Poisson’s Ratio of Sintered Materials for Structural Machine Parts

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SYNOPSIS

The relationships between Young’s modulus, shear modulus and Poisson’s ratio of sintered materials and porosity were investigated for use as practical P/M machine parts. Three types of steel powders were prepared and then compacted, sintered, and heat-treated under various conditions. Porosity had the greatest influence on Young’s modulus, shear modulus, and Poisson’s ratio. Especially, Poisson’s ratio was affected by the pore shape, which depended on the type of powder, sintering temperature and atmosphere, and heat treatment.

For the more practical use of powder compositions, there was little influence by the sintering atmosphere on the Poisson’s ratio of the sintered and heat-treated materials. For a partially alloyed powder (Fe-4mass% Ni-1.5mass% Cu-0.5mass% Mo)+0.8mass%C powder, Poisson’s ratio versus porosity depended only on the sintering temperature at a porosity below 20%. In this case, a simpler approximate equation of Poisson’s ratio of the sintered and heat-treated specimen versus porosity was proposed as follows: $v = 0.304 - 0.264P + 0.548P^2$ at 1423 K (sintering temperature) or $v = 0.300 - 0.266P + 0.579P^2$ at 1523 K.

KEY WORDS

P/M Machine Part, Young’s Modulus, Shear Modulus, Poisson’s Ratio, Porosity

1 Introduction

Many P/M machine parts are being used in automobiles. Recently, simulating the elastic deformation and stress analysis of parts has become very important when designing the automobile parts for actual production. Young’s modulus and Poisson’s ratio are always required and used in these simulations. Several studies on Young’s modulus of sintered materials have been conducted. However, few reports have been made on Poisson’s ratio of sintered materials. In some cases, the experimental Poisson’s ratio has not corresponded to an experimental or a theoretical equation. Panakkal et al. have suggested that Poisson’s ratio is very sensitive to experimental errors. Poisson’s ratio ($v$) is calculated by Young’s modulus ($E$), shear modulus ($G$), and the following equation:

$$v = 0.5 \cdot \frac{E}{G} - 1 \quad (1)$$

For example, if $E$ and $G$ are 210 and 86 GPa, respectively, $v$ becomes 0.22, and if $E$ and $G$ are 210 and 84 GPa, respectively, $v$ becomes 0.25. A shear modulus error of 2% led to a Poisson’s ratio error of 14%.

A measurement system that can reduce the errors in calculating Young’s modulus and shear modulus is required. Therefore, in this study, an acoustic pulse method for sintered materials was used to accurately measure the elastic moduli, and the influences of porosity, material composition, sintering conditions, and heat treatment on Poisson’s ratio were mainly discussed.

2 Experiments

Three types of raw base powders produced by Höganäs Co., Ltd., were prepared: Distaloy AE (Fe-4mass% Ni-1.5mass% Cu-0.5mass% Mo, partially alloyed powder), NC100.24 (reduced iron powder), and ASC100.29 (water atomized iron powder). The copper powder was water atomized to a size of 75 μm or less and to a purity of 98.5% or more. The natural carbon powder had an average particle size from 5.5 to 7.0 μm and purity from 96 to 97%. Each powder was mixed to produce the material compositions shown in Table 1.

Each mixed powder was compacted at up to 882 MPa. A floating-die process and a die wall lubricated with zinc stearate were applied. The compacting pressure mainly controlled the porosity of each sample.

The green compacts were tableted shaped with a diameter and thickness of approximately 11 and 5 mm, respectively.
They were sintered at 1423 or 1523 K for 1.8 ks in a NH atmosphere (component: 75 vol.% N2 + 25 vol.% H2) or a RX atmosphere (0.18 vol.% CO2 + 23.9 vol.% CO + 30.4 vol.% H2 + 0.04 vol.% CH4 + 0.4 vol.% H2O + Bal. N2). Only the sintered Type A material was heat-treated by oil-quenching with carburization at 1173 K for 3.6 ks and tempered at 453 K for 3.6 ks in air.

