Bending Fatigue Strength of Carburized Gears with an Artificial Notch at the Fillet*

Gang DENG**, Tomoya MASUYAMA***, Masana KATO**** and Katsumi INOUE***

The fatigue strength of carburized gears is influenced by the latent defect in the surface layer. To clarify this influence, the bending fatigue strength of carburized gears with an artificial notch is evaluated in this paper. The notches are processed by wire-cut electrical discharge machining (WEDM) and focused ion beam (FIB) etching to obtain the required depth. The fatigue strength of the tooth with the notch over 35 μm in depth decreases markedly in comparison with the nonnotched tooth. In the case where the notch is shallower than 20 μm, cracks initiated from the notch are not observed and the strength is not reduced. By assuming a crack of the same length as the notch, the stress intensity factor \( K_I \) is calculated considering the effect of residual stress. The strength expected from the stress intensity factor range is higher than the obtained strength of the gear with the notch.

**Key Words:** Gear, Notch, Fatigue, Fracture Mechanics, Nontraditional Machining, Wire-cut Electric Discharge Machining, Focused Ion Beam, Surface Integrity

1. Introduction

The load capacity of the power transmission gears is evaluated by comparing the working stress with the allowable stress, which is usually determined by the modification of the fatigue strength by the factor-of-safety. In recent years, the requirements for gear design have become strict, because our industry regards the achievement of lightweight machines, speed-up and increase of transmitted power as very important. However, the traditional method of design including factors of considerable margin, such as the factor-of-safety, cannot fully meet the requirements. Therefore, development of new methods for precise and reliable rating of load capacities are required.

Carburization is commonly used for heavy duty gearing because the hardened layer and residual stress enhance its strength. We have presented an experimental formula to express their influences. We have also evaluated the strength of carburized gears based on the linear fracture mechanics considering the effect of the residual stress and hardness distribution. These researches demonstrated that the fatigue strength of carburized gears should be evaluated from the viewpoint of the fatigue crack propagation and the crack initiation, the key to the evaluation was greatly influenced by the degree of surface integrity. The most notable surface integrity is considered with regard to the size of the latent defect in the surface layer. The latent defect involves the roughness of a machined surface, and presence of inclusions and voids in materials. In ordinary high-strength materials, the fatigue crack is initiated from the latent defect in the surface layer and propagates toward the core.
Table 1  Dimensions of test gears

<table>
<thead>
<tr>
<th>Tooth form</th>
<th>Standard spur gear</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure angle</td>
<td>20 deg</td>
</tr>
<tr>
<td>Module</td>
<td>5mm</td>
</tr>
<tr>
<td>Number of teeth</td>
<td>18</td>
</tr>
<tr>
<td>Face width</td>
<td>8mm</td>
</tr>
<tr>
<td>Cutter</td>
<td>ISO basic rack</td>
</tr>
<tr>
<td>Material</td>
<td>SCM415</td>
</tr>
<tr>
<td>Heat treatment</td>
<td>Carburization</td>
</tr>
<tr>
<td>Effective case depth</td>
<td>0.75mm</td>
</tr>
</tbody>
</table>

Table 2  Chemical composition of SCM415 (wt%)  

<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Mo</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.13-0.18</td>
<td>0.15-0.30</td>
<td>0.60-0.80</td>
<td>&lt;0.03</td>
<td>&lt;0.03</td>
<td>0.90-1.20</td>
<td>0.15-0.30</td>
</tr>
</tbody>
</table>

Fig. 1  Heat treatment of test gears

Fig. 2  Hardness at the fillet of test gears

Fig. 3  SEM image of the martensite and the nonmarten-sitic layer

To illustrate the strength of materials with a crack or defect, a diagram called Kitagawa-plot(4), which indicates the threshold stress of crack propagation against the size of defect or crack length, is used. Taylor and Clancy(5) showed that the strength of alloy steel under various surface conditions was represented by the Kitagawa-plot by considering the roughness instead of the crack length. Similarly, the crystal pore size is considered as the size of defect to indicate the strength of ceramics(6). Murakami et al.(7) studied the fatigue strength of annealed steels S10C and S45C by drilling a small hole, and found the existence of the threshold diameter of the hole, at which the fatigue strength was not affected. They showed that the threshold hole size was related to the arrested crack size.

Murakami et al.(9) and Maikuma et al.(10) carried out similar experiments to obtain the critical size for the high strength steels. However, they could not obtain it, because the hole size would have to be very small and the processing of such a small hole was not easy. As mentioned above, to determine the threshold defect size for carburized gears is very important for strength evaluation. In this study, therefore, artificial micronotches are used as a measure for the latent defect, and the threshold notch depth for the carburized gears is obtained. The micronotches are artificially processed by wire electrical discharge machining (WEDM) and focused ion beam (FIB) etching at the fillet of the tooth, and the fatigue bending test is performed to determine the critical notch depth which decreases the strength.

