Effect of Mean Stress on Fatigue Strength
of Carburized Steel*

By Toru HAYAMA** and Hiroyuki YOSHITAKR***

Although it is known that the fatigue strength of carburized steel is greatly influenced by the residual stress on the surface, it is very difficult to assess the effect quantitatively. In this report, the effect of mean stress on the fatigue strength of carburized steel is studied, and therefrom the effect of residual stress can be estimated.

Following results are obtained.
1) The fatigue strength of a high hardness and brittle steel, is more sensitive to mean stress, as compared to those of medium and low hardness steels.
2) As the Tempering temperature of carburized steel is increased, the effect of mean stress on the fatigue strength decreases.
3) During the fatigue test little change was observed in the residual stress and half value breadth of X-ray diffraction line of carburized steel.

On the basis of these results, the mechanism of fatigue failure of carburized steel was discussed.

1. Introduction

Although many papers have been presented about the effect of mean stress on the fatigue strength of metals, the following problems are left unsolved from the view point of designing.

1) the effect of compressive mean stress on the fatigue strength.
2) the effect of mean stress on the fatigue strength of hardened materials.

When a pulsating load is applied to a gear tooth, fatigue cracks are observed on the root fillet of the compression side (where compressive stress is repeated), although the crack does not lead to a final failure of the gear teeth(1). Hence, in order to determine the allowable stress, it is necessary to know the effect of mean stress on the fatigue strength, especially the fatigue behavior under compressive mean stress.

Generally, it is known that the effect of mean stress is indicated, on a mean stress-fatigue strength diagram, by a straight line through the two points representing the fatigue strength under completely reversed condition, and the true fracture strength (or sometimes tensile strength).

If this criterion is applied to hardened steel, it would be concluded that the effect of mean stress becomes less as hardness increases, because the fatigue strength does not increase as much as the static strength does. It is doubtful if it is true.

Moreover, since it is now one of the major problems in the study of fatigue phenomenon to know the effect of residual stress on the fatigue strength of hardened steel, it seems

<table>
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<th>Table 1 Chemical compositions (%)</th>
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<tr>
<td>C</td>
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<td>S 45C</td>
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<td>SNC21 (Notched)</td>
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<td>SNC 21 (Smooth)</td>
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important to elucidate the effect of mean stress to assess the effect of residual stress. In this paper, the effect of mean stress on the fatigue strength of carburized steel and quenched and tempered medium carbon steel has been investigated.

2. Specimen and testing method

Steel used in this investigation were S45C (0.45% carbon steel), and SNC21 (nickel-chromium low alloy steel), the chemical compositions and the mechanical properties of which are shown in Table 1.

The procedures for the preparation of specimens were as follows. The material for S45C specimens was received in the form of 60 mm diameter round bars, and forged into 10 mm thick plates. Then they were quenched (850°C) and tempered (550°C), and machined into the final shape of the specimens. The material for carburized SNC21 specimens was received in the form of 70 mm diameter round bars. They were annealed at 880°C, machined into the final shape of the specimens except the part of grip, and carburized according to the procedure shown in Fig. 1.

The tempering temperature of the smooth specimens was selected higher than that of the notched specimens, in order to make the residual stress measurement by X-ray easy. Finally, the grips of all the carburized specimens were finished by grinding.

The dimensions of the specimens are illustrated in Figs. 2 and 3.

Notched specimens with a circular notch only on one side were used, because the magnitude of the compressive stress on the notched side could be made larger than that of the tensile stress on the flat side when a bending moment was applied to the specimen.

This was necessary for investigating the fatigue damage caused by cyclic compressive

![Fig. 1 Condition of carburizing, quench and temper](image)

![Fig. 2 Notched specimen (in mm)](image)

![Fig. 3 Smooth specimen (in mm)](image)

![Fig. 4 Stress distribution on cross section of the notched specimen](image)

<table>
<thead>
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<th>Table 2 Mechanical properties of the specimens</th>
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<td>Yield point</td>
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<td>S 45C</td>
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stress.

The stress distribution in this specimen was calculated by Tamate\(^{(2)}\) as illustrated in Fig. 4. The hardness distributions on the critical section of specimens are shown in Fig. 5. The difference in hardness distribution between notched and smooth specimens is thought to be due to the difference in thickness and tempering temperature.

Examples of micro-structure on the surface of the specimens are shown in Fig. 6. The unusual structure, which is often found on the surface of a carburized machine component, was not observed at all.

A Shenck type plane bending fatigue testing machine with a capacity of 4 kgf m was used in this experiment. The frequency of loading was 3,000 cpm. For the residual stress measurement, a parallel beam type X-ray strain measuring apparatus, made by Toshiba Co. was used. The measuring condition is tabulated in Table 3, and residual stresses were determined by the \(\sin^{\circ}\) method.

