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Observation of Low-Cycle Fatigue Crack Initiation and Propagation in Anisotropic Rolled Steel under Biaxial Stressing*

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Crack initiation and propagation in anisotropic rolled steel, the anisotropy of which was caused by a laminated structure of ferrite and pearlite bands, were studied by means of micro- and macroscopic observations of specimen surface under biaxial stress conditions. Slip bands and microcracks were initiated at an early stage of fatigue life in ferrite bands. Their direction coincided with that of the maximum shear stress, independently of the directions of the principal axes of anisotropy. However, growth of the microcracks to macrocracks and propagation of these macrocracks were much affected by anisotropy. When the direction of ferrite bands coincided with one of the two maximum shear stress directions, the micro- and macrocracks grew, coalesced and propagated fast within and in the direction of the ferrite bands. When the direction of ferrite bands intersected the maximum shear stress directions, growth of the microcracks in a ferrite band was halted at the ferrite-pearlite interface. Their growth to a macrocrack and its propagation were caused by coalescence of the halted microcracks across the pearlite bands after a certain number of stress cycles, resulting in intermittent and slower propagation of macrocracks with zig-zag paths which coincided with the directions of the maximum shear stresses.

1. Introduction

It is widely known that rolled steel plates show anisotropy in static mechanical properties, especially in fracture ductility in rolling and thickness planes. The present authors have already examined the uniaxial and biaxial low-cycle fatigue properties in this kind of anisotropic rolled steel plates from macroscopic and mechanics points of view⁽¹⁾⁻⁽³⁾.

In this study, fatigue damage in specimen surface was observed microscopically as well as macroscopically by using an optical microscope, a scanning electron microscope and a liquid penetrant inspection technique. Fatigue crack initiation and propagation were observed for specimens with various relative angles between the rolling-induced anisotropy axis and the principal stress axis of the specimen. Discussion was made on correlation between the results obtained in the present study and previous investigations⁽¹⁾⁻⁽³⁾⁽⁵⁾.

2. Material

The material used was a mild steel supplied in the form of a 75mm thick rolled steel plate (SB56M; normalized at 920°C

for four hours, then tempered at 650°C). Chemical composition of this material is shown in Table 1. The mechanical proper-

Table 1 Chemical Composition of the material tested

C	Si	Mn	P	S	Mo	Ni
0.18	0.25	1.30	0.013	0.006	0.49	0.62

Table 2 Mechanical properties of the material tested along the three principal axes of anisotropy

Direction	Tensile strength (kg/mm ²)	True rupture stress (kg/mm ²)	Elongation (%)	Reduction in area (%)	Fracture ductility (%)
Rolling	62.1	124.5	46.1	65.3	105.9
Transverse	64.1	135.4	45.0	68.0	115.3
Thickness	67.2	85.1	36.4	39.0	50.5

Fig. 1 Microstructures of the material tested

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ties of this material along the three principal axes of anisotropy are tabulated in Table 2. Much anisotropy was found in fracture ductility. Fig. 1 indicates the microstructures of the material observed from the three different directions indicated in the figure. A typical rolling structure, which consists of an alternate lamination of pearlite and ferrite bands parallel to the rolling plane, is seen in the figure. All of the specimens for biaxial fatigue tests were cut out of the thickness plane. The positional distributions of hardness and tensile properties in the thickness direction were examined for checking a statistical homogeneity of this material, as was done in a previous study.¹⁾ No particular trend was found to exist in mechanical properties in the thickness direction. In what follows, therefore, this material is assumed in this respect as "homogeneous" in conducting experiments.

3. Test procedure and specimen

Biaxial low-cycle fatigue tests were conducted by using a principle of anticlastic bending of a rhombic plate as in a previous paper.⁽²⁾ Skew-symmetric equilibrated loads are applied at the four corners of the rhombic specimen, in order to produce a tension-compression biaxial plane stress state on specimen surface. This technique provide a clear and easy predetermination of the anisotropy axes-principal stress axes relationship in a specimen. Square plate specimens were used with a diagonal of 66 mm long (plate thickness 6 mm) as shown in Fig. 2. Fig. 3 illustrates schematically the relation between the principal stress axes and the anisotropy axes of the specimen, and its designations. The relative angle between the anisotropy axis (the direction of a laminated structure) and the principal stress axis was selected as 90° (designated as "90° specimen") and 45° (designated as "45° specimen").

