Factors Affecting Non-Propagation of Fatigue Crack in a Low-Carbon Steel*

(Effect of Oxide-Induced Crack Closure)

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Rotating bending fatigue tests were carried out in air and in pure argon to clarify the effect of oxide-induced crack closure on crack non-propagation. The materials used were Ti added extra-low-carbon steel with no strain ageing, 0.02% carbon steel with a single ferrite phase, and annealed 0.19% carbon steel. The results obtained are as follows. (1) Threshold stress for fatigue crack growth is lower for Ti added extra-low-carbon steel in argon than for that in air, though the fatigue crack has a tendency to propagate more slowly in argon than the air. The above result shows that oxide-induced crack closure plays a significant role in crack non-propagation. (2) It seems that the influence of oxide-induced crack closure on crack non-propagation is smaller than the influence of strain ageing and microstructure. (3) A non-propagating crack is observed in the steel with a single ferrite phase even when strain ageing and oxide-induced crack closure do not occur.

Key Words: Fatigue Limit, Strain Ageing, Crack Closure, Non-Propagating Crack

1. Introduction

It is known that a fatigue limit exists in low-carbon steel and that this fatigue limit represents the threshold stress for non-propagation of a crack^{(1),(2)}. Therefore, because the conditions for non-propagation of a micro crack are one of the most important technological problems, many researchers have investigated the non-propagation of a fatigue crack. The main factors affecting crack non-propagation include (1) those related to microstructure^{(3),(4)}, (2) work hardening and strain ageing at a crack tip, (3) crack closure induced by plasticity deformation that is formed with crack propagation⁽⁵⁾, (4) oxide-induced crack closure^{(6),(7)} in addition to (2) and (3), and (5) the crack tip becoming dull⁽⁸⁾. On the other hand, large-scale research was carried out to prove that the existence of a fatigue limit in a low-carbon steel was due to strain ageing. However, satisfactory results were not obtained because they could not eliminate

the ageing property completely in the material they used⁽⁹⁾. In this regard we conducted a rotating bending fatigue test of a plane specimen. The material used was Ti added extra-low-carbon steel, which is interstitial-free (IF), and has no ageing properties. In that experiment, we confirmed the existence of a non-propagating crack in the material and reported that strain ageing is not always necessary for the non-propagation of a fatigue crack⁽¹⁰⁾. In the present study, rotating bending fatigue tests of plane specimens are carried out in air and in pure argon, paying particular attention to the existence of strain ageing⁽¹¹⁾ and of the oxide-induced crack closure. The main purpose of this study is to clarify whether a non-propagating crack can exist when there is neither age hardening nor an oxide-induced crack closure. Moreover, the effect of oxide-induced crack closure on crack non-propagation is compared with that of strain ageing and microstructural factors. The materials used are Ti added extra-low-carbon IF steel with no strain ageing, 0.02% carbon Al-killed steel with a single ferrite phase, and an annealed 0.19% carbon steel with ferrite-pearlite microstructure.

2. Materials, Specimen and Experimental procedures

The materials used were an ingot of Ti added

* Received 1st March, 2000. Japanese original: Trans. Jpn. Soc. Mech. Eng., Vol. 65, No. 635, A (1999), pp. 1546-1551 (Received 13th January, 1999)

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Fig. 3 Experimental apparatus

the specimen remained sealed off from air during the experiment. However, because the replica method used the methyl acetate, it was difficult to avoid contamination of the argon atmosphere with methyl acetate vapor. Considering this influence, the contaminated argon gas (about 80% of the capacity of bag) was pumped out after gathering the replicas and pure argon gas was supplied. As described later, the influence of replicas on crack propagation was hardly observed.

