Fatigue Crack Growth Behavior of P/M Soft Magnetic Material with a High-resistance Surface Layer

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1. Introduction

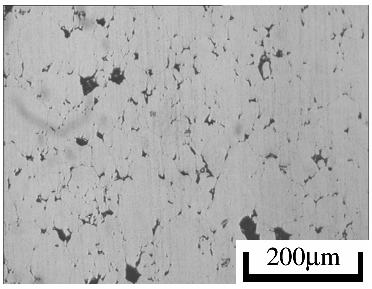
Recently, new magnetic material has been developed to meet the demands of miniaturization and high performance of electronic attachment. P/M (Powder metallurgy soft magnetic material with a high-resistance surface layer can improve efficiency of electronic machine by reducing core loss at AC magnetic field(1),(2). In addition, P/M process is expected to reduce the production cost because it is produced near net shape, with almost no raw material loss(3). Moreover, it has high recycle efficiency compared with traditional electrical steel sheets so that it can return to original powder by crushing. Since it has a lot of advantage, P/M soft magnetic material is one of promising candidate as the core of coil. There are few important reports about the mechanical property, especially fatigue characteristics on practical use although many reports about magnetic one were published(4),(5),(6). Therefore in this paper, the fatigue crack initiation and small crack growth behavior was observed in order to clear the effects of the binder resin and densities.

2. Specimen and experimental method

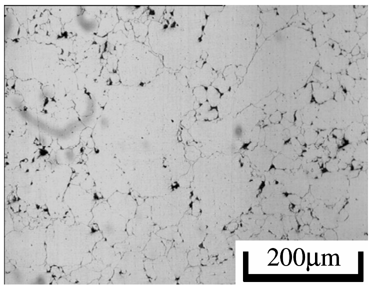
Pure iron powder covered with the phosphate glass as high resistance surface layer (Höganäs, somaloy500) is raw powder, and average grain size is 100μm. The materials to which binder resin were added and three kinds of materials with different density were used in this study. The binder resin is thought to improve the adhesive force between powders. This material with binder resin is referred as material BA. Material BA was modified in one hour at 673 K under the N_2 gas atmosphere after cold formed at 1GPa. Fig.1(a) shows metallurgical microscope micrograph of microstructure of the material BA. The pores of relatively large size were observed. In addition to the material BA, three kinds of materials were cold formed by different compacting pressure to improve. These materials are referred as material LD(Low density), MD(Medium density) and HD(High density) corresponding to the compacting pressure. These materials were done with the same thermal treatment after densities were changed under different compacting pressure with no binder resin. Table1 shows bending strength and density in each specimen. The bending strength of the materials with no binder resin was found to increase as the density became high. Fig.1 (b)-(d) shows the result of microstructure observation in each specimen. It was observed that the number and the area of pores decrease as compacting pressure becomes high. Fig.2 shows the shape of in-plane bending specimens used in this study. The specimen has a shallow notch, stress concentration factor of which is 1.26, so as to localize a crack initiation within a small area. The notch was polished by aluminum powder for observation of the small fatigue crack. Fully reversed fatigue tests were conducted using an electro-magnetic type bending machine as a frequency of 30 Hz in laboratory environment. Moreover, continuous observation of the fatigue crack initiation and small crack growth behavior was carried out by plastic replicas technique.

Table1. Mechanical property of specimens.

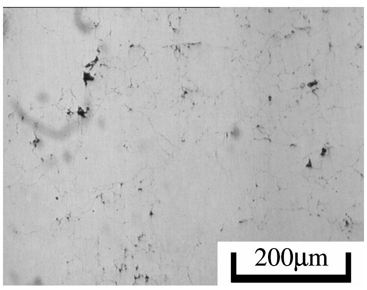
Specimen	Bending strength σ_B MPa	Density ρ Mg/m^3
BA	83	7.55
LD	83	7.13
MD	122	7.43
HD	160	7.58



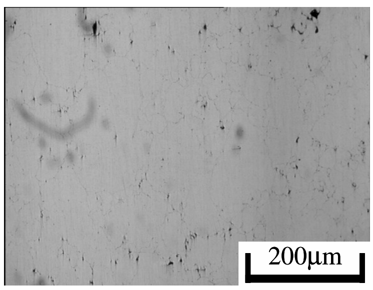
(a) Material BA



(b) Material LD



(c) Material MD



(d) Material HD

Fig.1 Microstructure of each specimen.

