Load-Carrying Capacity of Surface-Hardened Gears*  
(Influence of Surface Roughness on Surface Durability)

Tsutomu NAKANISHI**, Yasutsune ARIURA**
and Taku UENO***

The influences of material, heat treatment, tooth profile and surface roughness on the surface durability of surface-hardened gears were investigated. First, the effect of surface roughness on rolling/sliding contact fatigue was studied in detail by using a 2-roller-type contact fatigue testing machine. The results show that the initial surface roughness has a remarkable influence on the surface durability of surface-hardened steels, and that the decrease in surface roughness with running time does not always have an advantageous effect. Secondly, the load-carrying capacities of case-carburized gears and induction-hardened gears were investigated by using a power circulating-type gear testing machine. The phenomenon of "grey-staining", which consists of many micro-cracks and micro-pits, appears on the ground tooth surface under a heavy load. In these tests, it is clear that the surface failure "grey-staining", which causes degradation of the tooth profile and spalling, is most influenced by the initial tooth surface roughness. Furthermore, the effect of initial surface roughness on the surface durability of surface-hardened gears can be estimated quantitatively.

Key Words: Gear, Case-Carburized Gear, Induction-Hardened Gear, Surface Durability, Surface Failure, Surface Roughness

1. Introduction

Recently, the requirement of higher load-carrying capacity and smaller size of gear sets has increased for power transmission gears in many machineries.

In this paper, the surface durability of surface-hardened gears, the usage of which is increasing in recent years, is investigated from the viewpoint of gear-manufacturing methods (gear accuracy and tooth surface roughness).

The surface durability of surface-hardened gears made of case-carburized Cr-Mo alloy steel was studied experimentally by the authors. It was clear that the phenomenon of "grey-staining" appeared on the tooth surfaces of accurately ground gears under a heavy load. The area of grey-staining increases with increasing contact stress and stress cycles. The grey-staining phenomenon which looks like normal wear, cannot be neglected in gear failure because this surface failure causes degradation of the tooth profile and other surface failures such as pitting and spalling. Also, grey-staining consists of many micro-cracks and micro-pits which have the same shape as seen in normal surface fatigue (pitting).

Concerning the above facts, the influences of material, heat treatment, tooth profile and surface roughness on the surface failure "grey-staining" of surface-hardened gears were investigated. First, the effect of surface roughness on rolling/sliding contact fatigue was studied in detail by using a 2-roller-type contact fatigue testing machine. Secondly, the load-carrying capacities of case-carburized gears and induction-hardened gears were investigated by using a power circulating-type gear testing machine. The results show that the initial surface roughness has a remarkable influence on the surface durability of surface-hardened gears. Furthermore, the effect of initial surface roughness on the surface durability of surface-hardened gears can be estimated quantitatively.

* Received 10th June, 1986. Paper No. 85-0435 A
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JSME International Journal 1987, Vol. 30, No. 259
2. Roller Test

2.1 Experimental conditions and method

2.1.1 Test specimens

Figure 1 shows the dimensions of the test rollers. The material of the test rollers is 1%Cr-0.2%Mo alloy steel (JIS SCM 415). After heat treatment, the surface hardness of the test rollers is Vickers hardness number HV 750 (Brinell hardness number HB ≈ 690) and the effective case depth is about 1 mm.

2.1.2 Surface roughness

Rollers with two surface roughnesses (maximum height $R_{max} = 2 \mu m$ and $10 \mu m$) were finished by cylindrical grinding. The values of the D-ratio are about 3 and 8. Typical examples of the roughness profiles after grinding are shown in Fig. 2.

2.1.3 Roller test apparatus, lubricant and test method

The roller test apparatus used is a 2-roller-type contact fatigue testing machine with a maximum loading capacity of $4.9 \times 10^8 N$. The running condition of the roller tests is given in Table 1. The surface hardness and roughness of each pair of rollers are approximately the same.

![Dimensions of test rollers](image)

Fig. 1 Dimensions of test rollers

The test oil is SAE 30 base oil (specific gravity: 0.885 at 15/4°C, viscosity: $9.4 \times 10^{-6} m^2/s$ at 40°C, $11.1 \times 10^{-6} m^2/s$ at 100°C) containing no extreme pressure additives. The lubricant is supplied to the contact zone of the roller set by an oil jet. The inlet oil temperature is adjusted to $40 \pm 2^\circ C$ and the flow rate is held constant at 2 l/min.

