ORAL REFERENCE: ICF100859OR

SMALL FATIGUE CRACK INITIATION AND GROWTH BEHAVIOR OF Fe-0.5Ni-1Mo SINTERED STEEL

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ABSTRACT

The effects of porosity and worked layer on small fatigue crack initiation and growth behavior were investigated on Fe-0.5Ni-1Mo sintered steels and recompressed ones with high density. Reversed plane bending fatigue tests were carried out using an electro-magnetic type bending machine and small fatigue cracks were observed by means of plastic replica technique. A shallow notch was machined by using a milling machine (type-m) or an electric discharge machine (type-e) in the center of the specimen surface so as to localize the crack initiation site within a small area. The milling process resulted in the worked layer near the specimen surface and induced the compressive residual stress. Fatigue crack initiation lives of type-e specimens were found to be shorter than these of type-m specimens on both materials. Although fatigue cracks initiated from pores irrespective of materials, crack initiation site changed from the surface to the interior of the specimen by introducing the worked layer, resulting in the increase of fatigue crack initiation life. It was found that the recompression of porosity had small effect on crack initiation. Because the recompress process collapsed the pores but could not reweld the interfaces, the fatigue crack easily initiated from them. The crack growth resistance was found to be improved by the recompress process irrespective of machining method.

KEYWORDS

Powder metallurgy sintered alloy, Fatigue crack initiation, Small fatigue crack growth, Recompress process, Machining process, Pore, Worked layer

INTRODUCTION

It is well known that powder metallurgy (P/M) process leads to the development of alloy systems with high performance. The P/M process is efficient because it produces near-net shapes, with almost no raw material loss. During the last few decades, the demand for the reduction of weight resulted in the use of P/M steel for highly stressed fatigue-loaded components such as a non-lubricant bearing or a transmission gear of car. Although it was widely reported that the mechanical properties was affected by the porosity, and shapes and distribution of pores[1-4], there are few study on the effect of porosity on fatigue crack initiation and small crack growth behavior. In this study, reversed plane bending fatigue tests under constant amplitude loading were carried out on Fe-0.5Ni-1Mo sintered steels and a recompressed ones with high density using an electro-magnetic type bending machine. And the effects of porosity and machining on fatigue properties were investigated.

MATERIALS AND EXPERIMENTAL PROCEDURE

Two kinds of sintered P/M alloys were investigated. Fe-0.5Ni-1Mo alloy powder was produced by atomization process. The alloy powders were then compacted at room temperature under high pressure of 600 MPa followed by sintering at 1573 K for 1 hour in nitrogen gas environment. After that, the sintered alloy was hold at 1123 K for 1 hour, oil quenched and then tempered for 1.5 hours at the temperature of 473 K. For convenience, the alloy manufactured by this process will be referred to as material A hereinafter. In order to investigate the effect of porosity on fatigue behavior, the alloy with high density was manufactured by recompressing the material A. This Alloy will be referred to as material B. The chemical composition of these alloys in percentage mass is shown in Table 1. Table 2 shows the mechanical properties of the material A and B. Density and tensile strength of the recompressed material B is higher than that of material A. A fatigue test specimen is shown in Fig.1. A shallow notch, the stress concentration factor of which was 1.26, was machined by using a milling machine (type-m) or an electric discharge machine (type-e) in the center of the specimen surface so as to localize the crack initiation within a small area. Fully reversed plane bending fatigue tests under constant amplitude loading were carried out using an electro-magnetic type bending machine at a frequency of 30 Hz. The measurement of crack length and number of cracks were made by means of plastic replicas taken from the shallow notch area at the proper intervals during fatigue tests. Optical microphotographs of specimen surface at the notch root are shown in Fig.2. Pores are observed on the surface of notch root machined by the electric discharged machine irrespective of the materials. On the other hand, the surface machined by the milling is found to be smooth. Pores near the specimen surface were crushed under the milling process, resulting in the worked layer at the surface.