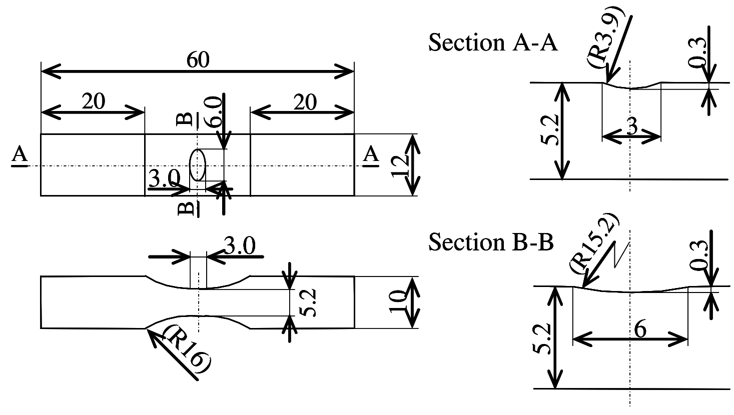


Fig.2 Shape and dimensions of specimen.

3. Experimental results and discussion

Fig.3 shows *S*-*N* curves. It is defined the cyclic number as the crack initiation life N_i when the main crack reached 0.1mm, and they are indicated as open mark. Then, the fracture life N_f is defined as the number of cycles when the main crack reached 1mm, and they are indicated as solid mark. Final fracture of the specimens is indicated as solid mark with subscript one. The fatigue strength becomes higher in the following of order, material HD, MD, LD and BA. As a result, the addition of the binder resin to P/M alloy, which was expected to improve adhesive force between powders, is not effective in improvement of strength. Furthermore, densification by increasing compacting pressure is effective to the improvement of fatigue strength.

