Mechanisms of Internal Fatigue Fracture for a Low Alloy Steel under High Cycle Region at Elevated Temperatures

K. Kanazawa[1], T. Nishimura[2], K. Matsuda[3] and K. Yamaguchi[4]

[1] Chuo University
[2] Graduate School, Chuo University
[3] Mitsubishi Heavy Industries
[4] National Institute for Materials Science

ABSTRACT: *Stepwise S-N curves were obtained under rotating bending fatigue tests at elevated temperatures for an 1Cr-0.5Mo low alloy steel, as well as fatigue tests at room temperature for surface hardened specimens by shot peening or carburizing treatment. In the high cycle region, internal fracture with fish-eye pattern was dominant. Why internal fracture does occur at elevated temperatures for specimens of the low alloy steel without any surface hardening treatments? It has been pointed out that the existence of oxidized surface layer plays an important role to prevent cracks from initiating at the specimen surface. But any evidence verifying the effect of oxidized surface layer on fatigue behavior has not been obtained. The steel used was hardened remarkably under cyclic stressing at intermediate temperatures due to dynamic strain aging. It is considered to be difficult for Stage□ crack to initiate at specimen surface, because the slip bands hardens gradually during fatigue test at elevated temperature. This process has to bring the same effect as surface hardening treatments of shot peening and carburizing on fatigue fracture behavior.*

INTRODUCTION

It was reported [1] that stepwise S-N curves were obtained under rotating bending fatigue tests at elevated temperatures for an 1Cr-0.5Mo low alloy steel. Internal fracture with fish-eye was dominant in the high cycle regions. The same phenomena as those were recognized [2,3] in fatigue tests for specimens subjected a surface hardening treatment such as shot peening or carburizing. It has not been clarified why internal fracture occurs at elevated temperatures for specimens without any surface hardening treatment.

In this paper, the mechanisms of internal fatigue fracture of the steel at high cycle region under elevated temperatures are discussed from additional fatigue tests and observations of fracture surfaces.

EXPERIMENTAL

The material examined was a normalized-tempered 1Cr-0.5Mo steel plate specified in JIS as SCMV2, which consists of ferritic and pearllitic structures. Fatigue tests were carried out at room temperature and 673K under a frequency of 100Hz using a 4-points rotating bending testing machine with an electric furnace. The test specimen used had a parallel part 8mm in diameter and 25mm in length.

□It is difficult to measure directly the strain on the surface of specimen under rotating bending at elevated temperatures. In this study, the strain was estimated by measuring the deflection at the loading point during the fatigue test. For the measurement, a non-contacting displacement measuring system was used, which is based on the eddy-current loss principle.

RESULTS AND DISCUSSION

Effect of oxidized surface layer on fatigue behavior

Figure 1 shows conventional and stepwise S-N curves obtained for the present material at room temperature and 673K, respectively [4]. Under low stress levels of stepwise S-N curve, fatigue crack initiated at interior of the specimen and fish-eye pattern was observed on the fracture surface. It has been pointed out [1] that the existence of oxidized surface layer plays an important role to prevent cracks from initiating at specimen surface. That is, as the oxidized surface layer prevents dislocations from going out through surface, Stage□cracks cannot be formed at specimen surface, and then fish-eye fracture occurs by the initiation and propagation processes of internal crack.

To clarify this assumption, fatigue tests were carried out at 673K and room temperature for specimens with oxidized surface layer, which specimens were exposed at 673K for 5 days before the fatigue tests. The results are shown in Figure 1. The fatigue lives scarcely changed compared with those for specimens without previous oxidized surface layer at both temperatures. According to the observations of the fracture surfaces, fatigue cracks initiated at the specimen surface and no fish-eye pattern was observed. These results suggest that oxidized surface layer itself has no effect on preventing fatigue crack from initiating at the specimen surface.

