The Effect of Surface Micropits upon the Fatigue Strength of High-Strength Steel*

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A study has been made of the influence of artificial semispherical surface flaws with diameters of 25 to 175 μm upon the fatigue limit of high-strength steel. This has been done to better understand the origin of the harmful effect of hard inclusions on the fatigue resistance of high-strength steel in which hard inclusions are poorly bonded to the matrix microstructure. An attempt has been made to estimate the true fatigue limit of the ideal inclusion-free microstructure of the steel, and the effect of inclusions on the fatigue strength of the steel has also been discussed quantitatively on the basis of the results of such an estimation of the true fatigue limit.

Key Words: Fatigue, High-strength Steel, Non-metallic Inclusion, Fatigue Limit, Microstructure, Surface Flaw, Micropit, Nonpropagating Crack

1. Introduction

It has been established that high-strength steels show an increase in fatigue strength with a rise in hardness and tensile strength, but no further improvement in fatigue strength can be obtained beyond a certain level of hardness or strength(1). As the reason for this, it has been pointed out that in high-strength steels, a nonmetallic inclusion provides a preferential site for crack initiation and acts as a metallurgical factor for suppressing the improvement of fatigue strength of the steel(2).

In addition, the previous studies of the adhesive property of inclusions with matrix microstructure in steel have revealed that a hard nonmetallic inclusion is poorly bonded to the matrix and is in an almost free state from the matrix at the very beginning of stress cycling(3) or in a stage before cyclic loading is applied(4); as a result, a situation which can be regarded as a microvoid prevails around the inclusion. In other words, the high-strength steel can be regarded as a material containing a large number of microvoids with diameter nearly equal to that of inclusions in the microstructure.

In making a study of the fatigue strength of high-strength steel, a better understanding of the following points would be important for clarifying the effect of inclusions on fatigue strength. (1) At what level does the fatigue limit of an ideal inclusion-free microstructure (true fatigue limit σω0) lie? (2) To what extent do inclusions give a harmful effect on the fatigue strength of an actual material?

In the present study, an attempt was made to estimate the true fatigue limit σω0 of the high-strength steel in accordance with the method described in the previous report(5). Discussions were made on the effect of hard inclusions on the fatigue strength of high-strength steel on the basis of the

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* Received 1st June, 1987. Paper No. 86-0254 A
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Vol. 30, No. 270, 1987

JSME International Journal
results of the estimation of $\omega_0$ and the examination of the fatigue strength characteristics of the specially prepared specimen with artificial defects in which the semispherical surface micropits with diameter of 25 to 175 $\mu$m were introduced to simulate the surface inclusion pits.

2. Materials and Test Method

Two types of materials, SAE 1552 and SAE 9254 steels, having the chemical compositions listed in Table 1, were used in the present study. These materials were subjected to induction hardening and tempering, under the conditions shown in Table 1, after machining the rotary bending fatigue specimen with minimum diameter of 6 mm. As a result, three types of specimens, which had almost the same prior austenite grain size but differed only in hardness, were obtained as shown in this table. The SAE 1552, the SAE 9254 with a lower hardness level of $HV=457$ and the SAE 9254 specimen with a higher hardness level of $HV=584$ are hereafter referred to as the A, B and C series materials, respectively.

After electropolishing the specimens, semispherical micropits were introduced at 4 positions on the minimum diameter surface of the specimen (see Fig. 1) by means of electrodischarge machining. Four different micropit diameters, 25, 45, 100 and 175 $\mu$m, were used. Two typical examples of the micropits are illustrated in Fig. 2.

The rotary bending fatigue test (2,850 rpm) was conducted with respect to 15 types of test pieces including the smooth specimens (A, B and C) and the specimens with artificial defects of the 4 different sizes mentioned above. Furthermore, in order to examine the relation between the existence of inclusions and the occurrence of cracking, the microscopic fatigue fracture process was observed on the surface and the fracture surface topography was also examined, using the optical and scanning electron microscopes.

