Evaluation of Stress Anisotropy and Shearing Stress Using an Eddy Current Method with a Tangential-Rectangular Coil*

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Abstract

In establishing a system to evaluate residual stress, it is important to design the system so that it can also evaluate the stress anisotropy, since this is introduced into metallic materials by surface processes such as grinding and polishing. The shearing stress is also an important parameter when the shear strength has to be considered, since tensile stress can cause stress corrosion cracking. Thus, a method to nondestructively evaluate the stress anisotropy and shearing stress in a short time is required. In this paper, a nondestructive eddy current method using a tangential-rectangular coil was used to accomplish this. The material under test was stainless steel, Japanese Industrial Standard (JIS) SUS316L, ground or polished by an angle grinder. The stress anisotropy caused by the grinding and polishing processes was evaluated by the eddy current method with the tangential-rectangular coil. To vary the stress state, some specimens were treated with cavitation peening after grinding with the angle grinder. The results demonstrate that the stress anisotropy, shearing stress and peening intensity can be evaluated by the eddy current method using the tangential-rectangular coil. From the results, it was concluded that the maximum shearing stress and the direction of the principal stress could be determined.

Key words: Electromagnetic Measurement, Nondestructive Inspection, Material Testing, Eddy Current, Residual Stress, Anisotropy

1. Introduction

Identifying the stress state is important in evaluating the reliability of metallic components because this affects the fatigue properties and the resistance of materials to stress corrosion cracking (SCC). An electromagnetic method is an appropriate method for evaluating the stress state, since this can be done both quickly and nondestructively.

Stress affects the fatigue strength and resistance to stress corrosion cracking (SCC). In particular, the introduction of tensile stress decreases the resistance to SCC (1). Surface processes, such as grinding, polishing and peening, can vary the stress conditions. Most industrial materials have stress anisotropy (2). To improve the fatigue strength of industrial metallic materials, peening techniques, such as shot peening (SP) (3), cavitation peening (CP) (4) and laser peening (LP) (5) are conducted. The stress state at the surface of the peened material is equibiaxial (6). Thus, knowing the residual stress and the stress anisotropy is important in order to have an indication of the resistance to SCC and the fatigue properties. The normal stress and shearing stress induced in metallic materials are the parameters considered when structural components are designed. Therefore, it is important to monitor...
the stress state and improve the reliability of the components. There are many methods for evaluating stress such as X-ray diffraction (7), ultrasonic methods (8) and electromagnetic methods (9). X-ray diffraction for measuring stress is widely used because of the precision of the measurements. However, the measurement time to obtain the results of the stress anisotropy is long. In the case of ultrasound, stress measurements at the surface and local characterization are difficult because both an ultrasonic transmitter and receiver are required. Electromagnetic methods have an advantage, in that they are sensitive to the material characteristics at the surface and the penetration depth can be varied with the frequency of the alternating current. In addition, the evaluation can be done relatively quickly and non-destructively. Also, measurement of the residual stress by the eddy current method can be applied to various metallic materials, from ferromagnetic to paramagnetic materials. There have been various reports of stress measurements using eddy current methods. Abu-Nabah and Nagy reported the variation in electrical conductivity of shot-peened materials due to the piezoresistive effect evaluated by an eddy current method (10). Sekine and Soyama reported that the electromagnetic properties of alloy tool steel, which is a ferromagnetic material, can be determined using an eddy current method combined with an inverse analysis (12). Yu and Nagy reported on an eddy current method using a race-track coil, with which the uniaxial electromagnetic properties could be evaluated, showing that the electrical conductivity of metallic materials varied with applied load (13). They reported on the variation of the electrical conductivity with uniaxial tension and compression (13). In general, the introduction of compressive stress into iron increases the electrical conductivity (14), due to the piezoresistive effect (15). Burke reported on the theory of eddy current signals using a tangential-circular coil, with which the direction of the generated eddy current could be completely determined, and that the eddy current signal of an anisotropic plate varied with the rotational angle of the coil (16). There are a number of reports on the evaluation of cracks by eddy current methods with tangential coils. Hoshikawa et al. used a tangential-rectangular coil, which can induce a uniform uniaxial eddy current, to show that the eddy current signal derived from a crack varied with the angle of the crack (17). Janousek et al. reported that the depth of cracks in the range of 10 ~ 20 mm can be clearly evaluated by the eddy current method using four tangential-rectangular coils (18). Morozov et al. revealed that the induced uniaxial stress affects the eddy current signal and the electrical conductivity evaluated by an eddy current method using a tangential-rectangular coil (19). However, the relationship between the induced stress and the eddy current output is considered to be uniaxial. If a uniaxial stress is induced into a metallic material, a negative stress is induced in the direction perpendicular to this. Therefore, the variation in the eddy current signal due to the biaxial stress state should be considered if the stress is applied uniaxially. Measurement of the stress anisotropy using an eddy current method enables evaluation of the shearing stress. The stress induced in metallic materials after peening is an equibiaxial compressive stress. The evaluation of the stress anisotropy by an eddy current method using the piezoresistive effect enables the peening intensity of metallic materials to be evaluated quickly and non-destructively. The anisotropy of the electrical conductivity can be evaluated using the eddy current method with a tangential-rectangular coil by varying the measurement angle (16). Thus, the stress anisotropy and shearing stress can be evaluated using an eddy current method with a tangential-rectangular coil.