In order to make crack observation easier, each specimen was ground, then was annealed in vacuum at 900°C for an hour, and finally one of the two specimen surfaces was electrolytically polished and etched by its central 10 x 10 mm² area. (electrolytic liquid; glacial acetic acid (900cc) + perchloric acid (100cc), liquid temperature; 20°C, and electric current per unit area; about 0.5 A/cm²) The other surface of the specimen was utilized to observe the macroscopic fatigue behavior by using a liquid penetrant inspection technique and to correlate the microscopic and macroscopic observations.

Biaxial fatigue tests were conducted by using a Shimadzu Autograph, IS-10T. The total strain range was controlled in these tests by detecting the central bending deflection of the specimen.

4. Experimental results and discussion

Fig. 2 Dimensions of the specimens used for biaxial fatigue tests

Fig. 3 Relation between the principal stress axes and the anisotropy axes of specimens

Fig. 4 Comparison of the final failure for both 90° and 45° specimens

4.1 Basic strain range-number of cycles to failure relation

In this study, the final failure of a specimen was defined as a state when the cyclic stress range decreased to 75% of its steady-state value observed in that test. Fig. 4 shows the fatigue test results for 90° and 45° specimens. The failure life of the 45° specimen is found about two thirds the life of the 90° specimen. This difference may be caused by a difference in the behavior of initiation and growth of both microscopic and macroscopic cracks.

4.2 Effect of laminated structure on the slip band formation, growth and microcrack initiation at an early stage of fatigue life

Observed results of slip band formation and microcrack initiation on specimen surface by an optical microscope are shown in Figs. 5 (a) and (b) for a 90° and a 45° specimen, respectively. The specimens

Fig. 5 Observation of slip band formation and microcrack initiation for a 90°- and a 45°-specimen by using an optical microscope

were fatigued under a constant total strain range of $\Delta\epsilon_{tocte}=2.64\%$. In both specimens, the formation of slip lines and bands during an early stage of the fatigue process was in ferrite bands of a laminated structure and in the direction coincident with that of the maximum shear stress, as illustrated by the arrows in the figures. In the case of the 90°-specimen, the slip bands thus initiated grew and reached the pearlite-ferrite interface, at which their extension was suspended. With further strain-cycling these slip bands were broadened and intensified, and finally changed into cruciform microcracks. This

* $\Delta\epsilon_{tocte}$ means an equivalent strain range computed on the basis of the octahedral shear strain theory.

type of microcracks were also observed at spots in ferrite bands where slip bands intercrossed.

In the case of the 45°-specimen, similarly to the foregoing case, slip bands were originated in ferrite bands and in the directions coincident with the maximum shear stress axes, one of which was parallel and the other vertical to ferrite bands in this case. Those parallel slip bands were easily linked up or coalesced with other slip bands, which were co-linearly located within the same ferrite bands, during the early stage of fatigue life. These linked slip bands grew fast to form microcracks. Figs. 6 and 7 show examples of microcrack formation for the 90°- and the 45°-specimen, respectively, observed by using a plastic replica technique.

Fig. 6 Microcrack formation for 90°-specimen observed by using a plastic replica technique

Fig. 7 Microcrack formation for 45°-specimen observed by using a plastic replica technique

4.3 Influence of a laminated structure on microcrack growth

As described in Section 4.2, microcracks were initiated from slip bands, which had been originated in ferrite bands in the directions of the two orthogonal maximum shear stresses, either by their intercrossing (45°- and 90°-specimens) or by blocking them at a pearlite-ferrite interface (90°-specimens). Fig. 8 shows a scanning electron micrograph of a cruciform microcrack originated by the slip band intercrossing.

