Recent Technology of Powder Metallurgy and Applications

Tadayuki Tsutsui
Hitachi Powdered Metals Co., Ltd.

Powder metallurgy has grown with the expansion of various industries since 1950. The expansion of the automotive industry especially, which came from the U.S., has been a big influence. Nowadays, over 90% of powder metallurgy products are used in the transportation market.

Recently, the automotive industry is in the trend of the post-oil due to increasing environmental concerns, and technologies for reducing fuel consumption have been rapidly developed, such as lightweight technology and engine downsizing for environmentally friendly vehicles. To achieve this reduction, powder metallurgy products, which are components of the latest systems, are also required to have higher performance. Moreover, the development of new field products such as magnetic materials is expected to meet the new trends of the automotive industry, electric and hybrid vehicles. Furthermore, the adoption of next generation applications in powder metallurgy is strongly required in growth markets such as information home appliances, sustainable energy, and life sciences.

In this report, the features and trends of powder metallurgy are first described, and the latest technologies and newest application examples in our company are introduced.

1 Introduction

1.1 Process and Features of Powder Metallurgy

Powder metallurgy (P/M) is a materials processing technology to create new materials and parts by diffusing different metal powders as raw ingredients through the sintering process. Products are created by P/M using the basic process shown in **Figure 1**.

The features of P/M can be seen in the following five areas: 1) alloys can be created from high melting point metals, including tungsten, molybdenum, and tantalum; 2) metal/non-metal composite materials as represented by Cemented Carbide, cermet, and friction materials can be created; 3) composites of metals that do not dissolve into each other, such as high thermal conducting materials (W–Cu, Mo–Cu), high density alloys, and electrical contact materials (Ag–Cu, Cr–Cu) can be created; 4) porous materials, such as oil-impregnated bearings and filters, can be created; and 5) P/M has excellent economic efficiency because products can be formed by pressing powders in molding tools.

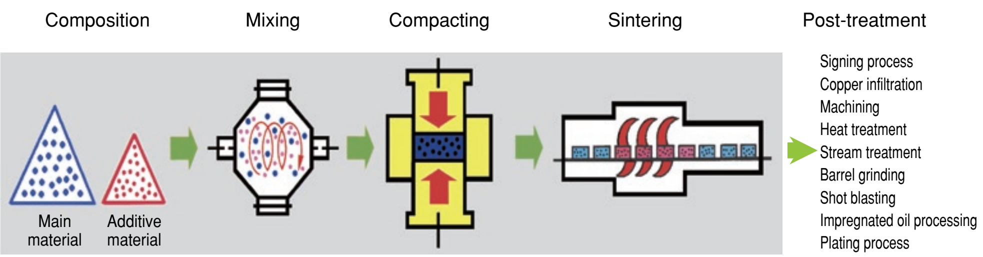


Figure 1 Fundamental process of powder metallurgy

Figure 2 shows the place of P/M in the material process technology industry. Powder metallurgy has a range of diverse uses, and has an important role in the advanced material process technology industry. By compacting and sintering, P/M can create a direct final product (net shaping) or a product near its final form (near net shaping). Furthermore, because it grants a great deal of freedom to the composition of alloys and micro structures of materials, it can obtain properties that general wrought steel cannot. At the same time, P/M is an economical production method with little waste.

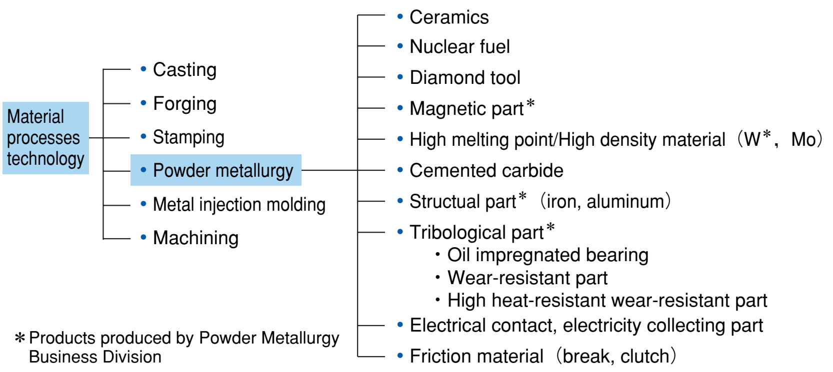


Figure 2 Position of powder metallurgy in material process technologies

1.2 Trends of Powder Metallurgy Technology

In the overall material process technology industry, there are a variety of products utilizing P/M. Currently, main P/M products of Hitachi Powdered Metals comprise structural parts , tribological parts (oil-impregnated bearings, wear-resistant parts, and high-temperature heat-resistant wear-resistant parts), and magnetic parts (soft magnetic materials). We are also engaged in the development of high performance parts as next-generation products.