TABLE 1 CHEMICAL COMPOSITION OF MATERIAL USED. (mass%)

C	O	Si	Mn	P	S	Ni	Mo	Fe
0.001	0.08	0.01	0.19	0.014	0.017	0.56	1.07	bal.

TABLE 2 MECHANICAL PROPERTIES OF MATERIALS.

Material	Tensile strength σ_B (MPa)	0.2% proof stress $\sigma_{0.2}$ (MPa)	Elongation δ (%)	Young's modulus E (GPa)	Poisson's ratio	Density ρ (Mg/m^3)	Porosity (%)
A	1461.2	1374.0	0.6	162	0.27	7.20	8.16
B	1558	-	0	172	0.26	7.41	5.48

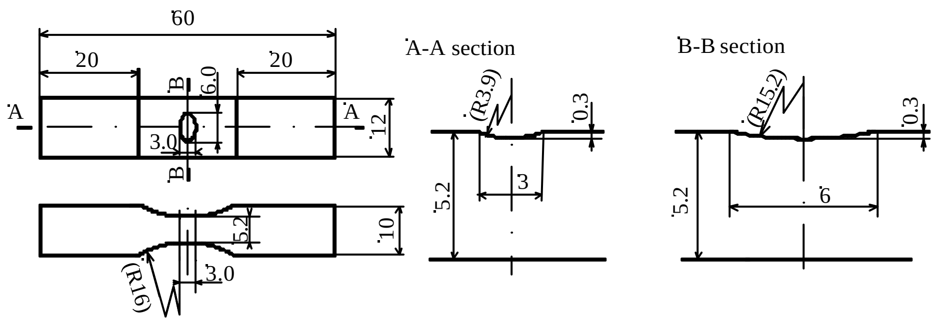
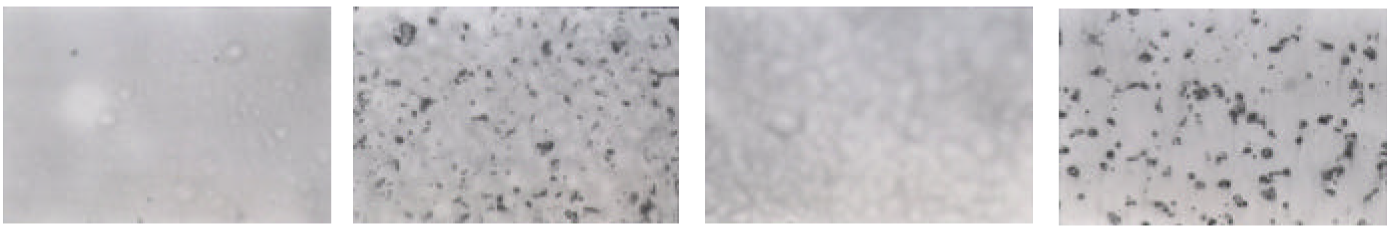


Figure 1: Test specimen configuration



(a)A-m specimen (b)A-e specimen (c)B-m specimen (d)B-e specimen

Figure 2: Optical micrographs of specimen surface at notch root.

EXPERIMENTAL RESULTS AND DISCUSSION

Figure 3 shows relationships between the stress amplitude at the notch root and the number of cycles to crack initiation, N_i, and that to failure, N_f. The stress amplitude indicated in the left hand ordinate means the local one at the shallow notch root, which is calculated by multiplying the stress concentration factor to the nominal stress. The crack initiation life, N_i, and the fracture life, N_f, are defined as the number of stress cycles at crack length of 0.2 mm and 2 mm, respectively. Fatigue crack initiation lives of type-e specimens were found to be shorter than these of type-m specimens on both materials. The effect of the machining on the crack initiation was observed. On the other hand, there found no effect of the recompress process on fatigue crack initiation and the endurance limit. In the case of type-e specimens, fatigue crack growth lives of the material B is longer than that of the material A, indicating that the recompress process resulted in the improvement of fatigue crack growth resistance.

