder material in a vacuum after atomization.[82-84] The 4100V shown in Table 5 is a 1Cr-1Mn (0.3Mo) steel powder produced by the vacuum reduction method. Low-oxygen Cr-Mn low-alloy steel powder is obtained by alloying an amount of C appropriate to the oxygen content in advance during atomizing, and then simultaneously decarburizing and deoxidizing the formed powder by heating it in a vacuum. Because Cr-Mn low alloy powder is superior in hardenability, it is used as a high-hardness material. It is also used as a material in applications requiring heat and wear resistance.

4.3.3 Ni-Cu-Mo partially alloyed steel powder

Ni-Cu-Mo partially alloyed steel powder is produced by diffusion alloying fine powders of Ni, Cu, and Mo onto the surface of iron powder particles by heat treatment. In some cases, not only fine metallic powders but also fine alloy powders of these elements have been used.[85] Because the iron powder is subjected to alloying only on its surface, it retains the ductility of iron, making it easier to obtain high densities during powder compaction in the mold. This type of powder is widely used as a raw material powder for high density, high strength sintered materials. As examples of this material type, 4Ni-1.5Cu-0.5Mo steel powder SIGMALOY 415S[86] and recently developed 2Ni-1Mo steel powder SIGMALOY 2010[87-89] are shown in Table 5. Demand for these partially alloyed steel powders is growing rapidly, as was shown in Fig. 1.

4.4 High Alloy Powders

As shown in Fig. 1, high alloy powders with alloy element contents of several percent or more have recently shown the same high rate of growth as low alloy steel powders. Although the high alloy powders mainly comprise stainless steel powders and high speed steel powd-

Table 5 Chemical compositions of KIP alloy steel powders (wt %)

Process	Powder	C	Si	Mn	P	S	Ni	Cu	Mo	Cr	N	O
Pre-alloyed	4600E	0.001	0.01	0.08	0.017	0.007	1.12	0.42	0.23	—	0.001	0.09
Pre-alloyed	4600A	0.003	0.01	0.08	0.009	0.004	1.45	0.53	0.47	—	0.001	0.12
Vacuum reduced	4100V	0.02	0.04	0.83	0.021	0.015	—	—	0.29	1.05	0.001	0.10
Partially alloyed	SIGMALOY 415S	0.004	0.01	0.05	0.005	0.005	4.31	1.50	0.48	—	0.001	0.11
Partially alloyed	SIGMALOY 2010	0.001	0.01	0.05	0.005	0.003	1.93	—	1.03	—	0.001	0.07

ers, some materials lying outside the definition of steel powders, such as super alloy powders and powders for surface hardening, may be included in this category.[2] In the manufacturing process for high alloy steel powders, carefully selected raw materials are melted in a high frequency furnace, atomized by the water or gas method, drained and dried, and then annealed in a vacuum. Finishing reduction of the type used in the low alloy powder process is generally not performed with high alloy powders.

In low alloy steel powders, this route frequently offers economic advantages over other production processes. In contrast, it is commonly applied to materials of the high alloy type when production would be difficult or the desired properties cannot be obtained by the ingot method, and thus can be regarded as using the special characteristics of powder metallurgy to greater advantage. As a general comment, because high alloy powders are difficult to reduce and are commonly used as atomized powders without further processing, the selection and precise control of atomizing conditions is critically important.[90-92]

5 Features of High Strength Sintered Materials

The previous sections have discussed the respective types of raw material powders for powder metallurgy applications. **Figs. 8** and **9** show the tensile strength and hardness of sintered compacts and of sintered and forged materials produced from these raw material powders, with emphasis on Kawasaki Steel's low alloy steel powders.

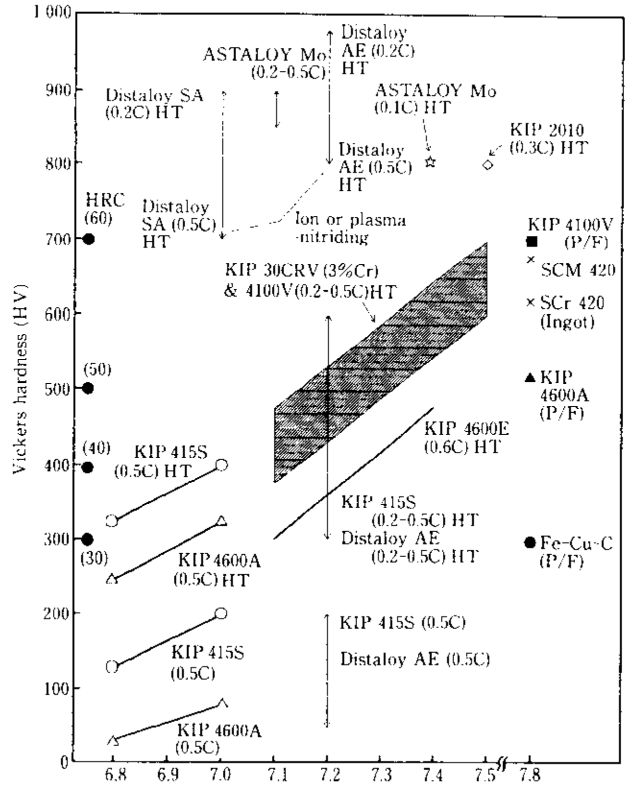


Fig. 9 Hardness of ferrous sintered materials from Kawasaki Steel's KIP and Höganäs's Distaloy and ASTALOY alloy steel powders (HT: heat treatment)