1.2.1 Structural parts

Structural parts make up a large portion of P/M products. Their main ingredient is iron alloys. Engineers have sought to improve their properties as they apply them successively to different products: home appliances, OA equipment, motorcycles, agricultural machinery, and automobile parts. As a result, their performance has grown, as has their demand. In the past ten years, parts for transport machinery have led to the growth in the demand of P/M products. Pulleys, sprockets, and parts for variable valve control systems in order to increase fuel efficiency have grown 1.5 times. Although this trend is not expected to change for a while even with the transition to hybrid electric vehicles and electric vehicles, P/M products are being developed to support greater fuel efficiency and the acceleration in the greening of technology by focusing on the following: making parts thinner and lighter, inhibiting degradation in dimensional precision with sintering and thermal processing, replacing thermal processing with sinter-hardening, and increasing cost performance by actively using low-cost chromium as an element for strengthening P/M products.

1.2.2 Tribological Parts

These parts are strongly related to abrasion and lubrication. The field has grown as original P/M alloy compositions and material microstructure are being actively utilized; these developments could not have been accomplished with wrought steel. Hitachi Powdered Metals is producing oil-impregnated bearings and wear-resistant parts as well as high-temperature heat-resistant, wear-resistant parts. The applications of oil-impregnated bearings have grown through their use in home appliances, audio equipment, office equipment, and automobiles. Recently, we have also been developing advanced technologies that support high contact pressure and low coefficient of friction for use in environmentally-friendly products, such as ICT(Information and Communication Technology) equipment and construction machinery. In the area of wear-resistant materials, valve guides and valve seats, which conventionally have been cast, are being replaced by low-cost yet high-performance sintered parts. The development of materials is helping engines perform better, making cars leaner for greater fuel efficiency and adapting to changes in the fuel environment due to flexible-fuel vehicles. Under the same trend, heat- and wear-resistant materials for turbochargers are also being developed to meet the rise in the temperature of fuel exhaust gases and the downsizing of turbochargers.

1.2.3 Magnetic Parts

In recent years, to support ICT equipment that rapidly continues to become faster, use higher frequencies, become smaller and denser, and save more energy, achieving high permeability and lower core loss in the high-frequency region is being required for soft magnetic materials. This means that the needs of advanced magnetic materials are growing for both present-day automobiles, in which electronic controls are becoming increasingly advanced, and for next-generation hybrid electric vehicles and electric cars. Hitachi Powdered Metals is making advances in the development of technologies including sintered magnetic parts consisting of structural and magnetic materials, and powder cores (or soft magnetic cores [SMC]) that feature low core loss in high-frequency regions.

1.2.4 Next-Generation High-Performance Parts

We are focusing on micronization as the next-generation technology for the fields of information home appliances and the life sciences. We are developing technologies for compacting micro parts that are difficult to industrially produce with machining and metal injection molding (MIM). Another area is the development of products that can directly contribute to the field of environmental energy. As a company participating in the century of the environment, Hitachi Powdered Metals is advancing the development of thermoelectric conversion technology that regenerates energy from waste heat and thermoelectric conversion modules as products utilizing this technology.

Hereafter, the developments of materials and their applied products in the four areas described above are discussed.

2 Recent Applied Products of Powder Metallurgy (P/M) Technology

2.1 Structural Parts[1)]

Structural materials have contributed to expanding the application range of sintered parts through the development of high-strength materials. On the other hand, increasing strength creates issues such as degradation of dimensional precision and degradation in machinability due to increased hardness. This has made it more difficult to take full advantage of near net shaping, an advantage of sintered materials. To address such problems, we have developed and commercialized materials with outstanding dimensional precision. We have also developed and commercialized sinter-hardening materials, which meet the demand for lowering cost and saving energy at the same time by omitting quenching process. These materials and the future developments are discussed below.

2.1.1 High-Strength Materials

To develop materials with a high strength, we began with the Fe–Cu–C system, added alloy elements with high hardenability, and optimized methods for adding these alloy elements to improve the materials' mechanical properties.[1)] ENKMA (Fe–4Ni–1.5Cu–0.5Mo–C), a high-strength sintered steel material developed in the 1980s with nickel, copper, and molybdenum partially diffusion bonded in pure iron powder, could especially achieve strength not possible with conventional materials. The material is used in high-load parts, including automobile transmissions, and has greatly contributed to expanding the application of sintered products. Products using ENKMA are shown in **Figure 3**.

Figure 3 Products made from high strength sintered material

2.1.2 High-dimensional Precision Parts

The applications of sintered materials have expanded greatly owing to the development of high-strength sintered materials (ENKMA). However, because ENKMA shrinks a great deal during sintering, there are cases when dimensional precision is degraded and processes such as recompression and machining are added. To reduce cost by eliminating such processes, we need materials that satisfy both strength and precision. A survey of the influences by different factors on sintered materials' dimensional precision found that the green density was a major factor. New compacting technologies are being developed to make the density inside individual pieces of products uniform. However, another effective method is to select materials that are not easily affected by the variation in density. To make the rate of change in dimensions constant when the density changes, we investigated alloy addition methods and alloy composition and developed a material called EHA–66 (Fe–0.5Ni–0.5Mo–0.55C). The relationship between the material's green density and the rate of dimensional change during sintering is shown in **Figure 4**. For EHA-66, tan θ , indicating the change in density, is low. This demonstrates that the rate of dimensional change is constant for EHA-66. This material is being commercialized for use in products that demand high dimensional precision and high strength.

