Effect of Notch Shape and Absorbed Hydrogen on the Fatigue Fracture below Fatigue Limit

Yoshiyuki Kondo[1,a], Hikaru Eda[2] and Masanobu Kubota[3,b]

[1,2,3] Kyushu University, 744, Moto-oka, Nishi-ku, Fukuoka, 819-0395, Japan

[a]ykondo@mech.kyushu-u.ac.jp, [b]kubota@mech.kyushu-u.ac.jp

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Abstract. It has been a common understanding that fatigue failure would not occur if all stress amplitudes are within the fatigue limit diagram. However, it was shown that fatigue failure occurred in some special cases of loading condition even when all stress amplitudes were kept within fatigue limit diagram in the case of small-notched specimen. The cause of such a phenomenon was examined using two-step loading pattern. In the case of constant stress amplitude loading, non-propagating crack was formed only at low mean stress and not formed at high mean stress. In the case of two-step loading in which the first step stress was chosen with zero mean stress and the second step stress was with high mean stress, a non-propagating crack was formed by the first step stress, which caused the fatigue fracture below fatigue limit. In this study, the effect of notch size, especially small notch, and root radius was examined. It was shown that a very small notch as small as 10μm deep notch caused the reduction of fatigue limit. The effect of absorbed hydrogen was also investigated. Absorption of 0.3ppm hydrogen caused more reduction of fatigue limit.

Introduction

The effect of mean stress on fatigue limit is usually evaluated using the fatigue limit diagram such as modified Goodman diagram. The fatigue limit line shows the critical condition of non-failure for constant stress amplitude condition. If the stress amplitude and mean stress were kept constant within fatigue limit diagram, fatigue fracture would not occur. In the previous study, however, it was shown that fatigue failure occurred in some special case of fretting fatigue even when all stress amplitudes were kept within fatigue limit diagram [1]-[2]. In this study, fatigue strength of small-notched specimen was studied using two-step loading.

Test Method

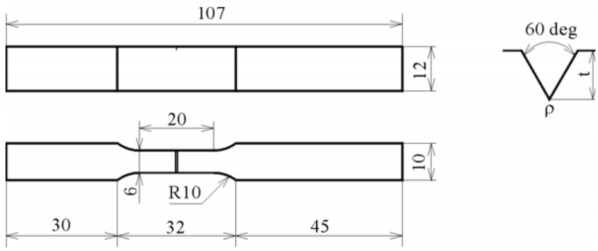
The test material is a low alloy steel designated as SCM440H in Japanese Industrial Standard. The material was oil-quenched at 1143K and tempered at 843K. The chemical composition and mechanical properties are shown in Tables 1 and 2, respectively. The configuration of test specimen

Table 1 Chemical composition of test material (mass %)

C	Si	Mn	P	S	Ni	Cr	Mo	Cu
0.42	0.22	0.80	0.017	0.02	0.03	1.04	0.16	0.02

Table 2 Mechanical properties of test material

$\sigma_{0.2}$ (MPa)	σ_B (MPa)	δ (%)	ϕ (%)	HV
911	1025	21	59	334



ρ	0.005	0.005	0.005	0.005	0.1	0.3
t	0.01	0.02	0.1	0.5	0.5	0.5

Fig.1 Test specimen with small notch (Dimensions are in mm)

is shown in Fig.1. The specimen has a two-dimensional machined notch. The specimen was stress relieved in vacuum at 873K for one hour after machining. Fatigue tests were done in air at ambient temperature at a frequency of 28Hz. Uniform bending moment in plane bending was applied to the specimen.

Effect of Notch Depth on the Fatigue Fracture below Fatigue Limit

Test Results for *t*=100μm Notch. Two-step stress sequence shown in Fig.2 was used. The first step stress (σ_{a1}) was chosen just equal to the fatigue limit for zero mean stress in this test. The first step stress was applied for 10^7 cycles. The second step stress (σ_{a2}) was with positive mean stress (σ_{m2}) and was chosen below the fatigue limit corresponding to each mean stress (σ_{m2}) as shown in Fig.3. All stress amplitudes were within fatigue limit diagram. The second step stress was applied until specimen fracture. The fatigue limit of two-step loading was defined by the non-failure after 10^7 cycles application of second step stress. Since 100μm deep notch gave the typical results, it is shown first hereafter.

