An Examination of the Notch Effect in Fatigue of Carbon Steels Based on Linear Notch Mechanics*

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Fatigue tests of 0.31% carbon steel specimens with a circumferential notch were made under a wide range of configuration parameters. As a result, it has been confirmed that linear notch mechanics (LNM) can be successfully applied to the evaluation of notch effects in fatigue. Master curves useful for the evaluation of notch effects in the fatigue of carbon steels were also obtained arranging the previously published data, based on LNM. Moreover, the fatigue limit of a specimen with a drilled hole was discussed using the above master curves.

Key Words: Fatigue, Stress Concentration, Notch Effect, Fatigue Limit, Linear Notch Mechanics, Carbon Steel

1. Introduction

The fatigue cracks in machines and structures are usually formed near where the stress is concentrated. Therefore, it is important to evaluate the fatigue strength of notched specimens. Many researchers have undertaken this task, thus many results have been reported to date.

In a previous paper, one of the authors⁽¹⁾ explained the conditions used to determine the crack initiation limit σ_{w1} and the branch point, based on the concept of the similarity of relative stress fields near the notch roots. Recently, the concept was named 'linear notch mechanics' (LNM)⁽²⁾ and it was recognized⁽³⁾ that it was also very useful for the evaluation of the crack propagation limit, σ_{w2} . However, its applicability to σ_{w2} was examined under the limited conditions that the diameter of the minimum section d is constant and the notch depth t is small.

Kikukawa et al.⁽⁴⁾ pointed out that it is necessary

to obtain the master curves useful for the estimation of notch effects in fatigue, based on the proper model by arranging the accurate fatigue data.

In this paper, considering the above points, fatigue tests are carried out on large specimens ($d = 10$ mm) of a 0.31% carbon steel which has been used previously in the fatigue tests of many small specimens ($d = 5$ mm)⁽⁶⁾. Further, the applicability of LNM to the notch effects in the fatigue is examined under a wide range of configuration parameters. Moreover, the master curves based on LNM useful for the estimation of notch effects in the fatigue of carbon steels are obtained by using the previous fatigue data of the electropolished specimens⁽⁶⁾⁻⁽¹⁴⁾. For the purpose, accurate values of stress concentration factors K_t are necessary. In this paper, the accurate values of K_t obtained recently by the body force method⁽⁵⁾ are used.

The fatigue limit of specimens with a drilled hole is also discussed by using the above master curves in order to examine the effectiveness of LNM in the members with a 3-D stress concentration source.

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2. Materials, Dimensions of Specimens and Test Procedure

The materials used were rolled cylindrical bars of a 0.31% carbon steel. The chemical composition is given in Table 1. The specimens were turned after annealing for one hour at 877°C. The mechanical properties are given in Table 2.

The dimensions of the notched specimens are shown in Fig. 1. The notches are of the circumferential 60 deg. V-shaped type. Considering that the fatigue tests of a small specimen ($d=5$ mm) with a shallow circumferential notch have been already carried out, large specimens ($d=10$ mm) with a deep circumferential notch were tested. Detailed dimensions of the notches are given in Table 3. Before testing, all specimens were electropolished to the depth of 15 μ m after annealing in vacuum for one hour

Table 1 Chemical composition, weight %

C	Si	Mn	P	S	Cu	Al	Ni+Cr
0.31	0.29	0.75	0.015	0.014	0.06	0.015	0.05

Table 2 Mechanical properties

$\sigma_{s\ell}$	σ_B	σ_T	ψ
309	537	971	56.2

Table 3 Relation between notch geometry and σ_{w1} or σ_{w2}

d	ρ	t	K_t	σ_{w1}	σ_{w2}	$K_t \sigma_{w1}$	$K_t \sigma_{w2}$
mm	mm	mm		MPa	MPa	MPa	MPa
10	0.5	0.5	2.37	123	-	292	-
		1.0	2.54	108	-	274	-
		5.0	2.72	98	-	267	-
	0.3	0.5	2.90	103	118	299	342
		1.0	3.18	93	103	296	328
		5.0	3.42	83	93	284	318
	0.1	0.5	4.30	83	118	357	507
		1.0	5.02	74	103	371	517
		5.0	5.60	64	88	358	493

Fig. 1 Dimensions of a notched specimen

at 600°C.

The machine used in the fatigue test was a rotating bending fatigue testing machine with a capacity of 100 Nm operating at 2 500 rpm.

Here the stress is defined as the nominal bending stress of the minimum section. The crack initiation limit σ_{w1} is defined as the stress required to develop microcracks after 10^7 cycles, where the size of the

Fig. 2 Relationship between σ_{w1} or σ_{w2} and K_t for 0.31% carbon steel

Fig. 3 Relationship between $K_t \sigma_{w1}$ or $K_t \sigma_{w2}$ and $1/\rho$ for 0.31% carbon steel

(The data in the parentheses represents the data beyond the effective range of LNM)

microcracks is approximately the same as that of a nonpropagating microcrack observed at the fatigue limit of a plain specimen. The step of the stress level used to determine σ_{w1} and σ_{w2} is 5 MPa.

