

Development of Sinter Diffusion Bonding for Rotor Core of Hybrid Car

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ABSTRACT

This research focused on composite technology to bond materials for rotor cores, which require both magnetic properties and mechanical properties at once, and analyzed diffusion bonding of sintered material and the bonding area as a factor affecting it. As a result, it was determined that the strength of the bonding zone depends on the bonding area, and diffusion bonding was verified as an applicable technique for bonding magnetic material and structural material, which are different materials. This report describes the establishment of a sinter diffusion bonding technique that provides satisfactory bonding strength. This was accomplished by improving the bonding area through application of pressure by press fitting of the inner and outer components, which was in addition to the difference in thermal expansion of the sintered material. Application of the developed material to rotor cores for use in hybrid cars has made it possible to achieve both functionality and strength, to significantly improve productivity, and to reduce costs by 50%.

1. Introduction

Decreasing automobile fuel consumption has become an issue that must be taken into consideration due to concerns about global environmental conservation and the depletion of petroleum resources. One measure for resolving this issue is the adoption of hybrid powerplants that combine combustion engines with electric motors. Given this context, Honda has also placed a hybrid car, the Insight, on the market. It will be necessary to further develop this approach and extend it to Honda's major product models. The issues of improving motor efficiency and lowering costs are crucial for realizing that purpose. The target here was cost reduction techniques for motor rotors, and the aim was to establish moderately-priced manufacturing techniques that would yield both the required magnetic properties and the mechanical properties, as shown in Fig. 1. The fabrication of ordinary motor rotors so that they will possess both magnetic and mechanical properties tends to involve cost increases because machining

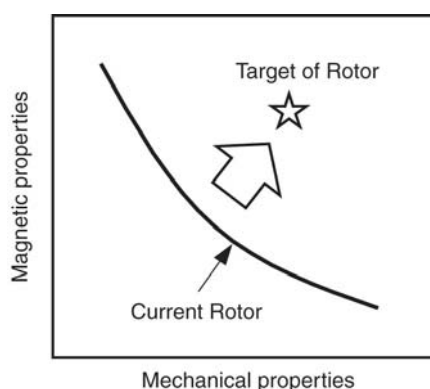


Fig. 1 Relationship between mechanical properties and magnetic properties

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is required after mechanical bonding or press fitting of the two kinds of material. Here, instead, near-net shape forming using powder metallurgy methods was explored as a way to reduce the machining process and lower the cost, and the possibilities for diffusion bonding of different materials were studied.

The diversification of uses for sintered machine parts has been accompanied by new demands for parts with complicated, undercut shapes, such as notched shapes and laterally undercut shapes, as shown in Fig. 2. Various different bonding methods have consequently been developed. Fig. 3 shows the kinds of bonding method for sintered machine parts.⁽¹⁾ In terms of bonding strength and cost, it is difficult to apply any of these methods to rotors except diffusion bonding, which makes use of the phenomenon whereby ions and atoms permeate another substance and are diffused through it. Liquid phase sintering (a method for causing shrinkage and diffusion bonding by generating a large amount of liquid phase in the sintering process) requires special chemical compositions. It also generates a large amount of liquid phase, so that dimensional accuracy becomes difficult to control. Solid diffusion bonding was used, therefore, as a bonding method that yields bonding strength sufficient for the rotor to function. This method makes use of the different thermal expansion in the combined materials during the sintering process to cause the materials to contact each other on their bonding surfaces and bond them by diffusion in their solid phase. This method is adopted with automobile engine sprockets and other such parts that have two sets of teeth.⁽²⁾

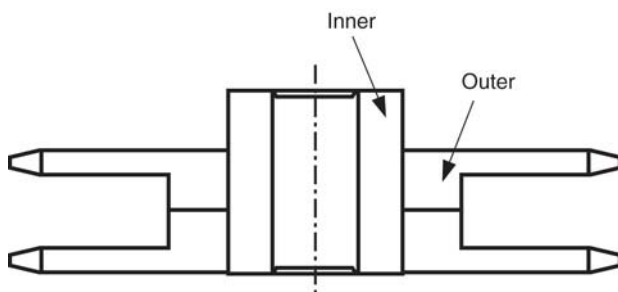


Fig. 2 Shape of undercut

The shapes of the inner and outer components of motor rotors, however, are different from automobile engine sprockets in that the outer component, in particular, is so thin that adequate bonding strength cannot be achieved by the difference in thermal expansion alone. This article reports on the consequent development of sinter diffusion bonding techniques that improve the bonding area and bonding strength. This was achieved by focusing on the properties of the sintering materials and on the initial inner part diameter over sized in order to clarify the primary factors that influence the diffusion bonding of different materials.