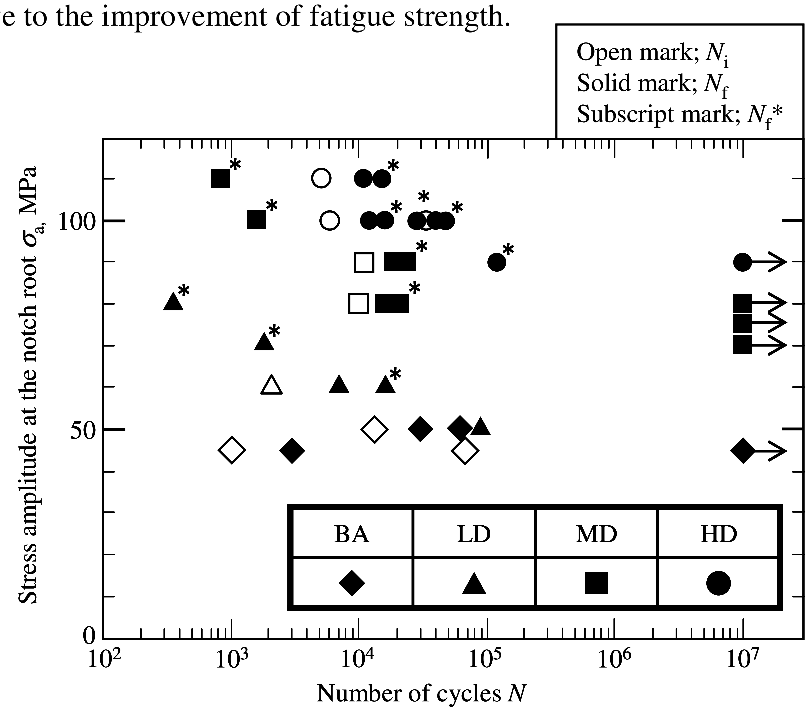
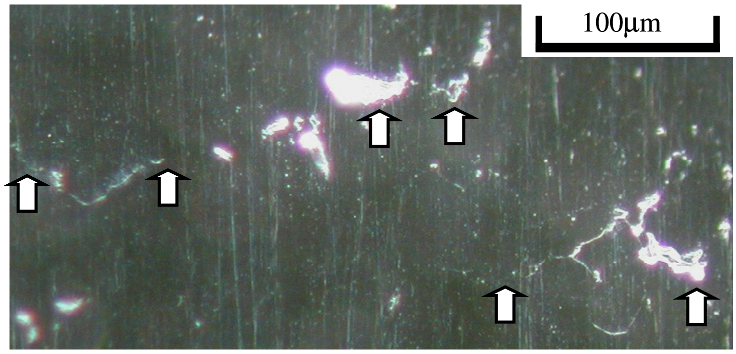
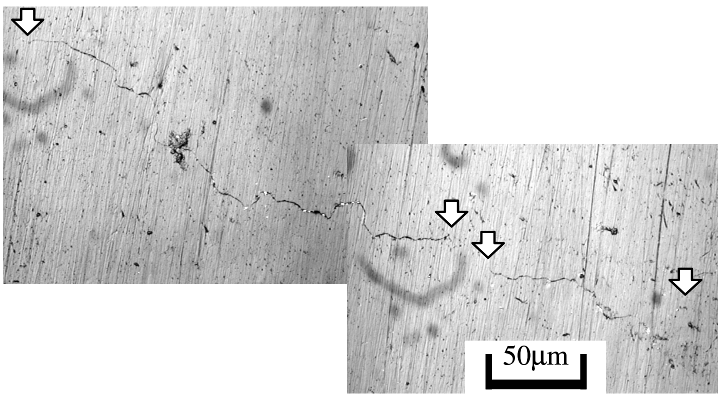


Fig.3 *S*-*N* curves.

In order to examine the cause of the fatigue strength, the fatigue crack initiation and small fatigue crack behavior of each specimen was observed in detail. Fig.4 shows optical micrograph of the fatigue crack propagation in each specimen. In all specimens, cracks initiated at multiple sites and each crack propagated with frequently deflection. Furthermore, cracks were coalesced frequently and specimen reached final fracture. Therefore, the effects of the binder resin and densities on the crack growth behavior were not recognized. Fig.5 shows SEM photographs of fracture surface in material BA and HD. Cracks propagated between powder boundary because powder grains were observed in each material. Propagation at powder boundary is the reason why cracks propagate with frequent deflection as mentioned above. The similar feature of fracture surface was observed in material LD and HD had.

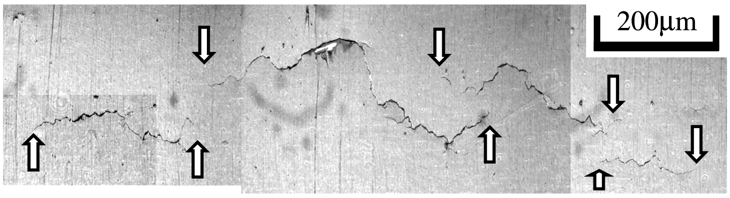


(a) Crack growth behavior of Material BA
($N=9.0\times10^3$ cycles, $N_f^*=3.0\times10^4$ cycles)

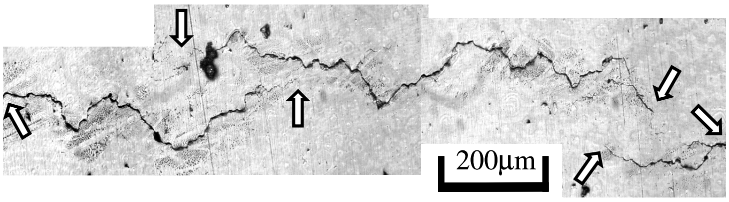


(b) Crack growth behavior of Material LD
($N=3.0\times10^3$ cycles, $N_f^*=1.6\times10^4$ cycles)

Fig.4 Optical micrograph of fatigue crack growth behavior.

