RESIDUAL STRESS DISTRIBUTION UNDER HARDENING LAYER
OF CARBURIZED TRANSMISSION GEAR
BY NEUTRON DIFFRACTION

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ABSTRACT

In order to understand deformation behavior of carburized steel parts after quenching and tempering, the residual stress field that was distributed under hardening layer of a transmission gear was nondestructively measured by neutron diffraction. The material was chromium-molybdenum steel, SCM420. The carburized case depth was first determined by microscope, and then was measured by micro Vickers hardness tester. The neutron diffractions from Fe-110 and 211 planes were used for stress measurement. In this study, residual stresses were calculated from lattice spacing changes. Unstressed lattice spacing was experimentally determined using reference coupon specimens that were cut from the same carburized gear. As the results, the interior of transmission gear deformed elastically to accommodate the generation of compressive residual stresses in surface hardening layer. This interior elastic deformation was found to result in the complicated residual stresses under hardening layer. Large tensile residual stress parallel to the axial direction of gear was generated in the shift fork groove. Furthermore, tensile residual stresses parallel to the hoop and axial directions were also generated in two gear wheels.

INTRODUCTION

Process of quenching and tempering is a useful technique for steel parts to harden and strengthen of the surface layer [1][2]. In case of carburized steel parts, the shape changes inhomogeneously before and after quenching. Almost parts should be machined after tempering so that the shape accuracy of parts is satisfied. Therefore, reduction of the production cost including machining cost is the most important problem that should be settled. In order to control the shape of carburized steel parts, residual stress field built in the parts during process of carburizing, quenching and tempering [1][3][4] should be understood. Residual stress field near the surface can be measured by X-ray stress measurement [1][4][5]. However, residual stress field that is distributed under hardening layer can’t be measured using X-rays. In this study, residual stress field distributed under hardening layer of a motorcycle transmission gear was nondestructively measured by scanning diffracting volume using neutron radiation, because of lower absorption of neutron.
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EXPERIMENTAL

The material used in this study was chromium-molybdenum steel with 0.2%C, SCM420 that was compliant with Japanese Industrial Standards. Table 1 summarizes chemical composition of raw material before carburizing. A motorcycle transmission gear was used for stress measurement, as shown in Fig. 1. Transmission gear was composed of two gear wheels, shift fork groove and dog clutches. This gear was carburized at 900 °C in carrier gas, and then was quenched from 850 °C in oil and tempered at 190 °C.

Table 1. Chemical composition of raw material (unit: mass %)

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cu</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.20</td>
<td>0.19</td>
<td>0.79</td>
<td>0.02</td>
<td>0.02</td>
<td>0.01</td>
<td>0.02</td>
<td>1.02</td>
<td>0.17</td>
</tr>
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</table>

In order to determine the case depth of gear, the tempered transmission gear specimen was cut by wire-electrical discharging. Using cut gear specimen, both microstructural change and hardness distribution were measured as a function of the distance from the hardening surface by optical microscope and micro Vickers hardness tester (HM-122, Akashi, Ltd.). Indentation load and holding time were about 2.9 N and 15 sec, respectively. Effective case depth was defined as the depth at 550HV.

Residual stress field that was distributed under hardening layer was nondestructively measured using neutron radiation of JRR-3 in Japan Atomic Energy Research Institute. The radial, hoop and axial strains, \( \varepsilon_r(z) \), \( \varepsilon_\theta(z) \) and \( \varepsilon_z(z) \), near the internal spline of transmission gear were measured by scanning diffracting volume along the \( z \)-direction, as shown in Fig.2. The wavelength of neutron beam was set at \( \lambda=2.07 \) Å to be diffracted from the same gauge volume. The diffractions from Fe-110 and 211 planes were used for stress measurement. Diffracting volume was adjusted to about \( 2.3\times4.1\times2.0 \) mm\(^3\) by incident and diffracted collimators with 2×2 and 2×15 mm\(^2\), respectively.

Three strains are calculated from the measured lattice spacing changes as follows:
\[ \varepsilon_r = \frac{d_r - d_{r,0}}{d_{r,0}}, \quad \varepsilon_{\theta} = \frac{d_{\theta} - d_{\theta,0}}{d_{\theta,0}}, \quad \varepsilon_z = \frac{d_z - d_{z,0}}{d_{z,0}}, \]  

where \( d_r, d_\theta \) and \( d_z \) are lattice spacing parallel to radial, hoop and axial directions in a cylindrical coordinate system (Fig.1). These lattice spacing were calculated from the diffraction peak positions, \( 2\theta \), that were determined by fitting with a Gaussian peak. The \( d_{r,0}, d_{\theta,0} \) and \( d_{z,0} \) are unstressed lattice spacing. In this study, unstressed lattice spacing of Fe-110 and 211 planes were experimentally determined using reference coupon specimens. The eight cubic small pieces with a width of 2 mm were cut at seven points, A, B, C, D, E, F and G, from the same tempered gear, as shown in Fig. 3. Surface layer of cut pieces was removed by sandpaper and electro polishing. Reference coupon specimens were put together from eight pieces using superglue, and then lattice spacing of coupons was measured as unstressed one [6].

