Hardened Layer and Bending Fatigue Strength of Induction Hardened Thermally Refined Steel Gears*

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Abstract
This paper presents a study on effects of the pre-treatment and the heating time on the hardened layer and the bending fatigue strength of induction hardened gears. The measurement of hardened layer and the bending fatigue test of induction hardened gears made of thermally refined and as-rolled S35C and S45C steels were carried out, and then profiles of hardened layer and $S-N$ curves were obtained. Effects of the pre-treatment and the heating time on profiles and micro-structures of hardened layers of induction hardened gears were examined. The relationship between the bending fatigue strength and the profile of hardened layer was determined. An optimum heating condition for the bending fatigue strength of induction hardened S35C and S45C steel gears were indicated.

Key words: Induction Hardening, Gear, Bending Fatigue Strength, Hardened Layer, Thermal Refining, As-Rolled, Heating Time

1. Introduction

The ability to heat-treat in-line, as opposed to batch processing in carburizing, with high productivity, less distortion, and a clean environment is an obvious benefit of induction heat treatment (1). The induction heat treatment is carried out in a much shorter time, so the pre-heat treatment of material before the induction heat treatment has much influence on the micro-structure of the hardened layer (2). It has been known that the austenite transformation of thermally refined steel for rapid heating is more superior to the case of as-rolled steel, but the results for induction hardened gears have not been published. In the previous papers, effects of hardening conditions on the hardened layer and the bending fatigue strength of induction hardened gears made of as-rolled S35C and S45C steels (3)-(5) had been published.

In the present paper, effects of the pre-treatment and the heating time on the hardened layer and the bending fatigue strength of induction hardened gears were investigated. The measurement of hardened layer and the bending fatigue test of induction-hardened gears made of thermally refined and as-rolled S35C and S45C steels were carried out, and then profiles of hardened layer and $S-N$ curves were obtained. Effects of the pre-treatment and the heating time on profiles and micro-structures of hardened layers of the gears were
examined. The relationship between the bending fatigue strength and the profile of hardened layer was determined. An optimum heating condition for the bending fatigue strength of induction hardened S35C and S45C steel gears were indicated.

2. Experimental Procedure and Apparatus

2.1 Test Gears

In order to examine the effects of the pre-treatment and the heating time on hardened layers and bending fatigue strength of induction hardened gears, measurements of hardened layer and bending fatigue tests were carried out. The test gears used in this experiment are standard spur gears and their main dimensions are module \( m = 4 \), standard pressure angle \( \alpha = 20^\circ \), number of teeth \( z = 18 \), and face width \( b = 10 \) mm. Test gears are made of thermally refined and as-rolled S35C and S45C steels specified in JIS, and induction hardened by using the heating coil shown in Fig.1. The heating coils are made of copper. Heating conditions (electric power \( P \), frequency \( f \) and heating time \( t_h \)) of test gears are shown in Table 1.

![Fig.1 Dimensions of heating coil and test gear](image)

<table>
<thead>
<tr>
<th>Gear sign</th>
<th>Material</th>
<th>Pre-treatment</th>
<th>Heating condition</th>
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<tbody>
<tr>
<td></td>
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<td>Electric power ( P ) (kW)</td>
</tr>
<tr>
<td>G3T1</td>
<td>S35C</td>
<td>Thermal refining</td>
<td>2.8</td>
</tr>
<tr>
<td>G3T2</td>
<td>S35C</td>
<td>Thermal refining</td>
<td>3.3</td>
</tr>
<tr>
<td>G3T3</td>
<td>S35C</td>
<td>Thermal refining</td>
<td>3.8</td>
</tr>
<tr>
<td>G3R1</td>
<td>S35C</td>
<td>As rolling</td>
<td>2.8</td>
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<tr>
<td>G3R2</td>
<td>S35C</td>
<td>As rolling</td>
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<td>3.8</td>
</tr>
</tbody>
</table>
2.2 Bending Fatigue Test

The bending fatigue test machine (5) used consists of a fuel injection pump for diesel engine and its driving apparatus ①, pressure controller ② and loading apparatus ③ as shown in Fig.2. The test gear is supported with a shaft and three teeth of an internal gear fixed to the bed of the test machine. The oil supplied from the fuel injection pump is introduced into a hydraulic cylinder and it pushes the piston and the tooth is thus loaded. The load is applied near the tip of the tooth using the loading bar attached to the piston. The applied load value is given from the oil pressure detected with a pressure transducer attached to the upper part of the cylinder. The frequency of load applications is about 700c/min.

