Gigacycle Fatigue Properties of Double-Melted SCM440 Steel and Size Effects

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Gigacycle fatigue tests were conducted on double-melted SCM440 low-alloy steel using larger and conventional specimens and comparing the results with those of single-melted steel. Although all specimens experienced internal fractures, size effects were minor in the double-melted steel, unlike in the single-melted steel: specifically, for the double-melted steel, differences in fatigue strength and inclusion size were minimal between the larger and conventional specimens. These results mean that the double-melted steel showed superior gigacycle fatigue properties to the single-melted steel when the larger specimens were used in the fatigue tests, whereas this superiority was doubtful when conventional specimens were used. When the inclusion sizes were estimated using the results for the larger specimens, the inclusion size for 150 kg of the double-melted steel was a maximum of 47 μm, one-third of that for the single-melted steel. The use of larger specimens is thus highly advisable for evaluating the gigacycle fatigue properties and the inclusion size of high-strength steels.

KEY WORDS: gigacycle fatigue; ultrasonic fatigue testing; size effect; internal fracture; inclusion.

1. Introduction

Internal fracture[1] occurs in high-strength steels whose tensile strength exceeds approximately 1 200 MPa,[2] resulting in gigacycle fatigue. In general, steel materials have fatigue limits of under 10^7 cycles, and surface fractures tend to predominate. In high-strength steel, on the other hand, the fatigue limits disappear, and the S-N curves (fatigue life curves) generally show a stepped shape.[3] In this case, the fracture mode above the stepped stress level is a conventional surface fracture, whereas it changes into an internal fracture below the stepped stress level. It is therefore understood that it is internal fracture that causes the disappearance of the fatigue limit.[4–10] Moreover, a two-fold S-N curve concept[11,12] has become widely accepted. This concept assumes that the S-N curves of internal and surface fractures exist independently, and that a combination of the two S-N curves determines the final shape of the S-N curve. Internal fracture behavior is thus the key to understanding gigacycle fatigue of high-strength steel.

If there is no fatigue limit, cutoff cycles of fatigue tests need to be extended, with the result that gigacycle fatigue tests up to above 10^9 cycles are required. Gigacycle fatigue tests are, however, very time-consuming: for example, 10^9 cycles, even at 100 Hz, takes 3.8 months. A solution to this problem is to employ ultrasonic fatigue testing.[13–17] Ultrasonic fatigue testing uses the very high frequency of 20 kHz, which is 200 times faster than the conventional 100 Hz, so the 10^9 cycles can be completed within a day. The drawback, however, to ultrasonic fatigue testing is frequency effects, since 20 kHz is too fast to make the test results fully credible. More specifically, slip bands are not formed at this frequency,[18] resulting in artificially high fatigue strengths being reported.[19] To investigate these frequency effects, the authors compared the 20 kHz test results with the conventional 100 Hz version for several materials and under several sets of conditions.[20–24] The results confirmed that the 20 kHz test results showed good agreement with the conventional 100 Hz under conditions where internal fractures occurred in high-strength steel. Internal fractures do not necessitate the formation of the slip bands, so frequency effects are negligible. These results mean that ultrasonic fatigue testing is effective for evaluating the gigacycle fatigue properties of high-strength steels that develop internal fractures.

On the other hand, size effects are very significant in the internal fracture of high-strength steels, i.e., large specimens show lower fatigue strength.[21] In an earlier series of studies on ultrasonic fatigue testing, the author experimented with larger specimens.[25] As well as using a larger diameter, a straight section was adopted at the minimum diameter section. This effectively enlarges the risk volume[26] which is a measure of the size of the region subject to high stress in fatigue-test specimens. The larger specimens produced good results; calculations showed that the stress distribution in the straight section was very close to uniform, and comparison with conventional fatigue testing demonstrated the ultrasonic fatigue test results to be valid. When the test results were compared between the larger and conventional specimens,
significant size effects were confirmed under conditions where internal fractures occurred in high-strength steel.\textsuperscript{25,27)} The size effects were investigated in single-melted JIS-SCM440 low-alloy steel and in commercial JIS-SUP7 spring steel. In both cases, the larger specimens revealed larger inclusions at the internal fracture origin, and the fatigue strength showed major degradation that was in excess of 20%. These large size effects suggest test results from larger specimens to be more reliable.