In the case of 90°-specimens, the microcracks thus initiated at the slip band intersections and/or the pearlite-ferrite interfaces were propagated with an increase in the number of stress cycles within each single ferrite band and resulted in network-like-distributed subcracks which intersected the pearlite-ferrite interfaces at an angle of $\pm 45^\circ$ (See Fig. 5(a)(iv), $n = 400 (n/N_f = 0.38)$). With further increase of stress cycles, these subcracks were extended across pearlite bands and were interlinked with other subcracks. The mode of this interlinking was sometimes vertical (as shown in Fig. 9) and in other cases parallel (as shown in Fig. 10) to the pearlite bands. The selection of these two modes in interlinking may be controlled by such factors as (1) local width of the pearlite band, (2) relative positions of the neighbouring subcracks to be interlinked, and so forth. Further microfracture-mechanical study will be needed in the future.

In the case of 45°-specimens, the behavior of microcrack extension was quite different from that of 90°-specimens. Each of the microcracks, which were initiated in ferrite bands by intercrossing of orthogonal slip bands was propagated in a single ferrite band or along a pearlite-ferrite interface. Among these microcracks, those vertical to the pearlite-ferrite interface were blocked at the interface, and their extension was suspended, as indicated by the arrows in Figs. 11 and 12. Fig. 13 shows an example of subcracks across a pearlite band, which was rather exceptionally observed in this study. Almost all subcracks were extended independently within single ferrite bands and grew up to microcracks running in parallel.

45°-specimen
 $\Delta\epsilon_{\text{toctc}}=2.64\%$, $n=300 (n/N_f=0.52)$

Fig. 11 An example of a microcrack which was suspended at the pearlite-ferrite interface

90°-specimen

$\Delta\epsilon_{\text{toctc}}=2.64\%$, $n=600 (n/N_f=0.56)$

Fig. 8 An example of a cruciform microcrack originated by the slip band intercrossing, observed by using a scanning electron microscope

90°-specimen

$\Delta\epsilon_{\text{toctc}}=2.64\%$, $n=600 (n/N_f=0.56)$

Fig. 9 Interlinking of subcracks which were extended vertical to a pearlite band

90°-specimen

$\Delta\epsilon_{\text{toctc}}=1.56\%$
 $n=2100 (n/N_f=0.63)$

Fig. 10 Interlinking of subcracks which were extended parallel to a pearlite band

4.4 Observation of macrocrack initiation and propagation by aid of liquid penetrant inspection technique

Figs. 14 (a) and (b) show the cracks detected by the liquid penetrant technique in a 90°-specimen and a 45°-specimen, respectively.

In the 90°-specimen, the number of macrocracks observable by this technique was two at a number of stress cycles $n=100$

45°-specimen

 $\Delta\epsilon_{\text{tocte}}=2.64\%$, $n=400$ ($n/N_f=0.70$)

Fig. 12 An example of a microcrack which was blocked at the pearlite-ferrite interface

($n/N_f=0.10$) and a little more than twenty at $n=200$ ($n/N_f=0.20$). These cracks were about 1 mm or less in length and were observed in the form of a dot or cross-mark. The dot-like cracks grew with progress of stress cycles independently to dash-like cracks as shown in Fig. 14 (a) by the arrows in sequence. At stress cycles ranging from 400 to 500 ($n/N_f=0.40$ to 0.50), these small cracks started to join up with neighbouring cracks. This joining seems to occur in a random manner, which might be controlled by such factors as their relative positions, size, etc. Since the length of cracks just before joining at $n=400$ to 500 was ranging from 2 to 4 mm, it is considered that these cracks had been extended across many pearlite bands in the direction coincident with one of the maximum shear stress by an interlinking mechanism as described in Section 4.3. When these cracks reached a size of 2 to 4 mm long, the cracks might intersect statistically or under the influence of external forces and interaction between cracks, resulting in a zig-zag path of macrocracks, as shown in Fig. 14 (a) (v) ($n=500$ ($n/N_f=0.50$)) by the upper arrow.