3. Results and Discussion

3.1 Examination of the effectiveness of LNM in a 0.31% carbon steel

The relationship between the notch geometries and σ_{w1} or σ_{w2} are given in Table 3. The accurate values⁽⁵⁾ of the stress concentration factor K_t were used.

Figure 2 shows the relationship between σ_{w1} or

Fig. 4 Relationship between $K_t \sigma_{w1}$ or $K_t \sigma_{w2}$ and $1/\rho$ for 0.1% carbon steel

Fig. 5 Relationship between $K_t \sigma_{w1}$ or $K_t \sigma_{w2}$ and $1/\rho$ for 0.2% carbon steel

σ_{w2} , and K_t , Figure 3 shows the rearranged results for the data in Fig. 2 and the previous data of the present material⁽⁶⁾, which are based on the concept of LNM.

From Fig. 3, it is seen that $K_t \sigma_{w1}$ is dependent on ρ alone in a wide range of geometrical conditions, while $K_t \sigma_{w2}$ is dependent on ρ alone except of the shallow notches ($t=0.1, 0.2$ mm). As a result, it can be concluded that LNM is more effective for the evaluation of σ_{w1} or σ_{w2} in the wider range than that previously shown⁽³⁾.

The fact that LNM is not effective for $K_t \sigma_{w2}$ in shallow notches corresponds to the fact that linear fracture mechanics is not effective in short cracks.

3.2 Master curves useful for the estimation of notch effects in fatigue of carbon steels

Fig. 6 Relationship between $K_t \sigma_{w1}$ or $K_t \sigma_{w2}$ and $1/\rho$ for 0.45% carbon steel

Fig. 7 Relationship between $K_t \sigma_{w1}$ or $K_t \sigma_{w2}$ and $1/\rho$ for 0.5% carbon steel

As it was confirmed in the previous section that LNM is effective for expression of notch effects in fatigue, the master curves useful for the estimation of notch effects in carbon steel were produced by means of LNM. For this purpose the typical fatigue data of electropolished carbon steel are represented in Figs. 4 to 7.

Figures 8 and 9 show the dimensionless master curves normalized by the fatigue limit of a plain specimen, σ_{w0} . The notch effects in an arbitrary carbon steel can be estimated from the ultimate tensile strength σ_B by using these figures.

3.3 Application to members with a 3-D stress concentration source

In the above discussions the circumferential notches were treated as the stress concentration source. Here, penetrated or nonpenetrated holes are treated as a 3-D stress concentration source. As an example, the fatigue limit of annealed 0.1% carbon steel specimens with a drilled hole, with a radius ρ and depth h , are shown in Fig. 10. Figure 11 shows the rearrangement of the result of Fig. 10 by LNM. The values^{(12),(14)} of K_t in Fig. 11 are those on the hole edge. The theoretical curves of $K_t\sigma_{w1}$ and $K_t\sigma_{w2}$ obtained from Figs. 8 and 9 are shown in Fig. 11 by the solid and dotted line, respectively.

The points which can be seen from these figures

are as follows.

(i) The values of $K_t\sigma_{w1}$ or $K_t\sigma_{w2}$ are determined approximately by ρ alone, independent of other geometrical conditions (Fig. 11).

(ii) Both relationships of $K_t\sigma_{w1}-\rho$ and $K_t\sigma_{w2}-\rho$ agree with respective those of the circumferential notches when ρ is greater than a certain value ρ_1 (in the present material, $\rho_1 \cong 0.2$ mm).

(iii) For the same value of ρ , the $K_t\sigma_{w2}$ of drilled specimens falls between the $K_t\sigma_{w1}$ and $K_t\sigma_{w2}$ of circumferentially notched specimens, when ρ is smaller than ρ_1 . The reason is that the form of the non-propagating crack of holes is three-dimensional and the characteristic stress field of a notch in the case of $\rho < \rho_1$ is not sufficient to describe the behavior of a non-propagating crack. This phenomenon is also recognized in the case of an extremely shallow circumferential notch^{(3),(15)}.

4. Conclusions

The obtained results are summarized as follows:

(1) In a 0.31% carbon steel, it has been confirmed that σ_{w1} and σ_{w2} are well estimated in a wide range of specimen configurations by LNM using a small of data.

(2) Some fatigue data of typical electropolished carbon steels were arranged by LNM. Based on the

Fig. 8 Master curves for estimation of σ_{w1} in carbon steels

Fig. 9 Master curves for estimation of σ_{w2} in carbon steels

Fig. 10 σ_{w1} or σ_{w2} of specimens with a drilled hole

Fig. 11 Rearranged result of Fig. 10 by LNM

results, the master curves useful for the estimation of notch effects in carbon steels were obtained.

(3) Master curves obtained from the circumferential notched specimen are available for the drilled specimen when the radius of the drilled hole ρ is greater than a certain value ρ_1 . The fatigue limit for the case of $\rho < \rho_1$ can be also estimated from the master curves, within the range when the drilled hole influences the fatigue limit of the specimen.

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