Studies on Impact Fatigue

(Part V, Impact Fatigue Strength of 0.22%C Carbon Steel under -100°C Low Temperature Atmosphere)

By Tsuneshichi TANAKA** and Hideshi NAKAYAMA***

As a sequel of the impact fatigue investigation in -50°C low temperature atmosphere, a series of the fatigue tests in -100°C low temperature atmosphere were conducted. It was revealed that the impact fatigue strength became higher than the ordinary fatigue strength in the whole range of the stress cycles experimented, and this strength behavior can be interpreted such that the strain aging is hard to occur under both load conditions in such a low temperature atmosphere of -100°C, so that the fatigue strength is determined by the accumulation of the hysteresis energy only.

1. Introduction

Now, the general property as to the impact fatigue strength of the metallic materials has not been clarified yet sufficiently, so that a fundamental study to obtain the impact fatigue strength is needed as a matter of course. On the other hand, it would be important as an approach from a different aspect to study an impact fatigue behavior in the low temperature atmosphere. And from such a standpoint, in the 4th report of this series, the authors reported on the results of the fatigue test done in the low temperature atmosphere of -50°C as the first stage of the study on the low temperature impact fatigue.

The study reported here is a sequel of the 4th report, and the impact fatigue test was conducted using 0.22%C carbon steel as an experimental material in the low temperature atmosphere of -100°C. The descriptions for the specimen, testing machine and the testing procedure are omitted because they were same as those given in the 4th report.

2. Experimental results and discussion

The results of the fatigue test done at a low temperature of -100°C are listed in Table 1. The results are discussed from the strength and the inelastic strain behavior aspects in each section respectively.

2-1. Fatigue strength

The relation between the stress amplitude and the number of stress cycles to failure, which are listed in the 2nd and the 3rd columns of Table 1, is represented on S-N diagram in Fig.1.

![Fig.1 S-N curves](image)

Besides, the results of the approval tests done with the material used in this study (material "C") in the room temperature atmosphere being also represented in Fig.1, the ordinary fatigue limit of the material used in this study is estimated at about 15kg/mm².

At first, from the fatigue behavior under the sinusoidally varying load at a low temperature of -100°C, it can be seen that the fatigue strength gets higher by 4kg/mm² in comparison with the results of the approval test done at the room temperature because higher stress is needed at the low temperature to

---

* Received 27th May, 1974.
** Professor, Faculty of Science and Engineering, Ritsumeikan University, Kita-ku, Kyoto.
*** Assistant Professor, Faculty of Junior College of Automobile Industry, Osaka Industrial University, Daito-city, Osaka.
Table 1 Experimental results