2. Bonding Mechanism and Technical Issues

In general, the factors that influence sinter diffusion bonding include sintering temperature, sintering time, and bonding area. Of these factors, sintering temperature and sintering time are under the constraints imposed by the manufacturing process. For the present development, therefore, it was decided to seek improvement of bonding strength by expanding the bonding area. The mechanism of bonding caused in particular by the factor of pressure was applied for this purpose. This mechanism is shown in Fig. 4.⁽³⁾ When pressure is applied to the bonding surfaces of two metals, the metal atoms approach each other to a distance as close as the Å level. When the atomic distance approaches the lattice constants (point a in Fig. 4), the atomic force reaches equilibrium so that electrons are shared and bonding takes place. Consequently, applying pressure effectively and increasing the bonding area are issues of great importance in diffusion bonding.

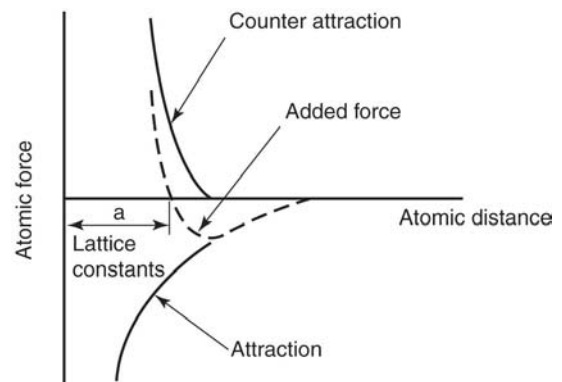


Fig. 4 Relationship between atomic force and atomic distance

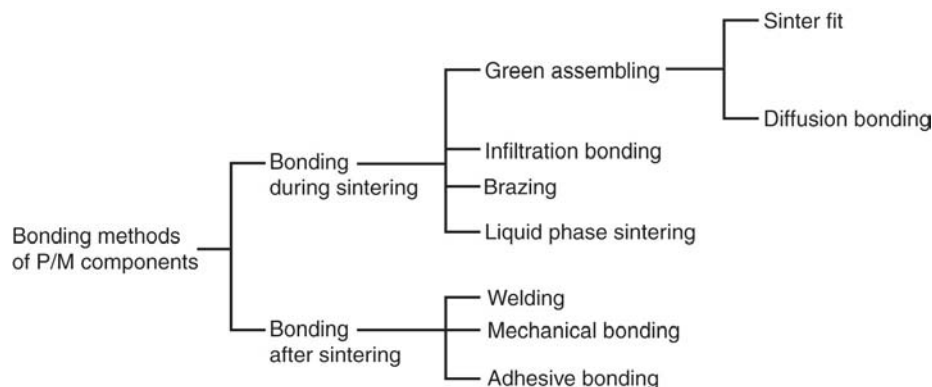


Fig. 3 Bonding methods of P/M components

3. Testing and Evaluation Methods

3.1. Rotor Material Specifications

Materials with mechanical properties and magnetic properties such as shown in Table 1 were used for the rotor materials. Fe-Cu-Ni-C material was used for the inner part for its mechanical properties, and Fe material was used for the outer part for its magnetic properties. Table 2 shows the chemical composition of each part.

The raw powder used in the inner part was based on pure iron powder with the addition of mixed powder containing copper, nickel, and carbon. Water atomized iron powder was used as the raw powder for the outer part.

Table 1 Mechanical and magnetic properties

Item	Inner	Outer
Tensile strength (MPa)	318	200
Yield strength (MPa) (0.2% Yield point)	260	–
Rotating bending strength (MPa)	190	–
Magnetic flux density (T)	–	1.04
Coercive force (A/m)	–	350
Resistivity ($\mu\Omega \cdot \text{cm}$)	–	16.4
Density (g/cc)	6.4 min	6.9 min
Apparent hardness	HRB 50 min	HRF 50 min

Table 2 Chemical composition

Chemical Composition (wt%)				
	Fe	C	Cu	Ni
Inner	Bal.	0.6	1.5	2.7
Outer	100.0	–	–	–

3.2. Measurement of the Thermal Expansion Curve

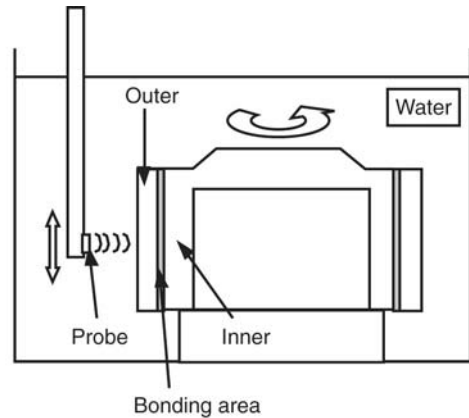
Fig. 5 shows the shape of the specimens used to measure the thermal expansion curves for the inner and outer parts. A Dilatometer 1,570 made by Tokyo Industry Co. was used as the test device. Measurement was conducted by raising the temperature from the ambient temperature to 1,130 °C in an atmosphere of endothermic gas, maintaining that temperature for 20 minutes, and then lowering the temperature back to the ambient temperature.



