SUMITOMO ELECTRIC TECHNICAL REVIEW

No. 100 · APRIL 2025

FEATURED TOPIC

Non-Magnetic and High-Strength Iron-Based Sintered Parts

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Iron-based sintered parts have traditionally been used as structural components across various fields due to their ability to be efficiently net-shaped into complex shapes using powder compacting technology, leveraging the excellent balance of strength and cost that iron offers. In recent years, the demand for smaller, lighter, high-strength, non-magnetic materials has been on the rise in sensing technology required for further advancements like electric vehicles, high-performance appliances, and smart factories. In response to these trends, we have developed a new non-magnetic, high-strength iron-based sintered material that goes beyond existing materials. This paper discusses the characteristics and benefits of this newly developed material.

Keywords: powder metallurgy, sintered materials, steel, non-magnetic materials, high-strength materials

1. Introduction

In recent years, the electrification of automobiles, the enhancement of the performance of home appliances, and the automation of factories have been progressing rapidly, and the importance of motors, which form the basis of these driving components, has been increasing even further. In addition, as sensing technologies diversify in preparation for the IoT society, demand for sensors using magnetism is also expected to increase. In these products that use magnetism, non-magnetic metal materials are often used around magnetic components to shield the magnetic field generated by the magnetic components, protect peripheral components that are vulnerable to magnetism, and control the magnetic flux.

Non-magnetic metals include copper, zinc alloys, aluminum, some steel materials, and titanium, but mass productivity and raw material costs limit the selection to zinc alloys, aluminum, and steel materials. Furthermore, depending on the actual use environment, steel materials may be selected instead of zinc alloys or aluminum for parts that require heat resistance, such as high-rotation type motors.

Now, in the case of secondary processing manufacturers and final manufacturers engaged in assembly, it is important to minimize the size and thickness of components as a means of differentiation from competing companies. However, the smaller the part is, the more force it receives per unit area, so it is necessary to increase the strength of the material. In response to such demand, wrought material manufacturers are releasing many high-strength non-magnetic materials that surpass the properties of conventional non-magnetic steel materials (SUS304 and SUS316).(1)

However, there is one problem with procuring final part shapes using the above high-strength materials. That is, the material cannot be formed beyond the maximum load of the forming machine owned by the sheet metal pressing manufacturer. Aside from forming and processing thin sheets of a few millimeters or less, the material must be soft in order to obtain thick, complexly shaped parts by plate forging or other press forming methods. On the other hand, since the final strength of soft material when it is formed and processed is low, the strength features cannot exceed the required specifications even if the material is formed and processed to the required shape.

It is also difficult to increase the strength of a material by heat treatment. Strengthening by “quenching,” as one might imagine for ordinary steel, takes advantage of the change from a non-magnetic austenite structure to a magnetic martensite structure, but when applied to non-magnetic steel materials, the non-magnetic property is lost. Rather, in the case of ordinary stainless steel, the martensitic microstructure generated during processing becomes magnetic, and heat treatment is performed to eliminate this microstructure, resulting in reduced strength in many cases.

In summary, there are some forming and processing challenges in obtaining high-strength, non-magnetic steel parts with complex shapes from wrought materials. To address these issues, we have investigated the use of sintered parts to increase the strength of non-magnetic steel materials and report the results of our development.

2. Conventional Strengthening Methods for Austenitic Steel Materials

Among steels, those that are non-magnetic are limited to austenitic steels. There are several conventional methods for strengthening austenitic steel materials. In this chapter, we will outline three general methods for both wrought and sintered materials: strengthening during material production, strengthening during forming, and strengthening by heat treatment after shaping into products.

2-1 Strengthening methods for wrought material

(1) Strengthening during the production of materials

Solid solution strengthening is a method of strengthening during material fabrication. As shown in Fig. 1, non-magnetic austenitic steel materials can be solid solution*1 strengthened with carbon and nitrogen atoms, which are interstitial elements, in the gaps of the crystal structure composed of iron atoms and transition metal elements. Interstitial elements have a greater strengthening capacity than substitutional elements, and steelmakers are developing high-nitrogen steels with higher nitrogen concentrations in molten metal. These steels have a high ratio of manganese, an austenite stabilizing element, to reduce the ratio of nickel, also an austenite stabilizing element. However, as mentioned above, one drawback of high manganese steels is that they are difficult to process because of their high-strength at the time of solidification.(1)

There are also methods of strengthening by dispersing fine oxides and the like. However, dispersing a large amount of fine oxides in molten metal is difficult because it causes agglomeration and coarsening of the reinforcing particles.