In the present study, in order to establish a method to evaluate the shearing stress and the peening intensity of metallic materials with anisotropic stress, non-peened and CP treated samples of austenitic stainless steel, Japanese Industrial Standard (JIS) SUS316L, were evaluated by an eddy current method with a tangential-rectangular coil. The surface of
the steel was ground by a depressed center grinding wheel using an angle grinder to give an anisotropic stress state. The reason for selecting CP as the peening method is that the increase in surface roughness after CP is smaller than that after SP (6). In addition, to vary the shearing stress, various surface finishing methods, such as polishing using an angle grinder were used. To measure the stress anisotropy, the measurement direction was varied. The eddy current results obtained were compared with the residual stress measured by X-ray diffraction. The results show that the stress anisotropy, the shearing stress and the peening intensity can be evaluated by the eddy current method with a tangential-rectangular coil. The results also show that the maximum shearing stress and the principal stress direction can be determined using the eddy current method. The direction of the principal stress reveals the direction in which the fracture propagates.

**Nomenclature**

\[ d_w : \text{Coil wire diameter mm} \]
\[ f : \text{Frequency MHz} \]
\[ h_{core} : \text{Height of air core of the coil mm} \]
\[ l_{coil} : \text{Length of the tangential-rectangular coil mm} \]
\[ N : \text{Number of turns of the coil turns} \]
\[ n : \text{Number of scans in the cavitation peening} \]
\[ R_a : \text{Arithmetic average roughness \( \mu \)m} \]
\[ r_{AV} : \text{Radius of the differential reactance’s circle \( \Omega \)} \]
\[ s : \text{Standoff distance of the coil mm} \]
\[ t_p : \text{Processing time per unit length s/mm} \]
\[ v : \text{Scanning speed for the cavitation peening mm/s} \]
\[ X : \text{Reactance \( \Omega \)} \]
\[ X_{\phi_0} : \text{Reactance at \( \phi_0 = 0 \) deg \( \Omega \)} \]
\[ X_{\phi} : \text{Reactance at the angle, \( \phi \) \( \Omega \)} \]
\[ \Delta X : \text{Differential reactance between \( \phi_h \) and \( \phi_r = 0 \) deg \( \Omega \)} \]
\[ \Delta X_{45} : \text{Differential reactance between \( \phi_h = 45 \) deg and \( \phi_r = 0 \) deg \( \Omega \)} \]
\[ \Delta X_{90} : \text{Differential reactance between \( \phi_h = 90 \) deg and \( \phi_r = 0 \) deg \( \Omega \)} \]
\[ \Delta X_{\phi} : \text{Differential reactance between specimen with applied stress and that without \( \Omega \)} \]
\[ x : \text{Axis in the direction of the compressive stress applied by the hydraulic jack} \]
\[ y : \text{Axis normal to the x axis} \]
\[ w_{coil} : \text{Width of the tangential-rectangular coil mm} \]
\[ \phi_h : \text{Angle between the rotating angle of the angle grinder and the measurement angle deg} \]
\[ 2\theta : \text{Diffractive angle for the stress measurement using X-ray diffraction deg} \]
\[ \sigma_{app} : \text{Applied stress MPa} \]
\[ \sigma_a : \text{Normal stress MPa} \]
\[ \sigma_{00} : \text{Normal stress at \( \phi_h = 0 \) deg MPa} \]
\[ \sigma_{060} : \text{Normal stress at \( \phi_h = 60 \) deg MPa} \]
\[ \sigma_{120} : \text{Normal stress at \( \phi_h = 120 \) deg MPa} \]
\[ \sigma_{\max} : \text{Maximum normal stress MPa} \]
\[ \sigma_{\min} : \text{Minimum normal stress MPa} \]
\[ \sigma_{\text{uni}} : \text{Applied stress in the direction of compression MPa} \]
\[ \sigma_{\text{uni}} : \text{Applied stress normal to the direction of compression MPa} \]
\[ \tau : \text{Shearing stress MPa} \]
\[ \tau_{\max} : \text{Maximum shearing stress MPa} \]
\[ \psi : \text{Angle between the normal to the surface and the normal to the lattice plane deg} \]
2. Experimental setup and Methods