Figure 4 shows the test result. Figure 4(a) shows the comparison of fatigue limit diagrams between constant stress amplitude and two-step loading. Open symbols show fracture data and solid symbols show the fatigue limit data. Circular symbols show the constant stress amplitude data. The fatigue limit diagram of constant stress amplitude shown by solid line was not linear like the Goodman line. The fatigue limit line steeply decreased at low mean stress region and it leveled off at high mean stress region. Figure 4(b),(c) and (d) show the micrographs of notch root for specimens indicated as A,B and C in constant stress amplitude test. The formation of non-propagating crack is dependent on

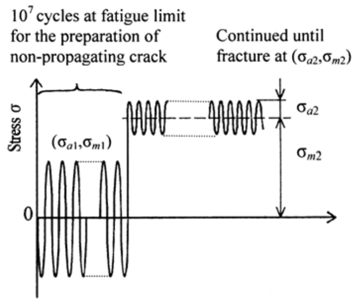


Fig.2 Two-step stress pattern

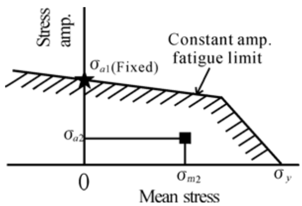
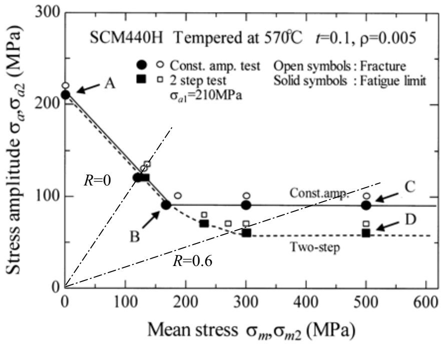
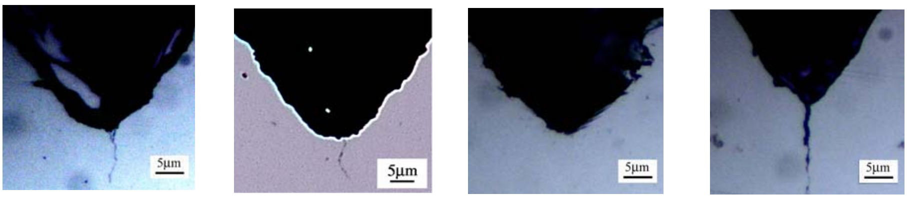


Fig.3 Two-step stress condition

mean stress level. Non-propagating cracks were observed in specimens A and B tested at low mean stresses. On the other hand, non-propagating crack was not observed in specimen C tested at high mean stress. Non-propagating cracks are difficult to be formed at high mean stress [3]. Square symbols show the result of two-step loading test. The fatigue limit line for the two-step test was shown by broken line. Although the fatigue limit line in low mean stress region was the same as the constant stress amplitude data. However, fatigue fracture occurred below the constant stress amplitude fatigue limit at high mean stress region. Figure 4(e) shows the micrograph of the specimen indicated as D. A clear difference was seen between specimens C and D. Non-propagating crack was not seen in specimen C, but a crack was observed in specimen D.



(a) Fatigue limit diagram



(b) Non-propagating crack in A (c) Non-propagating crack in B (d) No non-propagating crack in C (e) Non-propagating crack in D

Fig.4 Fatigue limit diagram for constant and two-step loading pattern for t= 100μm, ρ=5μm

These observations indicated that the difference in the fatigue limit diagrams of constant amplitude and two-step loading was caused by the difference in the formation of non-propagating crack. The application of first step stress σ_{a1} with low mean stress formed a non-propagating crack. This crack was subject to the second step stress σ_{a2} with high mean stress. This non-propagating crack acted as a pre-crack for the second step stress σ_{a2} and caused the crack growth, which lead to the fracture in two-step loading below fatigue limit. Consequently, the fatigue limit diagram was lowered compared to that of constant amplitude at high mean stress.