3. Experimental results

3-1 Fatigue test results on notched specimen

First, in order to clarify the effect of mean stress on the fatigue strength of quenched and tempered S45C, fatigue tests under pulsating tension, completely reversed, and pulsating compression were carried out.

In this paper, the pulsating tension and the pulsating compression mean pulsating bending, in which the direction of bending moment is selected in such a way that the stress on the notch root may become tension and compression, respectively.

The test results are shown in Fig. 7.

The process of failure of notched S45C specimens under pulsating tension was similar to that of gears. First, a fatigue crack initiated on the notch root (where compressive stress was repeated), propagated to some extent, and then stopped propagating. When a fatigue crack initiated on the other side (tension side without
notch), the specimen failed. And so long as
the fatigue crack on the other side did not
initiate, the specimen survived until the test
was terminated.

The S-N curve for pulsating compression
shown in Fig. 7 indicates the number of cycles
to failure when the failure originated from the
opposite side of the notch, and the mark "*" represnts the specimens which survived with
nonpropagating cracks on the notch root. It is
noteworthy that the endurance limit for crack
initiation under pulsating compression was
28 kg/mm², which is the same as that under
completely reversed. An example of the non-
propagating cracks observed on the notch root
is shown in Fig. 8.

The results of fatigue tests carried out on
carburized specimens are shown in Fig. 9. In
the test of pulsating compression on carburized
specimens, no fatigue crack was observed on
the notch root, and all the specimens failed
from the opposite side of the notch.

From these tests and some additional tests,
a mean stress-fatigue strength diagram, or the
so called endurance limit diagram, as shown in
Fig. 10 was obtained.

According to the diagram, the angle between
the horizontal axis and the line, representing the
endurance limit, or the so called endurance limit
line, of carburized steel is very close to 45 deg.
This indicates that the effect of mean stress
on the fatigue strength of this kind of materials
is great.

It is also noteworthy that no crack was
observed on the notch root in the fatigue test
under pulsating compression in the case of
carburized steel. This phenomenon could easily
be understood, from the following:

(1) The fatigue strength of carburized
steel under compressive mean stress is much
greater than that under tensile mean stress.

(2) The fatigue crack observed on the
notch root of S45C specimen under pulsating
compression is considered to have propagated
to some extent, because the compressive mean
stress was reduced during the fatigue test due
to the redistribution of the stress around the
notch root. Meanwhile, in the case of carburized
steel, the resistance to plastic deformation was
so high that the redistribution could not occur,
and thus a crack could not have propagated
even if it had initiated.

3-2 Reversed fatigue test

The effect of mean stress on the fatigue
strength for the final fracture has been dis-
cussed in the previous section. The process of
fatigue failure can be divided into two stages,
that is the stage of crack initiation and that
of crack propagation (the concept of crack here
includes a submicro crack).

Since mean stress is supposed to be effective
in the second stage, it is thought possible that
the specimens surviving under pulsating compres-
sion could have been damaged, and would have
failed easily by the cyclic tensile stress even if
the amplitude of tensile stress had been very
small. In the case of a similar experiment on
brass done by Nishitani and Yamashita, mean stress was effective only in the second stage(3).

The fatigue damage caused by cyclic compressive stress was investigated by carrying out a fatigue test of wave form shown in Fig. 11. In this fatigue test, "N₀" cycles of compressive stress were first repeated on the notch root. Then the pulsating tension test as mentioned above was carried out. The amplitude of the "N₀" cycles of compressive stress before the pulsating tension test was set equal to that of pulsating tension test. The test result on S45C specimen is shown in Fig. 12.

The curve drawn in the figure represents the result of pulsating test, already shown in Fig. 7. This curve corresponds to the case of "N₀"=0.

There is no appreciable difference between the results of the reversed test ("N₀"=5×10⁶, 6×10⁶) and pulsating tension test ("N₀"=0). This means that the fatigue damage done by cyclic compressive stress can be neglected, at least when the amplitude of compressive stress is less than the endurance limit under pulsating compression.

However, when the stress amplitude was 28 kg/mm² or larger, a fatigue crack was initiated on the notch root by the cyclic compressive stress, and the specimen failed within 10⁶~10⁷ cycles of tensile stress.

The result of the reversed test on carburized specimens is shown in Fig. 13. The fatigue damage caused by cyclic compressive stress can also be neglected at least when the amplitude of cyclic compressive stress is not much larger than the endurance limit under pulsating tension. The data under the amplitude much larger than the endurance limit under pulsating tension could not be obtained because the specimens failed at the opposite side of the notch under the pulsating

---Direction of bending stress

Fig. 14 Change in micro structure on the surface of S45C specimen caused by cyclic compressive stress
compression before the pulsating tension test.

