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Gigacycle fatigue properties of Ti–6Al–4V alloy under tensile mean stress

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ABSTRACT

The mean stress effects on the gigacycle fatigue properties of three heats of Ti–6Al–4V alloy were investigated by means of ultrasonic and electromagnetic resonance fatigue tests. All heats developed internal fractures under mean stress conditions of $R \geq 0$ with negligible frequency effects. The origins of the internal fractures proved not to be inclusions, but clusters of facets. Cross-sectional observations of the internal fractured specimen revealed the facets to have formed in the α-phase in an inclined direction. The gigacycle fatigue strength of the Ti–6Al–4V alloy at $R=-1$ matched that of quenched and tempered steel, while that under $R=0$ was clearly lower. Ti–6Al–4V alloy is more prone to internal fracturing under tensile mean stress conditions, resulting in reduced fatigue strength. Its gigacycle fatigue strengths are thus below the modified Goodman line at around $R=0$. This trend is very dangerous, since the modified Goodman line generally gives predictions with a good margin of safety.

1. Introduction

Ti–6Al–4V alloy shows gigacycle fatigue caused by internal fracture [1–8]. The *S*–*N* curves (fatigue life curves) generally show a stepped shape. The fracture mode above the stepped stress level is a conventional surface fracture; however, below the stepped stress level, it changes into an internal fracture. Conventional fatigue limits are thus eliminated by internal fractures. This behavior is similar to the gigacycle fatigue behavior of high-strength steels [9–14]. The major difference from the high-strength steels is the origin of internal fractures: in high-strength steel it is usually an inclusion, whereas in Ti–6Al–4V alloy it is facets formed in the matrix.

Ultrasonic fatigue testing [15–19] is a powerful tool for conducting gigacycle fatigue tests. It uses the very high frequency of 20 kHz, which is 200 times faster than the conventional 100 Hz. The use of 20 kHz accumulates 10^{10} cycles in a week, in marked contrast to the three years required for conventional 100-Hz testing. The frequency effects of ultrasonic testing, however, need to be elucidated, since 20 kHz is too fast to make the test results fully credible. To identify possible frequency effects, the authors compared 20-kHz test results with those obtained at the conventional 100 Hz. For high-strength steel, conventional 100 Hz fatigue tests were run for three years to reach 10^{10} cycles. The results were then compared with those from ultrasonic fatigue testing. Ultrasonic fatigue testing showed good agreement with conventional 100-Hz fatigue testing under conditions where the internal fractures occurred [20–23]. For the Ti–6Al–4V alloy [22–24], the frequency effects were also negligible under conditions where internal fractures occurred, but were present when conventional surface fractures developed. For surface fractures, ultrasonic fatigue testing showed higher fatigue strengths than the conventional 100-Hz version. We thus conclude that ultrasonic fatigue testing can be used safely under conditions where internal fractures occur. This means that ultrasonic fatigue testing can be useful for evaluating the gigacycle fatigue properties of Ti–6Al–4V alloy, since the long-life fatigue failure of Ti–6Al–4V alloy is mainly caused by internal fractures.

On the other hand, mean stress effects are important in the real world, since materials are used under various mean stress conditions. Zero-tension and tension–tension fatigue test conditions, i.e., tensile mean stress conditions, are particularly important. Evaluation of mean stress effects frequently uses a modified Goodman's diagram, which generally provides predictions with a wide safety margin [25]. For Ti–6Al–4V alloy, a modified Goodman's diagram gives a safe side predictions when the fatigue strength is evaluated at the conventional 10^7 cycles [26,27]. However, the mean stress effects on gigacycle fatigue properties have until now not been elucidated.

The mean stress effects on gigacycle fatigue properties can be evaluated by ultrasonic fatigue testing. Although conventional ultrasonic fatigue testing is conducted under zero mean stress conditions, tensile mean stress can be easily superimposed by installing the ultrasonic fatigue testing system in a load frame [16–19]. This method uses nodes of vibration to grip the ultrasonic fatigue testing system by the load frame, and ultrasonic fatigue testing is performed under a static load that is applied by the load frame. This system is available off the shelf. When the authors applied it to high-strength steel, the results confirmed the validity of the method: the ultrasonic fatigue test results showed good

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agreement with conventional servo-hydraulic fatigue test results under conditions where internal fractures occurred [28].

Based on the above-mentioned results, this study investigated the mean stress effects on the gigacycle fatigue properties of Ti–6Al–4V alloy using ultrasonic fatigue testing. This study used the same materials as in the previous study [24], which were three heats of Ti–6Al–4V alloy. In the previous study, one of the three heats revealed only surface fractures with visible frequency effects, while the other two showed internal fractures without any frequency effects.