**RESULTS AND DISCUSSION**

Figures 4(a), 4(b) and 4(c) show typical micrographs of cut gear specimen. The cross-sectional surface was etched with 3 \% nitric acid in ethyl alcohol. Burnished layer was observed near the outer surface (Fig. 4(a)). The microstructure changed from martensite (near the surface, Fig.4(b)) to mixture of low-carbon martensite and bainite (on the interior, Fig.4(c)). Figure 5 shows Vickers hardness distributions as a function of the distance from the surface. The surface hardness of
transmission gear was increased to about 700HV by carburizing, quenching and tempering. The effective case depth was about 0.5mm. Under the hardening layer, the hardness of interior base material in the shift fork groove was about 364HV, while in the gear wheels the hardness of interior was about 309HV. Hardenabilities of shift fork groove and dog clutches were found to be relatively higher than that of gear wheel, because of the difference in heat capacity.

Figure 6 shows the lattice spacing distributions, \( d_r(z) \), \( d_\theta(z) \) and \( d_z(z) \), in the radial, hoop and axial directions near the internal spline of transmission gear. The diffracting center position was translated along the \( z \)-axis within the gear wall thickness under hardening layer. In this figure, interpolation line of Fe-211 plane in the hoop direction was broken, because the diffraction peaks of Fe-211 plane could not be obtained from the gauge volume in the two gear wheels during the allotted time period. Instead of Fe-211 plane, the diffraction peaks of Fe-110 plane were measured. All lattice spacing of Fe-110 and 211 planes changed depending on the diffracting position. Especially, the \( d_\theta \) of Fe-110 plane in the gear wheel was relatively larger than that in the shift fork groove or dog clutches. On the other hand, the \( d_z \) of Fe-211 plane in the gear wheel was relatively smaller than that in the shift fork groove.

Figure 7 shows lattice spacing of coupon specimens. Lattice spacing of Fe-110 and Fe-211 planes was nearly constant for coupon specimens, A, B and F, that were cut from two gear wheels. In this figure, the mean values of A, B and F were shown by solid and dotted lines. On
the other hand, lattice spacing for coupon specimens, C, D, E and G, was relatively changed from the above mean value. In order to establish the cause for the difference in coupon specimens, the full widths at half-maximum intensity (FWHM), $W_{110}$ and $W_{211}$, of diffraction peaks for Fe-110 and 211 planes and the surface hardness of coupon specimens were measured.

Figure 8 shows the FWHMs of three diffraction peaks in the radial, hoop and axial directions of coupon specimens. For each plane, the FWHMs of coupon specimens, C, D, E and G, were relatively wider than those of the rest coupon specimens. The difference in FWHMs means the existence of residual stress or affected layer due to the process of carburizing, quenching and tempering or machining. Figure 9 shows the surface hardness of coupon specimens. In this figure, a dashed-dotted line shows the hardness of interior in transmission gear (at “Gear-1”-line in Figs. 4(a) and 5). The surface hardness of coupon specimens, A, B and F, was nearly constant, and equal to that of the interior base material. On the other hand, the surface hardness of coupon specimens, C, D, E and G, was increased. The hardening layer was slightly left in the surface of coupon specimens that were cut from the shift fork groove and dog clutches. Therefore, in this study, the mean value of coupon specimens, A, B and F, was defined as unstressed lattice spacing.

Figure 10 shows the residual strain distributions, $\varepsilon_r$, $\varepsilon_0$ and $\varepsilon_z$, calculated from Eq. (1). For calculating the residual strain, $\varepsilon_0$, in the hoop direction, the lattice spacing $d_{0,211}$ was used for shift fork groove and dog clutches, and the lattice spacing $d_{0,110}$ was used for gear wheels. For iron-based materials, the biaxial compressive residual stresses were known to be generated in the surface hardening layer of carburized steel parts after tempering. In fact, using the heat treated block spe-
cimen of the same material, biaxial compressive residual stresses were preliminarily observed in the hardening layer by X-ray stress measurement. The stress field of the interior in carburized steel parts could be expected to be small triaxial tension that balanced with the surface biaxial compression. Residual strain distributions under hardening layer near the internal spline were not small tensile strains. All strains changed complicatedly along the z-axis. The radial strain, $\varepsilon_r$, was compressive even though the diffracting position changed. On the other hand, the hoop and axial strains, $\varepsilon_\theta$ and $\varepsilon_z$, were tensile in two gear wheels. In the shift fork groove, the axial strain became larger than that in two gear wheels. Figure 11 shows the FWHMs of diffraction peaks near the internal spline of transmission gear. In this figure, the solid and dotted lines indicated the mean FWHMs of coupon specimens. In the all directions, the FWHMs of transmission gear were found to be wider than that of coupon specimens. Among three directions, the FWHM of the hoop direction became widest. Furthermore, the FWHMs of shift fork groove and dog clutches were relatively wider than that of two gear wheels. Therefore, the interior of transmission gear deformed elastically to accommodate the generation of surface compressive residual stresses. This interior elastic deformation was found to result in complicated residual strains distributed under the hardening layer. The FWHMs in the radial and hoop directions were thereby increased relative to the FWHM of stress-released coupon specimens.