3. Results and Discussion

3.1 Crack propagation in air and in argon

Figure 4 shows the fatigue endurance ($S-N$) curves in air and in argon for each material. At the same stress amplitude for steel H, fatigue life in argon tends to be longer than that in air. As shown in Fig. 5, this results from the difference in the crack propagation life. The crack propagated more slowly in argon than in air at the same stress amplitude. Endoh et al. reported a similar trend for 0.35% carbon steel⁽¹²⁾. As to why the crack propagates more slowly in argon than in air, it was proposed that because no oxide is produced on the new surface of the crack tip in argon, some part of the crack tip sticks again during the compression process, causing the decrease in crack growth rate⁽¹³⁾. On the other hand, Endoh et al. proposed that it is because of the decrease in surface energy of the crack tip owing to the chemical adsorption of oxygen⁽¹²⁾. In either explanation the reason is considered to be the same as that for the slower propagation of a crack in vacuum than in air^{(14),(15)}. Figure 6 shows the crack propagation curves of steel L. The growth rate of a crack less than 0.2 mm long tends to be slightly lower in argon than in air. However, fatigue life is almost same in both atmo-

Fig. 4 $S-N$ curves

Fig. 5 Crack propagation curves of steel H

Fig. 6 Crack propagation curves of steel L

spheres because of the increase in crack initiation life in air. Figure 7 shows the crack propagation curves of steel T. The crack also tends to propagate more slowly in argon than in air, as shown in the case of

stress amplitude $\sigma_a=170$ MPa. On the other hand, at $\sigma_a=150$ MPa, while the crack in air stops propagating after $N=10^7$ cycles and further increase in crack length is not detected even at $N=10^8$ cycles, the crack in argon propagates gradually and the specimen fractures at $N=1.36 \times 10^7$. In argon, the crack propagated and the specimen of steel T fractured even at a low stress amplitude. The results indicate that the threshold stress for fatigue crack growth of steel T was lower in argon than in air. The oxide-induced crack closure may be closely related to the non-propagation of a crack. This may be the reason why the fatigue lives of some specimens of steel T exceeded $N=2.0 \times 10^7$ cycles. In that case, the fatigue lives were also on the line correlating between fatigue life and stress amplitude (see $S-N$ curve). This indicates that the fatigue mechanism of steel T in the long-life field is the same as that in the short-life field. Figure 4 also

Fig. 7 Crack propagation curves of steel T

shows the results of experiments that were carried out to clarify the effect of using plastic replicas on fatigue life and crack non-propagation. Namely, two data of which fracture lives were almost equal are shown in Fig. 4 (steel T in argon, $\sigma_a=140$ MPa). One of them is the result of fatigue test during which replicas were gathered five times and the other is the result obtained from a continuous fatigue test. Moreover, the specimen of steel T did not fracture in argon at $\sigma_a=135$ MPa, both in the continuously test and the test with the replica method.

3.2 Successive observation of non-propagating crack in argon

Figure 8 shows the change in surface states around a crack in argon ($\sigma_a=135$ MPa). Fatigue damage accumulated at a grain boundary and a crack was initiated at this position up to $N=2.5 - 3.0 \times 10^7$ cycles. After that, no further crack growth is recognized up to $N=1.0 \times 10^8$ cycles. After 108 cycles of $\sigma_a=135$ MPa, the stress amplitude was increased to 150 MPa and the fatigue test was resumed. The non-propagating crack started to propagate and the specimen fractured at $N=1.58 \times 10^7$ cycles. Figure 8 also shows the crack that started to propagate again at $\sigma_a=150$ MPa. From this picture, the non-propagating crack tip can be recognized at $\sigma_a=135$ MPa. The propagation of upper side of the non-propagating crack tip was stopped by a grain boundary and that of the lower side of the crack tip stopped after growing in mode I at $\sigma_a=135$ MPa. Namely, a non-propagating crack is observed in steel that has no strain ageing and no oxide-induced crack closure. Figure 9 shows the successive observation of the crack on the surface

Fig. 8 Successive observation of steel T specimen surface by plastic replicas

Table 3 Experimental results (○: present, ×: absent)

material	Factors affecting non-propagation of fatigue crack			Experimental results				
	Pearlite	Strain ageing	Plasticity-induced crack closure, Grain boundary, and others	Non-propagating crack		Fatigue limit (MPa)		
				in air	in Ar	in air	in Ar	difference
Steel H	○	○	○	○	○	220	220	0
Steel L	×	○	○	○	○	170	165	-5
Steel T	×	×	○	○	○	150	135	-15

Fig. 9 Successive observation of specimen surface on steel H by plastic replicas

of steel H in argon at $\sigma_a = 220$ MPa. Though slip band increased gradually, the crack did not grow after $N = 1.0 \times 10^7$ cycles. For steel H, many crack tips were prevented from propagating by pearlite, but some crack tips stopped propagating in the ferrite grains or grain boundaries, as seen in Fig. 9.