2. Experimental methods

2.1. Materials

Table 1 shows the chemical compositions of the tested materials (heats A, B and C). All the elements of each heat satisfied ASTM specifications. Table 2 shows the heat treatment conditions. The heat treatment was STA: solution treatment and aging. The heat-treated materials were received in the form of round bars; Table 3 shows their mechanical properties. Although all three heats have a tensile strength of approximately 900 MPa, the tensile strength of heat C is slightly lower than those of heats A and B.

Fig. 1 shows microstructures in longitudinal cross section. The microstructure is of an α–β type. The α phases of heats A and C are nearly equiaxial, and the average grain sizes are approximately 7 μm. Those of heat B are elongated in the rolling direction, and the average grain sizes are approximately 20 μm. The microstructures of heats A and C thus resemble each other, but that of heat B is different to both.

2.2. Fatigue testing

Fatigue tests were conducted under axial loading using two kinds of fatigue testing machines: ultrasonic and electromagnetic

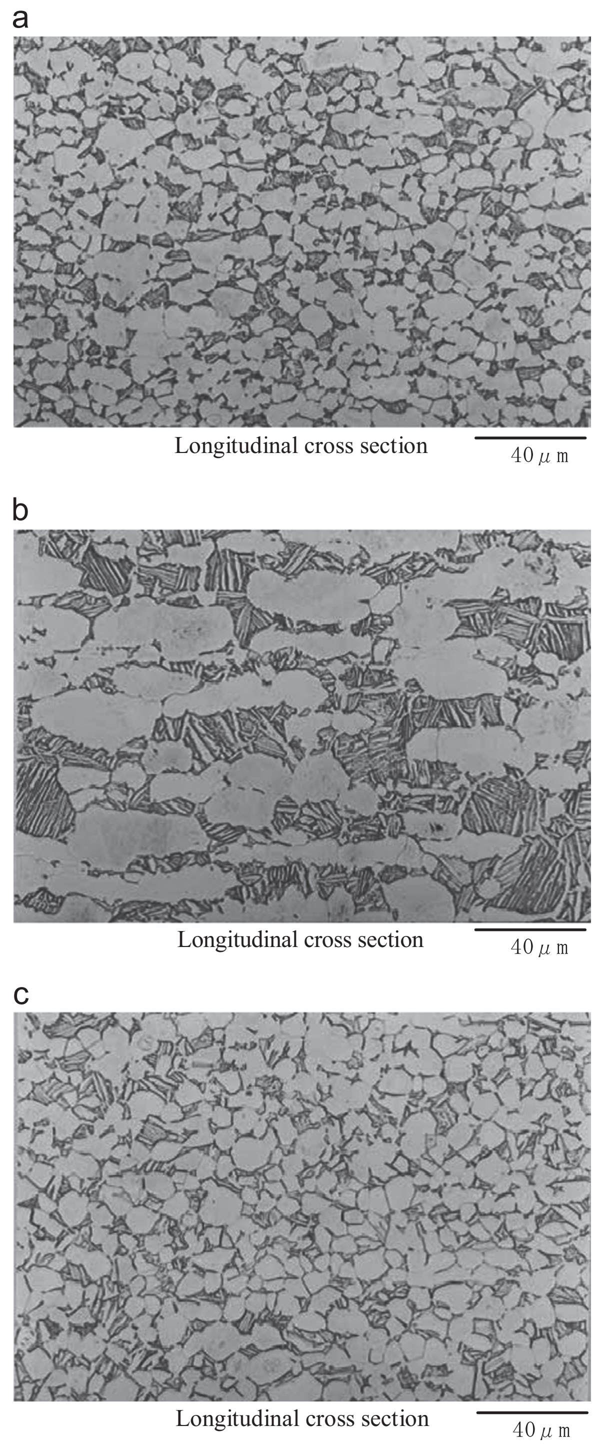

Fig. 1. Microstructures. (a) Heat A, (b) heat B and (c) heat C.

Table 1
Chemical compositions.

Heat	Element (mass%)						
	Al	V	Fe	C	N	H	O
A	6.27	4.30	0.21	0.016	0.0055	0.0048	0.18
B	6.39	4.31	0.18	0.012	0.0058	0.0120	0.17
C	6.11	4.39	0.17	0.004	0.0034	0.0074	0.17

Table 2
Heat treatment conditions.

Solution	Aging
930 °C/60 min, air cooled	705 °C/120 min, air cooled

Table 3
Mechanical properties.

Heat	Tensile properties				Charpy absorbed energy (J)	Vickers hardness (HV)
	0.2% Proof stress (MPa)	Tensile strength (MPa)	Elongation (%)	Reduction of area (%)		
A	916	960	21	45	32	326
B	897	967	18	42	43	319
C	866	906	23	56	36	319