Fig. 5 Heat expansion test specimen

3.3. Bonding Area Measurement Method

Supersonic flaw detecting was used as the method for non-destructive examination of the condition of the bond formed by sinter diffusion bonding of the inner and outer parts. Fig. 6 shows the measurement device. A rotor impregnated with oil was placed in water and rotated. As supersonic waves were directed vertically against the bonding surface, a probe was moved up and down that surface to measure the reflected wave. A smaller reflected wave indicates a better bond. Based on the results of this measurement, the rate of diffusion bonding area (R_s) was determined as the proportion of the diffusion bonding area that is actually sound in relation to the designed total bonding surface.



Device for supersonic flaw detecting: Canon M-500A

Fig. 6 Device for supersonic flaw detecting

3.4. Bonding Strength Test

The strength of the bonding surface was measured using specimens as shown in Fig. 7 and the method shown in Fig. 8 to measure the force of rupture of the bonded portion. The method used to derive the rotor bonding strength is shown below. The force of rupture per square millimeter (P_s) was calculated using formula (1), and the bonding area (S) was calculated using formula (2). These two were then substituted in formula (3) to obtain the bonding strength (P).

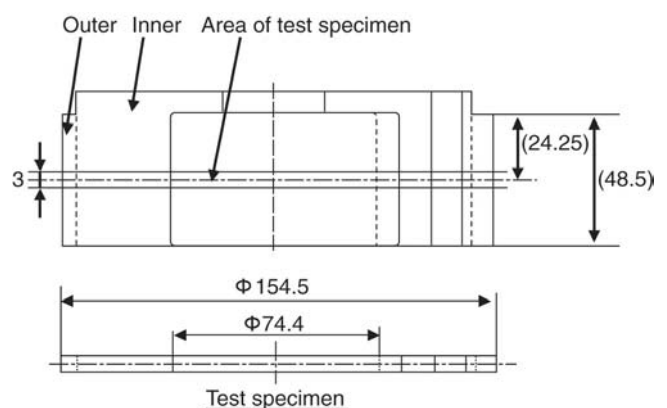


Fig. 7 Diffusion bonding test specimen

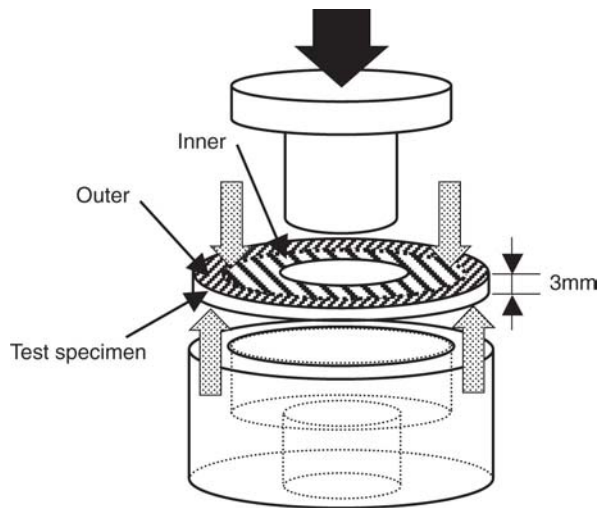


Fig. 8 Measurement method of diffusion bonding strength

$$\begin{aligned} P_s &= P_t / S_t & (1) \\ S &= A_0 \cdot (R_s/100) & (2) \\ P &= P_s \cdot S & (3) \end{aligned}$$

S : Diffusion bonding area of rotor (mm^2)
 A_0 : Calculated diffusion bonding area (mm^2)
 R_s : Rate of diffusion bonding area (%)
 P_s : Force of rupture per square millimeter (N/mm^2)
 P_t : Force of rupturing specimen (N)
 S_t : Diffusion bonding area of specimen (mm^2)
 P : Diffusion bonding strength of rotor (N)

4. Results

4.1. Thermal Expansion Characteristics

Fig. 9 shows the thermal expansion curves for the Fe material (EO material) and Fe-Cu-Ni-C material (ENK material) during the sintering process. These curves show similar tendencies up to 800 °C. Past that temperature, however, the quantity of thermal expansion in the Fe-Cu-Ni-C material begins to change, and at 1,083 °C, which is the melting point of Cu, the expansion of the copper causes the quantity of thermal expansion to be greater in the Fe-Cu-Ni-C material than the Fe material. Study was then done of combinations of the Fe material, which has superior magnetic

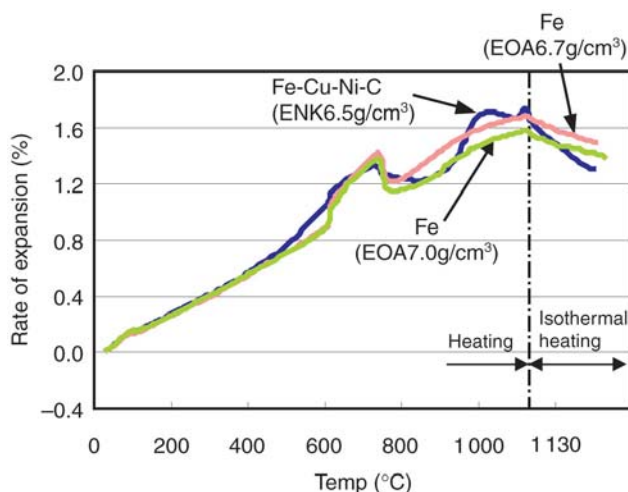


Fig. 9 Characteristic of expansion

properties, as the outer part, with the Fe-Cu-Ni-C material, which has strong mechanical properties, as the inner part, using the pressure resulting from the difference in the quantity of thermal expansion.