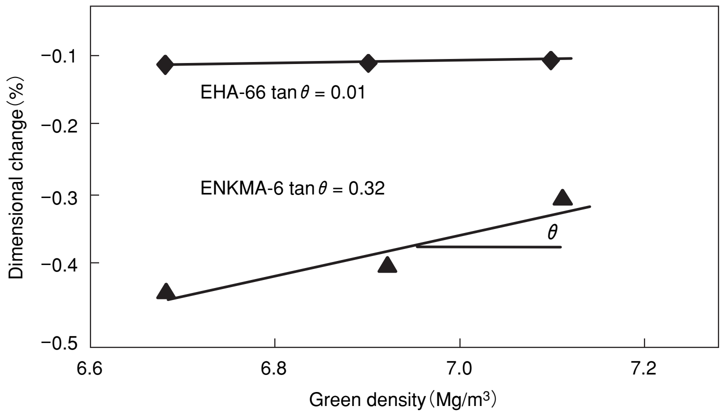


Figure 4 Relationship between green density and dimensional change of developed material

2.1.3 Sinter-Hardening Materials

For the iron-based sintered parts, sinter-hardening materials produced without quenching process have been in practical use. The sintering process of high-strength sintered materials includes a step of applying high temperature and another step of applying high temperature to strengthen the structure. By combining two heating steps to one, the quenching process can be shortened and the energy consumption is also saved. We evaluated hardenability dependent on the cooling step and investigated compositions of materials that enable the quenching process to be omitted. Conventional sintered materials must be sintered in furnaces equipped with rapid cooling apparatus to form martensitic microstructure by the cooling step. If the process can be shortened by using regular furnaces, its economic efficiency becomes even greater. Thus, we started the development of a material that can form martensitic microstructure at the cooling rate of regular sintering furnaces. **Figure 5** shows an overview of CCT(Continuous Cooling Transformation) diagram of this material.

We selected nickel, copper, and molybdenum as hardening elements and optimized their amounts and the method of addition, and then made a successful development of EHS–86 (Fe–6Ni–1Cu–0.5Mo–0.55C), which can form martensitic microstructure at the cooling rate of regular furnaces. **Figure 6** shows the micro structure of the developed material. EHS–86 achieves martensitic phase at the cooling rate of regular furnaces and higher strength than heat treated material.

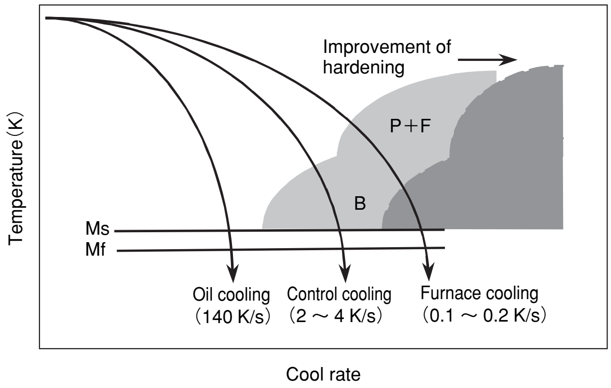
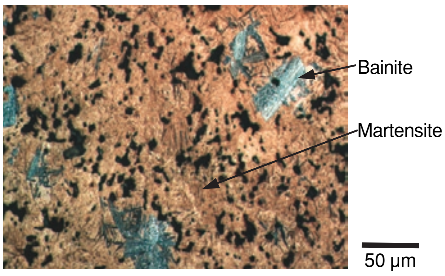


Figure 5 CCT diagram of sinter-hardening material

2.1.4 Future Developments

To strengthen sintered materials, nickel and molybdenum have been added for the purpose of improving hardness. However, the prices of these elements have climbed sharply in recent years. Also, worldwide demand for lowering the cost of sintered part including automobile parts is rising. Thus development of materials that achieve high strength with low cost elements has become necessary. Because chromium is an effective element for increasing the hardness and the strength of steel and because its price is stable, we can develop high-strength materials at a lower cost by utilizing chromium effectively. However, chromium is oxidized easily, so the technologies to be accomplished are the deoxidization during the production of raw powders and the control of the atmosphere during sintering and heat treatment process. We are proceeding with the development of these technologies.



EHS−86 : Fe−6Ni−0.5Mo−1Cu+0.6Gr

Figure 6 Microstructure of sinter-hardening material

2.2 Tribological Parts

Materials for tribology are actively practicalized by applying P/M because they form metallic microstructure and constituent which wrought materials cannot.[3] Materials for tribology are roughly classified into bearing materials having oil impregnated pores inside and heat- and wear-resistant materials.