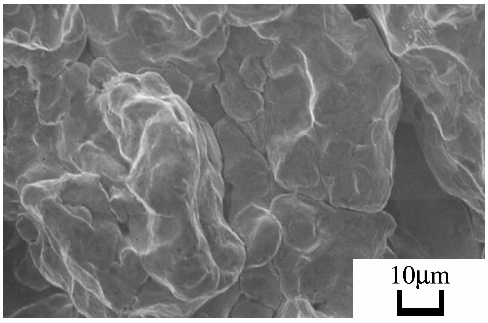


(c) Crack growth behavior of Material MD
(N=1.5×10^4 cycles, N_f^*=2.0×10^4 cycles)

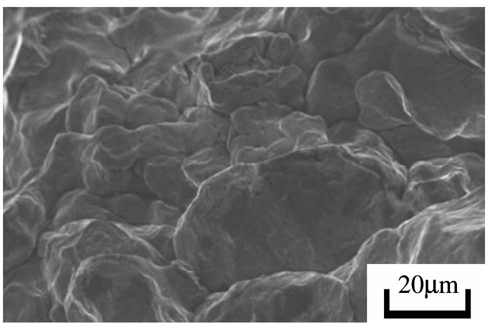


(d) Crack growth behavior of Material HD
(N=1.2×10^4 cycles, N_f^*=1.5×10^4 cycles)

Fig.4 Optical micrograph of fatigue crack growth behavior continued.



(a) Material BA



(b) Material HD

Fig.5 SEM photograph of fracture surface.

Figure.6 shows the relationship between fatigue crack growth rate da/dN and maximum stress intensity factor K_{max}[7]. In this figure, da/dN-K_{max} relationships of glass material[8] and iron[9] are also plotted. Although da/dN varied widely, the difference between the materials was not recognized in fatigue crack growth rate. Fatigue crack of P/M soft magnetic materials grew faster than the iron and also could propagate at low K value even below threshold stress intensity factor, K_{th}, of iron, which is about 3.5 MPam$^{1/2}$. This resulted corresponds to the fact that fatigue crack did not grow into powder. On the other hand, da/dN is lower than that of glass materials, indicating that fatigue crack did not grow in phosphate glass which covered pure iron powder. Therefore, it is thought that fatigue crack propagate at the powder boundary between phosphate glasses.

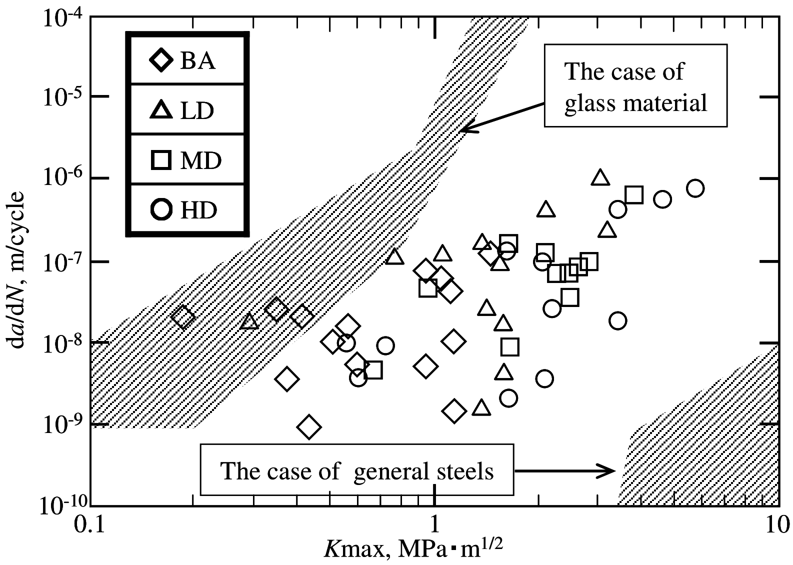


Fig.6 Relationship between stress intensity factor and fatigue crack growth rate.