4.2. Factors Influencing the Bonding Area

The factors affecting the bonding area were identified in order to select the optimum conditions for diffusion bonding of the outer Fe material and the inner Fe-Cu-Ni-C material.

4.2.1. Influence of density

The relationship between the density of the inner and outer parts and the rate of diffusion bonding area was investigated. Fig. 10 shows the relationship between the inner part density and the rate of diffusion bonding area. It was determined that the rate of diffusion bonding area did not change even when the density of the inner part was varied as much as 6.4–6.6 g/cm^3 , with the density of the outer part kept constant. Fig. 11 shows the relationship between the outer

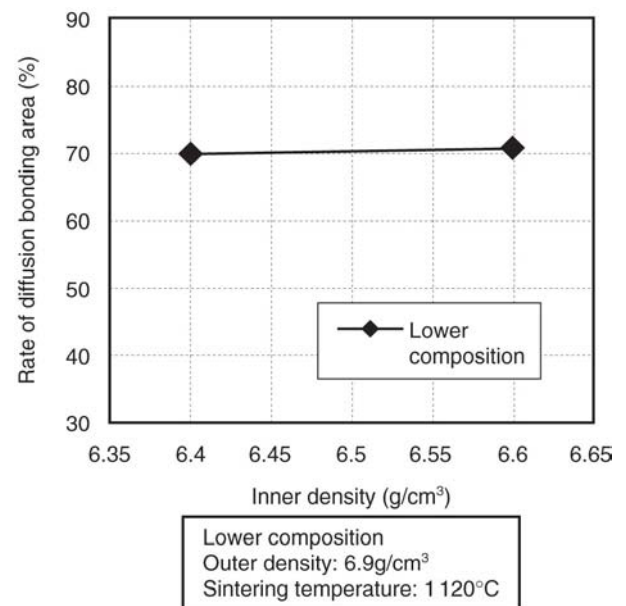


Fig. 10 Relationship between inner density and rate of diffusion bonding area

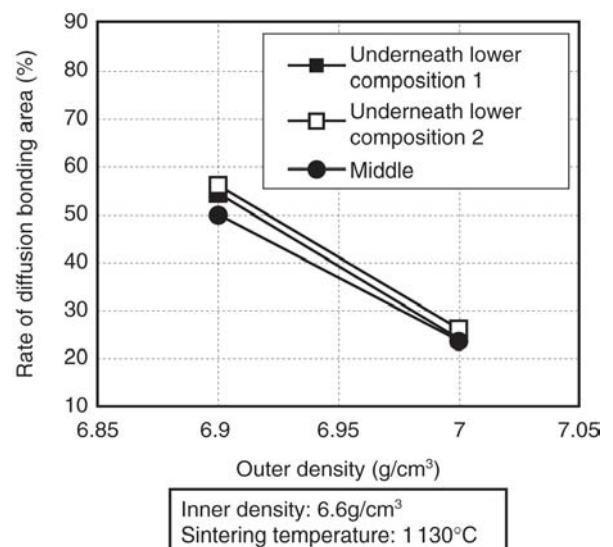


Fig. 11 Relationship between outer density and rate of diffusion bonding area

part density and the rate of diffusion bonding area. This shows that the rate of diffusion bonding area tends to decrease when the outer part density is high.

This finding is the opposite of what would be expected from the thermal expansion curves of these parts. That is, higher density of the outer part would ordinarily result in smaller thermal expansion. A larger quantity of thermal expansion in the inner part would lead to higher pressure, so that the bonding area would tend to increase. With this rotor bonding, however, more than just the difference in the thermal expansion of the parts was involved. Some strain in the outer part ascribable to the shape of the rotor was a factor, so that the bonding area could not be defined from the thermal expansion curves alone.

4.2.2. Influence of sintering temperature

Fig. 12 show the relationship between sintering temperature and rate of diffusion bonding area. It is apparent that the rate of diffusion bonding area decreases as the sintering temperature rises higher. According to the thermal expansion properties, the outer part continues to expand up to the vicinity of 1,150 °C, so that higher sintering temperatures result in lower pressure between the outer and inner parts, and diffusion bonding is impeded as a result.

4.2.3. Influence of chemical composition

The findings up to this point suggested that the reason diffusion bonding did not progress even when the thermal expansion of the two parts was significantly different was that the pressure on the outer part from the inner part was too high and resulted in strain in the outer part. Therefore, studies were done to alter the chemical composition of the parts in order to decrease the quantity of thermal expansion and determine the influence of the weakened pressure that would result. Table 3 shows the chemical composition of the inner part as decreasing amounts of Cu are added, and Fig. 13 shows the results from measurement of the rate of diffusion bonding area for those chemical compositions. The results clearly show little effect on the rate of diffusion bonding area even when the quantity of thermal expansion is decreased to lower the pressure. This showed that the conventional method of diffusion bonding that makes use of differences in thermal expansion would not work with the rotor shape.