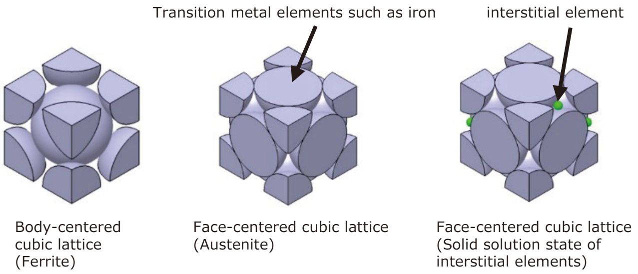


Fig. 1. Crystal structure of iron and steel materials and arrangement of interstitial elements

(2) Strengthening during the forming of materials

Strengthening by cold working (cold forging) occurs when a large external force is applied to forcefully deform the microstructure of the material. The strengthening mechanism is classified as grain refinement strengthening and dislocation strengthening. This method strengthens the material according to the degree of deformation, and its strengthening capacity is greater than that of other strengthening methods.

(3) Strengthening by heat treatment after shaping into products

This is a strengthening technique in which a long heat treatment is performed to generate second-phase particles with respect to the base phase, and is called aging treatment (age hardening, precipitation strengthening). Austenitic precipitation strengthening treatments typically include the precipitation of Ni_3Ti and Ni_3Al, with SUS660 as an example.(2)

Nitrogen solid solution strengthening is known as solid solution strengthening during heat treatment, which is performed by adding nitrogen to steel components. Although the strengthening capability is inferior to that of precipitation strengthening, the sintering process in atmospheric gas is relatively inexpensive and the equipment cost is also low.

2-2 Strengthening methods for sintered materials

Strengthening methods for sintered materials are generally more restrictive than for wrought materials.

(1) Strengthening during the production of materials

The method of strengthening the powder during raw powder production is difficult to apply because the powder does not deform well during pressing. As a result, the density of the compact is significantly lower. In addition, raw powder for powder metallurgical materials is often manufactured by water atomization; however, powders with a high percentage of manganese are challenging to manufacture due to their oxidation during this process.

(2) Strengthening during the forming of materials

In general powder press forming, the deformation of each particle of the raw powder is not large, and subsequent heat treatment (sintering) is required; therefore, this method cannot be applied.

(3) Strengthening by heat treatment after shaping into product

Precipitation strengthening is possible in principle as a method of strengthening during heat treatment. However, elements such as Al and Ti, which have a large strengthening capacity by precipitation strengthening, are easily oxidized during water atomization. On the other hand, solid solution of carbon and nitrogen are useful methods. As shown in Fig. 2, the intermediate material at the time of forming has open pores leading to the interior, and under a carburizing or nitriding gas atmosphere, the gases penetrate to the interior, strengthening the entire material.

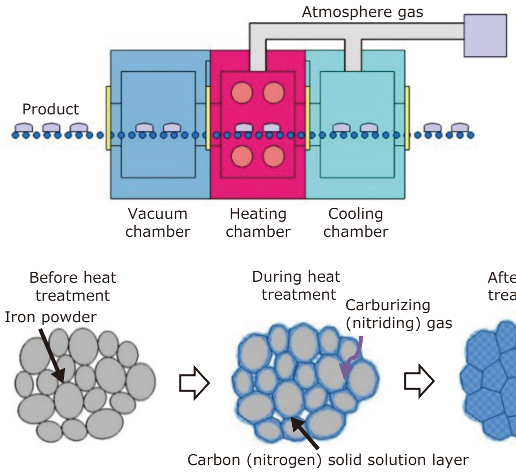


Fig. 2. Gas carburizing (nitriding) sintering method

Another technique that is applicable only in powder metallurgy is the elemental powder mixing method. By mixing hard particles with soft raw powder, it is possible to strengthen the sinterd material obtained as a product while maintaining press formability. This can be produced in two ways. One is by mixing oxide, carbide, nitride, boride, and other hard fine particles.(3)

The other method is to mix elements that easily diffuse, which will be discussed later.