In this report, the specimen was labeled, based on the sintering atmosphere (NH or RX), sintering temperature (1423 or 1523), powder type (A, B, or C), and heat treatment (HT). For example, NH1523AHT means that the Type A compact was sintered in the NH atmosphere at 1523 K and heat treated, also RX1423B means that the Type B compact was only sintered in the RX atmosphere at 1423 K.

The Young’s modulus, shear modulus, and Poisson’s ratio were measured by the acoustic pulse method. Fig. 1 shows a schematic diagram of the acoustic pulse method. A polyester film was coated on the specimen to prevent penetration of the coupler into the pores. Two acoustic probes for longitudinal waves and shear waves contacted the plane surface of the specimen to propagate the acoustic waves. The probe had a diameter of 6 mm and generated a frequency at 5 MHz.

The round-trip propagation time between the surface and bottom of a specimen was obtained by the acoustic pulse method. The sample thickness was measured with a micrometer, and the propagation times of the longitudinal waves and shear waves were defined as L, Tl, and Ts, respectively. The longitudinal wave velocity (Vl) and the shear wave velocity (Vs) were then calculated using Eqs. (2) and (3), respectively:

\[ V_l = \frac{2L}{T_l} \quad \text{(2)} \]
\[ V_s = \frac{2L}{T_s} \quad \text{(3)} \]

Young’s modulus (E), shear modulus (G), and Poisson’s ratio (v) were calculated using Eqs. (4), (5), and (6), respectively:

\[ E = \rho V_l^2 \left( V_l^2 - 4V_s^2 \right) / \left( V_l^2 - V_s^2 \right), \quad \text{(4)} \]
\[ G = \rho V_s^2, \quad \text{(5)} \]
\[ v = \left( V_s^2 / 2V_l^2 \right) / \left( V_l^2 - V_s^2 \right), \quad \text{(6)} \]

Where, \( \rho \) is the sintered density.

The porosity (P) was calculated from \( 1 - \rho / \rho_0 \), and \( \rho_0 \) is the theoretical density calculated from the density and material composition of each element in Table 1. The \( \rho_0 \)s of the sintered Types A, B, and C materials were 7.89, 7.84, and 7.84 Mg/m³, respectively. These were calculated using the densities\(^{(15)}\) of Fe, Ni, Cu, Mo, and C, which were 7.87, 8.90, 8.96, 10.22, and 2.27 Mg/m³, respectively.

In this report, the experimental value was the average value of three specimens made under the same experimental conditions (n = 3).

### 3 Results and Discussion

#### 3.1 Effects of Iron Powder Type and Heat Treatment on Microstructure

Fig. 2 shows optical micrographs of RX1423A, RX1423B, and RX1423C. The etching was applied using...
a solution of 5 vol.% nitric acid and methanol (5% nital). The matrix of sintered RX1423A was bainite with a heterogeneous structure, and those of RX1423B and RX1423C were pearlite. The partially alloyed powder of Type A was based on the atomized iron powder (ASC100.29). Therefore, the pore morphology (shape and size) of the sintered Type A material was similar to that of the sintered Type C material, and differed from that of the sintered Type B material based on the reduced iron powder. As shown in Fig. 2, RX1423B had fine spherical pores in comparison to RX1423A and RX1423C.

Fig. 3 shows the differences in the metal matrix structures for the as-sintered and for the after heat-treated materials. Regardless of the sintering atmosphere and temperature, the matrix of the as-sintered material was bainite, but that of the sintered and heat-treated material was martensite.