It is known that the magnetic properties of a rotor are

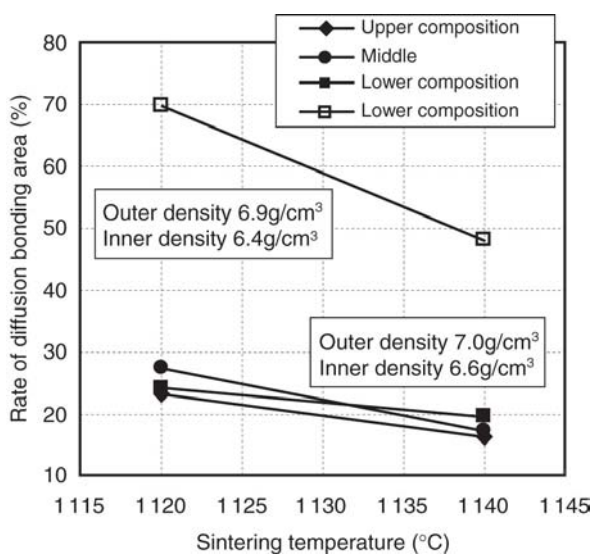


Fig. 12 Relationship between sintering temperature and rate of diffusion bonding area

Table 3 Inner chemical composition of decreasing Cu

(wt%)	Cu	Ni	C
Underneath lower composition 1	1.470	2.940	0.686
Underneath lower composition 2	1.455	2.910	0.679

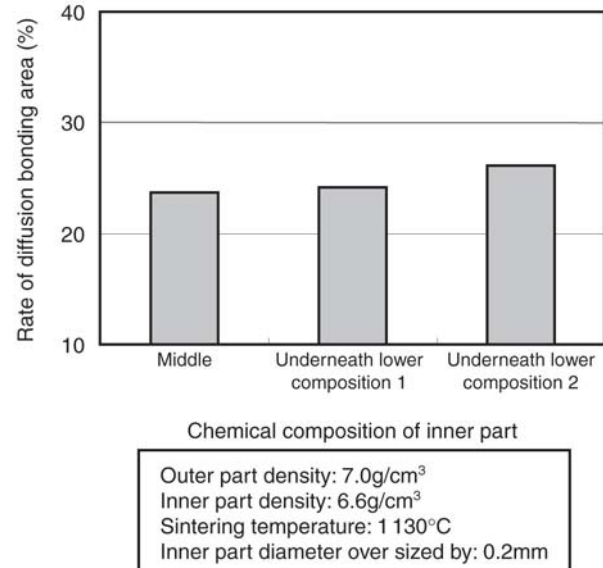


Fig. 13 Influence of chemical composition

generally improved by increasing the density of the outer part, and that the strength can be increased by using higher sintering temperatures. Under these conditions, however, the bonding area tends to decrease. Even changing the chemical composition of the inner part to reduce the quantity of thermal expansion of the copper in it had little effect on the bonding area. Means of applying pressure to the bonding surfaces other than by differences in thermal expansion were therefore investigated.

4.2.4. Influence of initial inner part diameter over sized

After fabrication of the various green compacts, a press fitting process is required in order to achieve diffusion bonding of the inner and outer parts. Fig. 14 shows the