3. Experimental Results and Discussions

3.1 Micro-Structure of Gear Materials before Induction Heat Treatment

Figure 3 shows photographs of micro-structure of thermally refined S35C and S45C steels, and as-rolled S35C and S45C steels before the induction heat treatment. It is seen from Fig.3 that the micro-structure of the thermally refined steel is finer than that of as-rolled steel in both the S35C and S45C steels.

![Fig.2 Bending fatigue test machine](image)

![Fig.3 Photographs of micro-structure of gear materials](image)
3.2 Hardened Layer

3.2.1 Effects of heating time and pre-treatment

Figure 4 shows photographs of macro-structure of induction hardened thermally refined S35C steel gears G3T1 and G3T2 and as-rolled S35C steel gears G3R1 and G3R2 shown in Table 1. In Fig.4 gear-side U, section M-M and gear-side L denote upper gear-side, middle section and lower gear-side in the induction hardening shown in Fig.1, respectively. It is seen from Fig.4 that the hardened depth near tooth root at the position of Hofer’s critical section of tangential angle $\theta=30^\circ$ ($\theta$: angle between center line of gear tooth and tangent to the fillet curve of tooth profile) increases with increasing heating time $t_h$ irrespective of the pre-treatment. The profile of hardened layer of thermally refined steel gear is almost the same with that of as-rolled steel gear for these heating conditions.

Figure 5 shows photographs of micro-structure of hardened layer near the position of Hofer’s critical section of test gears G3T1, G3T2, G3R1 and G3R2. The photograph of core is micro-structure at an unhardened position distant from the tooth surface of test gear. The micro-structure of hardened layer (surface) is perfect martensite structure in the case of thermally refined steel gear but mixed structures of ferrite and martensite in the case of as-rolled steel gear. This might be because parts not transformed to austenite remain for rapidly induction-heating process in the case of as-rolled steel gear.

Figure 6 shows hardness distributions in the direction normal to the tooth surface at the position of Hofer’s critical section for G3T1, G3T2, G3R1 and G3R2. In Fig.6 the abscissa denotes the distance from tooth surface, and the ordinate denotes Vickers hardness number ($HV$). It is seen from Fig.6 that the surface hardness of thermally refined steel gear is larger than that of as-rolled steel gear and that the effective hardened depth at $HV=400$ of
Fig. 5 Photograph of micro-structure of test gears (S35C, $P=50$ kW, $f=30$ kHz)

(a) G3T1 (Thermally refined, $t_h=2.8$ s)
(b) G3T2 (Thermally refined, $t_h=3.3$ s)
(c) G3R1 (As rolled, $t_h=2.8$ s)
(d) G3R2 (As rolled, $t_h=3.3$ s)

Fig. 6 Hardness distributions at Hofer’s critical section (S35C, $P=50$ kW, $f=30$ kHz)
Fig. 7 Photographs of macro-structures of test gears (S45C, $P=50$ kW, $f=30$ kHz)

Fig. 8 Photograph of micro-structure of test gears (S45C, $P=50$ kW, $f=30$ kHz)
thermally refined steel gear is also larger than that of as-rolled steel gear. The scattering of the hardness in the face width direction near the tooth surface of G3R1 is considerably large compared with the cases of other gears.

### 3.2.2 Effects of materials (S35C and S45C)

Figure 7 shows photographs of macro-structure of thermally refined S45C steel gears G4T1 and G4T2 and as-rolled S45C steel gears G4R1 and G4R2 shown in Table 1. It is seen from Fig. 7 that the hardened depth near tooth root at the position of Hofer’s critical section in the case of S45C is larger than that in the case of S35C (Fig.4). This might be because the hardenability of S45C steel is superior to that of S35C steel.

Figure 8 shows photographs of micro-structure of hardened layer near the position of Hofer’s critical section of test gears G4T1, G4T2, G4R1 and G4R2. The micro-structure of hardened layer (surface) is perfect martensite structure in the case of thermally refined S45C steel gear but mixed structures of ferrite and martensite in the case of as-rolled S45C steel gear as in the cases of thermally refined and as-rolled S35C steel gears (Fig.5).

