

# THE DEFECT SIZE DETERMINING THE FATIGUE LIMITS OF STEELS

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## ABSTRACT

One of the largest problems for the manufacture of steel is to know how much it must be purified to protect the detrimental effect of non-metallic inclusions on the fatigue strength. In this study, we have examined the sizes of non-metallic inclusions on the fracture surfaces for the fatigued specimens of 90 heat lots of steels with eight different specifications, which were provided for the NRI Fatigue Data Sheet Project. The fatigue limits tended to fall from the average level when the included defect sizes became over 45 $\mu$ m. The results were analysed in relation to the threshold  $\Delta J$  on the basis of elastic-plastic fracture mechanics.

## KEYWORDS

Fatigue limits; carbon steel; chromium low alloy steel; chromium-molybdenum low alloy steel; manganese steel; non-metallic inclusion; cyclic yield stress; threshold cyclic J-integral; non-propagating crack.

## INTRODUCTION

The detrimental effect of non-metallic inclusions on fatigue crack initiation in a smooth specimen has been well established (Epreman and Mehl, 1953; Frith, 1955; Yokobori, 1960; Shih and Araki, 1973; Fowler, 1979). Each non-metallic inclusion acts as a source of stress concentration. During cyclic loading local plastic flow can take place under the influence of stress concentration which can lead to fatigue crack initiation. On the other hand, the presence of clear fatigue limits in SN curves of usual structural steels implies that the condition of fatigue crack propagation is another controlling factor of fatigue limits, since a lot of non-propagating cracks are usually observed on the specimens fatigued in the neighborhood of fatigue limits (Wardsworth, 1961; Nishitani and Murakami, 1970; Nishitani and Chishiro, 1974). The National Research Institute for Metals (NR

IM) has conducted a series of fatigue tests on carbon steels and low alloy steels with nine different JIS specifications for machine structural use. The resulting data have been issued as NRRM Fatigue Data Sheets. In this study we have examined the fatigue-determining sizes of non-metallic inclusions on the fracture surfaces for the specimens of 90 heat lots of steels with eight different specifications among the materials provided for the Data Sheet Project. The results are compared with a fracture mechanics estimation taking into account the effect of cyclic deformation behavior in each material.

FATIGUE TESTS RESULTS AND FRACTURE SURFACE OBSERVATION

The materials were commercially supplied as 20 - 30mm diameter bars from several different companies in Japan. These were selected to obtain typical level of fatigue strengths for each specification of the steels manufactured in Japan. The detailed JIS specifications of the steels were low and medium carbon steels; S25C, S35C, S45C, S55C: chromium and chromium-molybdenum low alloy steels; SCr440, SCM435, SCM440: manganese steels; SMn 438 and SMn443. After rough machining all specimens except S25C were heated to austenising temperatures and then quenched, followed by tempering at one of temperatures, 550, 600 and 650°C. They were finished to 8mm in diameter at the gage part and the final polishing was done longitudinally by 600 grade emery paper. Figure 1 shows fatigue strength with 50% failure probability at 10<sup>7</sup> cycles under rotating bending  $\sigma_{wb}$  against tensile strength  $\sigma_B$  for all series of steels tested. This suggests a good correlation between  $\sigma_{wb}$  and  $\sigma_B$ , which is regressed to

$$\sigma_{wb} = 0.53\sigma_B \tag{1}$$

Almost equivalent relation was also obtained between  $\sigma_{wb}$  and the Vickers hardness  $H_v$  as (Tanaka et al, 1981)

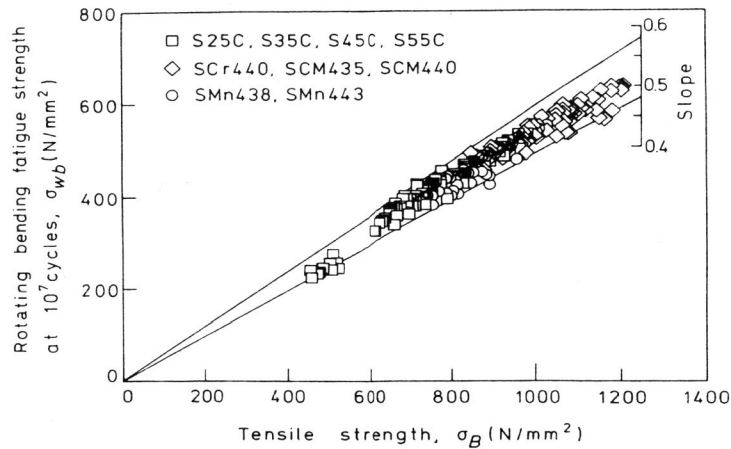


Fig.1. Fatigue limits under rotating bending test against tensile strength.