In the 45°-specimen, the number of macroscopic cracks observed at $n=100$ was about twenty, which corresponded to the number found in the 90°-specimen at $n=200$ ($n/N_f=0.20$), and their sizes were about 1 mm long or less. These cracks had an appearance of fine-lines and ran parallel to the band structure, the direction of which coincided in this case with one of the maximum shear stress directions. These relatively short cracks grew up to parallel long macrocracks before $n=253$ ($n/N_f=0.42$) and 300 ($n/N_f=0.50$). The parallel cracks in different ferrite bands were scarcely linked with one another as shown in Fig. 14 (b). However, few exceptional linkings of these parallel cracks across a pearlite band were observed, as indicated by the upper arrow in Fig. 14 (b) (v). The interlinking of neighbouring co-linear cracks located in a single ferrite band was most frequently observed in this specimen. The crack growth rate of the 45°-specimen was

45°-specimen

 $\Delta\epsilon_{\text{tocte}}=2.64\%$, $n=400$ ($n/N_f=0.70$)

Fig. 13 An exceptional example of a subcrack across a pearlite band

faster than that of the 90°-specimen, as would be understood from the extension behavior of cracks indicated by the lower-side arrows in each of Fig. 14 (a) and (b).

4.5 Macroscopic observation of specimen surface at the final failure

Figs. 15 (a) and (b) illustrate failed specimens of the 90°- and 45°-direction, respectively.

In the 90°-specimen, macrocracks initiated in the directions of the maximum shear stresses were extended in a zig-zag manner through the process of their intercrossing and linking, and grew up to a leading crack vertical to the maximum bending stress as indicated in Fig. 15 (a) by an arrow. The element of this leading crack, however, ran parallel to the laminated structure.

In the 45°-specimen a group of parallel macrocracks extended in one of the two maximum shear stress directions along the laminated structure were developed, and the final failure of the specimen was induced by some of these cracks formed near the specimen side parallel to the laminated structure, as shown by the arrow in Fig. 15 (b).

4.6 Discussion

Roughly speaking, the process of fatigue crack initiation and propagation of the material used in this study may be divided into two stages; (1) initiation of submicrocracks in ferrite bands and (2) their individual growth and coalescence with or without crossing of pearlite bands. Under the combined bending stresses adopted in this study, the latter was a controlling stage of fatigue life. In other words, the fatigue life was determined by the rates of growth and coalescence of cracks. The crack growth rate was closely related to a laminated structure, and was faster in ferrite bands than in pearlite bands. Therefore, what kind of paths the subcracks take in growth and linking across pearlite bands may determine the fatigue life of a specimen. That is, the fatigue strength of an anisotropic rolled steel plate may

Fig. 14 Macrocrack initiation and propagation for a 90°- and 45°-specimen detected by the liquid penetrant technique

(a) 90°-specimen

 $\Delta\epsilon_{tocte}=2.54\%$, $N_f=990$

(b) 45°-specimen

 $\Delta\epsilon_{tocte}=4.43\%$, $N_f=290$

Fig. 15 Appearances of specimen at the final failure

primarily depend on crack extension in or across pearlite bands. Prediction of the fatigue strength of this kind of materials under biaxial stressing could be made on the basis of the following informations; (i) crack propagation rate in pearlite bands based on fracture mechanics (ii) crack tip stress field for a crack initiated in a ferrite band and extended to a pearlite-ferrite interface, (iii) interaction between cracks which exist in neighbouring ferrite bands, (iv) statistical information about local variation of the width of pearlite bands, and (v) linking mode of subcracks, which were extended across a pearlite band. The real mode of fatigue crack extension observed in this study was of a mixed type of mode I and II for surface cracks, while a mixed type of mode I and III occurred for their inward growth. Although under a simplified condition, the authors have already started experimental studies to gather information about crack propagation in pearlite bands and the influence of the laminated structure on crack growth by using plate specimens with a center-notch under the pulsating load (Mode I) condition.⁽⁵⁾

Here discussion will be made on several problems relating to evaluation of fatigue life and correlation between uniaxial and biaxial data of rolling-induced anisotropic steel plates, using the results obtained in previous studies⁽¹⁾⁽²⁾ as well as the present study.

One of the most important problems in evaluation of fatigue life is the definition of "fatigue failure". This is particularly true in the present study, since the macroscopic aspects of crack growth and modes of final failure were quite different for different combinations of stress and anisotropy axes. "Crack initiation" and "separation into two halves" are the most widely adopted definitions of fatigue failure. Crack initiation may primarily be controlled by a shear stress or strain component acting at a small area, where a

crack is initiated.⁽⁴⁾ This would theoretically simplify the procedures of evaluating the fatigue life. However, one of the most serious disadvantages of this definition is in its ambiguity and arbitrariness in definition of "a crack". On the other hand, the separation into two halves provides a very clear definition of failure from a theoretical and practical point of view. However, this also has a disadvantage that this often is affected by many mechanical and metallurgical factors through the stage of crack propagation.