Figure 4 shows SEM photographs of fracture surface near crack initiation site of type-m and -e specimens on the materials A and the arrows in these photographs indicate the fatigue crack origins. In the type-e specimen, the fatigue crack initiated at the surface pore and grew to the interior. On the other hand, the worked layer, depth of which is about 50 μm, is observed at the specimen surface in the type-m specimen and the fatigue crack initiated at the internal pore of specimen. Introduce of the worked layer by the milling resulted in the change of the crack initiation site from the surface to the interior of specimen, although fatigue crack initiated from pores irrespective of the machining methods. The increase of crack initiation life was thought to be resulted from the compressive residual stress at the surface, which was about –200 MPa, and the decrease of the stress at the internal pore, at which crack initiated, due to the stress gradient.

Figures 5 and 6 show optical photographs of fatigue crack initiation and growth behavior in the type-e and the type-m specimens of the material A. In the type-e specimen, many pores were observed on the specimen surface and five fatigue cracks initiated at the surface pores (Fig.5(a)). The fatigue cracks coalesced and/or overlapped into the main crack and grew in the direction perpendicular to the loading axis.

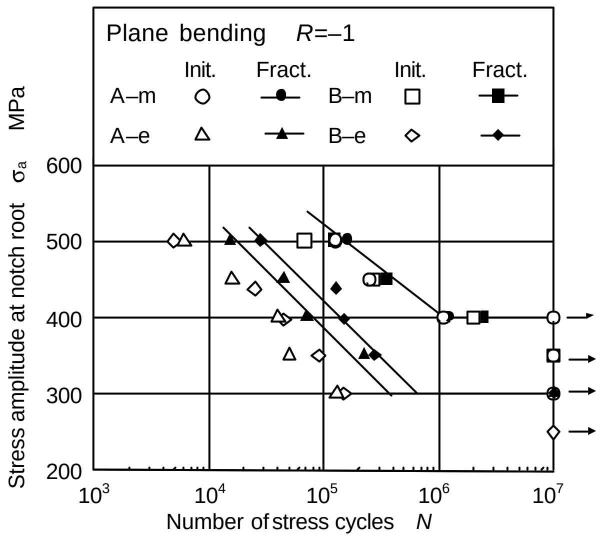
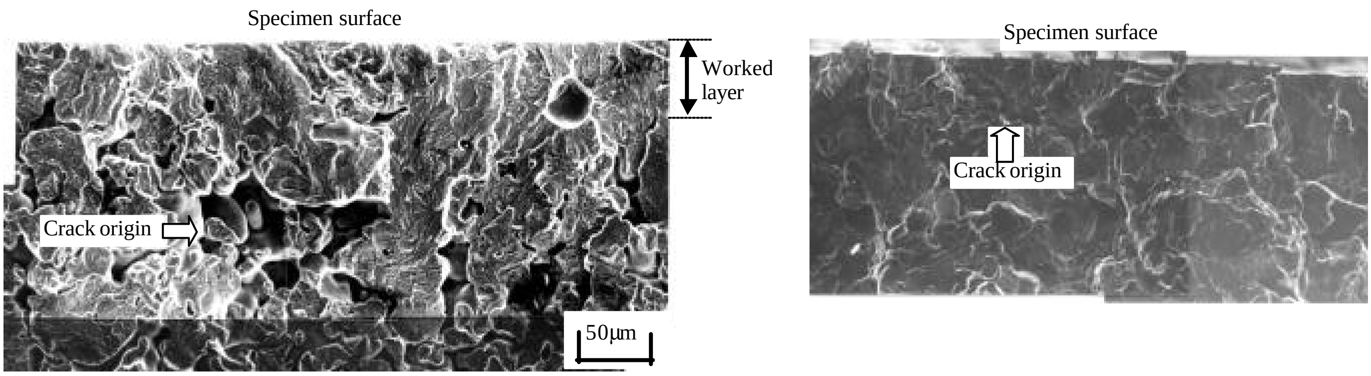
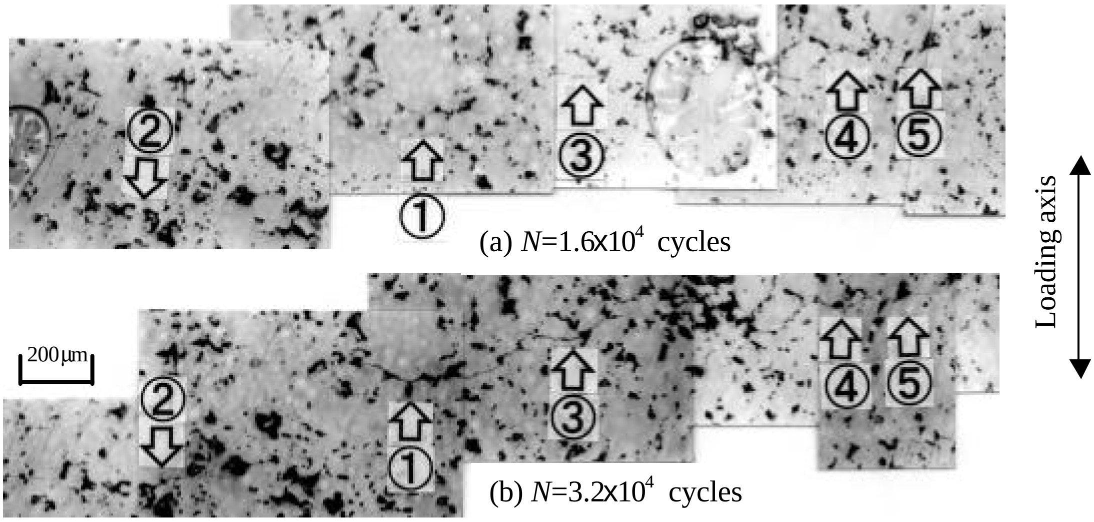