In order to evaluate the surface durability, the surface roughnesses are measured when the number of stress cycles reaches $N = 10^5$, $10^6$, $10^7$ or when surface failures occur. In addition, the appearance of the contact surfaces is observed at suitable intervals. The surface temperature of the test rollers is measured by a trailing (copper-constantan) thermocouple.

2.2 Experimental results and discussions

2.2.1 Experimental results

The experimental conditions and results of the roller tests are given in Table 2. Tests are performed in the range of maximum Hertzian stress $P_{max} = 0.7$ to 2.4 GPa or (0.1 to 0.4) HB kgf/mm². Fig. 3 shows the $P_{max}-N$ curves for surface failure in the roller tests. In Fig. 3, $P_{max}$ is the maximum Hertzian stress and $N$ the number of stress cycles when surface failure occurs, or $N = 10^7$ in the case of no failure. From these results, the value of the endurance limit for contact stress ($P_{max}$ at $N = 10^7$) is 0.3 HB kgf/mm² under the condition of an initial surface roughness $R_{max} = 2 \mu m$ and $0.1$ HB kgf/mm² under $R_{max} = 10 \mu m$. This indicates that the surface durability of rollers with a smooth initial surface is higher than those with a

### Table 1 Rolling/sliding condition of roller tests

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Lower speed roller (L)</th>
<th>Higher speed roller (H)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed of rotation rpm</td>
<td>2630</td>
<td>3190</td>
</tr>
<tr>
<td>Peripheral speed m/s</td>
<td>9.36</td>
<td>11.36</td>
</tr>
<tr>
<td>Specific sliding %</td>
<td>-21</td>
<td>17</td>
</tr>
<tr>
<td>Sliding velocity m/s</td>
<td>2.0</td>
<td></td>
</tr>
</tbody>
</table>

### Table 2 Experimental conditions and results of roller tests

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Material</th>
<th>Heat treatment methods</th>
<th>Surface hardness</th>
<th>Surface roughness</th>
<th>$R_{max}$ $\mu m$</th>
<th>Hertzian stress</th>
<th>$P_{max}$ GPa</th>
<th>$P_{max}$ kgf/mm²</th>
<th>Cycles run to $N$</th>
</tr>
</thead>
<tbody>
<tr>
<td>C - 1</td>
<td>SCM 415</td>
<td>Carburizing &amp; hardening</td>
<td>HV 750 (HB = 690)</td>
<td>2</td>
<td>1.6</td>
<td>2.0</td>
<td>2.35</td>
<td>0.35</td>
<td>6 $\times 10^5$</td>
</tr>
<tr>
<td>C - 11</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C - 12</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C - 13</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C - 14</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C - 15</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C - 16</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(1): Lower speed roller, (H): Higher speed roller, $10^5$: No surface failure at $N = 10^5$

Test No. [C-1] to [C-4]: 1300 rpm in higher speed roller (Commercial lubricant SAE 30)
rough surface. It is clear that the initial surface roughness has a remarkable influence on the surface durability of surface-hardened steels.

2.2.2 Discussions

Figure 4 shows the relation between maximum Hertzian stress and change in surface roughness in the roller tests. Fig. 5 shows the surface temperature and calculated EHL film thickness $h_{min}$ in relation to maximum Hertzian stress.

The surface roughness decreases to some extent with repeated contact stress even for surface-hardened steels. Nevertheless, this phenomenon has a close connection with surface failure. One of the reasons may be the difference in the work-hardening behavior of materials, that is, the strain-hardening coefficient is small in hard steels. Therefore, the decrease in surface roughness with running time does not always have an advantageous effect on the surface durability of surface hardened steels.

Under a heavy load, the surface temperature of the contact zone is high and the EHL film thickness decreases. It seems that the probability of metallic contact becomes high and then surface failure occurs. Therefore, the initial surface should be finished as smoothly as possible in order to obtain a high surface durability of surface-hardened steels.