2. Fatigue Strength of Gear without a Notch

The dimensions of the test gear used for this experiment are shown in Table 1. The gear blanks...
are made of low-alloy steel SCM415. The chemical composition of the alloy is standardized as shown in Table 2. The heat treatment condition is shown in Fig. 1. Before hobbing, the blanks are copper-plated to a thickness of about 20 μm to prevent the gear sides from carburizing. As a result, the hardness distribution and the metallurgical structure are almost uniform in the direction of the face width. The hardness distribution measured toward the depth at the fillet is shown in Fig. 2. Figure 3 shows a scanning electron microscope (SEM) image at the fillet. Although the structure in the deeper regions is martensite, the nonmartensitic layer is observed at the surface. The boundary of the 5 to 20-μm-thick nonmartensitic layer is not parallel to the tooth profile.

An electrohydraulic servo-controlled fatigue tester is used in the test. The diagram of the tester is shown in Fig. 4. The pulsating load is well controlled, and the fluctuation of the peak load is less than 2%. The load is applied at a position 0.5 mm below the tip, with a speed of about 40 Hz. To avoid impact loading to the tooth, the stress ratio \( R \) is set to 0.01. The fatigue test is terminated at the number of cycles \( N = 3 \times 10^6 \), and the tooth which is not broken by this life cycle is considered as a nonfailure. The S-N curve of the gear without a notch is shown in Fig. 5. The load is expressed by the true stress at the fillet. The mean fatigue strength is obtained as 842 MPa by a staircase method. In this test, the stress step was 60 MPa.

3. Processing of Artificial Notch at the Fillet

Artificial notches are machined by two processing methods according to the depth required. The notches of 50 μm to 200 μm in depth are formed by WEDM, while the notches shallower than 50 μm are formed by FIB etching.

For the carburized gears with the same dimensions as those of the test gear in this research, the shapes of a number of broken teeth were sketched after the completion of the fatigue test. Referring to the shape of the highest frequency, the position and the direction of the notch are determined as shown in Fig. 6, namely, the position is at 0.42 mm from the point of Hofer's 30 degrees tangent toward the tip along the fillet, and the inclination of notch is 0.3°.

3.1 Notches processed by wire electrical discharge machining

The deep notches are processed by WEDM at depths of 50, 70, 100, 140 and 200 μm. The width of the notches is about 70 μm. It is more than double the wire diameter because of the gap of discharge. Therefore, the notch deeper than 70 μm is U shaped as shown in Fig. 7, while the shallower notch is semicircular shaped as indicated in Fig. 8.

The notch is processed whole the face width and the depth of the notch is almost uniform, which is confirmed by the measurement of the fractured surface after the fatigue test. In addition, the standard deviation of dispersion of the notch depth, measured at both sides is less than 1/10 of the specified value. Therefore, the dispersion of depth in the test teeth is...
assumed to be negligible, and the specified depth is used in the discussion of fatigue test results. It is noted that the softened layer is produced by the electrolysis of water around the processed area\(^{(14)}\). The decrease of hardness is not observed in this research, although the measurement point is 50 \(\mu\)m from the notch even in the closest position. Consequently, the influence of softening by the processing is neglected.

### 3.2 Notches by focused ion beam etching

As explained in the previous section, it is difficult to accurately form notches shallower than 50 \(\mu\)m by WEDM. Therefore, FIB etching is used to process such a micronotch. Generally, the FIB is used to fabricate a specimen for tunnel electron microscopic observations, and for other applications such as cutting the wire in trial manufacture of ICs. The FIB processing utilizes the accelerated and focused Ga ions for sputter etching. The positioning accuracy of the apparatus used in this study is about 0.3 \(\mu\)m by a beam of 0.1 \(\mu\)m minimum diameter.

Since the apparatus is originally designed for processing a flat plate such as a wafer, the space inside the chamber for the specimen is too narrow to set the test gear on the original stage. Therefore, a part of the gear which is dispensable for the fatigue test is cut off so as not to interfere with the component in the chamber, and is fixed to the gear holder as shown in Fig. 9. The notch of full face width is obviously preferable to the shallower notch for the two-dimensional analysis, however, such a long notch cannot be processed because of restriction of beam scanning. The maximum notch processed in this research is 500 \(\mu\)m long in the direction of the face width. The shape and location of the notch are shown in Fig. 10. A photograph of a tooth fillet is also shown. As shown in Fig. 11, the corner of notch is rounded due to beam scattering, and the notch tip is U shaped. In the case where the ratio of elliptical crack depth to breadth exceeds 5, the stress intensity factor becomes closer to the two-dimensional value\(^{(15)}\). Therefore, the micronotch studied in this research is regarded as approximately two-dimensional.

The notch depth is regulated by the processing time. Under the conditions of the beam intensity and notch dimensions in this experiment, the process rate is 0.7 - 0.8 \(\mu\)m/hr as indicated in Fig. 11. Dispersion of notch width is approximately 5 \(\mu\)m. After the fatigue test, the fractured surface of tooth is observed under a microscope to measure the notch depth.