<table>
<thead>
<tr>
<th>Test condition</th>
<th>Stress amplitude $\sigma_a$ (kg/mm²)</th>
<th>Number of stress cycles to failure $N$</th>
<th>Inelastic strain amplitude at $n/N = 50%$ $\varepsilon$ strain</th>
<th>Mean inelastic strain amplitude $\overline{\varepsilon}$ strain</th>
<th>Hysteresis energy $\Delta W$ (kg-mm/mm²)</th>
<th>Mean hysteresis energy $\overline{W}$ (kg-mm/mm²)</th>
<th>Cumulative hysteresis energy for failure $W$ (kg-mm/mm³)</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_c=800kg$</td>
<td>26.2</td>
<td>0.222×10⁵</td>
<td>1100.0</td>
<td>907.1</td>
<td>115.2×10³</td>
<td>95.1×10³</td>
<td>3.1×10³</td>
<td>Unbroken</td>
</tr>
<tr>
<td></td>
<td>25.1</td>
<td>0.242</td>
<td>1515.0</td>
<td>1476.2</td>
<td>115.2</td>
<td>148.2</td>
<td>3.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>24.1</td>
<td>0.216</td>
<td>390.0</td>
<td>440.5</td>
<td>76.2</td>
<td>40.6</td>
<td>12.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>23.9</td>
<td>11.172</td>
<td>295.0</td>
<td>231.8</td>
<td>22.8</td>
<td>22.1</td>
<td>24.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>23.0</td>
<td>88.009</td>
<td>330.0</td>
<td>265.2</td>
<td>20.4</td>
<td>24.4</td>
<td>219.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>22.9</td>
<td>75.239</td>
<td>250.0</td>
<td>221.1</td>
<td>22.9</td>
<td>18.4</td>
<td>128.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>21.9</td>
<td>&gt;1.0×10⁶</td>
<td>24.0</td>
<td>22.7</td>
<td>2.1</td>
<td>2.0</td>
<td>19.2</td>
<td></td>
</tr>
<tr>
<td>$C_L=0.02$ mm</td>
<td>26.8</td>
<td>0.512×10⁵</td>
<td>270.0</td>
<td>623.2</td>
<td>28.9×10³</td>
<td>66.8×10³</td>
<td>3.4×10³</td>
<td>Unbroken</td>
</tr>
<tr>
<td></td>
<td>26.5</td>
<td>2.628</td>
<td>225.0</td>
<td>376.7</td>
<td>23.9</td>
<td>39.9</td>
<td>10.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>24.8</td>
<td>20.999</td>
<td>40.0</td>
<td>37.0</td>
<td>4.0</td>
<td>3.7</td>
<td>7.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>24.4</td>
<td>99.768</td>
<td>265.0</td>
<td>273.2</td>
<td>27.3</td>
<td>26.6</td>
<td>265.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>24.0</td>
<td>71.168</td>
<td>167.0</td>
<td>153.0</td>
<td>16.6</td>
<td>14.7</td>
<td>104.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>23.5</td>
<td>150.286</td>
<td>186.0</td>
<td>157.7</td>
<td>16.9</td>
<td>14.7</td>
<td>223.0</td>
<td></td>
</tr>
<tr>
<td>$P_c=500kg$</td>
<td>21.7</td>
<td>2.001×10⁵</td>
<td>510.0</td>
<td>553.6</td>
<td>44.2×10³</td>
<td>480.0×10³</td>
<td>9.6×10³</td>
<td>Unbroken</td>
</tr>
<tr>
<td>Approval test in R.T.</td>
<td>21.4</td>
<td>12.580</td>
<td>397.0</td>
<td>349.9</td>
<td>34.0</td>
<td>29.7</td>
<td>27.3</td>
<td>Unbroken</td>
</tr>
<tr>
<td>18.2</td>
<td>&gt;1.361×10⁶</td>
<td>180.0</td>
<td>159.5</td>
<td>15.0</td>
<td>17.8</td>
<td>174.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>18.5</td>
<td>&gt;1.10×10⁷</td>
<td>185.0</td>
<td>159.5</td>
<td>15.0</td>
<td>17.8</td>
<td>174.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 2 Aspect of S-N curves under three temperature conditions

Fig. 3 Value of fatigue strength ratio under three temperature conditions
initiate and to propagate the fatigue damage nuclei than at the room temperature.

Next, from the strength behavior aspect under both load conditions at a low temperature of -100°C, it is observed that the impact fatigue strength is higher than the ordinary one over the whole range of the experimental stress cycles, and this trend is different from the impact fatigue characteristic mentioned previously by the authors.

From Fig. 1, the fatigue strength for the stress cycles of 10^7 under the sinusoidally varying load condition is estimated at about 23 kg/mm², and that under the impact load condition is at about 24 kg/mm².

All the experimental results obtained in the experiments done in three sorts of the temperature atmosphere, i.e., room temperature, -50°C and -100°C using 0.25%C carbon steel as an experimental material are represented in Fig. 2 schematically. From the aspect of the variation of the fatigue strength accompanied with a lowering of the temperature atmosphere, it is said, under the sinusoidally varying load, that the strength at a low temperature of -50°C is higher than that at the room temperature, but there exists only a little difference of 1 kg/mm² at most between the strengths under both load conditions of -50°C and -100°C. And the slope of the S-N curve seems to become gentle with a lowering of the testing temperature.

Furthermore, estimating the impact fatigue strength at 10^7 stress cycles, it is observed that the strength at -50°C low temperature is higher than that at room temperature by about 4 kg/mm², moreover, the strength gets higher by 3 kg/mm² at -100°C low temperature.

To discuss such a strength variation accompanied with a lowering of the testing temperature in connection with the static strength, the value of the fatigue strength ratio $\sigma_{\text{f}}/\sigma_{\text{u}}$ under both load conditions are plotted against the testing temperatures in Fig. 1. According to the results of the low temperature fatigue tests reported up to the present, it is known that the value of $\sigma_{\text{f}}/\sigma_{\text{u}}$ rises following the lowering of the testing temperature for the carbon steels, while on the other hand, this value is held constant or gets lower with a lowering of the testing temperature for the alloys. In this study, it was observed that the value of $\sigma_{\text{f}}/\sigma_{\text{u}}$ got higher continuously under the impact load, but this value fell again at -100°C low temperature after the peak value observed at -50°C low temperature under the sinusoidally varying load.