The conclusion that the fatigue damage caused by cyclic compressive stress can be neglected, is inconsistent with the results by Nishitani or Taira et al.\(^4\) In order to investigate this point in detail, an observation of the change in the micro-structure on the notch root by cyclic compressive stress was made using an optical microscope.

In the case of S45C specimen, the change in the microstructure shown in Fig. 14 was observed, even though the stress amplitude was less than the endurance limit under pulsating compression. This change appears to be the fatigue damage. The reason why the damage did not shorten the fatigue life under pulsating tension was possibly that this specimen was notched and the process of crack propagation rather than the crack initiation was dominant in the whole fatigue life.

On the other hand, no change in microstructure was observed in the case of carburized steel.

3-3 Fatigue test on smooth specimens

It was mentioned in the previous section that the effect of mean stress on the fatigue strength of carburized steel was much greater than that of relatively soft materials. But, in Fig. 11, the effect of residual stress was not taken into account because the residual stress on such a notch root could not be measured.

In order to obtain an endurance limit diagram in which the residual stress is regarded as mean stress, fatigue tests on carburized smooth specimens were carried out, and the residual stress on the specimens was measured.

The result of the fatigue test is shown in Fig. 15. On the other hand, according to the result of residual stress measurement, the residual stresses on the surface of the specimens were within the range of \(\pm 5 \text{ kg/mm}^2\), and could be regarded as zero, considering the scatter of the residual stress and the accuracy of the measurement. These results of residual stress measurement could be understood by considering the hardness distribution shown in Fig. 5. From the results of the fatigue test and the measurement of the residual stress, an endurance limit diagram as shown in Fig. 16 was obtained.

It is clear that the slope of the endurance limit line for the carburized smooth specimen (270°C tempered) is much steeper than that for S45C notched specimens, although it is not so steep as that for the carburized notched specimens (200°C tempered).

3-4 The change in residual stress and half value breadth in process of fatigue

The change in the residual stress and half value breadth of X-ray diffraction line, from the carburized smooth specimen, caused by the cyclic stress, was investigated.

![Fig. 16 Endurance limit diagram for carburized smooth specimen (compared with that for notched specimen)](image)

![Fig. 17 Change in residual stress in the process of fatigue](image)
The behavior of the residual stress in the fatigue process is shown in Fig. 17, the ordinate of which represents the sum of the residual stress and mechanically applied mean stress. Since the residual stress in the specimen was almost zero, mechanical mean stress which is assumed to be equivalent to residual stress was applied, and a change in the residual stress caused by cyclic stress was investigated. The horizontal lines in the figure represent the mechanically applied mean stress, and the deviations from the line represent the residual stress.

According to these results, the change in the residual stress is very little and can be neglected practically. This indicates that the residual stresses in the cases of carburized specimens or machine parts do not change even if the applied alternating stress is larger than the endurance limit, as long as a plastic deformation does not take place in the core. Generally, since the residual stress in the case (or on the surface) exists so as to balance with the residual stress in the core, if a plastic deformation occurs in the core, the residual stress in the case will change along with that of core.

From this point of view, in order to discuss the relaxation of residual stress, it is insufficient to consider only the behavior of the case, and it is necessary to consider the hardness distribution, the residual stress distribution and the stress distribution due to the external load.

Considering the result mentioned above, it was supposed to be rather important to discuss the plastic deformation in the core, for prediction of the residual stress relaxation.

The change in the half value breadth of X-ray diffraction line, from the carburized smooth specimen, in the process of fatigue, is shown in Fig. 18. The half value breadth was obtained by taking photographs of diffraction patterns and taking the profile as a blackness distribution on the film, using a microphotometer.

![Graph showing change in half value breadth of X-ray diffraction line](image)

Fig. 18 Change in half value breadth of X-ray diffraction line in the process of fatigue

X-ray used in this experiment was Cr -Kα, and a double pinhole collimator of 1 mm diameter was used for collimation. According to the research by Taira, half value breadth of materials such as annealed or plastically deformed low carbon steel changes in the process of fatigue failure.

Meanwhile, as shown in Fig. 18, no change was observed in the half value breadth of carburized steel, even if the stress amplitude of alternating stress is 1.4 times as large as the endurance limit under pulsating tension.

3-5 Discussion on mechanism of fatigue failure of carburized steel

By reviewing these experimental results, we can find that the characteristics of the fatigue behavior of carburized steel are not the same as those of relatively soft materials, which have now been made clear by many researchers.