Figure 3: *S-N* curves.



(a)A-m specimen, σ_a=500 MPa (b)A-e specimen, σ_a=500 MPa

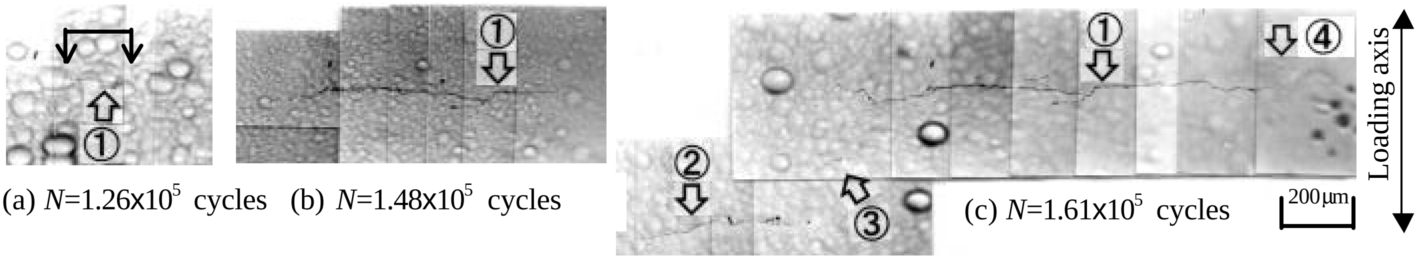
Figure 4 : Fracture surface near crack origin