Effect of the First Step Stress Level for *t*=100μm Notch. In the former test, the first step stress was chosen equal to the fatigue limit. Non-propagating cracks, however, can be formed even by stresses below fatigue limit. Therefore, the lower bound value of first step stress which causes the fracture below fatigue limit was examined. As shown in Fig.5, the second step stress (σ_{m2} , σ_{a2}) shown by the star symbol was chosen just equal to the fatigue limit for σ_{m2} and then the 1st step stress σ_{a1} shown by solid square was changed. Test result is shown in Fig.6. Fatigue fracture occurred under conditions indicated by open circles. Fatigue fracture did not occur in specimen A whose first step stress was 60% of the fatigue limit. The micrograph of the cross section of specimen A is shown in Fig.7. Non-propagating crack was not observed. It indicates that the fatigue fracture within fatigue limit diagram does not occur if non-propagating crack is not formed by the first step stress.

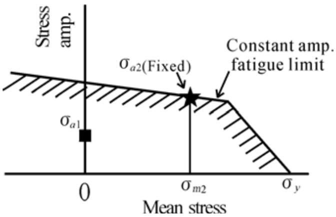


Fig.5 Stress condition to examine the effect of first step stress level

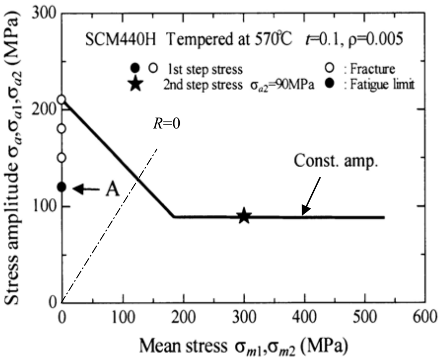


Fig.6 Effect of first step stress level

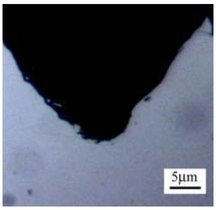
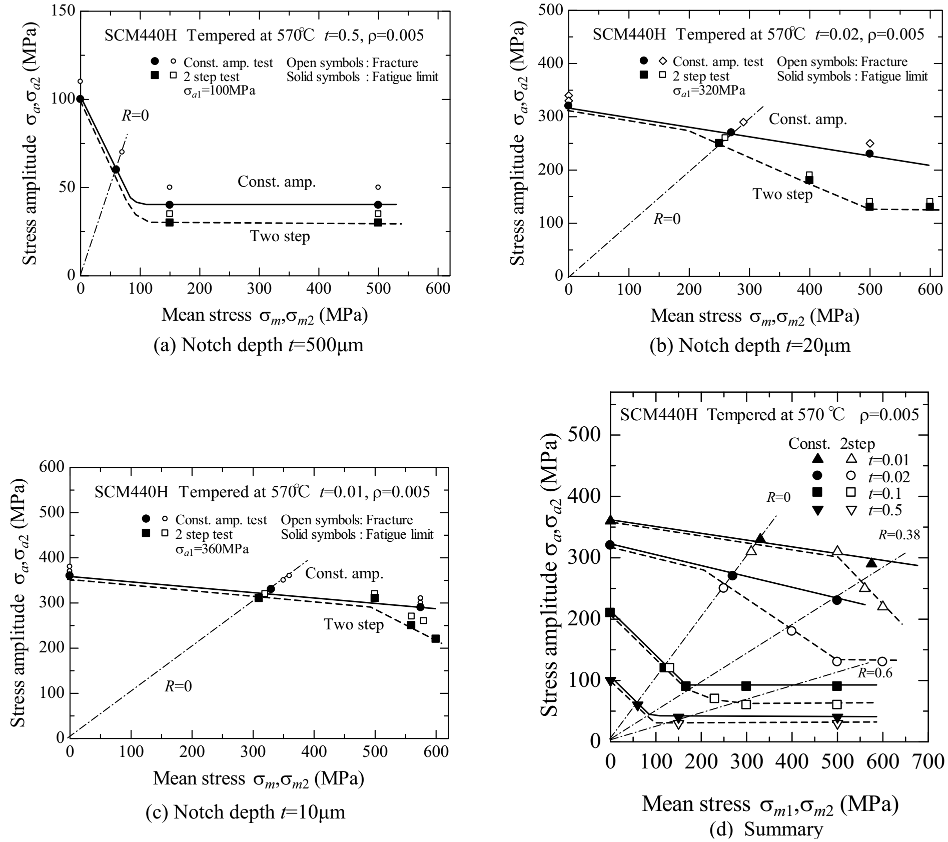