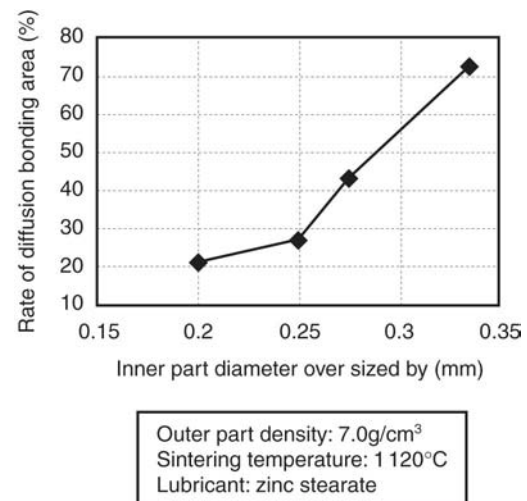


Fig. 14 Relationship between interference and rate of diffusion bonding area

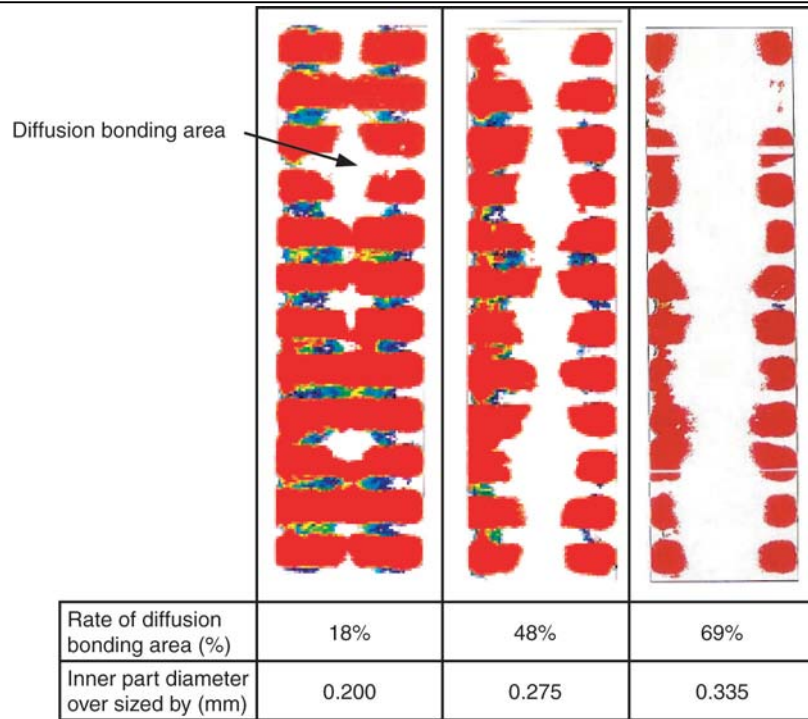


Fig. 15 Rate of diffusion bonding area measured by supersonic flaw detecting

relationship between the initial inner part diameter over sized and the rate of diffusion bonding area. The initial inner part diameter over sized refers to the difference between the internal diameter of the outer part and the external diameter of the inner part. It is apparent that as this inner part diameter over sized for an outer part increases, the rate of diffusion bonding area increases. Consequently, the initial inner part diameter over sized is an important factor in controlling the bonding area. When it is increased too much, however, there is a risk of cracking in the outer part. Tests showed that no cracking occurred when the initial inner part diameter over sized was increased to 0.335 mm. Thus the maximum inner part diameter over sized was estimated by calculation.

Asaka⁽⁴⁾ has defined the maximum inner part diameter over sized for when a tapered shaft is inserted into an outer part green compact of Fe-Cu-C material with a density of 6.7 g/cm^3 . According to this, the rate of rupture of the outer part will be 100% when the inner part diameter over sized is $-75 \text{ }\mu\text{m}$ for an outer part with an inside diameter of 30 mm. It was determined, therefore, that rupture results when the initial inner part diameter over sized is 0.25% of the inside diameter of the outer part. The inner part diameter over sized was calculated to be 0.360 mm when the inside diameter of the outer part was 144 mm, taking the shape of the rotor into consideration, and this was inferred to be the maximum inner part diameter over sized. With the present developed material, however, the outer part is made of Fe material, so the composition is different from Asaka's specimen. The density, however, is high at $6.9\text{--}7.0 \text{ g/cm}^3$, so Asaka's test results were used as a reference for improving the strength of the green compact.

4.3. Rate of Diffusion Bonding Area

Fig. 15 shows the measurement results for the bonding area of the rotor that is diffusion bonded. This shows an expanded view of the bonding state of the bonding surfaces. Supersonic waves penetrate the diffusion bonded parts with very little reflection, and these are shown in white, blue, and green. The other parts indicated in yellow and red show where the diffusion bonding is inadequate.

