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Acceleration and retardation of fatigue crack growth rate due to room temperature creep at crack tip in a 304 stainless steel

**Jie Zhao · Tao Mo · De-Fu Nie · Ming-Fa Ren ·
Xing-Lin Guo · Wei-Xing Chen**

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Abstract Room temperature creep (RTC) at a crack tip and its influence on the fatigue crack growth behavior of a 304 stainless steel have been studied at room temperature. A time-dependent deformation has been observed at the crack tips under various stress intensity factors. The deformation increases with increasing stress intensity factor. Either acceleration or retardation of fatigue crack growth rate is found after holding at K_{RTC}, which depends on the load pattern. A demarcation line is observed on the fracture surface following the holding period. This implies that the crack propagation root or mode changed after the hold time.

Introduction

Unlike elevated temperature creep deformation, creep deformation at room temperature for steels is usually small and has not received much attention [1]. Recently, with the improvement of measurement accuracy, the interest in room temperature creep (RTC) behavior has increased. Room temperature creep has been observed in low carbon steels, high strength steels and stainless steels [2–5]. In the research on SUS304 stainless steel, it was reported that the deformation did not cease even after 1,000 h [5]. It has been suggested that room temperature creep may be an important factor contributing to the crack growth during stress-corrosion cracking [6]. Since a yielding condition often exists at crack tips, room temperature creep may happen under an applied load. However, little work has been done to explicitly describe the time-dependent deformation in a cracked specimen and to investigate its influence on fatigue crack propagation.

The objective of this work was to study the room temperature creep deformation at a crack tip in a stainless steel and to investigate its effect on the fatigue crack growth behavior. The fracture characteristics after room temperature creep are also examined in these specimens.

Experimental procedures

The material used was a solid-solutioned SUS304 stainless steel with a chemical composition of: C: 0.059, Si: 0.5, Mn: 1.4, P: 0.027, S: 0.003, Cr: 17.36, Ni: 8.6, Al: 0.028 wt%. The microstructure of the steel consisted of the austenite phase with a small amount of δ-ferrite as shown in Fig. 1. The average grain size was about 50 μ.

Compact-tension (CT) specimens with dimensions of 39 mm in width (W), 50 mm in height (H) and 10 mm in thickness (B) were used to measure the time-dependent deformation behavior at the crack tip as well as to investigate its influence on the fatigue crack growth. The tests were conducted in air, at a constant temperature of 22 ± 2 °C and with a load frequency of

J. Zhao (✉) · T. Mo · D.-F. Nie · M.-F. Ren · X.-L. Guo
Department of Materials Engineering, The State Key Laboratory of Structural Analysis for Industrial Equipment, Dalian University of Technology, 116023 Dalian, P.R. China
e-mail: jiezhao@dlut.edu.cn

W.-X. Chen
Department of Chemical and Materials Engineering, University of Alberta, Edmonton, Canada

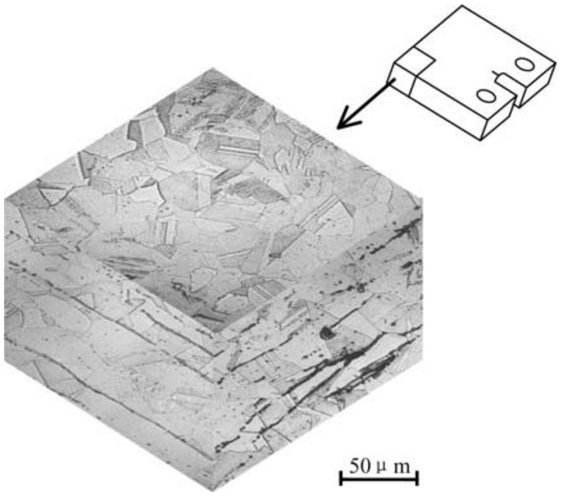
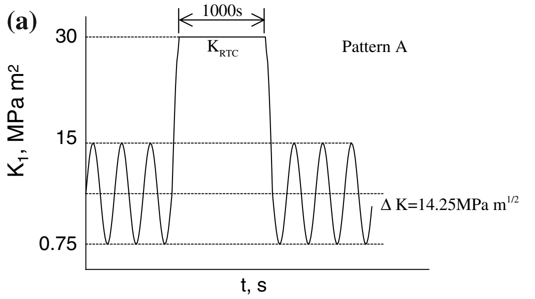


Fig. 1 Microstructure of solid solutioned 0Cr18Ni9 stainless steel

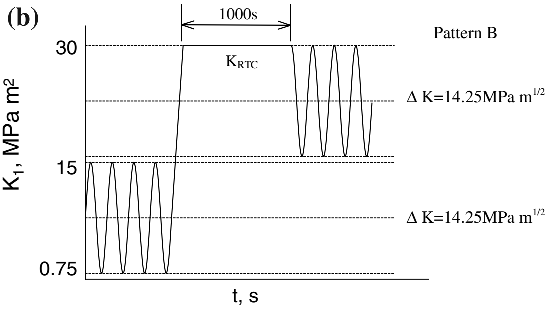
20 Hz using a MTS servo-hydraulic test machine. Crack length was measured by using a traveling microscope with precision of 10 μm.