Fig.7 Cross section of notch root of specimen A in Fig.6.

Test Results for other Notches. The formation of non-propagating crack is affected by the notch depth. The effect of notch depth was examined using different notch depths, especially small notches. 500μm, 20μm, 10μm deep notches were tested and the test results are shown in Fig.8(a),(b) and (c), respectively. In these tests, the first step stress was chosen equal to each fatigue limit for reversed loading. In every specimen, similar tendency was seen. The fatigue limit for two-step loading was almost the same as that of constant stress amplitude in low mean stress region. However, the fatigue limit line of two-step loading began to depart from the constant stress amplitude line and substantially decreased in the high mean stress region. Figure 8(d) shows the summary of all notches. Solid lines show constant stress amplitude line and broken lines show those of two-step loading. The stress ratio R of the second step stress seems to have governed the reduction behavior. The reduction of fatigue limit began to appear near the stress ratio R=0 or a little higher region for all specimens. The two-step test results shown by broken lines became to level off near R=0.6 and higher.

Here, the fatigue fracture within fatigue limit diagram occurred even in 10μm deep small-notched specimen in two-step loading. 10μm deep notch is in the order of surface roughness of actual machine component. This phenomenon should be taken into account in the design and fabrication of actual machine.



(a) Notch depth t=500μm

(b) Notch depth t=20μm

(c) Notch depth t=10μm

(d) Summary

Fig.8 Effect of notch depth on the fatigue fracture below fatigue limit in two-step loading

Governing Factor of Fatigue Limit for Two-step Loading. The governing factor of the fatigue fracture below fatigue limit in two-step loading was examined. The fatigue limits for constant stress amplitude loading and two-step loadings are shown in Fig.9 for typical stress ratios. Here, the crack depth is the sum of notch depth and each non-propagating crack depth. The threshold stress intensity factor ΔK_{th} was calculated using each fatigue limit and are shown in Fig.10. Short crack effect is seen for cracks shorter than 30μm deep crack only in R=-1 for constant stress amplitude (●) and R=0 for two-step step loading (■). No effect was observed at high stress ratios.

These data were plotted against stress ratio as shown in Fig.11. Solid symbols show the results for constant stress amplitude and open symbols show two-step loadings. Although, the comparison between constant stress amplitude and two-step loading can be done only for R=0, they are almost the same within a scatter. The hatched zone shows the conventional data for long cracks [4]. The open symbols for two-step loading are located in the hatched zone. This implies that the fatigue fracture within fatigue limit diagram is not an unexpected phenomenon but can be clearly understood as follows. The formation of non-propagating crack supplies a defect site for the second step stress, which acts as a pre-crack. If there appears no non-propagating crack, the notch can afford higher stress. The initiation of fatigue crack propagation by the second step stress is determined by the stress intensity factor for the second step stress. The threshold stress intensity factor is the same as that of constant stress amplitude condition. If inversely stated, relatively higher fatigue limit is achieved at high mean stress region in constant stress amplitude test, since it is achieved without the formation of non-propagating crack.