3.3 Effect of oxide-induced crack closure

Table 3 shows the factors affecting non-propagation of fatigue crack in each material and the results of experiments (fatigue limit and the existence of non-propagating crack). Here the fatigue limit is defined as the maximum stress where non-propagating cracks are observed.

In the case of steel T, the fatigue limit was 135 MPa in argon and 150 MPa in air. This difference of 15 MPa may come from the effect of oxide-induced crack closure. In the case of steel L, in which strain ageing was added as a factor affecting non-propagation, the fatigue limit was 165 MPa in argon and 170 MPa (only 5 MPa higher) in air. Due to the effect of strain ageing on the strengthening of crack tip, it may be difficult to detect clearly the effect of oxide. In the case of steel H, the fatigue limit in argon was equal to that in air. Regarding steel H, the threshold stress for fatigue crack growth did not change, by only removing the effect of the oxide-induced crack closure, because of the significant effects of strain ageing and microstructure, both of which act as a barrier against crack growth.

3.4 Factors affecting non-propagation of fatigue crack

A non-propagating crack of Ti added extra-low-

carbon IF steel (no strain ageing and single ferrite phase) was observed in argon. It was therefore proven that not only the existences of a secondary phase but also strain ageing and oxide-induced crack closure are not the essential factors affecting crack non-propagation in low-carbon steel. Other factors include plasticity-induced crack closure and crack closure caused by roughness of a crack surface^{(16),(17)}. It is thought that plasticity-induced crack closure becomes dominant in the case of a large crack such as that seen at the bottom of a notch. However, the effect of the latter factor may become significant in the case of a small crack that initiate at the grain boundary of a plane specimen, as seen in the present study of steel T. It seems that the above factors are strongly related to the non-deformation of a crack tip under repeated stress^{(18),(19)}. We have proposed a method of specifying the area in which fatigue damage accumulates by removing the slip band by slight polishing with buff⁽²⁰⁾. A rotating bending fatigue test was carried out previously using a specimen of an extra-low-carbon Al-killed steel with a small blind hole and a plane specimen of an annealed 0.19% carbon steel. In that study, repeated fatigue limit stress was applied again after removing, by polishing them slightly by buff, slip bands at the tip of the crack that was initiated by the stress and stopped propagating. It was reported that no fatigue damage such as slip band was observed at the non-propagating crack tip though some new slip bands appeared away from the crack tip⁽²¹⁾. This indicates that repeated slip does not occur at the non-propagating crack tip because

the crack tip opening ratio is zero. This phenomenon can sufficiently explain crack non-propagation.

4. Conclusion

Rotating bending fatigue tests on a Ti added extra-low-carbon steel, a 0.02% carbon Al-killed steel and an annealed 0.19% carbon steel were carried out in air and in pure argon, paying particular attention to the existence of strain ageing and oxide-induced crack closure. The results obtained are as follows.

(1) Threshold stress for fatigue crack growth of the Ti added extra-low-carbon steel in argon was smaller than that in air, though the fatigue crack had the tendency to propagate slowly in argon than in air. The above result indicated that oxide-induced crack closure plays a role in crack non-propagation.

(2) In the case of 0.02% carbon Al-killed steel, the effect of environment on the threshold stress for fatigue crack growth was small owing to the existence of strain ageing. Moreover, the effect hardly appeared in the case of annealed 0.19% carbon steel. It seemed that the influence of oxide-induced crack closure on crack non-propagation was small compared to that of strain ageing and microstructure.

(3) A non-propagating crack of Ti added extra-low-carbon IF steel (no strain ageing and single ferrite phase) was observed in argon. It was proven that not only the existences of a secondary phase but also strain ageing and oxide-induced crack closure are not the essential factors affecting crack non-propagation in low-carbon steel.

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