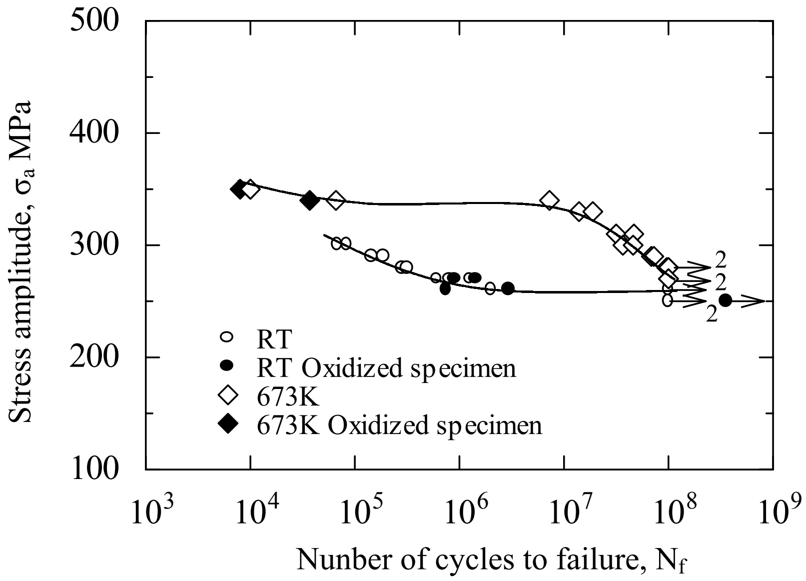
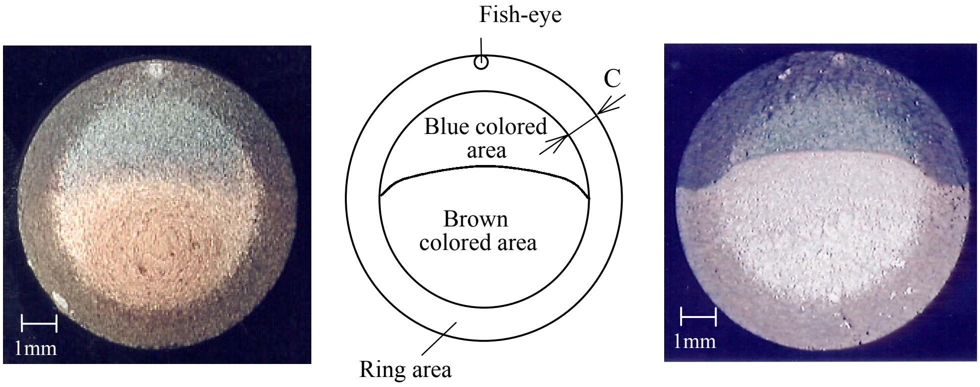


Figure 1 Rotating bending fatigue S-N curves and effect of oxidized surface layer on fatigue strength

Characteristic fracture surface with fish-eye

On fracture surfaces fatigued under low stress levels at 673K, not only fish-eye pattern but also a characteristic feature were observed macroscopically, as shown in Figure 2(a). The fracture surface can be divided into three parts, that is, a ring area including fish-eye for a certain depth from specimen surface, blue colored area and brown colored area as shown in Figure 2(b) schematically. Mean value of roughness of the ring area is 4μm, and those of the blue and brown areas are 12μm and 34μm, respectively. The brown area where is the roughest of all seems to be the final fracture region.

Figure 2(c) shows a fracture surface, which fatigue test was carried out at 673K, and interrupted just before final fracture. The final fracture was brought by test at room temperature. The front of crack growing at high temperature can be recognized clearly. This picture indicates that the boundary of the ring area is not a crack front at a certain time and that crack propagates underneath the surface with priority after formation of fish-eye. The ring area was recognized continuously on the fracture surfaces formed at 673K and at room temperature.

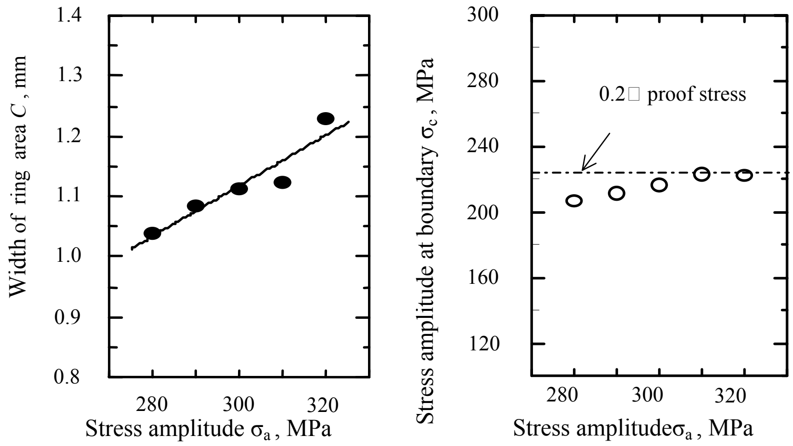


(a) Fracture surface, 673K, 290Mpa, N_f:3.78x10^7

(b) Schematic feature of fracture surface of (a)

(c) Fracture surface of a specimen interrupted fatigue test

Figure 2 Pattern of fracture surface with fish-eye.