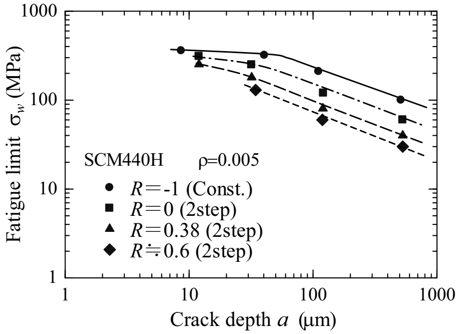


Fig.9 Fatigue limit of constant amplitude and two-step loading tests

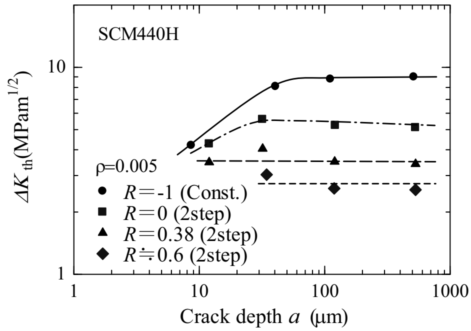


Fig.10 ΔK_{th} in constant amplitude and two-step loading tests

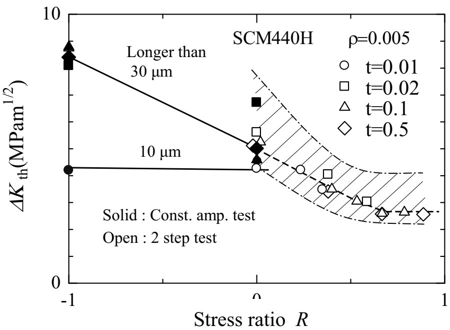


Fig.11 Effect of stress ratio R on ΔK_{th} in constant amplitude and two-step loading

Effect of Notch Radius on the Fatigue Fracture below Fatigue Limit

In the former section, notches with very sharp radius (ρ=5μm) were used. Since the formation of non-propagating crack is dependent also on the notch radius, notches with different notch radius were

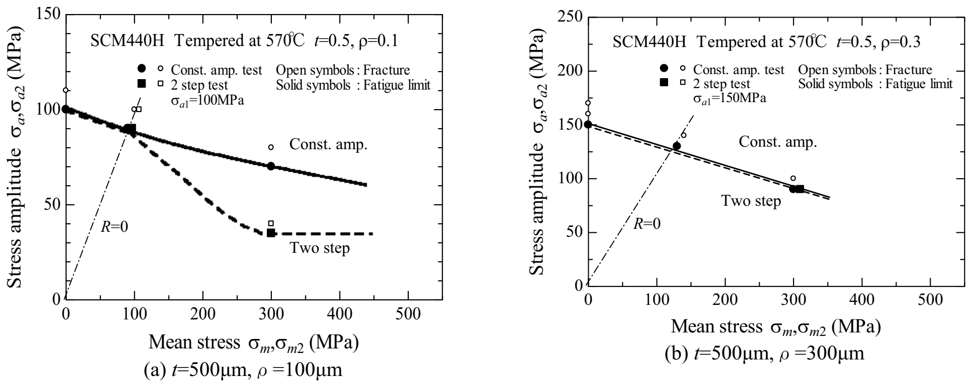


Fig.12 Effect of notch radius on fatigue limit diagram

examined. Test results for ρ=100μm and 300μm are shown in Fig.12. In the case of ρ=100μm shown in Fig.12(a), a quite similar trend as in a very sharp notch was seen. Fatigue fracture below fatigue limit occurred. In the case of ρ=300μm, however, fatigue fracture below fatigue limit was not experienced even at high mean stress.

Referring to the knowledge that the critical notch radius of low alloy steel for the formation of non-propagating crack under reversed loading is about 100μm, the present result is consistent with the knowledge. In the case of notch radius larger than 100μm, non-propagating cracks are not formed by the first step stress, which resulted in the experimental fact that fatigue fracture below fatigue limit did not occur for ρ=300μm as shown in Fig.12(b).