3. Results and Discussion

3.1 Fatigue strength characteristics of the smooth and defect specimens.

As an example, the result of the fatigue test on the C series material is shown in Fig. 3. The fatigue limits of all specimens are also shown together in Table 2. From Fig. 3, it is evident that the fatigue strength of the C series material is considerably affected by the presence of surface micropits; the larger the pit diameter, the more the fatigue strength decreases. In this case, the reduction in fatigue strength was remarkable in the infinite life regime. A similar tendency was also observed in the A and B series materials.

Next, for the purpose of examining the existence of nonpropagating cracks, surface observations were conducted on the specimens which had endured the

![Fig. 1 Position of micropits on the specimen surface](image-url)

![Fig. 2 Profile of micropit (a) on the surface and (b) on the longitudinal section](image-url)
stress cycling of $N=10^4$. As a result, in the A series material, a nonpropagating crack with length of about 15 μm was found originating from the inclusion at the stress level of the fatigue limit. In other series materials (B and C), however, nonpropagating cracks were not found.

In order to examine the preferential site for crack initiation in the microstructure, a microscopic observation of the microfracture behavior was performed on the specimens subjected to the stress cycling at the stress amplitude near the fatigue limit. As a result, it was made clear that in each series material, a fatigue crack started from the surface inclusion in smooth specimens, while in specimens with artificial micropits, the fatigue crack originated from the surface edge of the micropit and led to the final fracture of the specimen. Figure 4 shows a fatigue crack originating from an inclusion on the surface of the B series smooth specimen. Also in Fig. 5, a fatigue crack originating from the surface edge of a micropit (top of Fig. 5) and the fracture surface created by the propagation of this crack are shown.

From the results mentioned so far, the following description could be made concerning the relation between the fatigue limit and the surface flaw. (1) The fatigue limit of the A series smooth specimen corresponds to the critical stress for the onset of growth of nonpropagating cracks originating from surface inclusions. (2) In other specimens, their fatigue limits correspond to the critical stress for the crack initiation around inclusions (B and C series smooth specimens) or from the edge of micropits (A, B and C series specimens with artificial micropits). In all cases, the surface flaw controls the level of the fatigue limit of the materials.

![Fig. 3 Results of fatigue test (material C)](image)

**Table 2** Results of fatigue test

<table>
<thead>
<tr>
<th>E.F.L.</th>
<th>F.L.</th>
<th>G-ν/σ_0f</th>
<th>C-ν/σ_0f</th>
<th>F.L.</th>
<th>G-ν/σ_0f</th>
</tr>
</thead>
<tbody>
<tr>
<td>smooth</td>
<td>921</td>
<td>760</td>
<td>8</td>
<td>100</td>
<td>860</td>
</tr>
<tr>
<td>25 μm</td>
<td>685</td>
<td>673</td>
<td>0.69</td>
<td>588</td>
<td>0.64</td>
</tr>
<tr>
<td>45 μm</td>
<td>636</td>
<td>588</td>
<td>0.71</td>
<td>666</td>
<td>0.66</td>
</tr>
<tr>
<td>100 μm</td>
<td>592</td>
<td>543</td>
<td>0.43</td>
<td>450</td>
<td>0.47</td>
</tr>
</tbody>
</table>

F.L. : Fatigue limit (MPa)
E.F.L. : Estimated fatigue limit of the inclusion tree matrix (MPa)
  
  kcal
  
  kcal

![Fig. 4 Appearance of the crack initiation and propagation from the surface inclusion and of the fracture surface (Material B, σ=789 MPa)](image)

![Fig. 5 Initiation of fatigue crack at the surface edge of micropit (top) and fracture surface resulted from its propagation (Material C, σ=735 MPa, Nf=8.9×10⁵)](image)
3.2 Effect of inclusions on fatigue strength

As described in the previous chapter, at the stress level near the fatigue limit, fatigue cracks originate from inclusions in the smooth specimen, while in the specimen with artificial microcracks, a fatigue crack occurs at the edge of surface microcrack. It might, therefore, be thought that if we assume the fatigue limit $\sigma_{\infty}$ of the defect-free material having the microstructure with no inclusions nor pits, the level of such a potential fatigue limit would be much higher than that of the conventional fatigue limit of the original material. The fatigue limit of such an ideal defect-free material, $\sigma_{\infty}$, will be hereafter referred to as the true fatigue limit of a material.