The material under test was austenitic stainless steel, JIS SUS316L, which is generally used for pressure tanks and tubes. The thickness, width and length of the specimens were 6, 100 and 100 mm, respectively. To vary the stress state and the stress anisotropy and simulate materials treated by mechanical processing, the surface of the stainless steel was ground by a depressed center grinding wheel (GW) using an angle grinder. A Resibon Ace Gold was used as the GW, and the rotating speed of the angle grinder was set to 11 000 rpm. This specimen was designated the GW specimen. To make comparisons with the GW specimen, specimens with other surface finishes were produced. 3M Scotch-Brite Clean N Strip Bevel Black (CNS) with a silicon carbide abrasive grain, 3M Scotch-Brite Bevel Brown (SB) with an aluminum oxide abrasive grain and TRUSCO GP Top DX #100 (Flap) were used for abrading or polishing, with the rotating speed of the angle grinder set to 11 000 rpm.

In the present study, in order to avoid major variations in surface roughness after peening, cavitation peening (CP) was used as the peening method. Practical considerations led to the use of a cavitating jet in air for the CP. The experimental CP conditions were set to those reported in a previous paper. Concentric high speed and low speed water jets with respective pressures of 30 MPa and 0.05 MPa were injected into air. The inner diameters of the nozzles for the high and low speed water jets were 1 mm and 30 mm, respectively. The outer diameter of the nozzle for the high speed water jet was 16 mm, and the standoff distance, which is the distance from the outlet of the nozzle to the specimen’s surface was set to 45 mm. In the present study, 5 GW specimens were treated by CP with different processing times. The processing time per unit length, \( t_p \), was determined by the number of scans, \( n \), during CP processing and the CP scanning speed, \( v \), as follows:

\[
 t_p = \frac{n}{v} \quad (1)
\]

\( t_p \) was set to 0.25, 0.5, 1, 2, or 5 s/mm. To compare the results of the CP specimens, a non-treated GW specimen, which we call the non-peened (NP) specimen, was prepared.

Measurements of the electromagnetic properties using the eddy current method were conducted using a tangential-rectangular coil and an LCR meter, HIOKI 3532-50, directly connected to the coil. In the present paper, the coil reactance, \( X \), was measured. The properties of the coil used for the eddy current tests in this study are shown in Table 1. The angle of the coil with respect to the direction in which the surface was ground, \( \phi_R \), was varied. Figure 1 shows the coil geometry and defines \( \phi_R \). The angle grinder was used in order to induce a large tensile residual stress in the NP specimen. The frequency and peak-to-peak value of the alternating current generated by the LCR meter were 3.5 MHz and 0.8 mA, respectively. Under the conditions, the penetration depth considering the skin effect is 0.2 mm assumed that the electrical resistivity of SUS316L is \( 74 \times 10^{-8} \Omega \text{m} \).

The residual stress was also measured using the X-ray diffraction \( \sin^2 \psi \) method. A Cr tube was used to produce K\( \beta \) X-rays for the stress measurements. The operating voltage and current of the X-rays were 30 kV and 8 mA, respectively. The diffractive plane was selected as that of \( \gamma \)-Fe (311), and the diffractive angle without strain was 148.5 deg. The diffractive