$$\sigma_{wb} = 1.71H_v \tag{2}$$

when  $H_v$  is measured in unit of kgf/mm<sup>2</sup>. These fact imply that the cyclic deformation behavior primarily controlling the fatigue limit, since  $\sigma_B$  and  $H_v$  are linearly correlated with the cyclic yield stress  $\sigma_{yc}$  as (Tanaka et al, 1981)

$$\sigma_{yc} = 0.61\sigma_B = 1.96H_v \tag{3}$$

The fracture surfaces were examined by an optical stereographic microscope and a scanning electron microscope (SEM) for all specimens broken in the neighborhood of fatigue limits in all materials except S25C steel. Figure 2 shows an example of a non-metallic inclusion originating fatigue fracture in an S35C steel. Electron probe microanalysis revealed that such non-metallic inclusions consisted mainly of aluminum oxide. Most of the non-metallic inclusions were nearly spherical and situated just underneath the specimen surfaces. Their sizes were therefore meas-

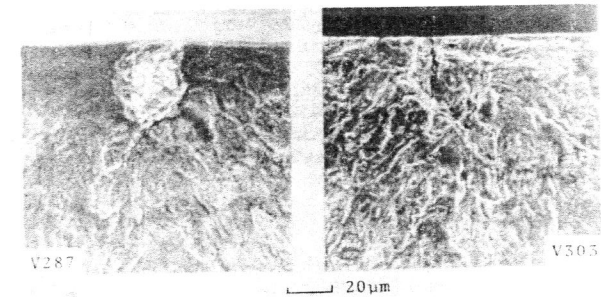


Fig.2. SEM photographs of a non-metallic inclusion observed on a fracture surface in S35C steel.

ured in the depth direction. The arithmetic mean of the largest three values obtained for the sample in an individual SN curve was regarded as a measure of defect size,  $\rho$ , determining the corresponding fatigue limit. It was found that the percentages of the test series showing inclusion-originating failure was 38 % in carbon steels, 63% in Mn steels and 86% in Cr and CrMo steels.

DATA SCATTER AT FATIGUE LIMITS AND DEFECT SIZES

Figure 3 represents a histogram of fatigue limits normalized by hardness,  $\sigma_{wb}/H_v$ . By this normalization, the effect of defects on the fatigue limits would be emphasized since  $H_v$  implicitly relates to the inherent cyclic strength of materials. The data in the figure show unsymmetrical distribution with a longer slope in the lower value region. Namely, most of the data tend to distribute around the average 1.71, while there are a fair number of data in the range lower than 1.6. The lower  $\sigma_{wb}/H_v$  value must be attributed to the large-sized defects. Figure 4 shows the relation between the fatigue strength ratio  $\sigma_{wb}/H_v$  and defect size  $\rho$  with different symbols for carbon steel, Mn steel,

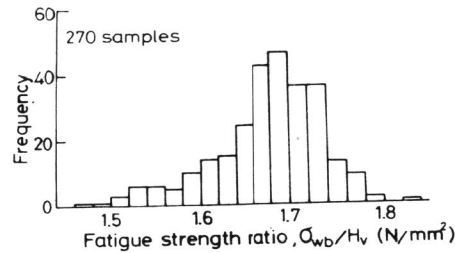


Fig.3. Histogram of  $\sigma_{wb}/H_V$  value against defect size.

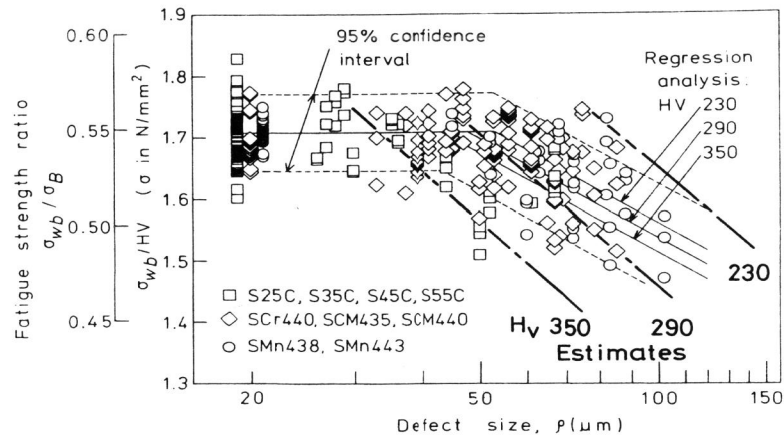


Fig.4.  $\sigma_{wb}/H_V$  value against defect size  $\rho$ .