(a) N=1.6x10^4 cycles

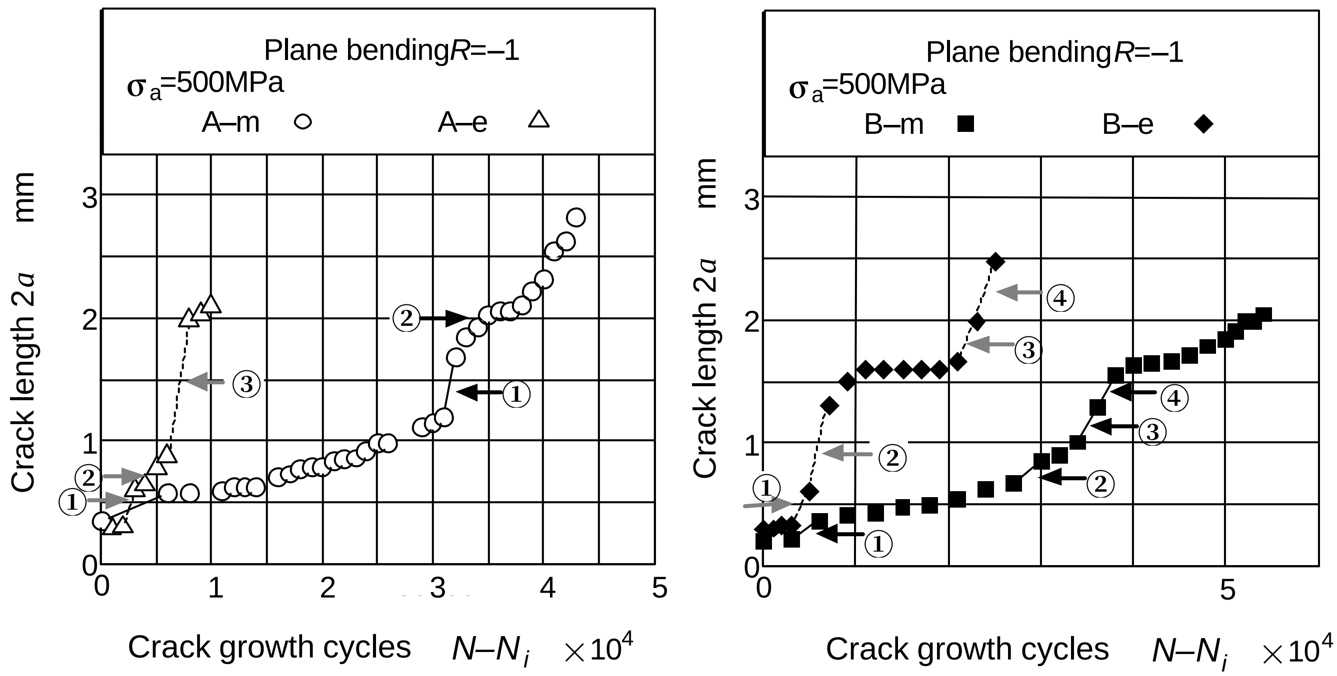
(b) N=3.2x10^4 cycles

Figure 5 : Observation of fatigue crack behavior in A-e specimen at σ_a=450 MPa.



(a) N=1.26x10^5 cycles (b) N=1.48x10^5 cycles (c) N=1.61x10^5 cycles

Figure 6 : Observation of fatigue crack behavior in A-m specimen at σ_a=500 MPa.

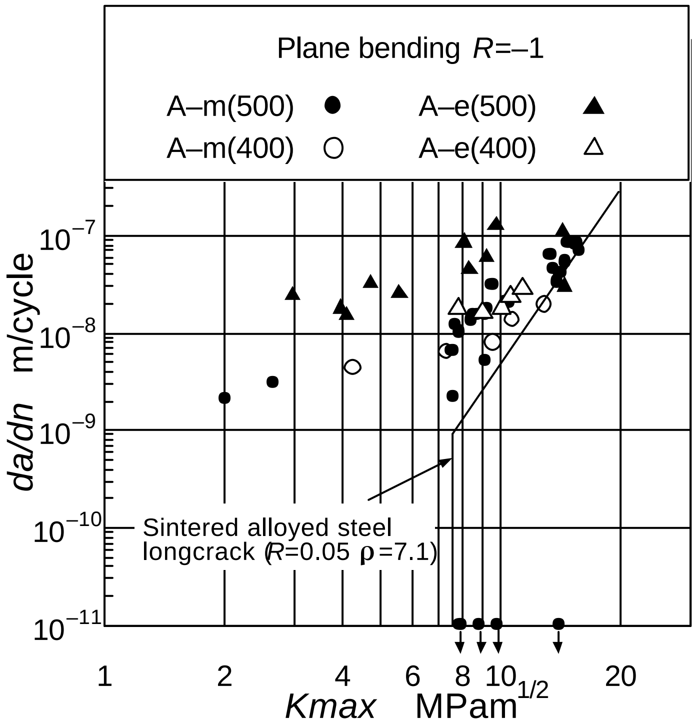


(a) Material A, σ_a=500 MPa (b) Material B, σ_a=500 MPa.