3. Concept of High-strength, Non-magnetic Sintered Parts

In the case of melt-solidified materials, cooling rate is basically slow because the parts produced are relatively large from the viewpoint of productivity. Therefore, carbides are easily formed due to segregation of carbon concentration during melting and solidification, and there is concern about strength reduction. For these reasons, carbon is basically an element that should be removed from non-magnetic steel materials. However, in powder metallurgy, due to the absence of a melting and solidification process, those products are more homogeneous compared to those produced by the melting method. And those products are manufactured by the net-shape*2 process, so they are small and easily cooled at the time of forming. Therefore, carbides are less likely to form and coarsen, and the carbon content can be increased compared to that of wrought steel.

Therefore, we decided to combine our original component development and heat treatment methods to obtain a high-strength material that surpasses existing steel sintered materials.

In particular, elements for solid solution strengthening are added as secondary materials, rather than hard materials such as fine oxides and carbides. In addition to the use of interstitial elements such as carbon, substitutional elements were also considered. We have found that some substitutional elements can be homogeneously diffused within a realistic heat treatment time for industrial use if the particle size, mixing ratio, and mixing method of the sub-materials are performed under appropriate conditions. As shown in Fig. 3, elements blended as sub-materials diffuse solid-phase with elements in the base-phase iron alloy during sintering, resulting in a material with homogeneously diffused reinforcing elements after sintering.

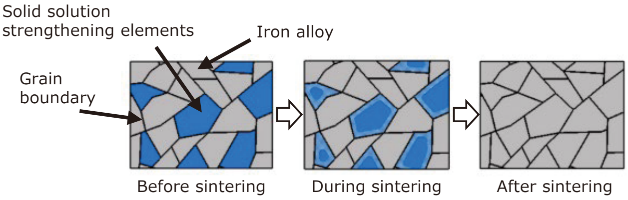


Fig. 3. Solid phase diffusion of elements during sintering

In addition to diffusing homogeneously into the base metal during heat treatment, it is also important that the composition of the powder used as a secondary material is mainly composed of austenite stabilizing elements to avoid inducing transformation to a martensitic structure with magnetic properties. The index is defined by elements that are Ni equivalent, such as Ni, Co, Mn, Cu, C, and N, and Cr equivalent, such as Cr, Si, Mo, V, Al, Nb, Ti, and W, as known from the Sheafflar phase diagram(4) (as improved by SCHNEIDER), as shown in Fig. 4. Among these, compositions that are completely in the austenitic region almost never undergo martensitic transformation even when subjected to strong working. However, although not shown in the Sheafflar phase diagram, in actual compositions, an excess of Cr results in a Cr alloy rather than an Fe alloy steel, and an excess of Ni results in a Ni alloy classification; Cr alloys are brittle at room temperature. Ni alloys have the same crystalline structure as Fe alloys and often have high-strength and non-magnetic properties, but they are less desirable because of their high cost.

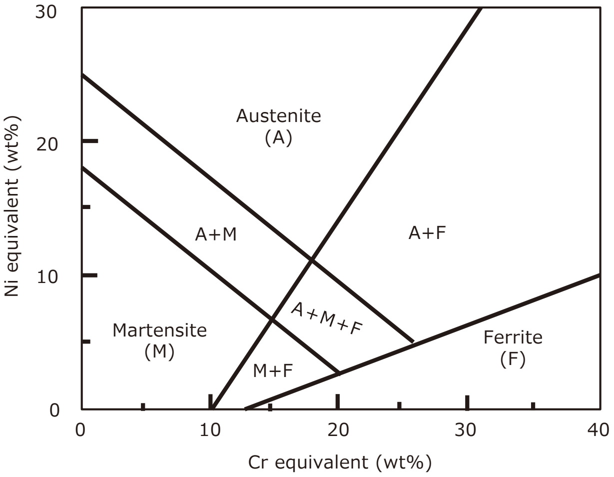


Fig. 4. Sheafflar phase diagram(4)

As shown in Fig. 5, excessive amounts of carbon and insufficient cooling speed lead to the formation and growth of excess carbides. This destabilizes the composition of the matrix phase and does not ensure non-magnetism.

Based on the above we optimized the alloy composition by adding highly diffusible elements to the steel and investigated the heat treatment conditions suitable for this composition. As a result, a sintered material that meets all the requirements, such as high-strength, non-magnetic properties, complex shapes, and productivity, was obtained, which was difficult to achieve with wrought materials.