2.2.1 Bearing Materials[4]

Sintered oil-impregnated bearings have a feature of self lubrication. The oil is supplied from the pores where oil is impregnated in advance. This feature can be applied to a wide range of use. However, a disadvantage is the loss of oil pressure due to pores in the material and the limit to the amount of oil that can be supplied. Thus the range of applications of oil-impregnated bearings is still limited. **Figure 7** shows the relationship between pressure P and sliding velocity V for different examples of applications of sintered oil-impregnated bearings. As shown in **Figure 7**, almost all cases were in region A, which means the application range of bearings was limited. We worked to develop bearing materials and lubricants that can be used under low speed rotation, high contact pressure, and high speed rotation. We also developed bearing shape and structures to expand the applications of sintered oil-impregnated bearings. Also in conventional PV region, we expanded the application range of bearings by improving the performance, such as lowering the friction coefficient, extending the life, and stabilizing the thermal properties. The bearings used under high contact pressure are described below.

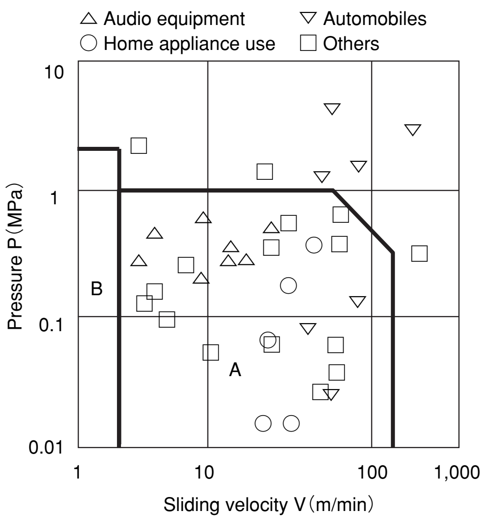


Figure 7 Applications of sintered bearings

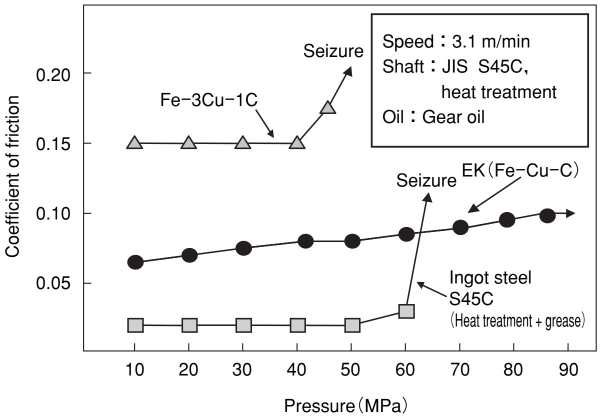


Figure 8 Seizure pressure in ferrous materials

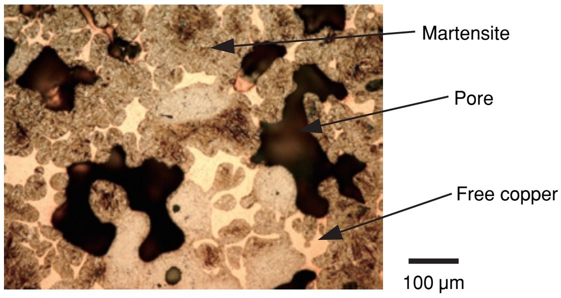


Figure 9 Microstructure of sintered bearing for high contact pressure

【High-Contact Pressure Bearings】

Joint bearings for construction machinery, as represented by oil-pressure excavators, are used under low speed and high contact pressure conditions. The contact pressure can reach a maximum of 80 MPa. Iron-based bearings which have high strength are used under such a high-contact pressure environment. **Figure 8** shows seizure load of different iron-based bearings. As comparison, the contact pressure limits of conventional wrought steel bearings are also shown. Conventional wrought steel bearings are applied with grease. However, grease must be applied frequently, and in our testing the grease ran out and the bearings seized. Also, conventional iron-based sintered materials have a high coefficient of friction, and seize up after exceeding a contact pressure of 50 MPa.

In contrast, the coefficient of friction of our newly developed EK material increases as contact pressure increases. Even at a contact pressure of 90 MPa, the bearings do not seize. The microstructure of EK is shown in **Figure 9**. The EK material is bearing material with a microstructure in which copper is dispersed to bases in the martensite phase. The material is well-balanced, having strength and hardness that can withstand high pressure and as well as conformability due to soft copper.[5] Currently, EK is being widely used as joint bearings for oil-pressure excavators. It has greatly expanded the range of applications for sintered oil-impregnated bearings in low-speed, high-contact pressure environments.

2.2.2 Heat- and Wear-Resistant Materials

Valve guides and valve seats, which are structural components of an engine valve train, are representative of widely used heat- and wear-resistant sintered alloys. **Figure 10** shows the region using the valve guide and valve seats. By the increasing demand for improving wear resistance and lowering cost since the 1980s as fuel efficiency and engine power improved, the use of sintered materials that can meet both of these demands has expanded.

The environment where valve guide are used has become severe because of miniaturization of itself, downsizing of the diameter, and rising temperature of exhaust gas in order to increase fuel efficiency. Also, sintered materials has become used for valve seats because the wear resistance of conventional materials, such as cast iron, were found to be insufficient as the usage of unleaded gasoline became popular.[6] Also, in recent years, the use of heat- and wear-resistant sintered materials in the exhaust system, such as turbocharger parts, has begun. These materials are dicussed below.

