Fatigue Crack Propagation Behavior in Commercial Purity Ti Severely Deformed by Accumulative Roll Bonding Process

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Fatigue properties of commercial purity titanium sheets severely deformed by the accumulative roll bonding (ARB) process were investigated. The ARB process was carried out up to 6 cycles (equivalent strain, \( \varepsilon_{eq} = 4.8 \)). The sheets ARB processed by 2-, 4- and 6-cycle consist of fine equiaxed grains and elongated lamellar grains. In the sheet ARB processed by 6-cycle, the mean size of fine equiaxed grain was 89 \( \mu \)m, and the mean thickness of the lamellar grains were 67 \( \mu \)m. The tensile strength increased with increasing the number of the ARB cycle. Fatigue crack growth tests were performed to clarify the fatigue properties such as the crack growth rate and threshold stress intensity factor range for crack growth (\( \Delta K_{th} \)). The \( \Delta K_{th} \) of the ARB processed specimens were smaller than that of the starting sheet. The \( \Delta K_{th} \) decreased with increasing the number of the ARB cycle until 4-cycle. However, the \( \Delta K_{th} \) of 6-cycle specimen was larger than that of the 4-cycle specimen. Fracture surface of the 6-cycle specimen was different from that of the 2- and 4-cycle specimens. Fatigue crack propagation behavior changes between 4- and 6-cycle specimens. On the other hand, the crack growth rate decreases with increasing the number of the ARB cycle.

Keywords: fatigue, crack growth rate, ultrafine grain, threshold stress intensity factor range

1. Introduction

Ultrafine grained (UFG) materials whose mean grain size is smaller than 1 \( \mu \)m have been much studied in the last decade, because they are expected to show the mechanical properties superior to conventional materials with coarse grains. The severe plastic deformation (SPD), which mechanically can induce the large strain (equivalent strain: \( \varepsilon_{eq} > 4.0 \)) into materials, can produce bulk UFG materials. Various kinds of SPD processes1–4) have been developed: accumulative roll bonding (ARB),2–4) equal channel angular pressing (ECAP),1–3) high pressure torsion (HPT)1,2) and so on. These processes actually succeeded in producing bulk UFG materials with nano- or sub-micro-meter sized grains in various kinds of metallic materials, and the UFG materials actually exhibited high strength.1–4) Hence, it is also expected that the UFG materials perform high fatigue properties.

Concerning the fatigue behaviors, crack growth rate (\( da/ \) \( dN \)) at \( \Delta K_{th} \) fatigue life (S-N curve),9–11) cyclic response (stress-strain curve, hysteresis loop),5–19) etc., have been reported in the UFG materials with F.C.C. or B.C.C. structure, such as pure Cu,11–15,17) Cu alloy,8) Al alloy,6,9,14,16,18) low carbon steel7) and so on.10,17,19) However, fatigue data of the UFG metals having H.C.P. structure are still quite limited.20–22) In addition, all of the UFG materials used for the fatigue studies in the references were fabricated by the ECAP process. Fatigue data of the materials fabricated by other SPD techniques are also required for understanding the universal fatigue behaviors of the UFG metals.

This study was carried out to clarify the fatigue crack propagation behaviors in the commercial purity Ti (H.C.P.) sheet with UFG structures fabricated by the ARB process. Ti sheets ARB processed by various cycles were prepared, and relationship between the number of the ARB cycle and mechanical properties, such as tensile strength and crack growth rate, was investigated.

2. Experimental Procedures

Commercial purity Ti sheets (JISH4600 TP340C: grade 2) were used in this study. The chemical composition of the sheet is shown in Table 1. The dimensions of the starting sheets were 2 mm in thickness, 25 mm in width and 150 mm in length. These sheets were provided to the ARB process. In the first ARB cycle, the rolling was not roll-bonding but conventional rolling from 2 mm to 1 mm thickness. The rolled sheet 1 mm thick was cut into two, stacked to be 2 mm thick after degreasing and wire brushing the surface, and then provided to the 50% roll bonding in the next ARB cycle. The Ti sheets ARB processed by 0-cycle (starting sheet), 2-cycle, 4-cycle and 6-cycle were fabricated in this study. Because the equivalent strain of 50% rolling is 0.8, the total equivalent strain accumulated in the sheet ARB processed by 6-cycle was 4.8. The rolling was done with lubricant by the use of a two high mill with a roll diameter of 310 mm at room temperature.