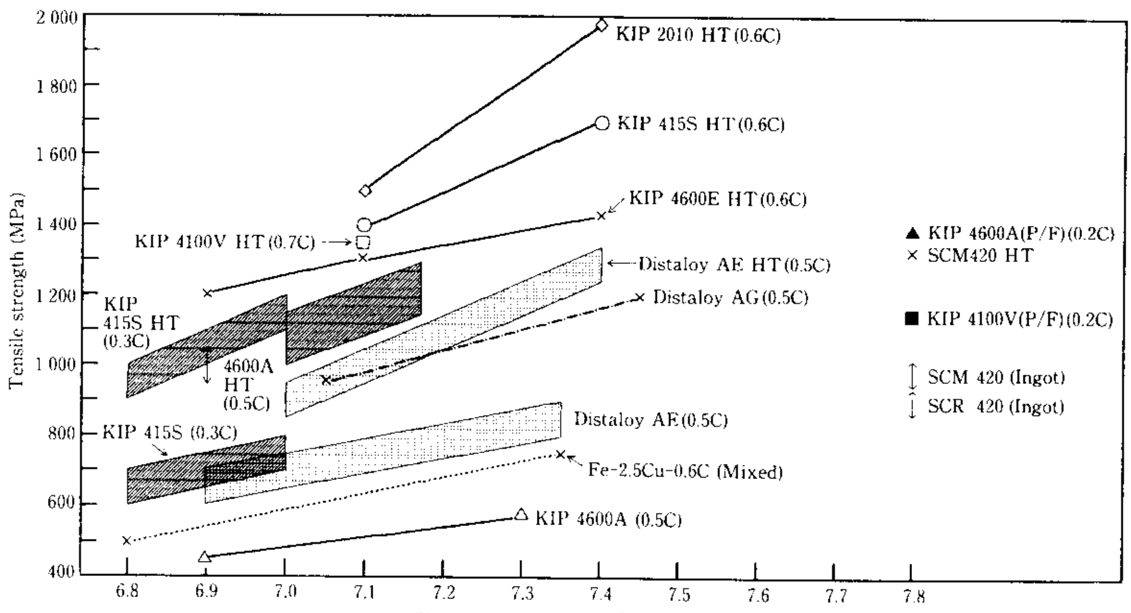


Fig. 8 Tensile strength of high strength sintered materials from Kawasaki Steel's KIP and Höganäs's Distaloy alloy steel powders (HT: heat treatment)

The standard parameters for the manufacture of sintered and heat treated compacts are as follows:

Compacting: 490, 590, 690 MPa (zinc stearic acid, 0.75, 1.0%)
Sintering: 1 130°C or 1 250–1 300°C, in AX or RX gas
Carburizing quenching: 850–930°C, 1–2 h
Tempering: 180°C, 1–2 h

The sintered densities of 7.0 Mg/m^3 and above in these figures were obtained by the 2P2S method (double pressing, double sintering). Particularly high strength is shown by Kawasaki Steel's SIGMALOY 415S, with a tensile strength of 1 380 MPa (2P2S: 1 720 MPa) and fatigue strength of 410 MPa (2P2S: 350 MPa), and by SIGMALOGY 2010, with a tensile strength of 1 500 MPa (2P2S: 1 920 MPa) and fatigue strength of 460 MPa (2P2S: 390 MPa). On the other hand, the conventional level of hardness was HV400–500 (HRA70–75), but recently values of HV500–700 (HRA75–80) have been obtained. High hardness materials of HV900 and above have been reported with special processes such as ion (plasma) nitriding. With sintered and forged materials having a true density of 7.8 Mg/m^3, it is possible to obtain values substantially equivalent to those with ingots. In generally, because elongation and impact values are low in powder metallurgy products, improvement is needed in these features and in fatigue values.

6 Conclusions

This paper has outlined market trends in iron powders for powder metallurgy, and has also described manufacturing processes for atomized iron powder and new products of these materials, which have been matters of considerable interest in recent years. Although powder metallurgy has expanded steadily in the past, the growth of this industry has been temporarily stalled by the recent recession. On the other hand, firmly rooted demand for sintered products promises renewed progress in the future.

The achievement of higher strength levels in the last several years has further increased users' confidence in iron powders for powder metallurgy, but increasing demand for even higher strength and higher product quality can be expected in the future. Kawasaki Steel is committed to the ongoing development of new products and new manufacturing technologies which will answer these customer requirements, and requests the continuing guidance and support of all concerned.

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