3. Gear test

3.1 Experimental conditions and method

3.1.1 Test gears

The specifications and dimensions of the test spur gears are given in Table 3 and Fig.6. The materials of the case-carburized gears are 1%Cr-0.2%Mo alloy steel (JIS SCM 415), its leaded free-cutting steel (SCM 415 L, Pb: 0.16%) and 3%Ni-0.8%Cr alloy steel (SNC 815). The materials of the induction-hardened gears are carbon steel (S43C) and its resulphurized free-cutting steel (S43C S2, S: 0.11%).

3.1.2 Hardness, accuracy and surface roughness of test gears

The heat treatment is conducted after hobbing. The
tooth surfaces are finished by grinding (Maag 0° method). The hardness of the top land of case-carburized gears and induction-hardened gears are Scleroscope (Shore) hardness number HS 80 and HS 70, respectively. The surface hardness of the test piece (φ30 X 40) case-carburized at the same time is HV800 and the effective case depth is about 1.5 mm.

The accuracy of the test gears is JIS class 0 ~ 2 (AGMA Quality number 12 ~ 10, ISO Accuracy grade 4 ~ 6). Typical surface roughnesses along the tooth profile are shown in Fig. 7. The tooth surface roughness after grinding have a maximum height $R_{max}$ of 1 ~ 6 μm.

3.1.3 Gear test apparatus, lubricant and test method

The test apparatus used is a power-circulating type gear testing machine (with a center distance of 156 mm, gear ratio $u=31/21$, operating speed 1800 rpm in the pinion and maximum power 800 PS).

The test oils are commercial lubricant SAE 30 (specific gravity: 0.884 at 15/4°C, viscosity: 112.4 X 10^-5 m²/s at 40°C, 12.5 X 10^-5 m²/s at 100°C) and ISO VG 150 (0.888, 153.9 X 10^-4 m²/s, 15.0 X 10^-5 m²/s). These oils contain no extreme pressure additives. The lubricant is supplied to the meshing zone by an oil jet. The inlet oil temperature is adjusted to 40 ± 2°C and the oil flow rate is held constant at 2 l/min.

In order to evaluate the load-carrying capacity, the gear accuracy and tooth surface roughness are measured when the number of stress cycles in the pinion reaches $N_i=10^6$, $5 X 10^6$, $10^7$ and sometimes $2 X 10^7$. In addition, the appearance of the tooth surfaces is observed at suitable intervals.

3.2 Experimental results and discussions

3.2.1 Experimental results

The experimental conditions and results of the gear tests are given in Table 4. In Table 4, (a) is the case of case-carburized gears and (b) the case of induction-hardened gears. Tests are performed in the range of maximum Hertzian stress $P_{max}=1.2 ~ 2.0$ GPa ($0.2 ~ 0.3$ HB kgf/mm²). In all tests, surface failure “grey-staining” appears. The area of grey-staining, which spreads with increasing stress and stress cycle, varies with the experimental conditions.

Figure 8 shows typical examples of the appearance of the tooth surface at $N_i=10^7$ for the case of induction-hardened gears. Fig. 9 shows typical scanning electron microscopy (SEM) micrographs of the grey-staining on the pinion surface and changes in the tooth profile and surface roughness of induction-hardened gears.

The calculated EHL film thickness $h_{min}$ in the gear tests is approximately 0.3 μm under the conditions of $P_{max}=1.57$ GPa ($160$ kgf/mm²) and oil temperature 90°C. Therefore, it seems that hard gears have a high probability of metallic contact on the tooth surface because the oil film thickness decreases remarkably under heavier loading conditions.

Because of the above reasons, the tooth surface should be finished as smoothly as possible in order to avoid surface failure of hard gears. The above aspect is confirmed by the roller tests which simulate tooth contact as described in the previous section.

3.2.2 Relation between tooth profile error, tooth surface roughness and grey-staining

Figure 10 shows the relation between tooth profile

<table>
<thead>
<tr>
<th>Table 3 Specifications of test gears</th>
</tr>
</thead>
<tbody>
<tr>
<td>Module</td>
</tr>
<tr>
<td>Pressure angle</td>
</tr>
<tr>
<td>Number of teeth</td>
</tr>
<tr>
<td>Pitch diameter</td>
</tr>
<tr>
<td>Facewidth</td>
</tr>
</tbody>
</table>