Figure7 shows observation result of the crack initiation site at specimen surface in material HD. As this result shows, cracks tend to initiate at defects. Moreover, many defects are included in each specimen as shown in Fig.1. Therefore, it is thought that the defect size affects on fatigue strength. The statistics of extreme value shown in Fig.8 was used to examine the maximum defect size included in a notch of each specimen(10). The largest defect size in the observation region, area of which, S_0, was 7.1×10^{-2} mm^2, was measured repeatedly 40 times. The area of the shallow notch, where fatigue crack initiated, S was 14mm^2. Therefore, the maximum defect size included in the shallow notch region of a specimen is estimated using the return period T, that is 200 from following formula; $T=(S+S_0)/S_0$. Table2 shows the estimated maximum defect sizes.

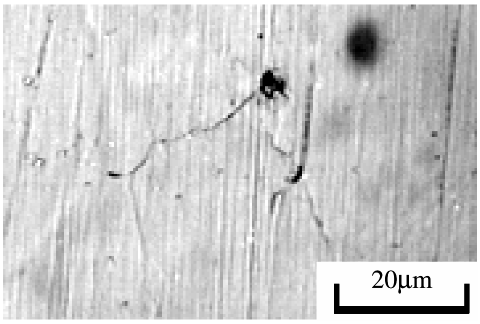


Fig.7 Micro crack from surface defect in Material HD
(N=2.0×10^3cycles, N_f^*=1.5×10^4 cycles)

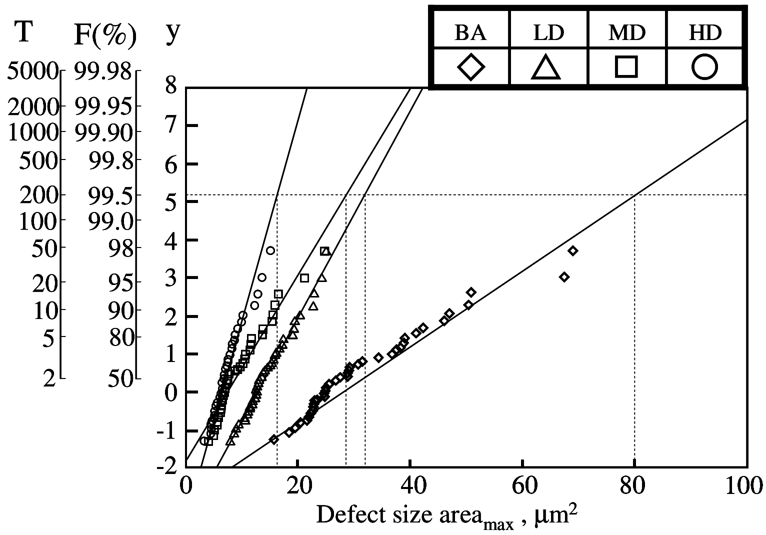


Fig.8 Estimation of defect size by the statistics of extreme value.

Table2 Estimated maximum defect size.

	BA	LD	MD	HD
$\sqrt{area}_{\max}$ μm	80	32	28	16

As the results, it is obvious that the compacting pressure strongly affects the defect size in this material and the maximum defect size becomes small as the compacting pressure becomes high. Therefore, increase of the compacting pressure is an effective way to improve fatigue property on powder metallurgy soft magnetic material. The relationship between initial stress intensity factor ΔK_0 calculated by using the area of estimated maximum defect and the fracture life N_f divided by maximum defect size, $N_f/\sqrt{area}_{\max}$, is shown in Fig.9.