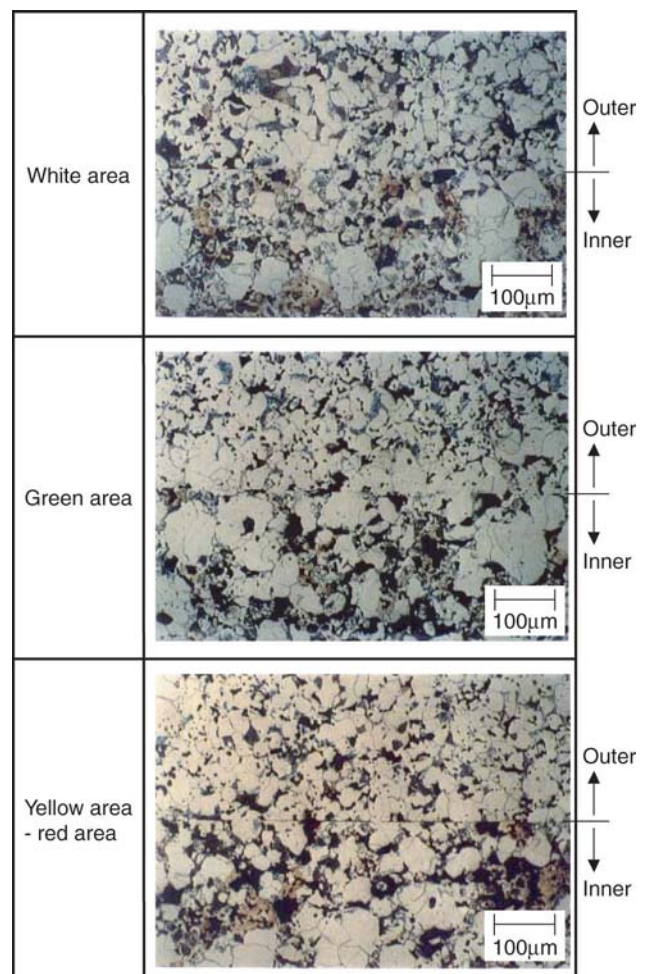


Fig. 16 Microstructure of boundary by diffusion bonding

When the rate of diffusion bonding area is 18%, the bonded parts shown from white to green appear in a regular ladder pattern. This occurs because the diffusion bonding is promoted mostly on the spokes of the inner part. During diffusion bonding, the quantity of thermal expansion becomes greater in the inner part than in the outer part. Since pressure is exerted on the outer part mainly from the spokes of the inner part, diffusion bonding is thought to be promoted in this part. In this state, however, the rate of diffusion bonding area is low. Consequently, when pressure due to the initial inner part diameter over sized is applied in addition to the difference in thermal expansion between the inner and outer parts, the bonding area increases from the center of the bonding surfaces, and rates of diffusion bonding area of 40–70% occur.

Fig. 16 shows the microstructure of boundary by diffusion bonding. The outer part displays a ferrite structure, while the inner part displays a mixed ferrite and pearlite structure. The diffusion bonded part (the white to green portions in Fig. 15 and Fig. 16) shows good ferrite grain growth extending beyond the bonding surfaces. The part that did not bond (the yellow to red portions in Fig. 15 and Fig. 16) was observed to form gaps of about 1 μm in the bonding surfaces.

5. Application to Motor Rotors

The knowledge obtained up to this point on sinter diffusion bonding technology will be illustrated below using application to motor rotors as an example.

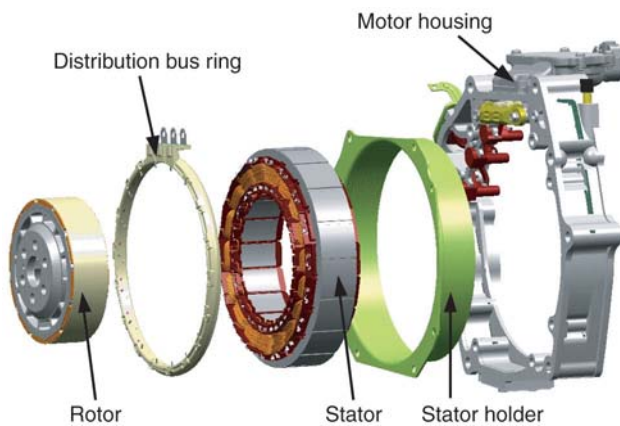


Fig. 17 Motor construction

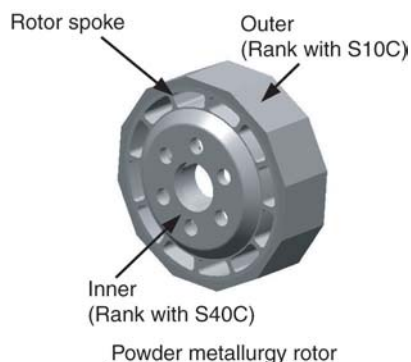


Fig. 18 Rotor construction

5.1. Structure of Sintered Rotor

Fig. 17 shows the construction of the motor. The stator is made up of a magnetic pole consisting of a divided concentrated winding of salient-pole and a bus ring molded by PPS, and a stator holder, which is a structural part that fixes the stator in place in the motor housing.⁽⁵⁾ The outer circumference of the rotor has rare-earth sintered magnet (Nd-Fe-B) affixed to it with glass fiber. For compactness, it is made to be connected directly to the engine crankshaft. Fig. 18 shows the construction of the sintered rotor for the motor. It consists of different materials in the outer part, which is made of material selected for its magnetic properties, and the inner part, which requires strength.

5.2. Sintered Rotor Bonding Conditions

It is necessary to set the optimum bonding conditions that take account of factors such as density and sintering conditions in order for the sintered rotor to have both magnetic properties and mechanical properties at the same time. First, as a strength evaluation of the diffusion bonded portion, the equipment shown in Fig. 19 was used to conduct twist tests for durability of a sintered rotor that had a rate of diffusion bonding area of 36%. The results showed that the spokes ruptured first and the bonded portion did not. Consequently, the fatigue strength of the diffusion bonded portion can be said to be greater than that of the spokes.