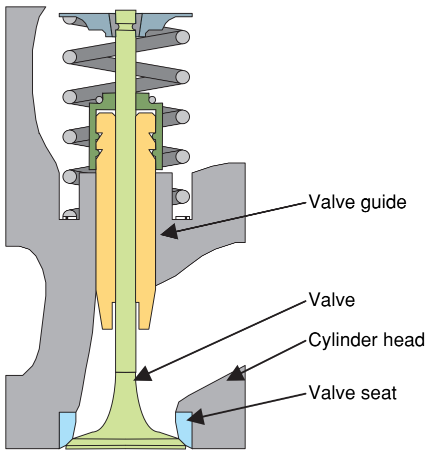


Figure 10 Valve train system of a gasoline engine

【Valve Guide Materials[7]】

The alloy design of sintered materials for valve guides, as represented by EB–4, is widely used due to its outstanding wear resistance achieved by the lubricity of free graphite, precipitated hard phase of Fe-P-C (MHv1200), and the conformability by phase dispersion of Cu-Sn. Also, oil retention is high due to the existence of pores. This lubricity is a major factor in sintered valve guide' s outstanding wear resistance compared to other manufacturing methods. The microstructure of EB-4 is shown in **Figure 11**.

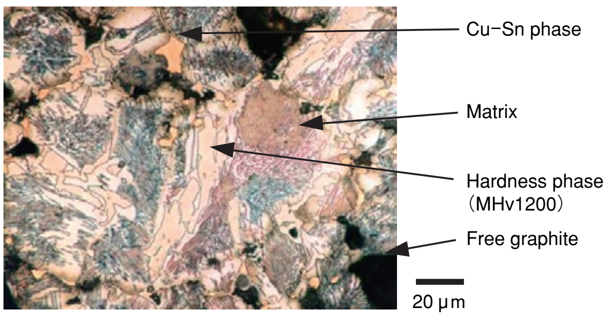


Figure 11 Microstructure of sintered valve guide material

【EGR and High-Chromium Heat-Resistant Wear-Resistant Material for Turbocharger】

In recent years, the development of environmentally friendly technologies has become more important. Exhaust gas recirculation (EGR) is being used by many engines to reduce NOx and improve fuel efficiency. Also, to make exhaust gas clear and to raise engine power, turbochargers (T/C) are currently being installed in almost all diesel engines.

The use of sintered materials for emission systems, such as EGR and T/C, has become active. The heat- and wear-resistant materials based on stainless steel or high chromium cast iron are mainly used for those systems. In the future the need for sintered materials is expected to grow along with the expansion of the market for exhaust system parts. High-chromium sintered materials have been developed for expected use in higher temperature environments. **Figure 12** shows the microstructure of the high-chromium sintered material, EW-50. EW-50 has the bases of chromium (approximately 20%) with uniformly dispersed chromium carbide (30% in area) and carbides precipitated more finely than high chromium cast steel. Thus EW-50 doesn't have discontinuity of chromium-poor layer and exhibits superior wear resistance and anti-oxidization ability in high-temperature environments of more than 700 °C.

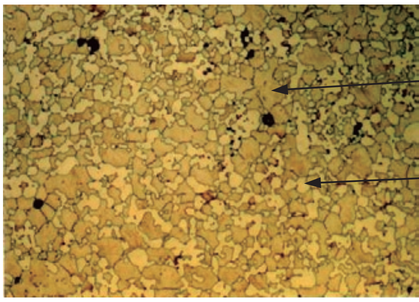


Figure 12 Microstructure of high-Cr-content sintered material with high heat and wear resistance

2.2.3 Future Developments

Materials for tribology have ingredients and microstructures that can only be produced by P/M methods. Thus we will contribute to addressing the severe environmental problems by developing new materials that sintering technology was not able to produce.

2.3 Magnetic Parts[8)]

The need for magnetic parts is growing as electric vehicles become popular. The most significant feature of magnetic parts produced by P/M methods is the ability to form three-dimensional magnetic circuits. These parts are roughly classified into sintered magnetic core materials, which are produced by regular P/M processes, and powder core materials, which are not sintered. Sintered magnetic cores are primarily formed by compression molding of pure iron-based materials to make them dense. They are being applied to various types of actuators and motor cores in low-frequency regions. On the other hand, powder cores are used in solenoid valves. These valves are applied to several types of reactors used in high frequency magnetic field with high resistance materials and common rail injectors of diesel engines utilizing high density compacting technology.

2.3.1 Sintered Magnetic Core Materials

The direct-current (DC) magnetic properties of a sintered core are primarily determined by the sintered core's composition of materials, its density, and its crystal particle size. A pure iron sintered core has high magnetic flux density. This magnetic flux density is strongly related to the object's purity and density. Therefore, a high-density sintered core using highly pure iron particles has a high magnetic flux density. When P is added to this material, its crystal particle size grows, resulting in high permeability. Iron-nickel-based sintered material, which has even high permeability, is called permalloy. It is used in magnetic shielding materials, etc.

