Experimental study of the mixed mode notched crack transformation propagation in 06Cr19Ni10 austenitic stainless steel with consideration of the material orientation

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Abstract. In this paper, experimental study is carried out for the mixed mode notch-crack transformation propagation in 06Cr19Ni10 austenitic stainless steel with consideration of the material orientation. It is found that after initiation, the new formed crack grows in a direction perpendicular to the applied load, making crack mode transferred from I+II mixed mode to Mode I. The material orientation has no effect on the crack growth path and little effect on the crack growth rate although experiments show that at low temperatures the impact toughness of the material is related to the material orientation. Metallographic analysis was also performed to find whether or not the grains are elongated to be responsible for the orientation effects.

Introduction

It's well known that by the definition of fracture mechanics, there are three basic kinds of cracks, namely Mode I, Mode II and Mode III cracks. However in engineering, most cases cracks are of the mixed modes which are composed of basic modes, for example, on the thin-walled pressure vessel cracks are mostly I+II mixed mode cracks. Mixed mode cracks usually change their growth direction when propagating under fatigue loading and a lot of researches have been carried out on the mixed mode crack propagation growth direction and growth rate. Among them, Zhang *et al.* [1] found that I+II mixed mode crack propagated along the 'zig-zag' path which may extend to the transverse crack in the edge. Li *et al.* [2] predicted the path of the I+II mixed mode fatigue crack on the basis of the experimental results and also computed the fatigue crack propagation rate. The factors affecting fatigue crack propagation have also been reported , such as the literature [3], In this article, Li *et al.* investigated the strain-strengthen effect on the existed I+II mixed mode crack transformation propagation in austenite stainless steel. Doquet[4] investigated the influence of the loading on fatigue crack growth under mixed-mode loading. Environmental and frequency effects on fatigue crack growth rate and paths can be seen in the paper[5].

The effects of microstructure on the fatigue crack initiation and propagation were addressed in the articles[6-8]. Hirohisa *et al.* [8] studied the fatigue crack propagation behavior of a titanium aluminide with a nearly fully lamellar microstructure on two different fatigue crack growth directions relative to the lamellar orientation, i.e. parallel and perpendicular to the lamellar orientation. The result was that resistance of the fatigue crack growth of the former was considerably lower than that of the latter. Close examinations of crack morphology revealed significant differences between the two fatigue crack propagation directions. Sarioglu and Orhaner [9] carried out fatigue crack growth tests on an Al–Cu alloy 2024 before and after heating with center cracked tension specimens machined in L–T, T–L and 60° orientations. It was found that the fatigue crack growth rate depends on the test direction in T3 condition. The orientation effect seemed to be lost after prolonged heating at 130°C. Mineur *et al.* [10] investigated the dependence of cyclic behavior, fatigue crack initiation and fatigue life, on crystallographic texture for a 316L austenitic stainless steel in the low cycle fatigue range. Specimens of five different orientations of the rolled sheet were compared to study different textures. It was shown that texture influences the stress–strain response of the material and the fatigue damage (crack density). Recently, Chen *et al.* [11] investigated effects of inclusions, grain boundaries and grain orientations on the fatigue crack initiation and propagation behavior in a 2524-T3 aluminum alloy using in-situ scanning electron microscope fatigue testing and electron back scattering diffraction. The results showed that potential fatigue cracks tend to nucleate along coarse and closely spaced inclusion particles or high-angle GBs. Coarse inclusion particles drastically accelerate local crack growth rates.

It is well-known that the steel sheets for pressure vessels are manufactured by rolling in the plant. As a result of rolling, grains may be elongated. Now the question is whether or not this elongation is also presented in the sheet plane and whether or not crack propagation is affected by the material orientation. In this paper, experimental study is carried out for the mixed mode notched crack transformation propagation in 06Cr19Ni10 austenitic stainless steel with consideration of the material orientation.

Specimen and testing procedure

Specimen material and geometry. The specimens are plates with the width of 48 mm, the height of 192 mm and the thickness of 6 mm. In the center of the each specimen, an angled through-thickness notched crack was machined as shown in Fig. 1. The specimen material is 06Cr19Ni10 or S30408 which is an austenite stainless steel and widely used in China to construct pressure vessels.

As the notched crack is inclined with an angle of β with respect to the loading axis of the test machine, the crack is a I+II mixed mode crack.