Comparing these two definitions, the crack initiation life may be preferred to the separation life because of its simplicity, when the fatigue life evaluation is made from an academic point of view. Indeed, when a small, reproducibly measurable size of crack initiated in a macroscopically homogeneous matrix (e.g., a microcrack in a ferrite band) is taken as a definition of a crack, which determines failure life, as indicated in Figs. 5 and 14, the effect of macroscopic anisotropy is eliminated in determining fatigue life, and "a general conclusion" is reached that the fatigue life is uniquely determined by the shear stress or strain component repeated at a critical point, irrespective of the relation between the anisotropy and stress axes. However, it is clear that this type of fatigue life has little meaning from an engineering point of view, since the fatigue life by this definition occupies only a negligibly minor portion of a total, practically useful life of this material and also this useful or load-carrying life, which is meaningful in engineering, is considerably affected by the relation between anisotropy and stress axes.

In this study, the crack initiation life was defined as a number of stress cycles, at which macroscopic cracks visible to naked eyes were initiated. However, this kind of definition of the fatigue life was not always appropriate in practice because

both the anticlastic deformation and the carrying load of rhombic plate specimens were still not affected at this number of cycles. In this study, therefore, the "fracture life" was defined at the number of cycles when the cyclic stress range reduced to 75% of that in the steady state, as shown in Fig. 4. This life also represented a critical number of stress cycles, beyond which the macroscopically uniform anticlastic bending of specimens did not hold. This kind of definition of the fracture life may serve as a reference life for evaluating the fatigue strength used in engineering design. However, prediction of this type of fatigue life from uniaxial data is not easy, as described in the foregoing.

In a previous paper,⁽²⁾ it is found that for a given equivalent cyclic shear strain range the biaxial fatigue lives of both 90°- and 45°-specimens were longer than those of uniaxial specimens, even if the lives were defined by initiation of considerably small cracks. This may be interpreted as follows. Because of the differences in crack extension modes between the uniaxial and biaxial fatigue specimens, processes of crack growth and coalescence from microcracks to macrocracks may be considerably different even if it could be assumed that microscopic crack initiation lives were same for both uniaxial and biaxial specimens. This might result in considerable differences in crack appearances and probability of finding small cracks. Under uniaxial push-pull loading, cracks may grow faster and be recognized more easily than in the case of the biaxial anticlastic bending loading. Further studies are needed to correlate the uniaxial data and the multiaxial test results of rolling-induced anisotropic steel plates.

5. Conclusions

Biaxial low-cycle fatigue tests of rolled steel plate were conducted. Macroscopic and microscopic fatigue behavior in specimen surface was consecutively observed. Slip band formation, its growth, and micro- and macrocrack extension mechanism were investigated. The results obtained are summarized as follows.

(1) Slip band formation at an early stage of fatigue life was all in ferrite bands. Their direction coincided with the direction of the maximum shear stress, irrespective of the principal anisotropy axes of the specimen.

(2) In 45°-specimen, in which the direction of ferrite bands coincided with one of the maximum shear stress directions, the slip bands formed in a ferrite band and in the ferrite band direction coalesced fast and grew up easily to microcracks. These microcracks were extended independently without joining microcracks in other ferrite bands to form a group of parallel macrocracks. The slip bands, which were formed in the other maximum shear stress direction vertical to the direction of the laminated structure, grew up and reached pearlite-ferrite interfaces,

and their growth was suspended.

(3) In 90°-specimen, the microcracks which were initiated in ferrite bands and suspended at pearlite-ferrite interfaces, were extended across and beyond pearlite bands. These cracks were linked with other subcracks, to form macrocracks with zig-zag paths.

(4) The initiation and growth of microcracks observed by the aid of an optical microscope agreed well with the macroscopic behavior of cracks observed by the liquid penetrant inspection technique.

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