In this chapter, the effect of inclusions on fatigue strength will be discussed on the basis of the results of the estimation of such a true fatigue limit $\sigma_{\infty}$ and the examination of the critical size of defect for the reduction in the fatigue limit of a material. The true fatigue limit $\sigma_{\infty}$ cannot be determined by the ordinary fatigue tests for obtaining the data of the final failure of the specimen. It is, however, possible to obtain an estimated value of $\sigma_{\infty}$ by carefully examining the microfracture process at the specimen surface and then determining the relation between the stress amplitude and the number of stress cycles for the initiation of fatigue crack in the microstructure, in dependently of the inclusion. The crack initiation S-N curves of the defect-free microstructure of the test materials estimated in this manner are given in Figs. 6 to 8, together with the ordinary S-N curves which were obtained in the previous chapter for specimens having microcracks with diameters of 25 to 175 $\mu$m. The true fatigue limits $\sigma_{\infty}$ of the A–C series materials can be estimated by the stress amplitude for the horizontal portion of the crack initiation S-N curves in these figures. However, there may be some doubts as to the appropriateness of such an estimation of $\sigma_{\infty}$, because there is some arbitrariness in the way of drawing the horizontal sections of the S-N curves. Thus, it is necessary to make a comparison of the $\sigma_{\infty}$ estimated in this manner with the value of $\sigma_{\infty}$ estimated by some other method. For this comparison, the results of the fatigue tests of the specimens having surface microcracks with various sizes can be appropriately used, because the estimated fatigue limit of the specimen with pit diameter of $d=0$, which is obtained through the extrapolation from the relation between the fatigue limit and the pit diameter, corresponds to the true fatigue limit of the material, provided that nonpropagating cracks do not develop during the fatigue fracture process and that the fatigue limit is determined by the critical stress for the initiation of fatigue cracks around inclusions or defects. The materials B and C belong to the material showing such fatigue behavior.

The values of $\sigma_{\infty}$ of materials B and C, as estimated from Figs. 7 and 8, were then plotted as the respective values of the fatigue limit corresponding to

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**Fig. 6** S-N curve for crack initiation in the microstructure independently of inclusion (S-N curves of specimens with artificial microcracks are also shown, Material A)

**Fig. 7** S-N curve for crack initiation in the microstructure independently of inclusion (S-N curves of specimens with artificial microcracks are also shown, Material B)

**Fig. 8** S-N curve for crack initiation in the microstructure independently of inclusion (S-N curves of specimens with artificial microcracks are also shown, Material C)

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the relation between fatigue limit and pit diameter was thus obtained. The results are shown in Figs. 9 and 10, where these estimated values of $\sigma_{av}$ are well located on the extrapolated line (dotted line) based on the observed relation between fatigue limit and pit diameter.

These findings reveal that the values of $\sigma_{av}$ obtained from Figs. 7 and 8 give a good approximation for the true fatigue limit of the materials B and C, and that the values of $\sigma_{av}$ of these materials are about 860 MPa and 1036 MPa, respectively.

Figure 11 shows the similar result for the material A. In this material, however, the fatigue limit corresponds to the critical stress for the onset of growth of nonpropagating cracks. Thus, further studies will be necessary for the interpretation of this result.

The horizontal lines (dotted line) in Figs. 9 to 11 give the stress levels of the fatigue limit for the smooth specimens of materials A~C. It should be noted that the fatigue limit of smooth specimens is equal to the fatigue limit of the specimen with artificial micropits having the diameter $d_c$ of about 15 $\mu$m for all materials.