(a) (b)

Figure 3 Relationship between width of ring area and stress amplitude, and stress amplitude at boundary of ring area

Figure 3 shows that the width of the ring area C increased with increasing stress amplitude of tests and that the value of stress amplitude applying at boundary of the ring area was the same as 0.2% proof stress approximately for the present material at 673K. This result means that a region of the ring area was exposed to cyclic strain amplitude including a plastic strain component.

Cyclic hardening during fatigue tests

It has been reported that 1Cr-0.5Mo steel the same as the present material hardens remarkably under uniaxial low cycle fatigue conditions at intermediate temperatures due to dynamic strain aging [5]. It is difficult to measure directly the strain on the surface of specimen under rotating bending. But, behavior of cyclic hardening under rotating bending conditions can be confirmed by measuring a change in deflection at loading point during fatigue test. Decrement of the deflection at loading point means the specimen hardens under cyclic stressing. Figure 4 shows an example of the change in the deflection at loading point with increasing number of stress cycles. The deflection at loading point decreased up to cycles of order of 10^7, and then it increased gradually. It is not clarify what

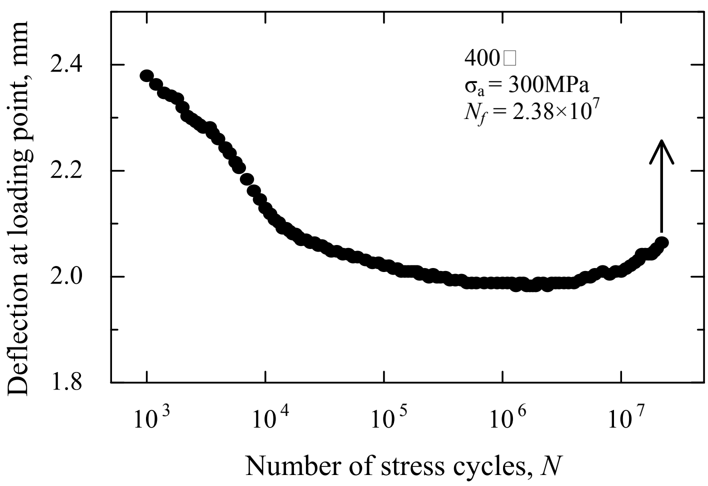


Figure 4 Change in deflection at loading point with increasing number of stress cycles.

kinds of mechanisms correspond with the change in the deflection at loading point, but the results indicates that present material hardens during early stage of rotating bending fatigue conditions at 673K.

Figure 5 shows the results of observation of hardness at cross sections of a specimen with fish-eye pattern tested at 673K and a specimen fatigued at room temperature. Hardness of a region underneath the surface increased strikingly for the fatigued specimen at 673K. This result suggests that the ring area was a region hardened during fatigue test.

Stepwise S-N curves were obtained for surface hardened specimens by shot peening or carburizing treatment [2,3]. For those specimens, it is difficult for a crack to initiate and to propagate at specimen surface, because of existences of hardened surface layer and of compressive residual stress, respectively.

The present specimens did not receive any surface hardening treatments before the fatigue tests. But the surfaces hardened during fatigue tests by dynamic strain aging at 673K.□ It is considered to be difficult for Stage□ crack to initiate at specimen surface, because slip bands harden gradually during fatigue test at elevated temperature. This process has to bring the same effect as surface hardening treatment of shot peening or carburizing on fatigue fracture behavior.