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Compact tension (CT) specimens with a notch were prepared for fatigue crack growth tests. Figure 1 shows the schematic illustration of the CT specimen. The width of the specimen was 17.1 mm. The thicknesses of the specimen for the starting sheet (0 cycle) and the ARB processed sheets were 2 mm and 1 mm, respectively. The notch is parallel to the transverse direction (TD) of the sheets. Surfaces of the specimens were polished before the test in order to measure the crack length. Fatigue crack growth tests were carried out at a stress ratio $R = 0.1$ with an electro servo hydraulic fatigue testing machine operated at frequency of 10 Hz at room temperature. Applied load in the test was measured with a load cell whose capacity is 1960 N. The fatigue crack growth test was carried out according to ASTM standard E647.23)

The log-log plot of the fatigue crack growth rate $(da/dN)$ versus the stress intensity factor range $(\Delta K)$ was obtained from the test. Although the thicknesses of CT specimens were 2 mm (starting sheet) and 1 mm (ARB processed sheet), the stress intensity factor $(K)$ was calculated from Eqs. (1) and (2) in ASTM standard E399.23)

$$K = \frac{P}{BW^{1/2}} \cdot f(k) \quad (k = a/W)$$

where $P$ is load (N), $B$ and $W$ are thickness (m) and width (m) of the specimen and $a$ is crack length (m). $\Delta K$ is a range between $K_{\text{max}}$ and $K_{\text{min}}$. 

$$\Delta K = K_{\text{max}} - K_{\text{min}}.$$ 

Crack length on the surface of the specimens was measured by the use of an optical microscope. Fracture surfaces after the fatigue crack growth tests were observed by scanning electron microscopy (SEM).

3. Results and Discussion

Figure 2 shows an optical micrograph of the starting sheet (0-cycle) of commercial purity Ti. The starting sheet had the equiaxed grains with the average grain size of 42 µm. Figure 3 shows the TEM images of the sheets ARB processed by (a) 2-, (b) 4- and (c) 6-cycle. The structures were observed from TD. The sheet ARB processed by 2-cycle has the dislocation cell structures with high dislocation density. The sheet consisted of the fine and elongated structures parallel to RD. The mean diameter size of the nearly equiaxed grains was 146 nm, and the mean thickness of the elongated grain was 550 nm in the sheet ARB processed by 2-cycle. The sheet ARB processed by 4-cycle was filled with fine equiaxed grains and fine lamellar grains. The mean size of the fine equiaxed grains and the thickness of the fine lamellar grains were nearly the same, 110 nm and 111 nm, respectively. The structure after 6-cycle of the ARB process also consisted of fine equiaxed grains and elongated lamellar grains, which was similar to that in the sheet ARB processed by 4-cycle. The mean size of the fine equiaxed grains and the thickness of the fine lamellar grains were 89 nm and 65 nm, respectively. In the ARB processed Ti sheets, not only the elongated lamellar grains but also the equiaxed grains were observed. The equiaxed grains are an unique microstructure in the ARB processed Ti because only elongated lamellar structures have been observed in the as-ARB processed cubic metals.24) Terada et al.25) pointed out that the microstructure evolution of Ti during the ARB process is affected by the recovery at inhomogeneous deformation regions such as shear bands. In addition, local adiabatic heating, which is enhanced by low thermal conductivity of Ti, might also assist the recovery.

Figure 4 shows the nominal stress-strain curves of the sheets ARB processed by 0-, 2-, 4- and 6-cycle. The tensile strength significantly increased by 2-cycle of ARB, although the elongation decreased. After the second cycle, the tensile strength slightly increased with increasing the number of the ARB cycle. The tensile strength of the sheet ARB processed
by 6-cycle reached to 850 MPa, which was about two times higher than that of the starting sheet.

The log-log plot of the \( \frac{da}{dN} \) versus the \( \Delta K \) is shown in Fig. 5. In ASTM Standard E647, the threshold stress intensity factor range for crack growth (\( \Delta K_{th} \)) is defined as the \( \Delta K \) at crack growth rates on the order of \( 1 \times 10^{-10} \text{ m/ cycle} \) or less. However, cracks did not propagate at crack growth rates on the order of \( 1 \times 10^{-10} \text{ m/ cycle} \) or less in the ARB specimens. The minimum \( \Delta K \) was used as the \( \Delta K_{th} \) in the ARB specimens. Therefore, the \( \Delta K_{th} \) for the 2-, 4- and 6-cycle specimens were 4.7, 2.2 and 3.6 MPam\(^{1/2} \), respectively. On the other hand, the \( \Delta K_{th} \) of the starting sheet (6.8 MPam\(^{1/2} \)) was higher than that of the ARB processed sheets. It has been reported that the \( \Delta K_{th} \) of Al alloys and low carbon steel decreased by the ECAP processing. It has been pointed out that the crack closure phenomena reduced by the ECAP. It is not surprising if the same thing happens in the ARB process. The \( \Delta K_{th} \) would decrease with decreasing the crack closure phenomena in the ARB processed Ti with H.C.P. structure as well as the ECAP processed specimens.

The \( \Delta K_{th} \) decreased with increasing the number of the ARB cycle until 4-cycle. However, the \( \Delta K_{th} \) of the 6-cycle specimen was larger than that of the 4-cycle.