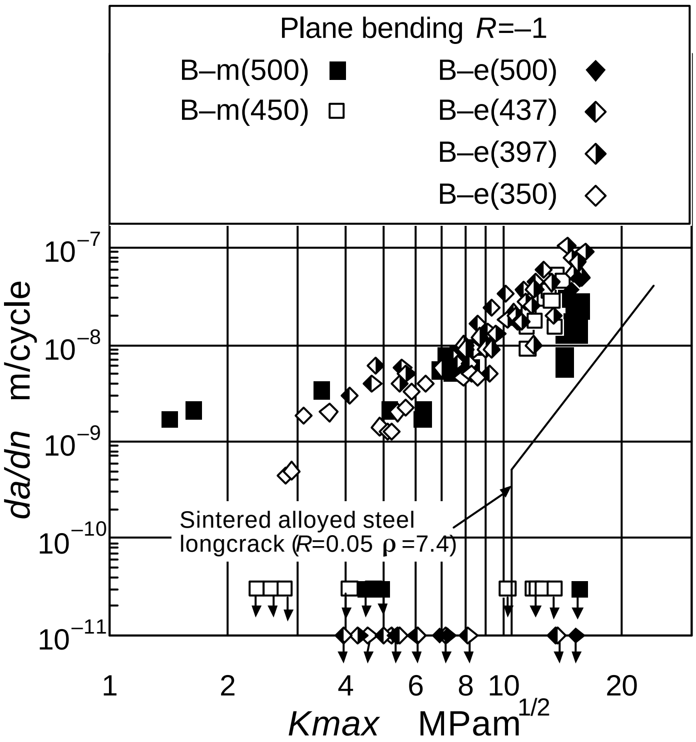
Figure 7 :Crack propagation curves.

In the type-m specimen, surface was very smooth and there was no pore on the specimen surface. The photograph shown in Fig.6(a) was taken when the crack was initially observed in the surface. In this photograph, the black arrows indicate the crack tips. Only one fatigue crack initiated and the crack length was about 200 μm at this stage, indicating that the fatigue crack initiated at an interior pore and grew until it breached the specimen surface, and it was longer than the initial crack length observed in the type-m specimen. In this case, the main crack, No.1, grew solely in the early stage and then overlapped with the relatively short subcracks, No.2 and No.3. Similar fatigue crack initiation and growth behavior was observed on the material B, and there found no effect of the recompress process on fatigue crack initiation behavior. It was considered that the fatigue crack easily initiated at the collapsed pores because the pores were collapsed by the recompress process but the interface was not adhered sufficiently.

Figure 7 shows crack growth curves of the materials A and B at σ_a=500 MPa. In these figures, the abscissa is the number of stress cycles after crack initiation, $N - N_i$. On both materials, fatigue crack growth life, defined as $N_f - N_i$ at the crack length of 2 mm, is found to be longer in the type-m specimen comparing with the type-e specimen. The arrows in these figures denote the crack coalescence or overlapping site and it was observed that fatigue cracks often coalesced or overlapped irrespective of the materials and the



(a) Material A



(b) Material B

Figure 8 : da/dn-K_{max} relationships.