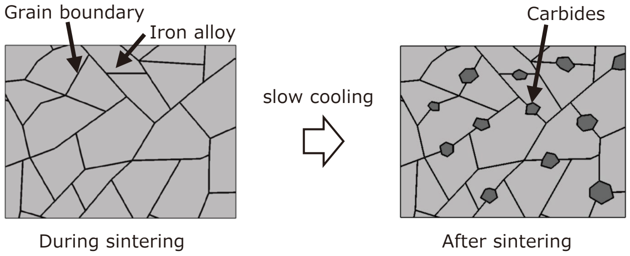


Fig. 5. Formation of carbides

4. Physical Properties of the Developed Material

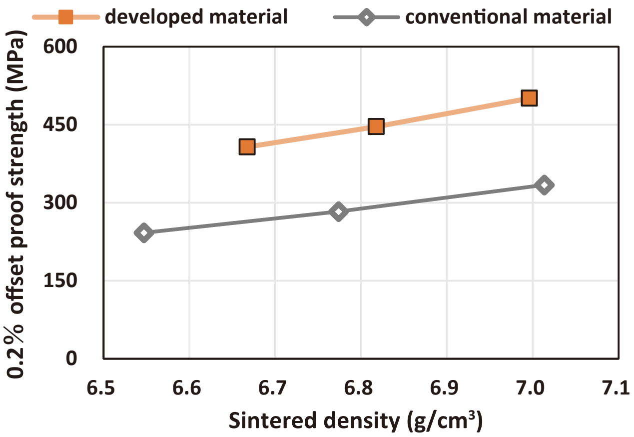
Table 1 shows various physical properties of the developed sintered materials compared to conventional materials. Although the properties of sintered materials have some fluctuations due to changes in the type and amount of secondary materials, forming conditions, and heat treatment conditions, the developed material shows significant improvements in tensile strength and hardness compared to our conventional sintered materials.

Table 1. Physical Properties of the developed materials and other materials

	Developed materials	Conventional materials
Density (g/cm^3)	6.7–7.0	6.5–7.0
0.2% offset proof strength (MPa)	340–390	150–190
Elongation at break (%)	Up to 18	Up to 20
Rockwell hardness (B scale)	68–81	24–49
Magnetism	Non-magnetic	Non-magnetic

Details of each property are described as below.

Figure 6 shows typical results of 0.2% offset proof strength measurements of materials as a function of density. The developed material has an approximately 200 MPa higher 0.2% offset proof strength compared to conventional materials with typical densities for powder metallurgy.



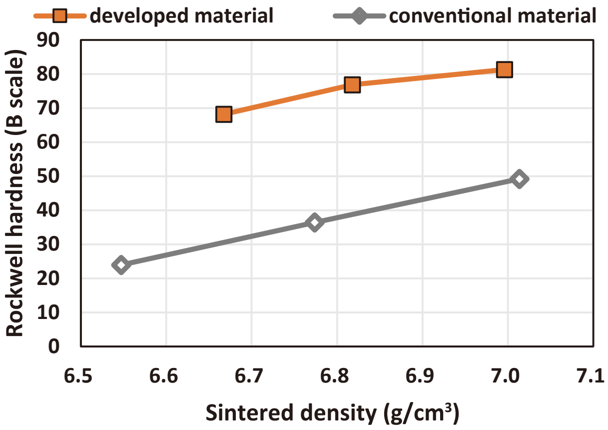
Specimens with a total length of 133 mm, parallel length of 32 mm, parallel width of 5.7 mm, and parallel thickness of 5 mm were prepared and evaluated.
Other test conditions conform to JIS Z2241:2022.

Fig. 6. Proof strength properties

Figure 7 shows typical evaluation results of the Rockwell hardness of materials as a function of density. The developed material exhibits an approximately 30–40 HRB higher hardness compared to conventional materials with typical densities for powder metallurgy.