Fatigue strengths about material MD and HD could be evaluated by estimation of maximum defect size because they had the same curve. However, the relationships of material BA and LD did not agree with that of material MD and HD, indicating that reduction of fatigue strength in material BA and LD could not be evaluated by maximum defect size base on the statistic of extreme value. It is thought that the fact that the coalescence of fatigue cracks in materials BA and LD occurred frequently in comparison with materials MD and HD is cause.

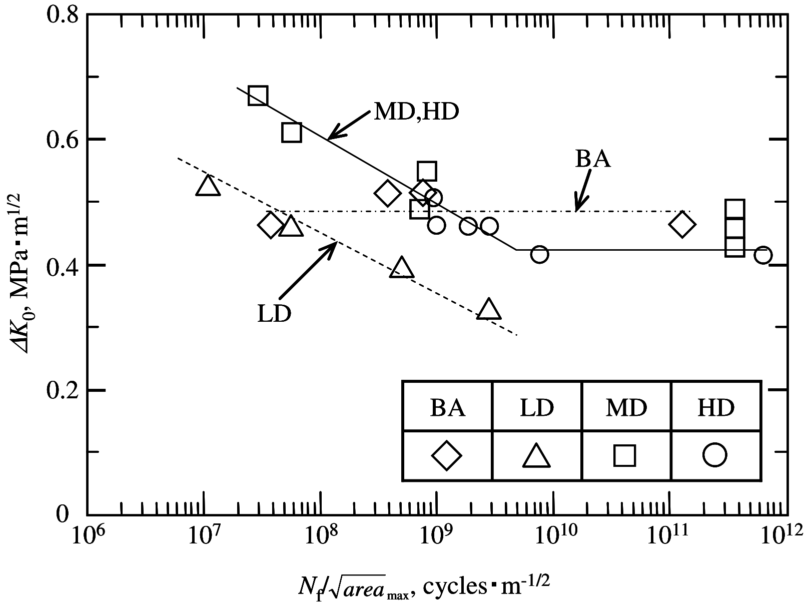


Fig.9 Relationship between ΔK_0 and $N_f/\sqrt{area}_{max}$

4. Conclusion

It was examined the influence of binder resin and density on fatigue property used P/M soft magnetic material with high-resistance layer. It became clear the following statement.

(1) In this study, the materials to which binder resin were added and three kinds of materials with different density were used. As a result of fatigue test, material BA which was added the resin to improve the adhesive force between powders indicated the worst fatigue strength. On the other hand material HD which had the highest density with no resin indicated the best one. Therefore, the addition of the binder resin to P/M alloy was not effective in improvement of fatigue strength. Furthermore, densification by increasing compacting pressure was effective to the improvement of fatigue strength.

(2) In all of the specimens, cracks initiated at multiple defects and each crack propagated with frequent deflection. Moreover, they were coalesced frequently and specimen reached final fracture. All materials fractured at powder boundary. Therefore, it was not admitted that the binder resin and densities affected on the crack growth behavior and fracture type.

(3) Relationship between fatigue crack growth rate, da/dN, and maximum stress intensity factor K_{max} was examined to evaluate fatigue property quantitatively in this material. Although da/dN varied widely, the difference between the materials was not recognized in fatigue crack growth rate.

(4) In this material, cracks tend to initiate at defects. The maximum defect size included in a notch of each specimen was examined by the statistics of extreme value because the defect size is thought to be effective on fatigue strength. As the results, increase of the compacting pressure to reduce the maximum defect size is an effective way to improve fatigue property on powder metallurgy soft magnetic material.

(5) As a result of the relationship between initial stress intensity factor DK0 calculated by using the area of estimated maximum defect and the fracture life N_f divided by maximum defect size, $N_f/\sqrt{area}_{max}$, fatigue strengths about material MD and HD could be evaluated by estimation of the maximum defect size. However, fatigue strengths about material BA and LD could not evaluated by the same way. It is thought that the fact that the coalescence of fatigue cracks in materials BA and LD occurred frequently in comparison with materials MD and HD is cause.

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