Fig. 6 Dimensions of test gears

Table 4  Experimental conditions and results of gear tests

(a)  Case-carburized gears

<table>
<thead>
<tr>
<th>Test No.</th>
<th>G-1</th>
<th>G-2</th>
<th>G-5</th>
<th>G-17</th>
<th>G-19</th>
<th>G-20</th>
<th>G-21</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pinion (P), Gear (G)</td>
<td>P</td>
<td>G</td>
<td>G</td>
<td>P</td>
<td>G</td>
<td>P</td>
<td>G</td>
</tr>
<tr>
<td>Material</td>
<td>SCM415</td>
<td>SCM415L</td>
<td>SNC815</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tooth surface roughness $R_{max}$ $\mu$m</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Tooth profile error $\mu$m</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>6</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Max. Hertzian stress GPa</td>
<td>1.37</td>
<td>1.96</td>
<td>1.37</td>
<td>1.57</td>
<td>1.76</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$P_{max}$ kN/m²</td>
<td>140 (0.22 HB)</td>
<td>200 (0.31 HB)</td>
<td>140 (0.22 HB)</td>
<td>160 (0.25 HB)</td>
<td>180 (0.28 HB)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cycles run in pinion</td>
<td>$N_i$</td>
<td>2 x $10^7$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grey-staining area ratio</td>
<td>$1$</td>
<td>$32%$</td>
<td>$65%$</td>
<td>$43$</td>
<td>$29$</td>
<td>$12$</td>
<td>$19$</td>
</tr>
</tbody>
</table>

Tooth surface-finishing method: Grinding,  OIL: Commercial lubricant SAE 30 (Test No. G-19, G-20)  ISO VG 150
$H_s$: Tooth surface hardness (Approx. value $HB = 650$),  $*1$: at $N_i = 10^7$,  $*2$: at $N_i \approx 0.7 \times 10^7$

(b)  Induction-hardened gears

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Pinion (P), Gear (G)</td>
<td>P</td>
<td>G</td>
<td>G</td>
<td>P</td>
<td>G</td>
<td>P</td>
<td>G</td>
</tr>
<tr>
<td>Material</td>
<td>S43C</td>
<td>S43C 52Cr</td>
<td>(Gear: S43C)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tooth surface roughness $R_{max}$ $\mu$m</td>
<td>6</td>
<td>3</td>
<td>5</td>
<td>2</td>
<td>6</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Tooth profile error $\mu$m</td>
<td>6</td>
<td>3</td>
<td>6</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Max. Hertzian stress GPa</td>
<td>1.18</td>
<td>1.37</td>
<td>1.57</td>
<td>1.38</td>
<td>1.37</td>
<td>1.57</td>
<td></td>
</tr>
<tr>
<td>$P_{max}$ kN/m²</td>
<td>120 (0.21 HB)</td>
<td>140 (0.25 HB)</td>
<td>160 (0.28 HB)</td>
<td>120 (0.21 HB)</td>
<td>140 (0.25 HB)</td>
<td>160 (0.28 HB)</td>
<td></td>
</tr>
<tr>
<td>Cycles run in pinion</td>
<td>$N_i$</td>
<td>10$^7$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grey-staining area ratio</td>
<td>$1$</td>
<td>$23$</td>
<td>$59$</td>
<td>$53$</td>
<td>$59$</td>
<td>$85$</td>
<td>$55$</td>
</tr>
</tbody>
</table>

Tooth surface-finishing method: Grinding,  OIL: Commercial lubricant SAE 30
$H_s$: Tooth surface hardness (Approx. value $HB = 570$),  $*1$: Resulfurized (free-cutting) carbon steel

Initial surface roughness, Grinding

$R_{max} = 1 \mu$m

$R_{max} = 3 \mu$m

$R_{max} = 6 \mu$m

![Initial surface roughness along tooth profile of test gears](image)

Fig. 7  Surface roughness along tooth profile of test gears

$P_{max} = 1.57$ GPa, $N_i = 10^7$, S43C

Pinion

![SEM micrographs of grey-staining](image)

Gear

Fig. 9  SEM micrographs of grey-staining and changes in tooth profile and surface roughness (Test No. G-22)

error (at $N_i=0$), tooth surface roughness (at $N_i=0$) and average grey-staining area ratio (at $N_i=10^7$)$*1$. For case-carburized gears and induction-hardened gears, though the initial tooth profile error of each test gear is different, the following is clear.