In order to investigate the effects of the material orientation on the crack propagation, specimens are divided into two groups as shown in Fig. 2. Group one is denoted by L-T whose length direction is perpendicular to the rolling direction of the steel sheet and Group two is denoted by T-L whose length direction is along the rolling direction of the steel sheet.

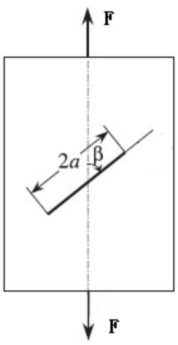


Fig. 1 Cracked specimen geometry

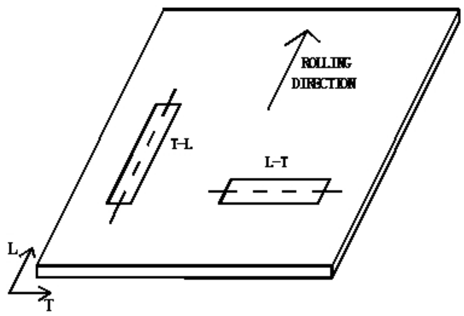


Fig. 2 Specimen and material orientation

Test apparatus. The fatigue crack propagation experiments were carried out on an INSTRON8800 electrohydraulic servo fatigue test machine. Crack propagation was recorded with an optical microscope connected to the computer.

Testing procedure. The fatigue load for the tests is varied in the range of 4.5-45 KN, i.e. the alternating amplitude of fatigue load is 20.25 KN and the stress ratio is 0.1. The load frequency for the test is 15Hz.

To describe fatigue crack problem, amplitude range of stress intensity factor ΔK is usually used. In this paper, finite element method with the software of ANSYS is used to calculate stress intensity factors at crack tips. The displacement approach is adopted in ANSYS with KCALC command for a linear elastic fracture mechanics to compute the stress intensity factors, which is based on $\Delta K_I = \sqrt{2\pi}\frac{2G}{1+k}\frac{|\Delta v|}{\sqrt{r}}$ and $\Delta K_{II} = \sqrt{2\pi}\frac{2G}{1+k}\frac{|\Delta u|}{\sqrt{r}}$ with Δv and Δu being the displacement differences at the crack faces respectively in the opening direction and shearing direction.

In this study, as the notched crack is inclined, both Mode I stress intensity factor ΔK_I and Mode II stress intensity factor ΔK_{II} are a function of the angle β. A smaller β would give a larger ΔK_{II}.

As mentioned before, the crack propagation was recorded with a camera connected to a computer which can give the vertical and horizontal positions of the crack tip. Every time when the crack grew a specific length or for a given load cycles, the testing was paused to take a picture for positioning crack tips and record the corresponding cycle numbers.

Experimental results and discussions

Under the uni-axial loading, the inclined notched crack is a mixed mode crack and it is found that a new crack would initiate at each notched crack tip. Here the crack initiation is defined as the new crack occurrence with a length of less than 0.5mm observed at the notched crack tip. After initiation, the new crack grows in a direction perpendicular to the applied load as shown in Fig. 3, making crack mode transferred from I+II mixed mode to Mode I. Fig. 3 indicates that in general, the material orientation has no effect on the crack growth path.


(a) Crack growth path in a T-L specimen (b)Crack growth path in a L-T specimen

Fig. 3 Crack growth paths in different specimens with $\beta = 30^o$

Calculations reveal that for all the specimens, Mode I stress intensity factor range ΔK_I increases with the crack growth, but the Mode II stress intensity factor range ΔK_{II} fluctuates although the magnitudes are very small. This result indicates that like in many materials, I+II mixed mode fatigue crack propagation in 06Cr19Ni10 also transfers to the direction along which ΔK_{II} =0 or in other words, the crack propagates in Mode I.

Fig. 4 is a log-log plot of the crack growth rate da/dN versus Mode I stress intensity factor range ΔK_I. All data with different group of specimens are covered but are separated into two groups. Clearly, the difference between the two groups of specimens is very small or in other words, the material orientation has little effect on the crack growth rate. Obviously from Fig 3, a linear relationship is presented between log da/dN and log ΔK_I for each group, which can be well represented by the Paris-Erdogan equation as follows:

For L-T specimen： $$\frac{da}{dN} = 5.65 \times 10^{-6} (\Delta K_{\mathrm{I}})^{4.70} \quad (1)$$

For T-L specimen： $$\frac{da}{dN} = 5.09 \times 10^{-6} (\Delta K_{\mathrm{I}})^{4.68} \quad (2)$$

As a supplement, tensile tests for the mechanical properties with different material orientations are performed to further investigate the anisotropic behavior of the material. The results are shown in Fig. 5 in which letters a and b are specimen numbering. Again, it is clear that no obvious material orientation influences are found.