In our past research, we used conventional specimens. One study indicated that the gigacycle fatigue strength of double-melted and single-melted steels were equivalent in spite of the fact that double-melting reduces inclusions.\textsuperscript{28)} This result perhaps needs review using larger specimens, since conventional specimens are less reliable. The author already has the test results for single-melted steel,\textsuperscript{25)} so the review would be achieved by simply adding the new results for double-melted steel. Hence, in this study we newly prepared double-melted JIS-SCM440 low-alloy steel and conducted gigacycle fatigue tests using both larger and conventional specimens. This study aimed to evaluate the gigacycle fatigue strength of double-melted steel as well as investigate size effects.

2. Experimental Method

2.1. Materials

Table 1 shows the chemical compositions of the tested steels. The double-melted steel was newly prepared, while the results for single-melted steel were cited from our previous report.\textsuperscript{25)} Both steels were melted under vacuum on a laboratory scale. The ingots were 150 kg in weight. Vacuum arc remelting (VAR) was applied to the double-melted steel. The ingots were forged into round bars 22 mm in diameter. Figure 1 shows the results of inclusion inspections in which extreme value distributions\textsuperscript{26)} of inclusion sizes were measured for inclusion types C and D using the 100 mm\textsuperscript{2} standard area of a mirror-polished surface. As seen in the Figure, the inclusions in the double-melted steel were smaller than those in the single-melted steel.

The heat treatments applied were quenching and tempering. The quenching conditions were oil-cooling after holding at 1 153 K for 30 min, and the tempering conditions were air cooling after holding at 473 K for 60 min. These heat treatments were conducted after pre-machining close to the final shape of the specimens but leaving a finishing allowance. Vickers hardnesses after heat treatment were HV611 for the double-melted and HV604 for the single-melted steels. Figure 2 shows microstructures revealing prior-austenite grain boundaries. Although both microstruc-

![Fig. 1. Extreme value distribution of inclusion size measured for inclusion types C and D using the standard 100 mm$^2$ mirror polished surface.](image)

![Fig. 2. Microstructure of the tested steels revealing prior-austenite grain boundaries.](image)
tures were tempered martensite, the prior-austenite grains of the double-melted steel were smaller than those of the single-melted steel. The difference in the prior-austenite grain sizes was attributable to nitrogen content, since the nitrogen content of the double-melted steel was higher than that of the single-melted steel. The measured nitrogen content of the double-melted and single-melted steels was 0.010% and 0.002%, respectively.

2.2. Fatigue Test

Fatigue tests were conducted by ultrasonic fatigue testing at 20 kHz up to $10^{10}$ cycles. In these tests, the runout specimens were forcibly fatigue-fractured at a higher stress amplitude at which internal fracture was expected. This forced fatigue fracture made it possible to check the inclusion sizes of the runout specimens by observing the fracture surface. The ultrasonic fatigue testing machine used in these tests was a commercial model (Shimadzu USF2000), modified to generate a higher displacement amplitude. This system is capable of providing a maximum displacement amplitude of 73 $\mu$m. An air cooling system is built into this system to suppress any temperature increase of the specimens. The air cooling system consists of a vortex tube-type cooler and a 5.5 kW-class compressor. Under these conditions, the conventional specimens showed a negligible temperature increase, even during continuous tests at 20 kHz. However, the air cooling system was not powerful enough to suppress the temperature increase of the larger specimens under continuous testing, so intermittent tests were applied in this case. The intermittent conditions were designed so as to maintain the specimen’s surface temperature at below 303 K. These fatigue tests were conducted at a stress ratio of $R = -1$.

Figure 3 shows the specimens used in these tests. The $\phi 8 \times 10$ mm specimens were the larger specimens, and the 3 mm-diameter specimens were our conventional ultrasonic fatigue test specimens. When the risk volumes are calculated as the region subjected to $>90\%$ of maximal stress, those of the $\phi 8 \times 10$ mm and 3 mm-diameter specimens are 781 and 33 mm$^3$, respectively. The narrowed area of the specimens was finished with 1 $\mu$m grit powder to eliminate any machining flaws. The fracture surfaces after the fatigue tests were observed using a scanning electron microscope (SEM), and the origin of internal fractures was analyzed using energy-dispersive atomic X-ray spectroscopy (EDX).