(1) For test gears with approximately the same tooth surface roughness, the area of grey-staining increases with increasing load. (ref. Test Nos. G-1, G
2, G-13, G-15, G-22 etc.).

(2) Under the same load, the smoother the tooth surface, the smaller the area of grey-staining.

(3) Tendencies (1) and (2) are little influenced by gear materials or heat treatments.

4. Influence of surface roughness on surface durability

Figure 11 shows the relation between maximum Hertzian stress and average grey-staining area ratio at \(N_t = 10^6\). In Fig. 11, which includes the data obtained in a previous investigation\(^a\), (a) and (b) represent the results for case-carburized gears and induction-hardened gears, respectively. For surface-hardened gears, it is clear that load and initial surface roughness have a remarkable influence on surface failure "grey-staining".

Figure 12 shows the relation between initial surface roughness \(R_{\text{max}}\) and endurance limit \(P_{\text{max}}/\text{HB}\) assuming no failure, that is, the average grey-staining area ratio \(\hat{s} = 0\%\) in Fig. 11 (a) and (b). From Fig. 12, which represents \(P_{\text{max}}/\text{HB}-R_{\text{max}}\) curves, the effect of surface roughness on the surface durability of surface-hardened gears can be estimated quantitatively. For example, the results show that a fourfold reduction in the initial tooth surface roughness triples the endurance limit. Namely, it is noticed that the tangential load of gears with a smooth initial tooth surface \(R_{\text{max}} \approx 1 \mu \text{m}\) is approximately ten times that of gears with a rough initial tooth surface \(R_{\text{max}} \approx 4 \mu \text{m}\).

The above fact is also confirmed by the roller tests. The values of the endurance limit in the calculation of surface durability should be considered as functions of hardness and roughness of the tooth surface. Therefore, for surface-hardened gears, the value of the endurance limit obtained from this investigation is approximately (i) \(0.1 \text{ HB kgf/mm}^2\) under the condition of rough initial tooth surface and (ii) \(0.3 \text{ HB kgf/mm}^2\) under the condition of smooth initial tooth surface.

5. Conclusions

The surface-durability of surface-hardened gears was investigated in relation to the tooth surface roughness.

First, the effect of surface roughness on rolling/sliding contact fatigue was studied in detail by using a 2-roller-type contact fatigue testing machine. For surface-hardened steels, the following results were obtained:

(1) The initial surface roughness has a remarkable influence on the surface durability.

(2) The decrease in surface roughness with running time does not always have an advantageous effect on the surface durability.

(3) The initial surface roughness is an important factor in obtaining a high surface durability and in designing the gears.

Secondly, the load-carrying capacities of case-carburized gears and induction-hardened gears were investigated by using a power circulating-type gear testing machine. The phenomenon of "grey-staining", which consists of many micro-cracks and micro-pits and which causes degradation of the tooth profile and spalling, appears on the ground tooth surface under a heavy load. The gear test results can be summarized as follows:

(1) The phenomenon of grey-staining in case-carburized (Cr-Mo alloy steel) gears is not a special one.

(2) In induction-hardened gears, the phenomenon of grey-staining appears under a heavy load.

(3) Surface failure "grey-staining" is most

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1. The average grey-staining area ratio \(\hat{s}\) is defined as follows: \(\hat{s} = (s_1 + s_2)/(a_1 + a_2)\) where \(s\) is the grey-staining area ratio on one tooth surface, \(a\) the number of teeth and suffixes 1 and 2 indicate pinion and gear, respectively. In Fig. 10, Fig. 11 and Fig. 12, the initial tooth profile error \(\epsilon\) and initial surface roughness \(R_{\text{max}}\) are mean values of the pinion and gear.

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Vol. 30, No. 259, 1987

JSMIE International Journal
influenced by the initial surface roughness of surface-hardened gears.

Furthermore, the results of roller tests and gear tests reveal that
(4) the effect of initial surface roughness on the surface durability of surface-hardened gears can be estimated quantitatively.

Acknowledgment

The authors wish to thank Sumitomo Metal Industries, Ltd. and Mitsubishi Oil Company for supplying test materials and lubricants. They also express their thanks to the personnel of the machining laboratory (Faculty of Engineering, Kyushu University) for their assistance in this study.

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JSME International Journal

1987, Vol. 30, No. 259