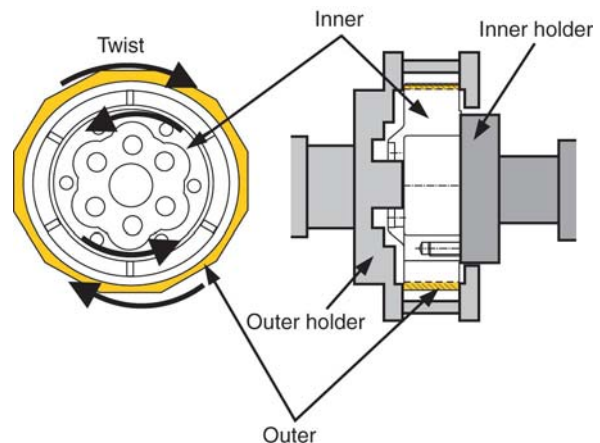


Fig. 19 Equipment of twist test for durability

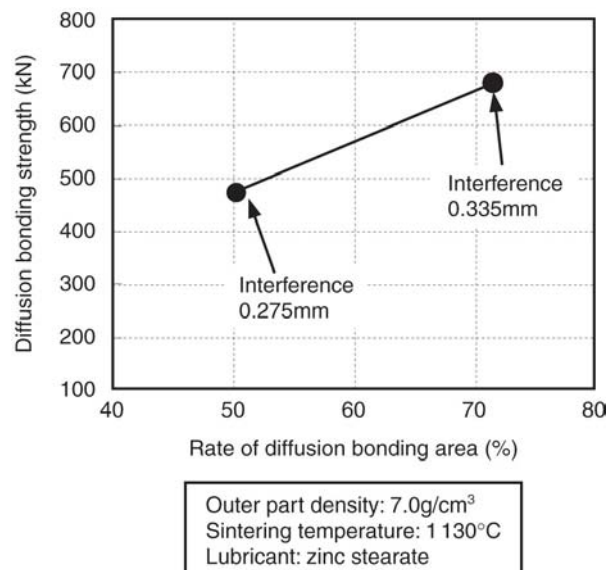


Fig. 20 Relationship between diffusion bonding strength and rate of diffusion bonding area

The safety for the rate of diffusion bonding area was set as the factor 1.3, and the lower limit of the rate of diffusion bonding area was set at 50% on the basis of those results. Fig. 20 shows the results from bonding strength tests of sintered rotors that were manufactured to satisfy these conditions. Sintered rotors displaying a rate of diffusion bonding area of 50% or over also had a higher bonding strength, and it was determined that they surpassed the guideline of 179 kN in engine tests for durability. The bonding conditions that will achieve sintered rotors with a rate of diffusion bonding area of 50% or over were selected as shown in Table 4 according to the density and sintering temperature of the inner and outer parts and the initial inner part diameter over sized. These yielded sintered rotors that joined different materials by diffusion bondings.

Table 4 Condition of diffusion bonding

Density (g/cm ³)	Outer	6.9 ~ 7.0
	Inner	6.4 ~ 6.6
Sintering temperature (°C)		1 120 ~ 1 140
Inner part diameter over sized by (mm)		0.275 ~ 0.335

5.3. Durability, Reliability, and Cost Effectiveness of Sintered Rotors

Next, the durability of the engine was evaluated by determining the fatigue strength of the spokes. The spoke fatigue strength was 190 MPa (3,432 N•m twisting torque), and this result yielded the fatigue limit diagram shown in Fig. 21. This shows that there is a 20-fold factor of safety relative to the maximum stress experienced in engine testing, and it was determined that the sintered rotor has adequate durability.

This sintered rotor also yielded near-net shape forming using sinter diffusion bonding, and significantly reduced the machining process. Therefore it achieved a 50% cost reduction over the rotor used in the Insight.

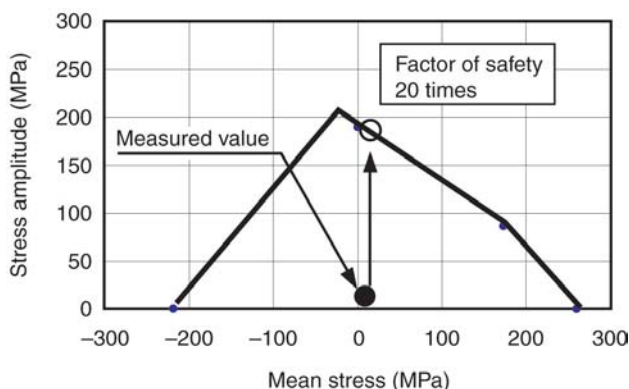


Fig. 21 Durability of boundary by diffusion bonding

6. Conclusion

Development of sinter diffusion bonding was conducted with a focus on the manufacturing of motor rotors using powder metallurgy methods to provide both magnetic properties and mechanical properties simultaneously. The following results were obtained:

- (1) Techniques were developed for sinter diffusion bonding of green compacts of two types of material with different

properties as a means of yielding both magnetic and mechanical properties simultaneously.

- (2) It was determined that it is important for the sinter diffusion bonding of motor rotors to apply pressure by means of the initial inner part diameter over sized, in addition to the conventional pressure on the bonding surfaces resulting from the difference in thermal expansion.
- (3) The application of diffusion bonding techniques satisfied the strength and durability requirements of actual engines, while near-net shape forming made it possible to provide motor rotors with a reduced machining process.

Motor rotors using this sinter diffusion bonding have been used in the Civic Hybrid since December 2001.

7. Acknowledgements

In conclusion, the authors express their profound gratitude to those persons involved at Hitachi Powdered Metals Co., Ltd. whose generous cooperation assisted greatly with the present development.

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