3. Experimental Results

3.1. Fatigue Test Results

Figure 4 shows the fatigue test results. Figure 4(a) shows the present results for the double-melted steel, while Fig. 4(b) shows the previous results for the single-melted steel. The results for the single-melted steel include the results of servo-hydraulic fatigue testing, as well as those of ultrasonic fatigue testing. The solid and open marks show the results for larger and conventional specimens, respectively. These results show no fatigue limit. Figure 5 shows a typical fracture surface around the internal fracture origin. All specimens experienced internal fracture, and most of the origins were oxide-type inclusions. Several specimens revealed no inclusion at the internal fracture origin, suggesting the internal fracture origin to be the matrix itself. The number of internal fractures matrix-originated were fewer in the double-melted steel than in the single-melted steel. The larger prior-austenite grain size of the single-melted steel is likely to have caused the increased prevalence of matrix-originating type of internal fracture.
As seen in Fig. 4, size effects were markedly different between the double-melted and single-melted steels. The larger single-melted steel specimens showed lower fatigue strength than the conventional specimens, whereas the difference was small in the double-melted steel. In the double-melted steel, differences in 1010-cycle fatigue strength were within 5% in spite of being over 20% in the single-melted steel. There is a difference in prior-austenite grain sizes between the double-melted and single-melted steels, while it was hardly imaginable that the difference in prior-austenite grain sizes would have influenced the size effects. A comparison of absolute values of the fatigue strengths between the double-melted and single-melted steels would reveal whether the difference in prior-austenite grain sizes would actually affect the result. However, the size effects were relative values derived from a comparison between the larger and conventional specimens of each steel. This was why prior-austenite grain sizes seemed unlikely to influence the size effects. This result thus demonstrates that the size effect in double-melted steel is smaller than that in single-melted steel.

3.2. Inclusion Sizes at the Internal Fracture Origins

Figure 6 shows inclusion sizes in $\sqrt{\text{area}}$ at the internal fracture origins plotted on Gumbel probability papers. As in Fig. 4, Fig. 6(a) shows the present results of the double-melted steel, while Fig. 6(b) shows the previous results of the single-melted steel. The solid and open marks show the results of the larger and conventional specimens, respectively. In Fig. 6(b), the ultrasonic ($\phi \times 10$ mm) and servo-hydraulic ($\phi \times 14$ mm) fatigue test results used different symbol marks, while both results were treated as the same data group of the larger specimens when calculating the Gumbel plots. Moreover, the results of the matrix-originating type of internal fracture were ignored when calculating the Gumbel plots.

As in the fatigue test results, there was a clear difference in size effects. In the single-melted steel, the inclusion sizes of the larger specimens were larger than those in the conventional specimens, while the difference was small in the double-melted steel. These results are in good agreement with the fatigue test results. Large specimens tend to have large inclusions, since the probability of large inclusions is higher in a higher volume. The large inclusions are what cause the size effect on fatigue strength. Nevertheless, the larger double-melted steel specimens revealed inclusions as small as those seen in the conventional specimens. Therefore, the size effect on the fatigue strength of the double-melted steel was small, indicating that double-melted steel is very clean.
4. Discussion

These experimental results show the size effect to be small in the double-melted steel, in contrast to the single-melted steel. In the light of these results, the gigacycle fatigue properties of the double-melted steel are discussed below. Figures 7 and 8 show fatigue test results and inclusion sizes, respectively. These figures use the same data as in Figs. 4 and 6, but show different comparisons: Figs. 4 and 6 show a comparison between two types of specimens, while the comparison in Figs. 7 and 8 is between double-melted and single-melted steels. In Figs. 7 and 8, solid and open marks show double-melted and single-melted steels, respectively.

As seen in Fig. 7, in the larger specimens, the double-melted steel shows higher fatigue strength than the single-melted steel, while in the conventional specimens, the difference between the two materials is small. The inclusion sizes seen in Fig. 8 successfully explain the fatigue test results: in the larger specimens, the inclusion sizes of double-melted steel are smaller than those in the conventional specimens, while the difference is small in the conventional specimens. We thus conclude that the gigacycle fatigue properties of the double-melted steel are superior to those of the single-melted steel, since the inclusion sizes of the double-melted steel are smaller. When using conventional specimens, however, the difference between the two materials is small, so the results from conventional specimens tend to be misleading, as seen in our past research. Hence, using larger specimens is strongly advisable to be able to correctly evaluate the gigacycle fatigue properties of high-strength steel. This also applies to the evaluation of inclusion sizes when an inclusion inspection employs fatigue testing. As seen in Fig. 8, it is more rational to evaluate inclusion sizes using larger specimens than with conventional specimens.