3.2 Effects of Iron Powder Type on Elastic Moduli

Fig. 4 shows the effect of the iron powders on the Young’s modulus and shear modulus in relation to the porosity. Young’s modulus and shear modulus decreased with the increasing porosity. Young’s modulus and shear modulus of RX1423A were nearly equal to those of RX1423C, but were slightly lower than those of RX1423B. These results mean that the pore size and shape, which depended on the iron powder type, affected Young’s modulus and shear modulus of the sintered material. However, the difference in the metal matrix structures did not affect Young’s modulus and shear modulus in comparison with the effect of porosity.

The differences between the sintered reduced iron and the sintered atomized iron were the pore shape and size. The effect of the base iron powder is shown as the differences in the pore shape and size in Fig. 2, and also in the elastic moduli in Fig. 4. The pore size did not affect Young’s modulus$^3$. The pore shape factor ($\eta$) from the equation$^5$ of $E/E_0=(1-P)/(1+\eta P)$ was evaluated.

The results are shown in Fig. 5. The $\eta$ of each specimen increased in a curve with an increase in porosity. The $\eta$ of RX1423A had a curve similar to that of RX1423C and was higher than that of RX1423B. In the case of $\eta=1$, the pore shape was spherical. Therefore, the pore shape of RX1423B was more spherical than that of the others. The Type B powder included fine inner pores. These fine pores became more spherical than the complicated-shaped large pores during sintering. In fact, the pore shape of RX1423B was more spherical than that of the others, as shown in Fig. 2.

![Fig.3 Optical images of cross-sectional sintered steel as sintered and after heat treatment (compacting pressure: 686 MPa, etched) for sintering atmospheres and temperatures.](image1)

![Fig.4 Young's modulus and shear modulus vs. porosity of sintered steel.](image2)

![Fig.5 Pore shape factors of sintered steel vs. porosity.](image3)
The main factor, which affects the elastic moduli of the sintered steel, was porosity, and the second factor was the pore shape. The influence of alloying elements was little observed. Additionally, the spherical pores were useful for increasing Young’s modulus and shear modulus.

As shown in Fig. 6, Young’s modulus and shear modulus slightly increased with an increase in the sintering temperature. At a high porosity, the Young’s modulus and shear modulus of the heat-treated materials were lower than those of the as-sintered materials. However, in Fig. 6, the specimens marked by the arrows were the same specimen before and after the heat treatment. The porosity, Young’s modulus, and shear modulus changed from 29% to 27%, from 69.7 GPa to 71.7 GPa, and from 27.5 GPa to 28.2 GPa, respectively, before and after the heat treatment. Young’s modulus and shear modulus of RX1423AHT were slightly higher than those of RX1423A.

Subsequently, the effect of pore shape on Young’s modulus and shear modulus was evaluated using $\eta$. The $\eta$ of materials sintered at 1523 K decreased more than that sintered at 1423 K because the pores became more spherical as a result of a higher sintering temperature. Fig. 7 shows the relationship between $\eta$ and the porosity of the sintered steels. The $\eta$ of materials after heat treatment was larger than that of the as-sintered materials.

As described above, the Young’s modulus and shear modulus became higher after heat treatment of the same specimen. This seems to be due to the additional sintering by reheating during heat treatment, which also decreased the porosity. However, at the same porosity, these moduli of specimens after heat treatment were slightly lower than those before the heat treatment. This means that the pores of the specimens after heat treatment had a more complicated shape than those of the as-sintered ones; however, the pore shape after heat treatment observed by optical microscopy was similar to that of the as-sintered materials. The other effects on the $\eta$ might be considered, however, in comparison with the porosity, the effect of the heat treatment on $\eta$ was small. Furthermore, the $\eta$ values of the specimens sintered in the NH atmosphere were similar to that of the specimens sintered in the RX atmosphere. Consequently, the effects of the sintering atmosphere and heat treatment on Young’s modulus and shear modulus were ignored.

However, small differences in Young’s modulus and shear modulus affected the Poisson’s ratio, because the ratio is calculated using the ratio of Young’s modulus to the shear modulus (Eq. 1). Therefore, Poisson’s ratio was discussed in greater detail.