2-2. Inelastic strain behavior and low temperature impact fatigue behavior

In this experiment, the inelastic strain generated on the specimen surface during the fatigue process was measured with the strain gages mounted on the specimen. And the discussion was made based on the inelastic strain amplitude $\Delta e_{\text{in}}$ and the hysteresis energy $\Delta W$.

2-2-1. Inelastic strain amplitude and low temperature impact fatigue behavior

The aspect of the variation of the inelastic strain amplitude under the sinusoidally varying load condition is shown in Fig. 4, which is an observational result of the approval test done at the room temperature with the material used in this study (material "C"), where, in the cycles ratio r/N(%) taken as the abscissa, n is the number of cycles, and the ordinate, $\Delta e_{\text{in}}$ is the inelastic strain amplitude.

![Fig. 4 Variation of the inelastic strain amplitude (R.T., Fc=500kg)](image)

![Fig. 5 Variation of the inelastic strain amplitude (-100°C, Fc=500kg)](image)
number of stress cycles when the observation was done and N is the number of stress cycles to failure or the number of stress cycles when the experiment was finished without the specimen coming to failure.

From Fig. 4, the characteristic of the variation trend is clearly observed. That is, the fatigue failures occurred after a gradual increase of the inelastic strain amplitude which followed a distinct fatigue softening-hardening stage in the early life fraction.

On the other hand, as to the unbroken specimen (●), the aspect of the saturation or the hardening is observed after a gradual increase up to 200μstrain at most.

The aspects of the variation of the inelastic strain amplitude at a low temperature of -100°C are represented in Figs. 5 and 6 respectively. It can be seen from these figures that the variation trend at -100°C low temperature differs from that at room temperature shown in Fig. 4.

At first, as to the variation under the sinusoidally varying load shown in Fig. 5, the fatigue softening-hardening phenomenon observed at the room temperature is not observed in such a temperature condition, the inelastic strain amplitude increases continuously following an increase of the stress cycles, and finally failures occur. Besides, the reason why the inelastic strain amplitude increases considerably rapidly is probably that the motion of the dislocations multiplied is not restrained by the solute atoms such as carbon and nitrogen.

On the other hand, the unbroken specimen (●) showed a little value of the inelastic strain amplitude of about 20μstrain in the whole range of the experimental stress cycles. This behavior suggests that the magnitude of the stress amplitude ε₀ = 21.9kg/mm² is not such a value as to move the locked dislocations existing from the beginning.

Then, from Fig. 6 showing the aspect of the variation under the impact load, it can be said as follows. That is, though the trend of the variation is similar to that under the sinusoidally varying load, the rapid increasing stage of the inelastic strain amplitude is delayed to a certain degree in comparison with that under the sinusoidally varying load. And it is observed that the fatigue failure occurred with the inelastic strain amplitude of about 40μstrain over the whole stress cycles range for the specimen under the stress amplitude ε₀ = 24.8kg/mm² (●).

The above discussion is done from the standpoint of the trend of the variation of the inelastic strain amplitude. Then a discussion from the quantitative aspect is made. For this purpose, the relation between the mean inelastic strain amplitude ∆ε_mean and the number of stress cycles to failure is represented on the log-log paper in Fig. 7. Though it has been an ordinary

![Fig. 7](image_url)

**Fig. 7** ∆ε_mean - N curve

![Fig. 8](image_url)

**Fig. 8** Relation between ∆ε_mean and ε_0
way to take the value of $\Delta h_{50}$ which was the value at the stress cycles ratio $R=50\%$ as a representative value on the occasion of such a discussion, the mean value against the number of stress cycles, $\Delta h_{\text{mean}}$ was selected as the representative value instead of $\Delta h_{50}$ because the trend of the variation was not a regular one and moreover the range of the variations was considerably wide in this experiment.

From Fig. 7, where the results of the load tests are given too, it can be said as follows: At first, the results under the sinusoidally varying load well agree with the results of the approval test. And, though it was mentioned in the 4th report of this series, that the value of 200 stress cycle was defined as the endurance inelastic strain amplitude under both temperature conditions of the room temperature and the low temperature of $-50^\circ\text{C}$, by designating the stress cycles of 10 a value of about 200 $\mu$strain is to be accepted as the endurance inelastic strain amplitude too in this study. Thus the magnitude of the inelastic strain amplitude seems to be a regulating factor for the fatigue failure in the range of this experiment.