### 4. Fatigue Strength of Gear with an Artificial Notch

#### 4.1 Decrease of strength due to deep notch

The up-and-down fatigue test based on Little's
method is used for the estimation of strength against the notch depth. The loading speed is 40 to 60 Hz. Other conditions of the test procedure are the same as those for the test of the gear without a notch described above.

The notch appears on the fractured surfaces of all the broken teeth, but the point of crack initiation cannot be determined. The relationship between the notch depth and the fatigue strength is shown in Fig. 13. The strength of the tooth with the notch of 50 \( \mu \text{m} \) depth is 505 MPa. The strength is decreased by more than 40% in comparison with the tooth without a notch. As the notch depth increases, the strength decreases. In the case of a notch of 200 \( \mu \text{m} \), the strength is about 422 MPa which is approximately 1/2 the strength of the tooth without a notch.

4.2 Evaluation of the threshold depth of notch

The fatigue test result of the gear with a micronotch is shown in Fig. 14. The tooth which was not broken at the life cycle of \( N = 3 \times 10^6 \) is indicated by a circle (○). The broken teeth are indicated by a triangle, and they are divided into two groups. One group contains the teeth whose fractured surfaces include the processed notch, and the other group contains the teeth which do not include the notch in the fractured surfaces. The former is indicated by the open triangle (△), and the latter is indicated by the filled triangle (●). The teeth with the notch shallower than 19 \( \mu \text{m} \) break excluding the notch. This demonstrates that the existence of the notch does not influence the tooth failure. On the other hand, the teeth with a notch deeper than 20 \( \mu \text{m} \) always break including the notch. Although the point of crack initiation is not clarified yet, the existence of such a notch obviously reduces the bending strength. Consequently, the threshold notch depth, termed as \( a_{\text{th}} \) of
carburized gear, at which the fatigue strength is not affected, is determined as 20 \text{\textmu}m.

The fatigue strength of tooth without a notch ($\sigma_f = 842$ MPa) is also indicated in Fig. 14. The fatigue strength of the tooth with the notch over 35 \text{\textmu}m in depth decreases markedly in comparison with the nonnotched tooth. The line which represents the critical notch depth is shown in the figure. This line is close to the line of fatigue strength at the $\sigma_{\text{fu}}$.

5. Relationship between Crack Length and Strength

5.1 Comparison with the strength based on the linear fracture mechanics

For discussing the strength of gears with defects, the stress intensity factor $K_I$ is calculated from the crack opening distance (COD), stress distribution and residual stress by the weight function method\textsuperscript{[16,17]}, COD and stress distribution due to the tip load are calculated by the finite element method. On the other hand, we have presented the threshold stress intensity factor range $\Delta K_{th}$ as the function of hardness $H [\text{Hv}]$, therefore $\Delta K_{th}$ can be evaluated from the hardness at the crack tip. To equalize it with $K_I$, the critical stress, which is the threshold of crack propagation, is estimated, and this gives the strength based on fracture mechanics. The estimated strength is shown in Fig. 15 as a thin line. The fatigue test result is shown by a thick line. Although they have similar declination, the value of the former is larger than that of the latter. The difference at 40 \text{\textmu}m of crack length is approximately 400 MPa. The longer the crack, the smaller the difference. The difference may depend on the accuracy of determination of threshold stress intensity factor range $\Delta K_{th}$ and calculation for stress intensity factor $K_I$. The value is larger in the region with a short crack, because of the ineffectiveness of linear fracture mechanics to apply such a short crack.

5.2 The threshold size which influences the strength

The relationship between crack length and stress intensity factor $K_I$ at $S = 842$ MPa, and the fatigue strength of nonnotched teeth, is shown in Fig. 16. In the case of a crack shorter than 72 \text{\textmu}m, the crack will not propagate since $K_I$ is smaller than $K_{th}$. In other words, the crack shorter than 72 \text{\textmu}m does not influence the strength. Therefore, the threshold crack length which is the limit of nonpropagation is determined. We have defined this crack length as the endurance length $a_0$. There is a large difference between both, although the reason remains unclear. The size of the latent defect...
in the surface layer may be the most influential factor of strength. The threshold notch depth $a_{th}$ can be used as the index of the size of the latent defect, but it is difficult to determine the latent defect which triggers crack propagation. A new method of strength evaluation can be established by clarifying the relationship among $a_{th}$, $a_0$ and the latent defect size.

6. Conclusions

The fatigue strength of carburized gears is greatly influenced by the degree of surface integrity, particularly the latent defect. Substituting the artificial micronotch for the defect, the bending fatigue test was carried out to determine the critical notch depth. The conclusions are summarized as follows:

1. The FIB processing was effective to obtain a micronotch shallower than 50 μm.
2. The threshold notch depth $a_{th}$ that did not affect the fatigue strength was 20 μm.
3. The relationship between the fatigue strength and the notch depth was clarified.
4. The fatigue strength of notched teeth is lower than the estimated strength, based on the linear fracture mechanics.
5. The threshold notch depth $a_{th}$ is shorter than the endurance length $a_0$.

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References