Fatigue crack tests were performed under constant ΔK according to the ASTM standard test method for measuring fatigue crack growth rates (ASTM E647-95a) by manually shedding the load with crack growth. The load shedding intervals were chosen so that the maximum ΔK baseline levels variation was smaller than 2%. The load patterns to detect room temperature creep deformation at the crack tips and to perform subsequent fatigue crack growth tests are schematically illustrated in Fig. 2. In Pattern A, the subsequent fatigue crack growth test was carried out at the same ΔK level and stress ratio as former one. In Pattern B, the subsequent fatigue crack growth test was carried out at the same ΔK level as former one, while $K_{\max}$ was equal to K_{RTC} during the holding time.

The time-dependent strain at the crack tip was measured with an accuracy of 0.001 μm by means of a clip gauge attached to the crack mouth. As the strain is very sensitive to the applied load, the variation in load during the hold-tests was kept to within 0.5% of maximum load. The load during the holding period was higher than $K_{\max}$ in the prior fatigue crack growth test to avoid any plastic zone effects. After the hold period, the cyclic loading was continued to investigate the influence of room temperature creep at the crack tip during fatigue crack growth. Crack closure measurements were made by using a clip gage mounted at the crack mouth. Scanning electron microscopy (SEM) observations were carried out directly on the fracture surfaces after the experiment in order to examine the fatigue fracture morphology.



Load pattern A



Load pattern B

Fig. 2 Schematic of the load patterns

Experimental results and discussion

Room temperature creep deformation at the crack tip

Figure 3 shows the relationship of displacement at crack mouth, δ, with time, t. An obvious time-dependent deformation is observed which can be attributed to room temperature creep at the crack tip. The deformation increases with increasing stress intensity factor.

Dislocations play a vital role in room temperature deformation. Alden demonstrated that room temperature creep is a consequence of time-dependent dislocation glide and normally exhibits features of work hardening [7, 8]. In the case of specimens with cracks, unlike high temperature creep crack growth, no propagation of the crack was observed even after holding for several days. The deformation tends to saturate with time and produce deformation accumulation at the crack tips.

Influence of room temperature creep on fatigue crack propagation

The influence of room temperature creep on fatigue crack growth behavior is shown in Fig. 4. A retardation of fatigue crack growth was obviously found under load

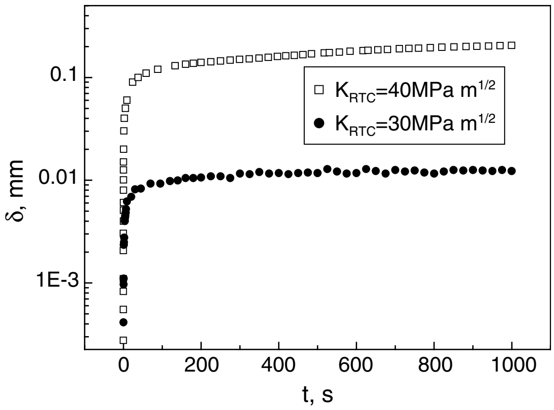


Fig. 3 Relationship between displacement at crack mouth, δ, and time, t

pattern A, while an acceleration of crack growth rate was observed under load pattern B.

In the case of single wave overload, retardation is usually produced which is attributed to (1) crack tip blunting; (2) crack deflection; (3) crack tip strain hardening or residual stresses ahead of the crack tip; (4) plasticity-induced closure or roughness induced closure [9, 10]. We tried to detect crack closure by using a clip gage mounted at the crack mouth. Meaningful crack closure levels were not detected after the holding period as well as during fatigue crack growth, which implies that the role of crack closure should be discussed further. From the observation of the crack tip after room temperature creep, see Fig. 5, crack tip blunting is clearly seen, and there is almost no crack branching and the crack propagates continuously. As acceleration of fatigue crack growth rate is obvious in the case of pattern B, and an immediate acceleration after load pattern A is also observed, it assumed that crack tip blunting or crack branching are not the dominant factors affecting the retardation.

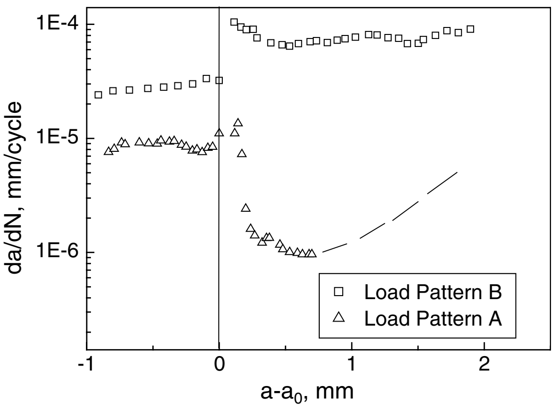


Fig. 4 Influence of room temperature creep on the fatigue crack growth behavior under two load patterns