In Fig. 5, the curves have a linear part where the crack propagation is stable above the \( \Delta K_{th} \). The slope of a linear part decreased with increasing the number of the ARB cycle until 4-cycle. However, the slopes for the 4- and 6-cycle specimens were nearly the same. The crack growth rates of the 0-, 2- and 6-cycle were compared at the stress intensity factor range above 7 MPam\(^{1/2} \) in Fig. 5. The crack growth rate decreased with increasing the number of the ARB cycle (increasing strain).

Figure 6 shows optical micrographs of the crack propagation profiles in the starting and 2-cycle specimens during the fatigue crack growth test. The fatigue crack propagates macroscopically straight but with small zigzag pattern in the starting sheet. On the other hand, the smooth fatigue crack profile without the zigzag pattern was observed in the ARB processed specimens, which was also the case in the 4- and 6-cycle specimens.

Figure 7 shows SEM images of the typical fracture surfaces of the specimens. Fatigue crack propagates from left to right in the micrographs. In the observed areas, the crack growth rates of 0-, 2-, 4- and 6-cycle were 3.73 × 10\(^{-9} \) m/ cycle, 6.99 × 10\(^{-9} \) m/ cycle, 1.45 × 10\(^{-9} \) m/ cycle and 1.70 × 10\(^{-9} \) m/ cycle, respectively. Similar fracture
surfaces were also observed at other crack growth rates after the $\Delta K_{th}$. The rough fracture surface was observed in the starting sheet (0-cycle). Striation-like-pattern, which is a typical characteristic of fatigue fracture surface, was partially observed on the fracture surface of the 0-cycle specimen. Flat surfaces were also observed in local areas. The flat surface is considered to be formed by cleavage fracture in the fatigue test. The fracture surface of the ARB processed specimens was much different from that of the starting sheet. In the 2-cycle specimen, many granules like patterns were observed on the fracture surface. The morphology of the fracture surface of the ARB processed specimen was much different from that of the starting sheet. In the 2-cycle specimen, many granules like patterns were observed on the fracture surface. The morphology of the fracture surface of the 4-cycle specimen was similar to that of the 2-cycle specimen, although the size of the patterns was different. The fracture surface of the 6-cycle was different from those of the both 2- and 4-cycle specimens. The aggregation of the granule patterns, which was observed in the both 2- and 4-cycle specimens, was not clearly observed on the surface of the 6-cycle specimen. In addition, the fracture surface seems to be elongated to the direction of the fatigue crack propagation. Therefore, the fatigue crack propagation behavior probably changes between 4- and 6-cycle specimens.

The data of the crack growth test for the UFG materials are still quite limited.\textsuperscript{5–7} The relationships between $da/dN$ and $\Delta K$ for the UFG materials have been reported in Al alloys\textsuperscript{5,6} and a low-carbon steel\textsuperscript{7} fabricated by the ECAP. In the references, it was clearly shown that $\Delta K_{th}$ decreased by the ECAP deformation. In the present study, the $\Delta K_{th}$ of the ARB processed Ti having H.C.P. structure was smaller than that of the starting sheet (0-cycle). This tendency agrees with the results in the previous references, although the SPD technique and crystal structure is difference.

However, the $\Delta K_{th}$ of the 6-cycle was larger than that of the 4-cycle and fracture surface also changed between 4-
cycle and 6-cycle specimens. These results suggest that the effect of the crack closure phenomena on the crack growth rate increases, or that the mechanism of the crack propagation behavior changes between 4-cycle and 6-cycle specimens. Further systematic investigations on the relationship between fatigue data and the microstructural characteristics are required, and it will be carried out in our future studies.

4. Conclusions

The fatigue crack propagation behaviors in the commercial pure Ti sheets severely deformed by the accumulative roll bonding (ARB) process were investigated. The main results are summarized below.

(1) Ultrafine microstructures were formed in the Ti specimens by the ARB process. The sheets ARB processed by 2-, 4- and 6-cycle consist of the fine equiaxed grains and elongated lamellar grains. After 6-cycle, the mean size of fine equiaxed grain was 89 nm, and the mean thickness of the lamellar grains were 67 nm, respectively.

(2) The tensile strength increased with increasing ARB strain, although the total elongation decreased. The tensile strength of the sheet ARB processed by 6-cycle reached to 850 MPa, which was about two times higher than that of the starting sheet.

(3) Fatigue crack growth rate decreased with increasing the number of the ARB cycle at high stress intensity factor range. Threshold stress intensity factor range ($\Delta K_{th}$) decreased with increasing the number of the ARB cycle until 4-cycle. However, the $\Delta K_{th}$ of the 6-cycle specimen was larger than that of the 4-cycle specimen.

(4) Fracture surface of the ARB processed specimen was much different from that of the starting sheet. The fracture surfaces of both 2- and 4-cycle specimens were nearly the same. However, the fracture surface of the 6-cycle specimen differed from that of the 2- and 4-cycle specimens.

(5) It was suggested from the fracture surface observations and change in $\Delta K_{th}$ that the fatigue crack propagation behavior changed between 4- and 6-cycle specimens.

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