The alternating-current (AC) magnetic properties of a sintered core are largely related to the shape of the part, as well as the composition of materials and the density of the sintered core. Core loss occurs when the sintered core is used in an AC magnetic field. As shown in Equation 1, besides the properties of the material, the core loss is related to the thickness of the iron core material.

$$W = Wh + We = k_1 B^{1.6} f + k_2 B^2 t^2 f^2 / \rho \qquad (1)$$

Wh : Hysteresis loss We : Eddy current loss k_1, k_2 : Coefficients
B : Magnetic flux density f : Frequency t : Thickness of iron core
ρ : Resistance inherent to iron core material

As the formula makes clear, eddy current loss increases by the square of the thickness of the iron core. Therefore, an iron core that can be applied to sintered magnetic cores is generally composed of many thinner parts.

Figure 13 shows the rotor core used in a hybrid electric vehicle. Its outer circumference uses a sintered magnetic core material made of pure iron. The interior portion requires a high degree of strength because motor torque is directly transferred

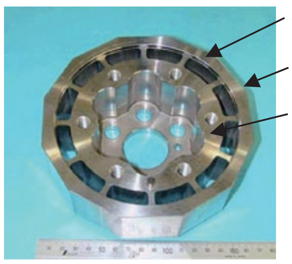


Figure 13 Rotor core for motor of HEV by diffusion bonding at sintering

to the shaft. Thus it is composed of Fe–Ni–Cu–C-based material, and is combined into a single body by diffusion bonding at sintering.

2.3.2 Powder Core Materials

Powder magnetic cores are insulated by 100-µm magnetic powder particles one by one. By reducing the thickness of the magnetic material down to 0.1 mm, the material can lower the core loss in an AC magnetic field. **Figure 14** shows an schematic diagram of the elements forming the powder core. The surface of pure iron powder particles about 100 µm in size are coated with an inorganic insulator. After they are mixed with a small amount of organic resin binder, they are compression-compacted and heated to produce the magnetic core. Therefore the powder core, unlike sintered magnetic core materials, cannot be expected to be densified in the sintering process. Thus densification is required during the compacting process. **Figure 15** shows the relationship between the frequency and magnetic flux density for different types of magnetic materials. Ferrite has little core loss in the high-frequency region, but its magnetic flux concentration is low, so it has the disadvantage of the iron core becoming large. Also, the magnetic flux density of a silicon steel sheet is high, but in high-frequency regions core loss becomes high, so it cannot be used. The application of powder cores (or soft magnetic core [SMC]) can compensate in both of these magnetic materials.

Figure 16 shows the solenoid cores used in common-rail injectors of diesel engines. Powder core material is applied to these cores. This product is an electromagnetic part that precisely opens and closes the fuel injector in the system improving the power of diesel engines and suppressing toxic components in exhaust gases. For such a product, high magnetic flux density and low core loss are required.

2.3.3 Future Developments

From here on, we are seeking to pioneer new applications of magnetic materials to support the expected growth in the demand for electric cars. We will do this by improving magnetic properties and advancing the development of net shaping methods in order to produce cores that are even more difficult to form.

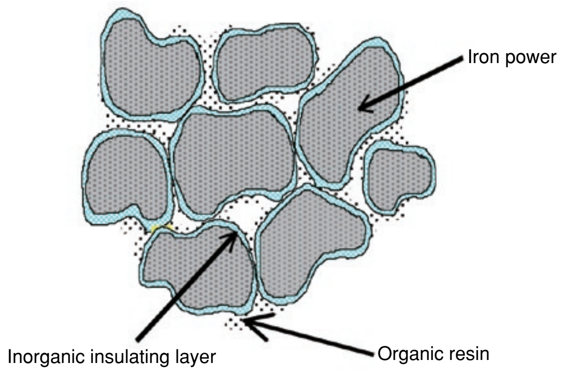


Figure 14 Construction image of soft magnetic

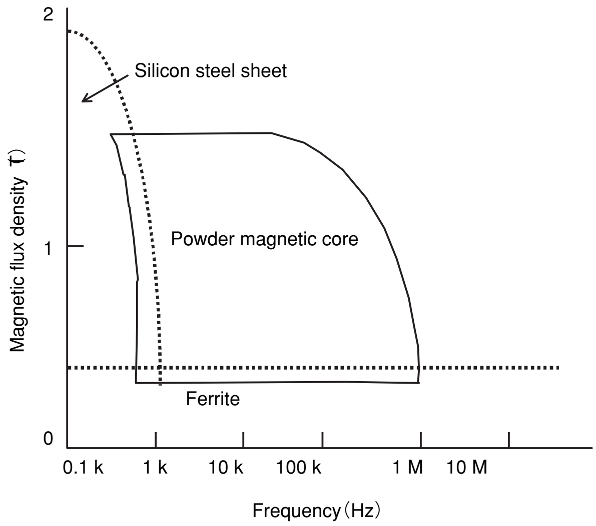


Figure 15 Relationship between frequency and magnetic flux density of each magnetic material