In comparison with the relation $\Delta h_{\text{mean}}$ and $N$ under the sinusoidally varying load as mentioned above, it is said that the fatigue failure occurred with less value of the inelastic strain amplitude under the impact load, and, such a trend is consistent with the impact fatigue characteristic from the inelastic strain behavior aspect revealed by the authors. However, as a whole, the discrepancy observed under both load conditions in this study is not so large as that observed at room temperature or $-50^\circ\text{C}$ low temperature. Next, the value of the inelastic strain amplitude generated under both load conditions at $-100^\circ\text{C}$ is plotted against the stress amplitude in Fig. 8. Besides, the results obtained in the experiment done under the sinusoidally varying load and at the room temperature with the material used in the material "A" are shown as a broken line, and the results of the approval test done under the same testing condition as mentioned above with the material used in this study (material "C") are also represented in this figure.

In this relation obtained in the experiments done with 0.53% carbon steel and 59.9% pure aluminum of commercial base reported in the 2nd and 3rd reports respectively, it could be observed that there did not exist any discrepancy due to the difference of the load condition in the high stress amplitude range, but that a larger inelastic strain amplitude was generated under the impact load than under the sinusoidally varying load in the low stress amplitude range. And, it was speculated that this inelastic strain behavior under the impact load was due to the disturbance of the impact load pattern.

By the way, referring to the relation at $-100^\circ\text{C}$ low temperature shown in Fig. 8, it is observed that less inelastic strain amplitude is generated under the impact load than under the sinusoidally varying load both conditions in the whole testing stress amplitude range. And this trend of the inelastic strain behavior is same as that observed in a series of the experiments done at room temperature with the material used in this study.

A quantitative difference of the inelastic strain amplitude generated under both load conditions seems to be the effect of the load pattern. From the figure, it is considered that the sinusoidally varying load is more effective than the impact load to generate the inelastic strain.

2-2-2. Hysteresis energy and low temperature impact fatigue behavior

In this article, a discussion based on one of the parameters obtained from the hysteresis loop, i.e., the hysteresis energy is made. The meaning of the hysteresis energy $\Delta W$ is same as that explained in the previous report.

At first, the relation between the mean hysteresis energy per unit stress cycle $\Delta W_{\text{mean}}$ and the number of stress cycles to failure $N$ is represented in Fig. 9. As shown in this figure, this relation under the sinusoidally varying load and at $-100^\circ\text{C}$ low temperature agrees with the results of the approval test conducted at room temperature. Then, from the comparison of this relation under the sinusoidally varying load with that under the impact load, it can be said that, though there existed a case where the impact fatigue failure occurred with a little value of $\Delta W_{\text{mean}}$ with which the ordinary fatigue failure did not occur, for example the impact fatigue failure with $\Delta W_{\text{mean}}=2.7\times10^{-3}$, there was not any distinct difference due to the difference of the load pattern as observed in the previous report was observed in this study as a whole.

And from Fig. 10 showing the relation between the mean hysteresis energy and the stress amplitude under both load conditions, it can be observed that the value of the hysteresis energy generated under the impact load is less than that under the sinusoidally varying load in the whole stress amplitude range,
and this trend is similar to the relation between $\Delta \theta_{\text{mean}}$ and $\Delta \alpha$ shown in Fig. 8.

Next, to discuss the low temperature fatigue behavior under both load conditions from the standpoint of the accumulated hysteresis energy, the aspect of the hysteresis energy accumulation is shown against the number of stress cycles in Fig. 11. As to the trend of the hysteresis energy accumulation, there exists no discrepancy, and as to the relation between the accumulated hysteresis energy needed for failure and the number of stress cycles to failure, there exists no difference either except for the plot of the impact fatigue failure which occurred with $W = 7.7 \times 10^6$ kg-mm/mm$^2$, and a broken line is adopted as a boundary line for the fatigue failure under both load conditions. That is, considering the results shown in Fig. 11 as a whole, it can be said that the ordinary and the impact fatigue failures occurred with almost same amount of the accumulated hysteresis energy in the case of this experiment.

Furthermore, all of the relations between the accumulated hysteresis energy for failure and the number of stress cycles to failure obtained in a series of the experiments done under the three temperature conditions of room temperature, $-50^\circ \text{C}$ and $-100^\circ \text{C}$, low temperatures using 0.22% carbon steel as the experimental material are shown in Fig. 12, where a boundary band for failure with a breadth of scattering which envelopes the experimental results under the sinusoidally varying load is drawn.