and Cr and CrMo steel. The results of the samples in which no inclusions were found at the fatigue initiating points on their fracture surfaces are plotted on the line  $\rho = 20\mu\text{m}$ , and their average and the standard deviation are 1.707 and 0.038, respectively. These values may be regarded as those inherent to the fatigue properties of the steels tested. The trend of the data indicates that the  $\sigma_{wb}/H_V$  values appear almost independent of defect size in the region where  $\rho$  is less than  $45\mu\text{m}$ . Thus the average and the 95% confidence interval in the region are constructed assuming that they are constant and equal to the inherent ones. In the region where  $\rho$  is larger than  $45\mu\text{m}$ , the  $\sigma_{wb}/H_V$  values tend to decrease as the increase in the defect size and the tendency slightly varies with the hardness of materials. Hence, the  $\sigma_{wb}/H_V$  values in the region are linearly correlated with the defect size  $\rho$  on the semi-logarithmic scale. The regression is done separately in the following three hardness groups;  $H_V < 260$ ,  $260 < H_V < 320$  and  $H_V > 320$ . The results are plotted in Fig.4 by the three different lines with an equal

slope, being marked respectively by the median values of the three hardness groups; 230, 290 and 350. The 95% interval is constructed on the same assumption as in the region where  $\rho$  is less than  $45\mu\text{m}$ .

#### ESTIMATION OF DEFECT SIZES DETERMINING FATIGUE LIMITS

It is well known that the effect of a notch or defect on the fatigue strength varies considerably with material strength (Peterson, 1974). A fracture mechanics analysis is attempted for the estimation of critical size determining the fatigue limits of the steels as a function of material strength. This is based on the assumption that the crack propagation stage of small cracks initiated from the defects controls the fatigue limits. In the case of an elastic crack, the critical length  $2a_{cr}$  under an applied stress  $\Delta\sigma$  is given by

$$\Delta K = f(a)\Delta\sigma(\pi a_{cr})^{1/2} = \Delta K_{th} \quad (4)$$

where  $\Delta K_{th}$  is the threshold stress intensity range and  $f(a)$  a geometrical factor equal to  $1.12(2/\pi)$  in the case of half-penny crack with a radius  $a$ . For relative high stress state at fatigue limits in smooth specimens, the effect of cyclic plastic deformation cannot be neglected. This may be taken into account if the  $\Delta J$ -conception is used (El Haddad et al, 1980; Tanaka, 1983). Assuming plane stress condition, the corresponding critical condition for crack propagation is evaluated extending the elastic solution as

$$\Delta J = \Delta J_{th} = \Delta K_{th}^2/E, \quad (5)$$

where  $E$  is the Young's modulus. An approximate solution for  $\Delta J$  may be obtained based on the estimation that has been made by Shih and Hutchinson (1976) for tension loaded cracked members (El Haddad et al, 1980),

$$\Delta J/(\Delta K^2/E) = 1 + (E\varepsilon_{pa}/\sigma_a)[3.85(1-n')/\pi n'^{1/2} + n'], \quad (6)$$

where  $\sigma_a$  is the applied stress amplitude,  $\varepsilon_{pa}$  the plastic strain amplitude, and  $n'$  the cyclic strain hardening exponent. The value of  $n'$  for the steels tested in this study did not widely vary with material strength and nearly equal to 0.17 (Tanaka et al, 1981). Consequently, if  $\Delta K_{th}$  is known as a function of  $\sigma_B$  or  $H_V$ , the critical crack length  $2a$  will be computed equating  $\Delta J$  with  $2\sigma_{wb}$  and using eqns (1) through (6). However, the  $\Delta K_{th}$  values have not yet been measured for the steels tested in this study. Hence the dependence of  $\Delta K_{th}$  on material strength is estimated based on literature data of tempered martensitic steels at  $R$  (stress ratio) = 0 as (Tanaka et al, 1981),

$$\Delta K_{th,R=0} = 7.39 - 1.97 \times 10^{-3} \sigma_B, \quad (7)$$

where  $\Delta K$  values are measured by the units of  $\text{MPam}^{1/2}$ . The  $\Delta K_{th}$  values under alternating stresses ( $R = -1$ ) are obtained by the conversion from those under zero-to-tension ( $R = 0$ ) according to the empirical formulation proposed by Klesnil and Luckas (1972) as

$$\Delta K_{th,R=-1} = 2^\gamma \Delta K_{th,R=0}, \quad (8)$$

where  $\gamma$  is an empirical constant equal to 0.71 for the case of steel.