An attempt was made to clarify the significance of this critical pit size of $d_c=15\mu$m. As a result, it has become evident that in material A, the critical pit size of $d_c=15\mu$m agrees well with the size of the nonpropagating crack formed at the stress level of the fatigue limit, and that the micropit smaller than such a critical size does not cause a reduction in the fatigue strength, as observed in the earlier study conducted by Murakami et al. In the materials B and C in which nonpropagating cracks did not develop, the critical pit size $d_c$ is closely related to the size of the largest inclusion in the surface microstructure. Figure 4 gives evidence showing that the fatigue crack leading to the final fracture of specimen (material C) originated from the inclusion of the largest size which was only slightly less than the $d_c=15\mu$m mentioned above (i.e., $\sim10\mu$m).

From these results, it can be concluded that high-strength steels, in which fatigue fractures originate from inclusions in the surface microstructure, can be regarded as containing defects equivalent to semis-
Fig. 12 Relation between normalized fatigue limit $\sigma_{us}/\sigma_{ul}'$ and diameter of micropit

...pherical surface flaws with diameter of $d_c$. Furthermore, such a size of $d_c$ corresponds to (1) the length of a nonpropagating crack at the stress level of the fatigue limit for the case of material A, in which the fatigue limit is determined by the critical stress for the onset of growth of a nonpropagating crack, and (2) the size of inclusions which cause the crack leading to the final fracture at the stress level near the fatigue limit (materials B and C).

Finally, Fig. 12 shows the relations of the relative fatigue limit to the true fatigue limit $\sigma_{us}/\sigma_{ul}'$ and the diameter of micropit for the materials A, B and C. Here, the smooth specimen has been assumed to be equivalent to the specimen with artificial defect which possesses a micropit equivalent to the inclusion of the largest size (diameter about 15 $\mu$m) in the surface microstructure, and its fatigue limit has been taken as the point at which $d_c=15\mu$m. From this, it could be inferred that when the hardened steel at a hardness level of $HV=460~580$, as in the test steels, contains an inclusion with a maximum diameter of about 10~15 $\mu$m, the fatigue limit of the smooth specimen is about 80% of the true fatigue limit of the steel, $\sigma_{ul}'$; thus, the fatigue limit is reduced by about 20%, owing to the presence of inclusions.

4. Conclusions

Based on the results of the investigation into the fatigue strength characteristics and fatigue fracture process of various specimens containing artificial defects in which micropits of 25~175 $\mu$m in diameter were provided by electrodisharge machining to simulate the inclusion pits in the surface microstructure of high-strength steel, the effect of the inclusions on the fatigue strength of high-strength steel was studied. The results obtained are summarized as follows. (1) The fatigue limit of the specimen containing artificial defects increases gradually as the size of the spherical micropit becomes smaller, and the micropit smaller than a certain critical size ceases to contribute to a reduction in the fatigue strength. Such a critical size of micropit $d_c$ is approximately 15 $\mu$m in diameter for the present materials. This critical size $d_c$ corresponds to (i) the length of microscopic nonpropagating crack (surface length at the stress level of the fatigue limit for the material in which the fatigue limit is determined by the critical stress for the onset of growth of a nonpropagating crack and to (ii) the size of the largest inclusion in the surface microstructure for the material in which the critical stress for the crack origination from inclusions controls the fatigue limit. (2) The true fatigue limit of the material (fatigue limit of ideal inclusion-free microstructure) cannot be attained usually in high-strength steels; the actual fatigue strength of high-strength steel is limited to the level corresponding to the fatigue limit of the specimen with artificial defects (surface micropits), the size of which is nearly equal to that of the largest inclusion. This is due to the harmful effect of an inclusion on the fatigue strength. The true fatigue limit of the steels investigated in this study with hardness levels of about $HV=460~580$ is estimated to be $900~1000$ MPa, and the actual fatigue limit of smooth specimens is about 80% of this true fatigue limit.

Acknowledgments

The authors would like to thank Prof. T. Kunio, Drs. K. Yamada and S. Sohmiya for their encouragement throughout this study and Messrs. Y. Ishikawa and T. Hayashi for their contribution in carrying out the experiments.

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JSME International Journal

1987, Vol. 30, No. 270