From Fig. 12, it can be observed that the plots for the impact fatigue failure lie mainly on the lower side of the boundary band, and this trend under the impact load becomes distinct in higher stress cycles range than $10^7$ stress cycles. Such an appearance of the impact fatigue characteristic suggests that a long life fatigue test is needed to discuss the impact fatigue strength more precisely.

From the above discussion, it seems to be impossible, to correlate the phenomenon from the strength and the inelastic strain behavior aspects observed in this study, to make an assumption such as done in the 2nd report of this series, i.e., the localization of the inelastic strain behavior. Referring to the results of this experiment, it is said that...
the load varying pattern of the impact load did not so much attribute to the inelastic strain as the sinusoidally varying load, while nearly the same amount of the accumulated hysteresis energy was needed under both load condition, so that, the fatigue strength under the impact load became higher than that under the sinusoidally varying load because more stress cycles were needed to accumulate the hysteresis energy under the impact load.

Besides, the discussion done above is interpreted such that the strengthening mechanism during the fatigue process due to the strain aging is hard to function at -100°C low temperature. That is, though it was considered as one of the reasons for the lowering trend of the fatigue strength under the impact load that the strain aging was hard to occur under the impact load, as shown from the aspect of the S-N curve under both load conditions at the room temperature, this trend shown at room temperature vanished at -100°C low temperature because the strain aging did not occur under both load conditions in -100°C low temperature atmosphere. Thus the fatigue failure at such a low temperature is to be estimated only from the initiation and the growth of the fatigue damage nuclei during the fatigue process, which can be detected as an inelastic strain. From the above consideration, a discussion based on the accumulated hysteresis energy for failure becomes possible.

3. Conclusions

Following the previous report on the impact fatigue behavior at -50°C low temperature, a series of the fatigue tests in -100°C low temperature were conducted using 0.22% carbon steel as an experimental material. The results were discussed from the strength and the inelastic strain behavior aspects. Major conclusions obtained are as follows.

(1) As to the strength aspect, it was observed that the fatigue strength under the impact load was higher than that under the sinusoidally varying load in the whole stress cycles range experiment, which differed from the former results obtained. However, though it seems to be possible to consider that the intersection of these S-N curves occur, and so the fatigue strength under both load conditions are reverse to each other, this was not confirmed because of the restriction in the testing condition.

(2) Taking notice of the inelastic strain amplitude under the sinusoidally varying load, the relations between the inelastic strain amplitude and the number of stress cycles to failure obtained in the experiments done at the room temperature, -50°C and -100°C low temperature were similar qualitatively and quantitatively to one another. Furthermore, The yield of the inelastic strain amplitude of about 20% strain could be adopted as the endurance inelastic strain amplitude in -100°C low temperature as well as in other temperature conditions. And, though there existed a case where the impact fatigue failure occurred with less value of the inelastic strain amplitude than that of the endurance inelastic strain amplitude, the discrepancy was a little as a whole.

(3) Referring to the relation between the hysteresis energy generated under the impact load, the unit stress cycles number and the fatigue failure, the difference of the trend due to the difference between both load conditions observed at room temperature and -50°C low temperature vanished at -100°C low temperature. And only a little discrepancy could be observed as a whole though there existed a case where the impact fatigue failures occurred with less value of it.

(4) The values of the inelastic strain amplitude and the hysteresis energy generated under the impact load were small in comparison with those under the sinusoidally varying load, which suggested that the sinusoidally varying load was more effective to generate the inelastic strain than the impact load at such a low temperature.

(5) Strength behavior at -100°C low temperature mentioned in (1) in this can be discussed as follows from the standpoint of the inelastic strain behavior. That is, the fatigue failure can be estimated from the inelastic strain behavior detected with the strain gauge mounted on the specimen surface, because the promoting mechanism of the fatigue damage nuclei depending on the load pattern of the impact load does not function due to the non-existence of the strain aging at -100°C low temperature.

Considering the experimental results based on such an estimation and the description above it seems that the ordinary fatigue strength gets higher than the impact fatigue strength because more stress cycles are needed to accumulate the hysteresis energy under the impact load than under the sinusoidally varying load.
References


(8) Hildesheimer, H., ETH (Zürich, Switzerland) Promotionarbeit, No. 2783 (1959).