Figure 5 gives the theoretical curves thus obtained together with some available experimental data. Assuming half-penny crack, the calculation is done in two cases; the solid curve is for elastic crack ( $\Delta K_{th}$  criterion) and the dash-dotted one for elastic-plastic crack ( $\Delta J_{th}$  criterion). In this calculation, the saturating tendency of  $\sigma_{wb}$  against  $\sigma_B$  is taken into account in

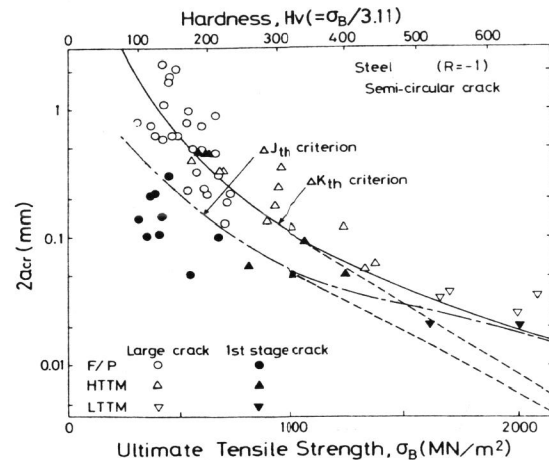


Fig.5. Dependence of critical crack length on tensile strength.

the region where  $\sigma_B$  becomes larger than 1000MPa, since the linear correlation in eqn (1) consists only in the strengths below 1000MPa (Nishijima, 1977). For a reference, estimation is also performed on the assumption that the linear correlation can be extrapolated to the higher strength region. The results are indicated by the dotted extrapolated curves in the figure. The empty symbols represent the experimental data collected by Ouchida et al (1975) with various microstructures, which are classified as ferrite/pearlite (F/P), martensite tempered at high temperatures (HTTM) and martensite tempered at low temperatures (LTTM). These were obtained for relatively large through or part-through cracks with lengths,  $a$ , ranged from 33 $\mu$ m through 433 $\mu$ m, and thus the corresponding crack lengths are converted to those for half-penny shape using the appropriate geometrical factors in eqn (4). The theoretical curves for  $\Delta K_{th}$  criterion agree with the experimental data but predict slightly smaller sides. This is quite reasonable since the calculation is conducted using the value of  $\sigma_{wb}$  for smooth specimens, while the experimental fatigue limits for cracked specimens were by a factor up to 0.31 lower than those expected from eqn (1) (Ouchida, 1975). The solid symbols indicate literature data for the lengths of non-propagating stage 1 cracks examined on smooth specimens tested in the vicinity of fatigue limits under rotating bending (Nishitani and Murakami, 1970; Nakazawa and Kobayashi, 1970;

Nishitani and Chishiro, 1974). The theoretical solid curve due to  $\Delta J_{th}$  criterion shows a comparable agreement with the data for non-propagating cracks in tempered martensitic steels, but predicts about a factor of two longer crack lengths for those in ferritic steels with low strengths.

On the basis of  $\Delta J_{th}$  criterion, the critical defect sizes are estimated for the cases  $H_v = 230, 290, 350$  and plotted in Fig.4 by the respective dash-dotted lines assuming that  $a_{cr}$  corresponds to critical defect size  $\rho$ . The theoretical lines explain correctly the tendency of the experimental data; steels with higher hardness yield lower defect size. However, the dependency of the estimated critical defect size on hardness appears much stronger than that of the experimental one. There is not yet any complete justification for the discrepancy. Particularly, there is a problem to evaluate the equivalent size of a spherical defect as that of a half-penny crack. However, one of possible explanations for this may be given in the following. The observed sizes of stage 1 cracks in Fig.5 are almost comparable with the sizes of non-metallic inclusions in Fig.4 in the steels with strength less than 1000MPa. On the other hand, figure 5 also suggests that the theoretical critical lengths for stage 2 crack propagation are larger than the experimental stage 1 non-propagating cracks in the same strength range and that the tendency becomes stronger as the decrease in the strength. This means that the non-metallic inclusions in the low strength steels would also affect the formation of stage 1 cracks or assist their growth. In the other words, the stage 2 crack propagation would not occur until the stage 1 crack initiated from a defect grows sufficiently as long as the critical size which is predicted in Fig.5. Contrary to this, in the case of high strength steels, the cracks originated from the defects would soon attain to the critical size and then begin to propagate as stage 2 crack.

#### SUMMARY

The fatigue limits of a series of steels tested for the NRIM Fatigue Data Sheets Project were discussed in relation to the sizes of non-metallic inclusions observed on the fracture surfaces of specimens. When the defect sizes were less than 45 $\mu$ m, the fatigue limits were proportional to tensile strength and hardness as  $\sigma_{wb} = 0.53\sigma_B = 1.71H_v$ . When the defect sizes became larger than 45 $\mu$ m, the fatigue limits decreased relative to the static strengths and the tendency became stronger as the increase in the static strength of steels. The critical defect sizes for the propagation of crack at the fatigue limits were estimated on the basis of elastic-plastic fracture mechanics ( $\Delta J_{th}$  criterion). The theoretical curves explained well the sizes of non-propagating cracks found at the fatigue limits under rotating bending. They also agreed comparably with the experimental relation between  $\sigma_{wb}/H_v$  and defect size obtained in this study.

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