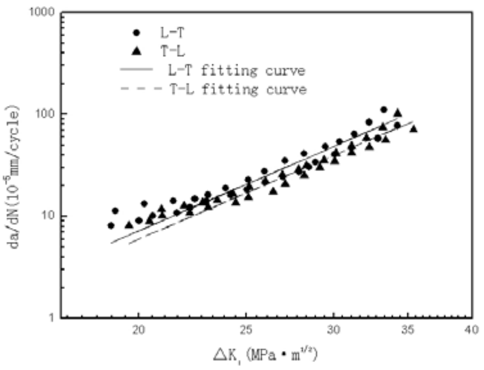


Fig. 4 Crack growth rate as a function of the mode I stress intensity factor range

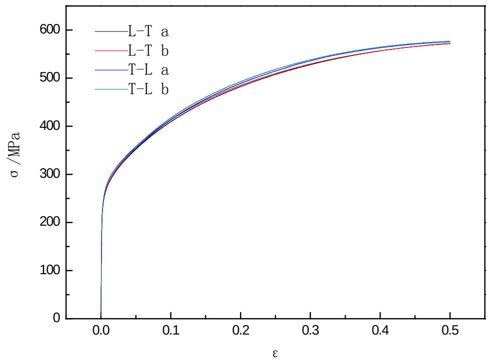
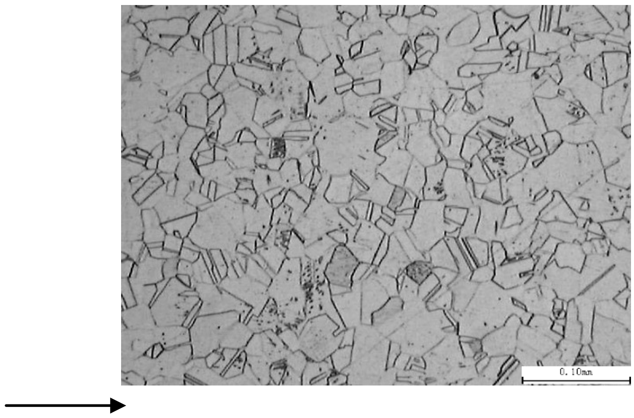


Fig. 5 Stress-strain relationships of the material

To explain these results, Micro-morphology analysis is performed to see if there is elongation of the grain along the rolling direction in the sheet plane. A microstructure picture in the sheet plane of the material is shown in Fig. 6. Clearly no elongation of the grain in this plane can be found, which means the material is isotropic in the sheet plane. An isotropic material should yield an identical property in all directions. Fig. 6 implies that when a steel sheet is wide enough and the rolling process is followed by the solid solution treatment, the material orientation effect would disappear and the isotropic behavior can be achieved in the sheet plane.



Rolling direction

Fig. 6 Microstructure of the material in the sheet plane

But it should be pointed out that the impact toughness of the material seems to be related to the material orientation as listed in Table 1. The toughness in Table 1 is obtained from the impact tests after the specimens are taken out from a liquid nitrogen at -196°. The reason for the difference of the impact toughness of the material is not clear. A possible reason is that at a low temperature, the material properties are more sensitive to the micro-structure of the material.

Table1 Impact toughness of the material

	T-L specimen	L-T specimen
Impact work KV_2 /J	220	169
	215	185
	213	187

Conclusions

In this paper, experimental study is carried out for the mixed mode notched crack transformation propagation in 06Cr19Ni10 austenitic stainless steel with consideration of the material orientation. Conclusions are drawn as follows.

(1) After initiation, the new formed crack grows in a direction perpendicular to the applied load, making crack mode transferred from I+II mixed mode to Mode I. The material orientation has no effect on the crack growth path.

(2) Effect of the material orientation on the crack growth rate is very small. A linear relationship is presented between log da/dN and log ΔK_I for the crack growth,

(3) Microstructure indicates that no elongation of the grain is found, which means the material is isotropic in the sheet plane. But the impact toughness of the material seems to be related to the material orientation toughness. A possible reason is that at a low temperature, the material properties are more sensitive to the micro-structure of the material.

Acknowledgments

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