It is interesting whether any compressive residual stress is produced at

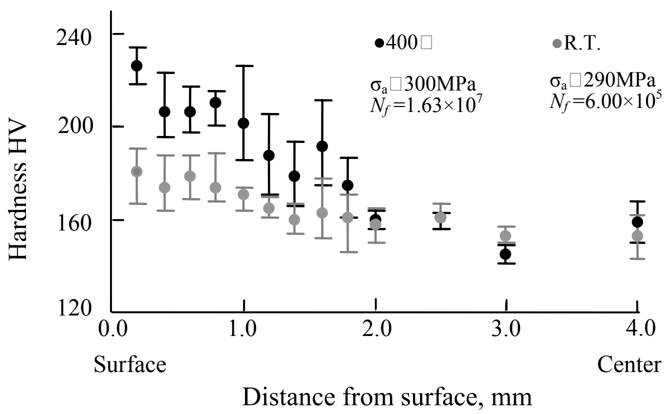


Figure 5 Hardness distribution measured at cross section of fatigued specimen.

specimen surface by hardening due to dynamic strain aging, or not. According to results of stress measurement by X-ray method, there is no residual stress at surface of hardened specimen fatigued at 673K.

Effects of surface improvement by dynamic strain aging on fatigue strength

The specimen surface hardened due to dynamic strain aging during the early stage of fatigue tests at elevated temperatures just as received surface hardening treatments. As the result, it is considered that the internal fracture occurs accompanying with fish-eye pattern. The specimen surface looks like to be improved during fatigue test. For the present material, it was reported [1] that fatigue strengths at 573K and 673K were higher than the strength at room temperature as shown in Figure 1 and that the temperature dependence of fatigue strength was the same as that of cyclic proof stress. These results indicate precisely that the specimen surfaces are improved during fatigue test at elevated temperatures. Therefore, if specimens were fatigued under some stress and cycle conditions at elevated temperatures previously and then fatigued at room temperature, the fatigue strength and the fatigue lives must be improved compared with those for virgin specimens.

To verify this assumption, pre-fatigued specimens at 673K under stress amplitudes of 280 to 320 MPa for 10^7 cycles were prepared and then fatigue tests were carried out. As shown in Figure 6, fatigue strength and fatigue lives improved drastically. It should be noticed that the improvement depends on pre-fatigue conditions. For example, in fatigue test at room temperature for a pre-fatigued specimen at 673K under 300 MPa for 2.6×10^7 cycles, fish-eye fracture occurred and improvement in fatigue strength was not recognized.

CONCLUSION

As for mechanisms of internal fatigue fracture for 1Cr-0.5Mo steel, under high cycle region at elevated temperatures, following results can be obtained.

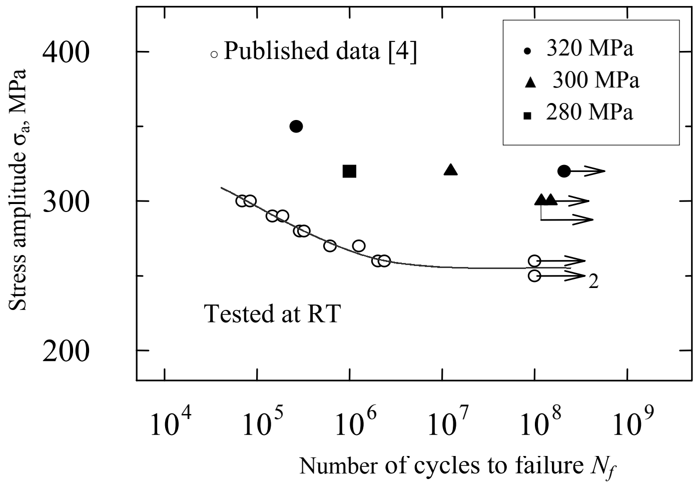


Figure 6 S-N plots for pre-fatigued specimens at 673K.

(1) Oxidized surface layer itself has no effect on preventing fatigue crack from initiating at the specimen surface.
(2) Specimen surface hardens during rotating bending fatigue test at 673K due to dynamic strain aging.
(3) It is difficult for Stage□cracks to initiate at specimen surface, because slip bands harden gradually during fatigue test.
(4) Effects of surface improvement by dynamic strain aging on fatigue strength can be recognized.

REFERENCES

1. Kanazawa, K. and Nishijima, S. (1997) Journal of the Society of Materials Science Japan **46**, 1396.
2. Masuda, C., Ishii, A., Nishijima, S., Sumiyoshi, H., Tanaka, Y. and Kanazawa, K.(1985) Trans. of the Japan Society of Mechanical Engineers **51**, 1193.

3. Tange, A., et. al., (2000) Technical Report of JSSR Meeting June 2000, 5.
4. National Research Institute for Metals, Japan (1992) NRIM Fatigue Data Sheet No.72.
5. National Research Institute for Metals, Japan (1996) NRIM Material Strength Data Sheet Technical Document No.14.