When comparing the gigacycle fatigue properties between the double-melted and single-melted steels in this study, differences in microstructure also needed to be taken into account, since, as seen in Fig. 2, the prior-austenite grains of the double-melted steel are finer than those of the single-melted steel. The fine microstructure also has the potential to enhance the gigacycle fatigue properties. As seen in Fig. 8(b), inclusion sizes in conventional double-melted and single-melted steel specimens are almost identical. On the other hand, the fatigue test results in Fig. 7(b) show a slight difference between the two materials. This slight difference in fatigue test results is probably caused by differences in the microstructure, since the inclusion sizes are almost identical. Figure 7(a), which shows the results for
the larger specimens, illustrates the combined effects of the inclusion sizes and the microstructure, while Fig. 7(b), which shows the results for conventional specimens, reflects the effects of the microstructure alone. A comparison of Figs. 7(a) and 7(b) reveals that the effect of the inclusion sizes is more significant than that of the microstructure.

Next, the inclusion sizes of the double-melted steel are evaluated based on the results of this research. Figure 9 shows the results of extreme value analysis \(^{26,31,33}\) of the inclusion sizes. This analysis uses the inclusion sizes of the larger specimens and estimates maximal inclusion size as a function of the volume of steel. As seen in Fig. 9(a), the inclusion sizes of the larger specimens show good linearity on Gumbel plots, so the inclusion sizes are in fact extreme value distributions. One data point for single-melted steel is an outlier due to its unusually large size, so this data point is excluded from the analysis. The resultant fitted lines are obtained, as shown in Fig. 9(a). By substituting reduced variate \(y\) for the fitted lines, the maximal inclusion size can be estimated for a particular volume of steel. The relationship between reduced variate \(y\) and the volume \(V\) is as follows:

\[
y = -\ln[-\ln((T - 1)/T)], \quad T = (V + V_0)/V_0 \quad \ldots \quad (1)
\]

where \(T\) is the return period and \(V_0\) is the standard inspection volume. In Fig. 9(a), the standard inspection volume is equal to the risk volume of the specimens, so the standard inspection volume is \(V_0 = 781 \text{ mm}^3\).

Figure 9(b) shows the estimated maximal inclusion sizes. Although the double-melted steel shows smaller maximal inclusion sizes than the single-melted steel, the difference widens with increasing volume of steel. When the maximal inclusion size is estimated for \(1.9 \times 10^7 \text{ mm}^3\) (= 150 kg), which corresponds to the ingot size of these steels, the maximal inclusion sizes of the double-melted and single-melted steels are 47 and 138 \(\mu\text{m}\), respectively. The maximal inclusion size of the double-melted steel is thus almost one third of that of the single-melted steel. Moreover, although whether or not the maximal inclusion size exceeds 100 \(\mu\text{m}\) is a notable point, the maximal inclusion size in double-melted steel never exceeds 100 \(\mu\text{m}\).

As discussed above, fatigue testing using the larger specimens demonstrated the excellent gigacycle fatigue properties of double-melted steel. Although its superiority was not apparent when using conventional specimens, the double-melted steel showed clearly higher gigacycle fatigue strength than the single-melted steel when using the larger specimens. The inclusion size in the double-melted steel was no greater than 47 \(\mu\text{m}\), one third of that of the single-melted steel. These inclusion sizes were obtained only when using the larger specimens. Using the larger specimens was thus very important to be able to correctly evaluate the gigacycle fatigue properties of high-strength steel.

5. Conclusion

In this study, we carried out gigacycle fatigue tests on double-melted steel using larger and conventional specimens, and the results were compared with our previous results for single-melted steel. The following conclusions were obtained.

(1) All specimens ended in internal fracture, and no fatigue limit was observed up to \(10^{10}\) cycles. In the double-melted steel, only small differences in fatigue strength were observed between the larger and conventional specimens in contrast to the case of single-melted steel.

(2) Although most of the internal fracture origins were an oxide-type inclusion, size effects in double-melted steel were small also with respect to the inclusion sizes seen in internal fracture origins. This was in good agreement with the fatigue test results.

(3) Fatigue testing using the larger specimens demonstrated that the gigacycle fatigue strength of the double-melted steel was higher than that of the single-melted steel, while the difference between the two materials was not apparent when using conventional specimens.

(4) Extreme value analysis using the results for the larger specimens estimated that the inclusion size for 150 kg of the double-melted steel was no greater than 47 \(\mu\text{m}\), one third of that of the single-melted steel.
(5) These results indicate that fatigue testing using the larger specimens more precisely evaluated the gigacycle fatigue properties and the inclusion sizes of the high-strength steel.

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