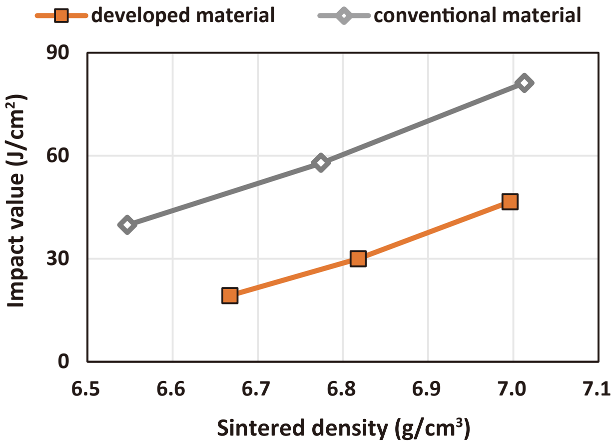
Figure 8 shows the Charpy impact test results. The strengthening principle of the developed material is solid solution strengthening, which significantly increases strength, but tends to lower the impact values.

An example of the evaluation results of the magnetic permeability*[3] of the developed material is shown in Fig. 9. The developed material and a commercially avail-



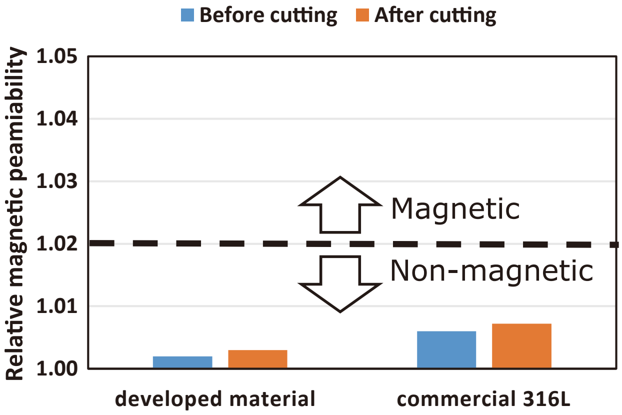
Test conditions conform to JIS Z2245:2021.

Fig. 7. Hardness properties



Specimen dimensions: length 55 mm, width 10 mm, thickness 10 mm.
However, the specimens were evaluated without notches.
Other conditions conform to JIS Z2242:2018.

Fig. 8. Charpy impact value properties



The side surface of a φ35 ×10 specimen was cut 2 mm in the depth direction by an end mill at a rotation speed of 2500 rpm and a tool feed rate of 500 m/min, and the relativemagnetic permeability was measured before and after the cutting process. The measurement of relative magnetic permeability was conducted using a relative magnetic permeability meter Ferromaster manufactured by Stefan Mayer Instruments.

Fig. 9. Permeability properties

able SUS316L wrought material were used for comparison. Both materials have a magnetic permeability of 1.02 or less, which is generally considered non-magnetic, but the developed material has a lower magnetic permeability than the commercial material both before and after processing. Austenitic materials can become magnetic due to work-induced martensitic transformation from the austenite phase during processing. This is likely due to adjustments in the composition that enhance the stability of the austenite phase, resulting in lower magnetic permeability.

5. Conclusion

In this research, we have worked on the development of high-strength and non-magnetic materials that achieve the miniaturization and weight reduction that are increasingly needed in sensing technology, which is required to evolve further in recent years for the electrification of automobiles, the enhancement of the performance of home appliances, and the expansion of smart factories. Results are summarized as below:

(1) We developed new steel-based sintered components that combine all the following criteria: high-strength, non-magnetic properties, degree flexibility, and productivity, where the composition of the sintered components was also developed.

(2) The developed materials show significant improvements in their physical properties. The developed materials have approximately 200 MPa higher 0.2% offset proof strength and 30–40 HRB higher hardness compared with conventional materials. The relative magnetic permeability was more stable on the non-magnetic side compared to conventional materials.

Based on the above results, we believe that the developed material is superior to conventional materials in terms of compactness and weight reduction needs. The number of applications that require advanced sensing technology will increase dramatically in the future, including autonomous driving and robots, which are expected to become widespread. In order to contribute to these social needs, we will not only mass-produce the developed material, but also continue to promote research and development to further improve performance.

Technical Terms

∗1 Solid solution: A state in which other atoms are introduced into the crystal structure of a metal but the original crystal structure is maintained; such a material is called a solid solution.

∗2 Net shape: Powder molding technology that realizes complex shapes of finished products without machining or other post-processing. A powder molding method that achieves the final product shape only by pressurized molding using a die, without any post-processing such as machining.

∗3 Permeability: The proportionality constant when the relationship between the magnetic field strength H and the magnetic flux density B is expressed as B = μH.

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