Figure 9 shows hardness distributions in the direction normal to the tooth surface at the position of Hofer’s critical section for G4T1, G4T2, G4R1 and G4R2. It is seen from Fig.9 that the surface hardness of thermally refined steel gear is larger than that of as-rolled steel gear and that the effective hardened depth at $HV=400$ of thermally refined steel gear is also larger than that of as-rolled steel gear. The scattering of the hardness in the face width direction near the tooth surface of G4R1 is considerably large compared with the cases of other gears as in the case of the induction hardened S35C steel gear (Fig.6). From Figs. 6 and 9 the effective hardened depth of the induction hardened thermally refined S45C steel gear is larger than that of the induction hardened thermally refined S35C steel gear.

![Hardness distributions](image)

Fig.9 Hardness distributions at Hofer’s critical section (S45C, $P=50$ kW, $f=30$ kHz)
3.3 Bending Fatigue Strength

Figure 10 shows bending fatigue test results for test gears shown in Table 1. In Fig. 10, the abscissa denotes the number of load cycles $N$, and the ordinate denotes the normal tooth load $P_n$ and the root stress $\sigma_t$ calculated by the practical formula proposed by Aida and Terauchi (6). It is seen from Fig. 10 that the maximum bending fatigue strength of the induction hardened gear made of thermally refined steel is larger than that of the induction hardened gear made of as-rolled steel in both cases of S35C and S45C steels. In Fig. 10(b), the bending fatigue limit $\sigma_{tu}$ of G4T2 is smaller than $\sigma_{tu}$ of G4T1 and larger than $\sigma_{tu}$ of G4R2. This might be because the hardened depth of G4T2 is larger than that of G4T1 and is too large for the bending fatigue strength (7), and that the micro-structure of hardened layer of G4T2 is different from that of G4R2 as shown in Fig. 8.

Figure 11 shows bending fatigue limits $\sigma_{tu}$ obtained from the bending fatigue test results of Fig. 10. It is seen from Fig. 11 that $\sigma_{tu}$ takes the maximum value at certain $t_h$ for each heating condition ($P$, $f$), and the maximum value of $\sigma_{tu}$ of the induction hardened gears made of thermally refined S35C and S45C steels is 2.3 and 2.6 times, respectively, as large as $\sigma_{tu}$ of as-rolled S35C steel gear (G3R) which has not been induction hardened. Hence, it
is considered that there is a suitable value (that is hardened depth) of \( t_h \) for the bending fatigue strength of the induction-hardened gear as in the case of case-carburized gears \(^{(7)}\). The maximum value (G4T1) of \( \sigma_{tu} \) of induction hardened gears in Fig.11 is almost equal to \( \sigma_{tu} \) of the case-carburized gear \(^{(8)}\).

The bending fatigue tests of gears induction hardened under various heating conditions (electric power \( P \), frequency \( f \) and heating time \( t_h \)) and materials have been carried out by the authors, and the method to select the suitable heating condition and the material for the bending fatigue of induction hardened gear is being investigated. The comparison between bending fatigue strengths of the induction hardened gear and the case-carburized gear will be published together with the method to select the suitable heating condition and the material in the future.

4. Conclusions

Main results obtained from this investigation are summarized as follows.

1. The effective hardened depth \( d_e \) (for \( HV_{400} \)) at the tooth root of the induction hardened gear increases with an increasing heating time \( t_h \). \( d_e \) at the tooth root of the induction hardened gear made of S45C steel is larger than that made of S35C steel.

2. The micro-structure of hardened layer of the induction hardened gear is perfect martensite structure in the case of thermally refined steel gear but mixed structures of ferrite and martensite in the case of as-rolled steel gear.

3. It is considered that there is a suitable value of \( t_h \) for the bending fatigue limit of induction hardened gear.

4. The maximum bending fatigue limit \( \sigma_{tumax} \) of the induction hardened gear made of thermally refined steel is larger than \( \sigma_{tumax} \) of the induction hardened gear made of as-rolled steel. \( \sigma_{tumax} \) of the induction hardened gears made of thermally refined S35C and S45C steels are 2.3 and 2.6 times, respectively, as large as \( \sigma_{tumax} \) of as-rolled S35C steel gear which is not induction hardened. The maximum value of \( \sigma_{tumax} \) of induction hardened gears used in this investigation is almost equal to \( \sigma_{tu} \) of the case-carburized gear.

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References