Next, the residual stress field that was distributed in the interior near the internal spline under the hardening layer was calculated as follows. In the case of unknown stress state, more than six strains in the different directions have to be measured. On the other hand, in the case that the
radial, hoop and axial directions accorded with principal axes such as thermal residual stress filed of cylindrical parts, residual stresses in the radial, hoop and axial directions, $\sigma_r$, $\sigma_\theta$ and $\sigma_z$, can be given by $[\text{5}][\text{7}]$,

$$
\sigma_r = \frac{E_N}{1 + \nu_N} \left\{ (1 - \nu_N)\varepsilon_{\text{r}} + \nu_N (\varepsilon_{\theta} + \varepsilon_{\text{z}}) \right\},
$$

$$
\sigma_\theta = \frac{E_N}{1 + \nu_N} \left\{ (1 - \nu_N)\varepsilon_{\theta} + \nu_N (\varepsilon_{\text{r}} + \varepsilon_{\text{z}}) \right\},
$$

$$
\sigma_z = \frac{E_N}{(1 + \nu_N)(1 - 2\nu_N)} \left\{ (1 - \nu_N)\varepsilon_z + \nu_N (\varepsilon_{\text{r}} + \varepsilon_{\theta}) \right\},
$$

where $E_N$ and $\nu_N$ are neutron elastic constants for the selected diffraction plane. For simplicity radial, hoop and axial directions of transmission gear were assumed to correspond to principal axes, residual stresses could be calculated from above Eq.(2)

Figure 12 shows the residual stress distributions calculated from Eq. (2). The interior material of transmission gear was the heat treated chromium-molybdenum steel with 0.2%C (SCM420). In our case, Fe-110 and 211 planes were used for stress measurement. Neutron elastic constants, $E_N$ and $\nu_N$ of Fe-100 plane are theoretically equal to those of Fe-211 plane, respectively $[\text{5}][\text{7}]$. In this study, mechanical elastic moduli of base material SCM420, $E=204$ GPa and $\nu=0.27$, were substituted as neutron elastic constants. The maximum tensile residual stress, $\sigma_z$, parallel to the axial direction was observed at the center of the shift fork groove. Furthermore, the tensile residual stresses, $\sigma_\theta$ and $\sigma_z$, parallel to the hoop and axial directions were also observed in two gear wheels. The residual stress, $\sigma_r$, parallel to the radial direction became compression that might balanced with two other tensile residual stresses. It's not exactly that the above assumption can hold all over the transmission gear. For rigorous analysis for the shape control of carburized steel parts, the residual stress state should be caught.

In any case, by measuring residual stress field that was distributed under the hardening layer of transmission gear, the complicated residual stresses due to heat treatment process were found to be generated elastically in the interior, and then carburized steel parts including the interior base material were locally deformed after tempering.

**CONCLUSIONS**

In order to understand the shape change of the motorcycle transmission gear during the continuous process of carburizing, quenching and tempering, the residual stresses under hardening
layer near the internal spline was nondestructively measured by scanning diffracting volume using neutron radiation. The results are summarized as follows:

1. Residual strain distributions under hardening layer near the internal spline were not small tensile strains. The radial strain was compressive and the hoop and axial strains were tensile in two gear wheels. In the shift fork groove, the axial strain became larger than that in two gear wheels.

2. The FWHM of diffraction peaks in the all directions of transmission gear were wider than that of coupon specimens. Among three directions, the FWHM of the hoop direction became widest. The FWHMs of shift fork groove and dog clutches were relatively wider than that of two gear wheels. The interior of transmission gear deformed elastically to accommodate the generation of surface compressive residual stresses. This interior elastic deformation was found to result in the complicated residual strains distributed under the hardening layer.

3. The maximum tensile residual stress parallel to the axial direction was observed at the center of the shift fork groove. The residual stresses parallel to the hoop and axial directions were tensile and the residual stress parallel to the radial direction was compressive in two gear wheels. The residual stresses under hardening layer near the internal spline changed complicatedly.

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REFERENCE