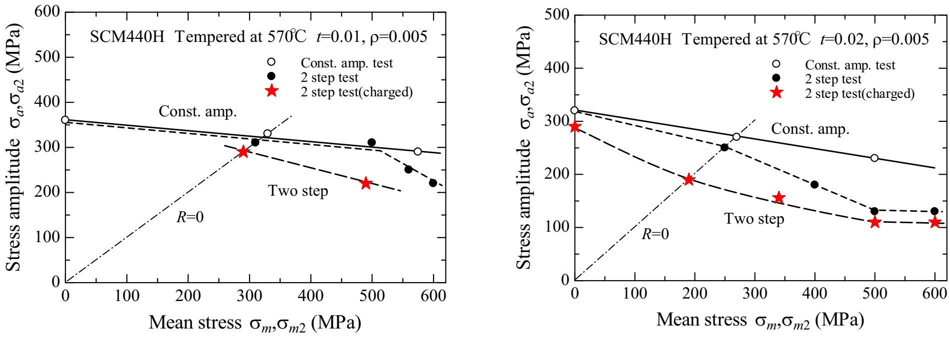
Effect of Hydrogen on the Reduction of Fatigue Limit

The absorption of hydrogen into the material causes the reduction of fatigue strength. Especially in short crack region, the reduction of threshold stress intensity factor range ΔK_{th} was pronounced [5]. As mentioned above, the fatigue fracture within fatigue limit diagram is a problem of short crack. The effect of absorbed hydrogen was investigated.

Small (t=10μm and 20μm) and sharp-notched (ρ=5μm) specimens were used. Hydrogen was absorbed into the specimen after the application of first step stress. Hydrogen absorption was done by an electrochemical method. The specimen was cathodically polarized using galvanostat in dilute sulfuric acid with pH=2 at ambient temperature. The current density was 26.1 A/m^2. The charging time was 24 hours. The average hydrogen content was about 0.3ppm.

The application of the second step stress was done after the absorption of hydrogen and the test was done in air. Two-step loading results for t=10μm and t=20μm are shown in Fig.13(a) and (b), respectively. The fatigue limit for two-step loading is shown by star symbols. The absorption of hydrogen caused additional reduction of fatigue limit. The reduction caused by hydrogen somewhat scatters and it caused 10-30% more reduction compared to that without hydrogen absorption (shown by ●).

The reduction of fatigue limit caused by hydrogen was compared with the result of constant amplitude ΔK_{th} data as shown in Fig.14. Solid symbols are the previous data [5]. Solid symbols show the reduction of ΔK_{th} by hydrogen charge for various steels with different material hardness. Open circles show the result in this study for two-step loading. They are almost the same. The enhancement of the reduction of fatigue limit in two-step loading can be reasonably explained.



(a) t=10μm, ρ =5μm (b) t=20μm, ρ=5μm

Fig.13 Effect of absorbed hydrogen on the reduction of fatigue limit in two-step loading

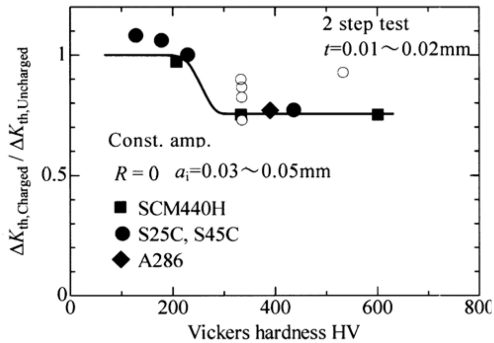


Fig.14 Effect of material hardness on the reduction of ΔK_{th} by hydrogen charge

Conclusion

The mechanism of fatigue fracture below fatigue limit diagram was examined using small-notched specimen made of low alloy steel by two-step loading pattern.

(1) Fatigue fracture within fatigue limit diagram occurred even in 10μm deep small-notched specimen when the load history contains mean stress variation between zero and high mean stresses.

(2) In the two-step loading, a non-propagating crack is formed by the first step stress (R=-1) below fatigue limit. Thus-formed non-propagating crack functioned as a pre-crack for the second step stress with high mean stress and the crack propagated under a stress well below the fatigue limit.

(3) 60% of reversed loading fatigue limit was sufficient as the first step stress to cause the fatigue fracture below fatigue limit.

(4) Fatigue fracture within fatigue limit diagram did not occur in a dull notch whose notch radius was larger than the critical notch radius for the formation of non-propagating crack.

(5) Fatigue fracture within fatigue limit was triggered when the ΔK of non-propagating crack calculated using the second step stress exceeded the ΔK_{th} of constant amplitude.

(6) Absorbed hydrogen caused additional reduction of fatigue limit in two-step loading test.

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