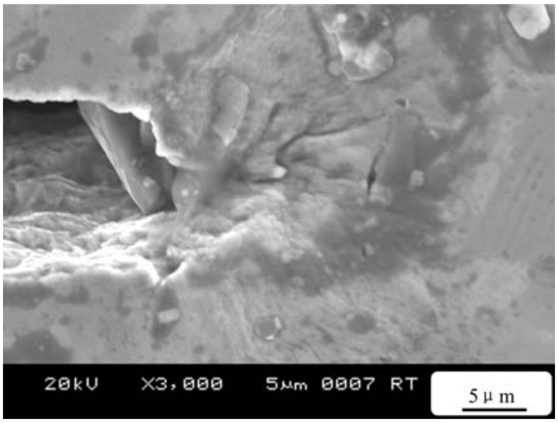


Fig. 5 Blunting of a crack tip after room temperature creep

The characteristics of fatigue crack growth behavior after room temperature creep are attributed to an additional crack tip plasticity. In the case of pattern A, the additional deformation enhances the residual compressive stress ahead of a crack tip and therefore enhances the retardation effect. In the case of pattern B, as the stress intensity factor for room temperature creep K_{RTC} is same as that for $K_{\max}$ during subsequent fatigue crack growth, there are no such compressive residual stresses as that caused by an overload effect, while the time-dependent deformation accumulation may increase the driving force for further fatigue crack growth and accelerate the crack growth rate.

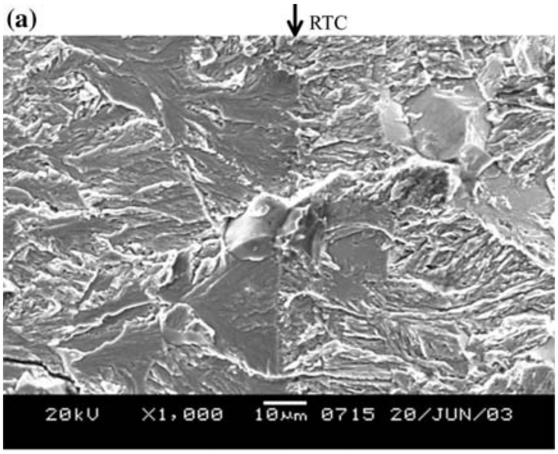
Fractography after room temperature creep

Figure 6 shows the features of the fracture surface in the region of room temperature creep (holding period). Figure 6(a) was obtained close to the center of the specimen and Fig. 6(b) was obtained from close to the surface. A demarcation line can be observed following the holding period. This implies that the crack propagation mode changed after the hold time.

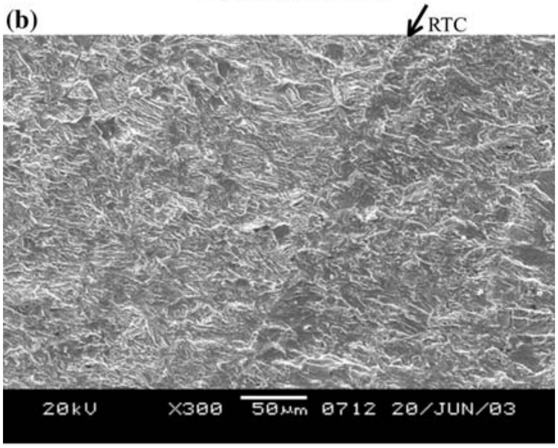
Conclusions

1. Time-dependent deformation is clearly seen at the crack tip under various stress intensity factors. This is attributed to room temperature creep. The time-dependent deformation increases with increasing stress intensity factor.
2. Either acceleration or retardation of fatigue crack growth rate is found after room temperature creep, and depends on the load pattern. A demarcation line can be observed on the fracture surface following the holding period. This implies that the

crack propagating root or mode changed after the hold time.



Center of the specimen



(b) Close to the surface

Crack growth direction →

Fig. 6 Fractographs of the region after room temperature creep (the symbol RTC indicates the demarcation line due to room temperature creep) (**a**) Center of the specimen; (**b**) Close to the surface

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References

1. Alden TH (1987) Metall Trans A 18A:51
2. Wang SH, Chen W (2002) Mater Sci Eng A 325:144
3. Liu C, Liu P, Zhao Z, Northwood DO (2001) Mater Design 22:325
4. Liu C, Liu P (2001) Mater Design 22:325
5. Tendo M, Takeshita T, Nakazawa T, Kimura H, Abo H (1993) Tetsu-To-Hagane/J Iron Steel Instit Jpn 79:98
6. Oehlert A, Atrens A (1994) Acta Metall Mater 42:1493
7. Alden TH (1987) Metall Trans A 18A:811
8. Alden TH (1987) Metall Trans A 16A:375
9. Sadananda K, Vasudevan AK, Holtz RL, Lee EU (1999) Int J Fatigue 21:S233
10. Borrego LP, Ferreira JM, Pinho da Cruz JM, Costa JM (2003) Eng Fract Mechan 70:1379