Figure 16 Fuel injector core of a diesel engine

2.4 Next-Generation High-Performance Parts

2.4.1 New Technologies for Home Information Appliances and Life Sciences: Compacting Micro Parts

In recent years, demands of miniaturization and thinner component parts have been growing, corresponding to the increase of miniaturized and multi-functional digital home appliances or advanced medical equipment. However, conventional die compacting method by free-filling raw powders into die cavities cannot meet the demands for smaller and thinner parts due to effects including frictional resistance and Van der Waals force produced between particles and dies, and the effects of air. Thus we have focused on metal injection molding (MIM) of raw materials, which are superior for molding parts with complex shapes.

We have also developed new powder compacting methods by using flow molding that utilizes the plasticity of the binder inside a heated die. **Figure 17** shows the compacting process for micro parts. The movement distance of fluid compounds are shortened to an extreme degree, and the loss of pressure is minimized. This process allows the compacting of 0.025 modules that surpass 0.1 modules, which represent the limit of micro gears made by the conventional P/M method. Our new methods can also produce two-stepped gears with complex axis.

Figure 18 shows the appearance of a micro gear formed by the above compacting method.

Figure 19 shows the trend in compacting technologies and material technologies in powder metallurgy in the future. The technologies developed by Hitachi Powdered Metals make it possible to achieve a high level of productivity in the micro size region not possible with conventional compacting and machining technologies. Also, by combining the technologies with micro die manufacturing technologies and nano-crystal powder, we are anticipating high-performance properties such as super high strengthening.

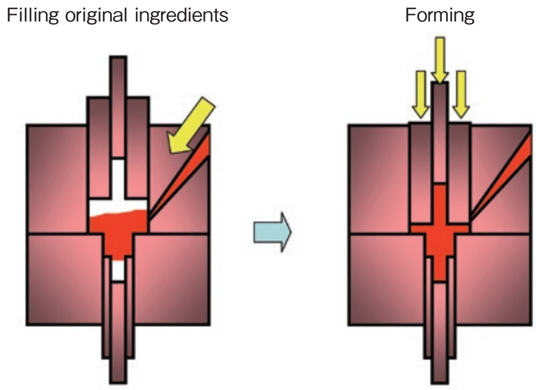


Figure 17 Developed compacting process for micro parts

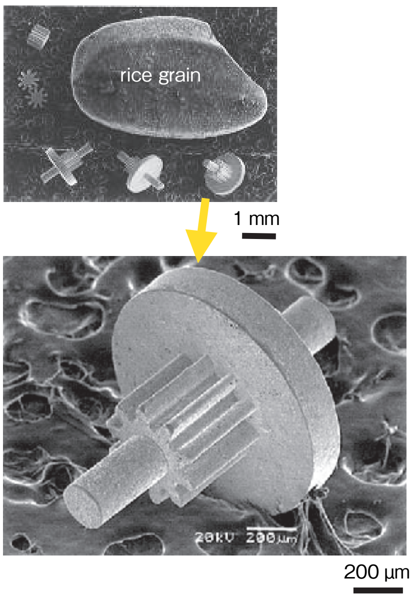


Figure 18 Appearance of micro gears

Size	1 nm DNA · 1 µm Visible light Capillary · 1 mm Smaller artery · 1 m
Fields of application	Microsensors · Medical equipment · Medical / precision equipment · Industrial machinery · Automobile
Micro forming	Micro forming technology · Conventional forming technology LIGA / electron beam / ion beam ← Electrical discharge processing / grinding / mechanical processing Nano powder ← Microscopic metallic powder ← Metallic powder for powder metallurgy
Nano organization	Nano amorphous · Microcrystal · Conventional crystal size Nano powder ← Microscopic metallic powder ← Metallic powder for powder metallurgy

Figure 19 Trends of compacting and material technologies in P/M

2.4.2 New Technologies in the Environmental Energy Field: Developing Thermoelectric Conversion Modules[10),11)]

A great deal of heat is wasted by steel manufacturing, refining, ceramics, and heat treating, such as P/M production of Hitachi Powdered Metals. Thus, research to retrieve and regenerate energy is accelerating. Hitachi Powdered Metals has also positioned new products in the field of environmental energy, and is developing thermoelectric conversion technologies.

A thermoelectric conversion technique is to convert thermal energy (difference in temperature) to direct electric energy by using thermoelectric semiconductors (this technique is called thermoelectric generation or Seebeck generation). It is the only method that is expected to use unused energy effectively in high-temperature regions of nearly 500 °C. However, in order to construct a thermoelectric conversion module that can be used under such a high temperature, many problems that involve each part, such as thermal stress, diffusion between components, and corrosion due to atmospheric gas must be resolved. We have developed an encapsulated Si-Ge module that overcomes these challenges (see **Figure 20**).

This module uses Si-Ge in the thermoelectric semiconductor.