3.3 Effects of Powder, Sintering Conditions, and Heat Treatment on Poisson’s Ratio

Fig. 8 shows the effect of the powder used on Poisson’s ratio in relation to the porosity. Poisson’s ratio of RX1423A was similar to that of RX1423C. However, RX1423B had a lower ratio. In Fig. 2, RX1423B showed many fine pores...
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In comparison with RX1423A and RX1423C.

As shown in Fig. 8, Poisson's ratio did not linearly decrease with an increase in the porosity. The difference in the base iron powder is shown as the difference in the pore shape (Fig. 2), and elastic moduli (Fig. 4). Therefore, the pore shape also affected Poisson's ratio. Young's modulus and shear modulus of RX1423B were higher than those of the others, but Poisson's ratio of RX1423B was lower. Consequently, based on Eq. 1, fine spherical pores affect the increase in the shear modulus in comparison with Young's modulus.

Figs. 9 and 10 show the effects of the sintering conditions and heat treatment on Poisson's ratio. As shown in Fig. 9, Poisson's ratio of the sintered Type A material increased with the increasing sintering temperature. The discrepancy in Poisson's ratio of the material sintered in the RX atmosphere was slightly greater than that in the NH atmosphere. The effect of heat treatment on Poisson's ratio is shown in Fig. 10. Poisson's ratio of RX1423AHT increased with the increasing porosity above 20% in comparison with that of RX1423A. In Fig. 9, Poisson's ratio of RX1523A was slightly higher than that of NH1523A; however, Poisson's ratio of NH1523AHT was the same as that of RX1523AHT (as shown in Fig. 12).

In Figs. 6 and 9 (below a porosity of 20%), Young's modulus, shear modulus, and Poisson's ratio decreased with an increase in the porosity, and the moduli increased with an increase in the sintering temperature. Consequently, when the pores became more spherical during the sintering, Young’s modulus, shear modulus, and Poisson’s ratio increased. Therefore, the spheroidizing of pores creates a greater increase in Young’s modulus than that of the shear modulus. At the same porosity, Young’s modulus and shear modulus were lower after heat treatment and Poisson’s ratio was higher than those of the as-sintered materials. These parameters are influenced by the pore shape, which became more complicated at a higher porosity, as shown in Fig. 7. Therefore, if the pore shape becomes complicated, the shear modulus decreases more than Young’s modulus even at the same porosity.

Figs. 8–10 show that the decreasing trend in Poisson’s ratio changed at a certain porosity. For a porosity above 20%, almost all the pores became connected to each other. The pore connectivity also affected Poisson's ratio in relation to the porosity. When the pore shape became more complicated with the increasing pore connectivity, the shear modulus decreased more than Young’s modulus at the same porosity as explained above, and Poisson’s ratio increased.

For application of the data obtained in this study to P/M manufacturing, the relationship between the porosity and Poisson's ratio were investigated. The following approximate equations of E vs. P were used here:

\[ E = E_0 \exp(-b \cdot P) \]  
\[ E = E_0(1-a \cdot P)^n, \text{ and} \]  
\[ E = (E_0 - K_E \cdot P)(1-P) \]

Where, \( E_0 \) was \( E \) at \( P = 0 \); and \( a, b, \) and \( K_E \) were experimental constants. When \( a \) and \( n \) were 1 and 3.4, respectively. Eq. 8 was derived by McAdam\(^a\).

