The Improvement in Strength of Sintered Machine Parts

Sintered machine parts are used in many industrial fields. Especially, these are widely used for automotive parts. It is essential for the increasing use to improve mechanical properties of sintered parts. However, the pores in the sintered body are a dominant factor for the strength of sintered parts. Therefore, various kinds of trial to decrease pores in the sintered body, or to increase sintered density were reported. This article introduces the method of improvement of density and strength, and the mechanical properties of high-density sintered machine parts.

1. Introduction

Sintered machine parts have been adopted in diverse fields as they can be made into complex shapes and are suitable for inexpensive, large volume production. The production volume of sintered machine parts in Japan amounted to approx. 90,000 tons in 2013 and more than 90% of that volume was for transportation machines.

Recently, in particular, sintered machine parts have been actively used in the automotive industry, with 9.0 kg used per vehicle; 50% of these are for the engine. 1) In order to expand the scope of sintered machine part applications, improvement in their mechanical properties is vital. However, since sintered compact is porous, ordinary sintered machine parts are not as strong as molten steel parts. Therefore, reduction of pores in the sintered compact, namely, by methods to increase density, is being attempted to improve mechanical properties.

In this paper, we will present methods to make the sintered machine parts higher density/higher strength through materials or compacting and machining processes and improvement in mechanical properties.

2. Sintered alloy steel

Sintered alloy steel is used in many sintered machine parts 2). Powders for sintered alloy steel have a particle size of approx. 300 μm or less and include alloy elements such as copper (Cu), nickel (Ni), chromium (Cr) and molybdenum (Mo), in addition to iron (Fe). Other elements include those specified in JIS Z 2550, which complies with the ISO Standards that specify their chemical contents. The specification for sintered alloy steel is different from molten steel. For example, Cu, which is treated as an impurity in molten steel, is actively used in sintered alloy steel for improving sintering properties at low temperature and enhancing sliding properties. Also, carbon (C) is added as graphite powder to be solidified into iron during sintering. This is to avoid significant deterioration of formability if graphite is solidified into iron in the powder form as the powder becomes hardened. Material manufacturers are developing proprietary powders outside the specification so that the optimum materials can be selected depending on the intended use.

The base metal powder is either mixed powder with all the additive elements, completely alloyed powder with additive elements pre-alloyed and homogenized, or diffusion alloyed powder which uses pre-alloyed additive elements with no negative effect of compaction and the remaining additive elements diffusion bonded by thermal diffusion.

* Advanced Technology R&D Center
Table 1 shows the classification of metal powder of typical sintered alloy steel; Table 2 shows the features of completely alloyed powder and diffusion alloyed powder; Fig. 1 shows SEM micrographs. The following are typical sintered alloy steels used for machine parts.

### Table 1 The classification of metal powder of typical sintered alloy steel

<table>
<thead>
<tr>
<th>Powder type</th>
<th>Sintered alloy steel</th>
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<tbody>
<tr>
<td>Mixed powder</td>
<td>Fe-Cu-C base</td>
</tr>
<tr>
<td>Completely alloyed powder</td>
<td>Fe-Ni-Mo-C base</td>
</tr>
<tr>
<td>Diffusion alloyed powder</td>
<td>Fe-Cr-Mo-C base</td>
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### Table 2 Feature of completely alloyed powder and diffusion-alloyed powder

<table>
<thead>
<tr>
<th>Homogeneity of powder</th>
<th>Completely alloyed powder</th>
<th>Diffusion alloyed powder</th>
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<tbody>
<tr>
<td>Compaction property after</td>
<td>Low</td>
<td>High</td>
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<tr>
<td>forming process</td>
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**Fig. 1** SEM micrographs of completely alloyed powder and diffusion-alloyed powder

**2.1 Fe-Cu-C base**

Fe-Cu-C based material is widely used as sintered material for machine parts. Cu has a melting point of 1085°C and melts under the general sintering conditions of sintered alloy steel.

Therefore, Cu exists in the liquid phase between iron particles and is alloyed as sintering progresses. This results in high-strength. In addition, Cu is known for volume expansion when sintered with Fe powder. It can be used to control size change since the volume generally shrinks with sintering. Mixed powder is frequently used mixing pure iron powder with pure copper powder or graphite, etc.

**2.2 Fe-Ni-Mo-C base**

Fe-Ni-Mo-C based material is used to obtain high-strength sintered compact by various tempering and annealing processes after sintering. Wear resistance can also be obtained by applying a surface hardening process in addition to high-strength. Improvement of steel toughness can also be expected by Ni. Ni is frequently used with completely alloyed powder or diffusion alloyed powder.

**2.3 Fe-Cu-Ni-Mo-C base**

Fe-Cu-Ni-Mo-C based material is made by diffusion bonding of fine powders of Cu, Ni, Mo, etc. to pure iron powders. This is done to combine the features of the above two previous materials. It is currently widely used as high-strength sintering material since it has both high compaction and excellent mechanical properties.

**2.4 Fe-Cr-Mo-C base**

Cr, as an element for alloy, is generally used as machine structural parts in molten steel. On the other hand, when used as sintering material, it is difficult to reduce oxygen content as it has high affinity with oxygen. This means that high compaction and high density are difficult to obtain. However, with recent technological progress by material manufacturers, powders with low oxygen content are developed with improved compaction properties. Fe-Cr-Mo-C based material is used in completely alloyed powder due to the above mentioned affinity with oxygen.
3. Methods for densification/strengthening

Densification methods can be performed during molding, sintering and after sintering. Table 3 shows those densification methods in each process.