For instance, the effect of mean stress on the fatigue strength of carburized steel is much greater than that of relatively soft materials.

Moreover, while almost no change was observed in the residual stress and the half value breadth in the fatigue process of carburized steel, a considerable change was observed in the residual stress and the half value breadth in the fatigue process of relatively soft materials. This seems to suggest that we should distinguish between soft materials and hardened material, in discussing the mechanism of fatigue failure.

Morrow et al.\(^{(3)}\) paid special attention to the fact that as hardness increase, the fracture in the test of static torsion changes from shear mode to tensile mode.

He extended this idea of the transition from shear to tensile mode to fatigue failure.

In the case of soft materials, repeated slip plays a very important role in the fatigue failure. The role of repeated stress is thought to be that of increasing the stress or decreasing the strength so that a local rupture can take place. Hence, the resistance to slip is the controlling factor in fatigue failure. On the other hand, at high hardness, the resistance to slip is less important or it is no longer the controlling factor in fatigue. The material itself is brittle enough and a local rupture can take place with a little repeated slip. Instead, maximum tensile stress is supposed to be important in the process of local rupture of hardened steel.

This theory can explain the behavior observed in this investigation, concerning the effects of mean stress, change in residual stress and half value breadth, and change in micro-
structure.
Next, the difference between the slope of the endurance limit line for notched specimens (200°C tempered) and that for smooth specimens (270°C tempered), in Fig. 16, was discussed. Strictly speaking, since the shape and the residual stress of these two kinds of specimens were different, the results obtained from them could not be compared directly.

However, considering that a fatal fatigue crack of a hardened material initiates in a very small region, the test results could be compared in terms of maximum stress, such as maximum stress on the notch root. On the basis of this idea, both mean stress and alternating stress of the notched specimen were multiplied by 1.5 (the theoretical stress concentration factor), and were compared with those of smooth specimens.

While the residual stress of the notched specimen is unknown, the effect of residual stress is thought to be expressed as the parallel shift of the endurance limit line, as long as the relaxation of residual stress is negligible.

Hence, the difference in the slope of the endurance limit line between them can be regarded as the expression of the difference in metallurgical factors.

According to the figure, the slope of the endurance limit line for the carburized and 200°C tempered steel is much steeper than that for the carburized and 270°C tempered steel.

For reference, photographs of X-ray diffraction lines of both specimens are shown in Fig. 19. These photographs indicate that the diffraction line of 200°C tempered is much broader than that of 270°C tempered.

It is supposed that as the broadness of the line increases, the resistance to slip or shear mode fracture increases, but on the contrary, resistance to tensile mode fracture decreases.

The difference in the effect of mean stress can be attributed to this aspect of mechanical behavior of materials.

In conclusion, increasing the hardness is equivalent to increasing the resistance to slip or shear mode fracture, but this does not necessarily correspond to increasing the fatigue strength. Especially, sometimes under high tensile mean stress, the fatigue strength decreases as hardness increases. In order to use hardened materials effectively, it is important to use them under compressive residual stress or mechanically applied compressive mean stress.

4. Conclusions

Plain bending fatigue tests on a carburized steel and a quenched and tempered medium carbon steel were carried out and the effect of mean stress on the fatigue strength of these materials was discussed. In addition, the fatigue damage caused by cyclic compressive stress was also discussed. Following conclusions were obtained.

(1) The effect of mean stress on the fatigue strength of a hardened steel, such as a carburized steel, is much greater than that of relatively soft materials. In order to use hardened materials effectively, it is important to use them under high compressive residual stress or mechanically applied compressive mean stress.

(2) Sensitivity to mean stress of the fatigue strength of a carburized steel is reduced by tempering it at high temperature.

(3) Almost no change in the residual stress and half value breadth of X-ray diffraction line was observed in the pulsating bending tests on a carburized steel. This seems to
indicate that only little a cyclic plastic strain is necessary for the fatigue failure of a carburized steel.

(4) The fatigue damage caused by cyclic compressive stress is negligible, when the amplitude of compressive stress is comparable to the fatigue limit under pulsating tension.

(5) When the notch root of notched specimens of a relatively soft material, such as a quenched and tempered medium carbon steel, was subjected to cyclic compressive stress, a fatigue crack initiated, propagated to some extent, and stopped propagating.

5. Acknowledgement

The authors wish to express their special thanks for the useful advice given by Prof. Taira of Kyoto Univ. concerning the X-ray approach to the problem of the mechanical behavior of materials.

6. References

(5) Morrow, J., et al., Int. Conf. on Fracture, Sendai, (1965).