The above equations applied the relationship between the shear modulus (\( G \)) and porosity, while the relationships between Poisson's ratio and porosity were represented as Eqs. v1–v3:

\[ \nu = 0.5 \left[ E_0 \exp(-b_1 \cdot P) \right] \left[ G_0 \exp(-b_2 \cdot P) \right]^{-1}, \]

\[ \nu = 0.5 \left[ E_0(1-a_1 \cdot P)^n \right] \left[ G_0(1-a_2 \cdot P)^n \right]^{-1}, \text{ and} \]

\[ \nu = 0.5 \left[ (E_0 - K_E \cdot P) \right] \left[ (G_0 - K_G \cdot P) \right]^{-1} - 1 \]

And

\[ \nu = 0.5 \left[ (E_0 - K_E \cdot P)(1-P) \right] \left[ (G_0 - K_G \cdot P)(1-P) \right]^{-1} - 1. \]

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The decreasing trend in Poisson’s ratio versus porosity was considered and the matching curves calculated using Eq. v3 were plotted in Figs. 8-10.

Furthermore, $v=f(P)$, assumed to perfectly describe the relationship between $P$ and $v$, was modified to Eq. v4.

$$v = C_0 + C_1 \cdot P + C_2 \cdot P^2.$$  \hspace{1cm} (v4)

Here, $C_0$, $C_1$, and $C_2$ were experimental constants.

Fig. 11 shows the approximate curves obtained by Eqs. v1-v4. The average correlation coefficients ($R_{ave}$) calculated using Eqs. v1, v2, v3 and v4 were 0.916, 0.988, 0.987 and 0.995, respectively; the $R_{ave}$ obtained by Eq. v1 was the lowest. The differences between the measured data and calculated data are shown in Fig. 11, and the approximate curve obtained by Eq. v1 did not correspond to the measured data.

If Eqs. v1 to v4 were applied to the sintered machine parts, the porosity below 20% was considered. In the porosity range, the Poisson’s ratio simply decreased with the increasing porosity, and the $R_{ave}$ values obtained by Eqs. v1, v2, v3 and v4 were 0.986, 0.994, 0.970 and 0.996, respectively.

Eq. v4, which was the best fitting equation, was used for the sintered and heat-treated Type A material at a porosity below 20% for practical use as a P/M machine part. As shown in Fig. 12, Poisson’s ratio depended on the sintering temperature in comparison with the sintering atmosphere.

Therefore, when the sintering temperatures were 1423 K and 1523 K, Eq. v4 became, respectively:

$$v(1423K) = 0.300 - 0.266P + 0.579P^2$$

$$v(1523K) = 0.304 - 0.264P + 0.548P^2.$$  \hspace{1cm} (v4)

Based on these equations, Poisson’s ratio of fully densified sintered Distaloy AE was found to be 0.30.

The effects of alloy elements on the relations discussed above are now being studied and will be presented in a future report.

4 Conclusions

The relationships between Young’s modulus, shear modulus, Poisson’s ratio, and porosity for sintered steels prepared under conventional P/M machine manufacturing conditions were investigated and the following results were obtained.

(1) Porosity had the greatest influence on Young’s modulus, shear modulus, and Poisson’s ratio in comparison with the type of iron powder, sintering conditions and heat treatment.

(2) The pore shape depended on the P/M manufacturing parameters, such as powder type, sintering atmosphere and temperature, and heat treatment. These parameters slightly affected Young’s modulus and shear modulus, but had an effect on Poisson’s ratio at a high porosity.

(3) Although Poisson’s ratio increased with an increase in the sintering temperature and by heat treatment at a high porosity, the influence of the sintering atmosphere on Poisson’s ratio after heat treatment was not observed at a porosity below 20%.

(4) An approximate equation of Poisson’s ratio ($v$) versus the porosity ($P$) below 20% of sintered steel, prepared with partially alloyed powder (Fe-4 mass% Ni-1.5 mass% Cu-0.5 mass% Mo)+0.8 mass% C powder, was evaluated. The relationships between $P$ and $v$ of the specimens sintered at 1423 K and 1523 K, respectively,
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and then heat-treated were proposed as follows:

\[
v(1423K) = 0.300 - 0.266P + 0.579P^2 \quad \text{and} \quad v(1523K) = 0.304 - 0.264P + 0.548P^2.
\]

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