<table>
<thead>
<tr>
<th>Process</th>
<th>Method</th>
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<tr>
<td>During molding</td>
<td>Warm forming</td>
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<td></td>
<td>Warm forming with mold lubrication, etc.</td>
</tr>
<tr>
<td>During sintering</td>
<td>2 forming 2 sintering</td>
</tr>
<tr>
<td></td>
<td>Infiltration, etc.</td>
</tr>
<tr>
<td>After sintering</td>
<td>Sinter forging, etc.</td>
</tr>
</tbody>
</table>

3.1 Warm forming

Warm forming is a method to obtain high-density green compact by heating the powder and mold to 80-300˚C during molding of metal powder. This reduces the yield strength of metal powder and increases compaction property.

Since this method is lower in cost compared with the 2-forming 2-sintering method and sinter forging method described later, it is used for sprockets of vehicle engines, etc.

3.2 Warm forming with mold lubrication

In general, metallic soap, such as Zn and Ca, or a resin based lubricant is added/mixed to reduce friction between the metal powder and mold when metal powder is molded; however, since the lubricant disappears during sintering, it inhibits densification. Warm forming with mold lubrication is a method to reduce lubricant by pre-applying the lubricant to the mold, in addition to the above warm forming method, to obtain high density green compact.

Since it is possible to obtain a value close to the true density, it is used in connecting rods of vehicle engines, etc.

3.3 2-forming 2-sintering

Also called 2P2S (2Press-2Sinter). This is a method to obtain high density sintered compacts by first forming powder under a predetermined pressure and applying preliminary sintering with a relatively low temperature of 1000˚C or below. Then the compact is formed under a predetermined pressure again and sintered with a higher temperature than the preliminary sintering. This is used in synchronizer hubs of vehicle transmission, etc. where strength is required.

3.4 Infiltration

Infiltration is a method to infiltrate melted material of a low-melting point into the pores of a sintered compact. Material is communicated from the surface using capillary phenomenon to fill in the pores. Specifically, the sintered compact and the green compact of low-melting point material are placed in contact with each other and heated to a temperature more than the melting point of the green compact and less than the melting point of the sintered compact for infiltration.

Since it is possible to close the pores in the sintered compact, it is used in the applications where high air-tightness is required such as compressor components or hydraulic pressure resistant components.

3.5 Sinter forging

Sinter forging is a method to obtain product by forming and sintering metallic powder, and inserting the heated sintered compact into a mold for closed die forging. A regular forging method, such as hot forging of sintered compact, with a shape close to the formed product, is also adopted. Since it is possible to obtain a value close to the true density, it is used in connecting rods of vehicle engines, etc.

4. Development of high density sintered machine parts

NTN is working on development of high density sintered machine parts with potential for various applications. The following is an example of mechanical properties of the developed materials.

4.1 Method for making test piece

We made a 23.2 mm OD x 16.4 mm ID x 7 mm H ring-shaped test piece by warm forming of 80˚C from the Fe-Ni-Mo-C based material. This was made of diffusion alloyed powder of Fe and diffusion bonded Ni and Mo with a predetermined amount of graphite mixed with lubricant, using floating die method. Next, the green compact was sintered in a mixed atmosphere of Nz and H2, then carburized tempering/annealing was applied. In addition, we prepared Fe-Cu-Ni-Mo-C based material as conventional high-density sintered compact as a control.

4.2 Mechanical properties

Fig. 2 shows sintered density and radial crushing strength. The sintering density of the developed material is 7.63 g/cm³ which is approx. 97% of true density of 7.8 g/cm³. The radial crushing strength is 2180 MPa which is an improvement of 30% or more from the 1630 MPa of the control. Fig. 3 shows the cross section micrograph of the sintered compact. It
can be observed that the number and size of the internal pores are both reduced.

We evaluated the fatigue properties of the high-density sintered compact with ring compression test. The ring compression fatigue test evaluates fatigue strength by repetitively applying compressive load on the ring outer surface which produces tensile stress on the inner surface of the ring in the direction of the load. Fig. 4 shows an overview of the measuring method. The test condition was set with a stress ratio $R=0.1$ and load frequency 50 Hz. The fatigue strength was defined as the stress amplitude when the repetitive load of $10^7$ times did not break the test piece. Here, the stress ratio is a ratio of the minimum stress over the maximum stress and the stress amplitude is the amplitude of the variable stress waveform shown in Fig. 5. Fig. 6 shows the stress-endurance diagram of the fatigue test. The fatigue strength of the developed material was 405 MPa, which was 2.25 times the control (180 MPa). The fatigue strength of the developed product is equivalent to molten steel, SCM440 thermal refined steel.

4.3 Improvement of mechanical properties by cold working

We attempted to improve mechanical properties of the sintered compact made in Section 4.1 by applying cold working to reduce pores. The cold working was applied after sintering and before thermal processing. Fig. 7 shows an overview of cold working. The sintered compact is placed between the outer restraint jig and the compression jig. The sintered compact was rolled by 0.25 mm, pressing the sintered compact by rolling the compression jig; then carburized tempering/annealing was applied.
Fig. 8 shows the cross section micrograph. By this cold working, the compact was densified in the area 0.5 mm from the surface, which is twice the rolling amount with porosity of less than 0.5%. The fatigue strength after cold working was 450 MPa, which is more than a 10% improvement from 405 MPa before cold working.

5. Conclusion

In this paper, we presented densification/strengthening methods of sintered machine parts and mechanical properties of high-density sintered machine parts. We have obtained high-density sintered compacts by applying optimum methods in each process and we have obtained fatigue strength equivalent to molten steel SCM440 thermal refined steel. In addition, it is possible to further improve strength by applying cold working, etc.

We are poised to expand application of this developed material to the machine parts that require high strength, as well as to continue developing materials with even higher performance and expanding their applications as well.

References