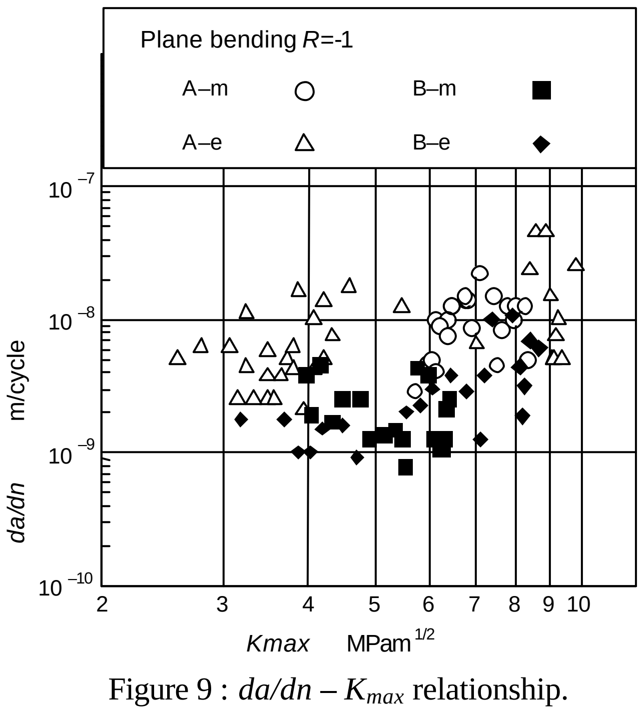


Figure 9 : $da/dn - K_{max}$ relationship.

machining types. The crack growth increment caused by the crack coalescence or overlap in the type-m specimens is larger than that in the type-e specimens. The four cracks overlapped at point 3 in the A-e specimen and the five cracks coalesced at the point 2 in the B-e one. Such large number of coalesced cracks is thought to result in the short crack growth life in the type-e specimen. Comparing crack growth curves during crack extension from 0.5 to 1 mm, the slope of the type-m specimen is found to be gentle. It was thought that residual compressive stress in the worked layer induced by the milling process resulted in the relatively slow crack growth in the type-m specimen.

Figure 8 shows da/dn-K_{max} relationships of both materials. The stress intensity factor was calculated by the Newman-Raju[5] equation using the aspect ratio of the bounding rectangle that fully contained the area of a semi-circular crack or coalesced cracks. Data on crack growth acceleration caused by the crack coalescence were omitted in these figures. The solid lines in these figures indicate the da/dn-K_{max} relationships of long fatigue crack on Fe-4Ni-1.5Cu sintered alloy. Growth rates of small fatigue crack were found to be higher than that of long crack in the low K region irrespective of the materials, and also it could grow at the maximum stress intensity level even below the crack growth threshold. It was found that crack growth rates in the type-m specimens is slightly lower that that in the type-e ones irrespective of the materials. This low growth rates was thought to be resulted from the residual compressive stress in the worked layer. Figure 9 shows the comparison crack growth rates of the material A with these of the recompressed material B. Crack growth rate of the material B was found to be lower than that of the material A, indicating that the recompress process improved the fatigue crack growth resistance. The low growth rate on the material A was thought to be resulted from that the fatigue crack frequently coalesced with internal pores ahead of the fatigue crack.

CONCLUSIONS

The effects of porosity and worked layer on small fatigue crack initiation and growth behavior were investigated on Fe-0.5Ni-1Mo sintered steels and recompressed ones with high density. Reversed plane bending fatigue tests were carried out using an electro-magnetic type bending machine and small cracks were observed by means of plastic replica technique. The results obtained can be summarized as follows;

(1)In the materials without the worked layer (type-e specimen, shallow notch of which was machined by the electric discharge machine), there observed a large number of pores at the specimen surface and many fatigue cracks easily initiated at pores, resulting in the short fatigue crack initiation life. When the shallow notch was machined by milling machine, test specimen had worked layer and pore was hardly observed at the specimen surface (type-m specimen). In these specimens, fatigue crack initiated at the internal pore and crack initiation life was increased.

(2)There was no effect of the recompress process on the fatigue crack initiation behavior. It was considered that the fatigue crack easily initiated at the collapsed pores because the recompress process collapsed the pores but could not reweld the interfaces.

(3)In the type-e specimen, a large number of fatigue cracks initiated and frequently coalesced, resulting in the crack growth acceleration and the decrease of fatigue crack growth life.

(4)It was found that the recompressing process resulted in the increase of crack growth resistance since it reduced the porosity and decrease the frequency of crack coalescence.

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