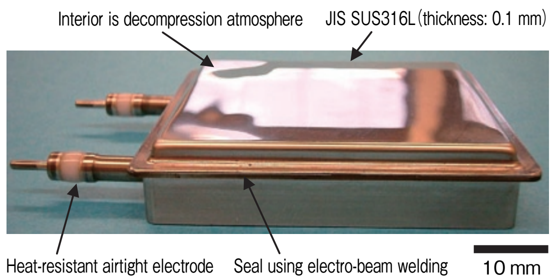


Figure 20 Encapsulated Si-Ge thermoelectric module

It can generate 8.4 W under a high temperature of 650 °C (ΔT: 630 °C) (see **Figure 21**). We confirmed that it can endure 1,400 heat cycles and 900 hours of continued use. We are currently making progress in the development of a module using high-performance Mg_2Si elements.

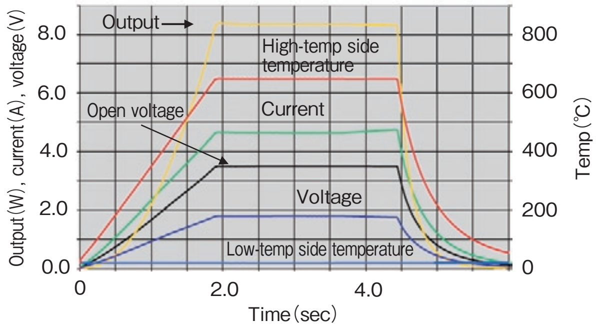


Figure 21 Generation performance of encapsulated Si-Ge thermoelectric module

3 Summary

P/M parts produced by Hitachi Powdered Metals have grown greatly with structural and tribological parts. These parts fulfill both the material properties particular to P/M technologies and economic efficiency. From here on, we must develop products that support both the transformation of automobiles and global needs. We must also focus on growing non-automobile fields. To satisfy these needs, besides developing raw materials, we must develop production technologies that stably maximize the properties of materials at low prices. Sometimes, we tend to limit our development to inexpensive production method. However, we will continue the effort to take advantage of the uniqueness of P/M technology that produces high quality which the wrought materials cannot achieve. We also develop high valued-added products by discovering potential needs of our customers.

Markets have entered an era in which the word “environmental friendly” cannot be disregarded. Hitachi Powdered Metals has begun to promote a new environmental action plan with the goal of realizing a sustainable society. Thus we have set the goal of raising the percentage of products that meet environmental standards to 72% by the end of FY2011. Under these circumstances, P/M products play a critical role. We challenge the development of new technologies, including structural parts and tribological parts that can contribute to making current automobile engines more efficient; magnetic parts that support the evolution of power source of next-generation vehicles such as hybrid electric vehicles and electric vehicles; and thermoelectric conversion products that are effective to regenerate energy from waste heat. We hope that we will be appreciated in worldwide by our contribution to “manufacturing in harmony with environment.”

【References】

1) Tadayuki Tsutsui: “Technology Trend and Future Outlook of Structural Materials”, *Hitachi Powdered Metals Technical Report*, No. 7 (2008), pp. 2-6
2) Tadayuki Tsutsui , Kei Ishii, Sumihisa Kotani, Junichi Kamimura: “Development of High Strength PM Steel without Quenching Process”, *Proceeding of the 1998 Powder Metallurgy World Congress*, EPMA, 2 (1998), pp. 607-612
3) Hideshi Miura: *The Science of Powder Metallurgy*, Uchida Rokakuho (1996), pp. 2-12
4) Shikata, Hideo: “Technological Transition of Oil-Impregnated Sintered Bearings”, *Hitachi Powdered Metals Technical Report*, No.2 (2003), pp. 2-8
5) Yanase, Takeshi, Motohiro Miyasaka: “Sliding Property of Cu-C Sintered Materials under High Contact Stress and at Low Sliding Velocity”, *Hitachi Powdered Metals Technical Report*, No.1 (2002), pp. 19-23
6) Endo, Hiroyuki: *Basic Research on Development of Manufacturing Technologies for Combustion Parts*” (2005), pp. 68-120.
7) Kawata, Hideaki, Kunio Maki: “Recent Trends in Heat Resistant / Wear Resistant Sintered Alloys”, *Hitachi Powdered Metals Technical Report*, No.6 (2007), pp. 2-8
8) Kazuo Asaka, Chio Ishihara: “Technical Trends in Soft Magnetic Parts and Materials”, *Hitachi Powdered Metals Technical Report*, No.4 (2005), pp. 5-9
9) Japan Powder Metallurgy Association: “Japan Powder Metallurgy Association Annual Report FY2009” (2010), pp. 25-26.
10) Kei Ishii : “The Approach of PM Technology for Environment Protection”, *Hitachi Powdered Metals Technical Report*, No.8 (2009), p.7
11) Takahiro Jinushi, Zenzo Ishijima, Mitsuru Kanbe: “Development of the High Performance Encapsulated Thermoelectric Modules for High Temperature Conditions”, *Hitachi Powdered Metals Technical Report*, No. 8 (2009) 18, pp. 21-22