<table>
<thead>
<tr>
<th>Properties</th>
<th>Values</th>
</tr>
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<tbody>
<tr>
<td>Number of turns</td>
<td>( N ) (turns)</td>
</tr>
<tr>
<td>Wire diameter</td>
<td>( d_w ) (mm) 0.1</td>
</tr>
<tr>
<td>Coil width</td>
<td>( w_{\text{coil}} ) (mm) 10</td>
</tr>
<tr>
<td>Coil length</td>
<td>( l_{\text{coil}} ) (mm) 10</td>
</tr>
<tr>
<td>Lift off</td>
<td>( s ) (mm) 0.5</td>
</tr>
<tr>
<td>Thickness of air core</td>
<td>( h_{\text{core}} ) (mm) 2</td>
</tr>
</tbody>
</table>

Fig. 1 Schematic illustration of the coil geometry
angle, $2\theta$, was set to vary from 143 deg to 153 deg in 0.2 deg steps. An iso-inclination method was used for the measurements and X-rays were counted every 4 s for each step with a scintillation counter. The angle $\psi$ between the normal to the surface and the normal to the lattice plane was set to 0, 22.8, 33.2, 42.1, or 50.7 deg during the measurements. Under these conditions, the stress factor was -369.5 MPa/deg. In the present study, to determine the normal and shearing stress, 6 normal stresses, $\sigma_n$, in different directions were measured using X-ray diffraction. The measurement direction, $\phi_R$, was set to 0, 60, 120, 180, 240 or 300 deg in consideration of Mohr’s stress circle and $\psi$-spirit which is derived from the direction of principal stress and distribution of the residual stress in the penetration depth of X-ray. To calculate the residual stress, the relationship between $\sin^2 \psi$ and $2\theta$ is required. In the present study, to consider the $\psi$-spirit, the residual stress was calculated from the relationship between $\sin^2 \psi$ and $2\theta$ for the following pairs of angles: $\phi_R = 0, 180$ deg, $\phi_R = 60, 240$ deg, and $\phi_R = 120, 300$ deg. Mohr’s stress circle was determined from the normal stress measured using the X-ray diffraction method.

To determine the affect of applied stress, the variation in eddy current signal with compressive stress induced by a hydraulic jack was investigated. The width, length and thickness of the specimen were 30, 30 and 10 mm, respectively. The tangential-rectangular coil, whose properties are shown in Table 1, was placed on the upper side of the specimen, and strain gauges were attached to the other side. The coil was placed in the same direction as that of the compressive stress. Under these conditions, the variation of the eddy current signal at $f = 3.5$ MHz with the applied stress was measured.

3. Results

3.1 Measurement of the Applied Stress

In order to investigate the sensitivity of the stress measurement by the eddy current method using a tangential-rectangular coil and understand the behavior of the coil sensing the stress, the eddy current signal from stainless steel with stress applied by the hydraulic jack was measured. The differential reactance, $\Delta X_a$, which is the difference between the reactance with and without applied stress, was recorded. Figure 2 shows the relationship between $\Delta X_a$ and the applied stress, $\sigma_{app}$. In this paper, the x axis is set in the direction of the stress applied by the hydraulic jack, and the stress in the x direction is designated as $\sigma_{uni}$. The stress perpendicular to the x axis is designated as $\sigma_{uni}$. In Fig. 2, the results with the coil winding parallel to the x axis are shown by the black line, whereas those with the coil winding parallel to the y axis are shown by the gray line. The gradient of the relationship between $\Delta X_a$ and $\sigma_{uni}$ shown by the black line in Fig. 2 is $400 \pm 140 \ \Omega/\text{TPa}$, and that between $\Delta X_a$ and $\sigma_{uni}$ shown by the gray line in Fig. 2 is $1600 \pm 500 \ \Omega/\text{TPa}$. These gradients are clearly different, whereas, theoretically, they should have the same value. The cause of the difference seems to be derived from the uniaxial stress state. If a compressive
stress is induced, a tensile stress is induced perpendicular to this. The difference between the applied compressive stress and the tensile stress perpendicular to it increases with applied load. Thus, a biaxial stress state should be considered. From the difference between the gradients, an evaluation of the stress anisotropy can be conducted by the eddy current method with a tangential-rectangular coil. Figures 3 and 4 show the relationships between $\Delta X_a$ and $\sigma_{x_{uni}} - \sigma_{y_{uni}}$ and between $\Delta X_a$ and $\sigma_{y_{uni}} - \sigma_{x_{uni}}$, respectively. The gradient of the relationship between $\Delta X_a$ and $\sigma_{x_{uni}} - \sigma_{y_{uni}}$ in Fig. 3 is almost the same as that between $\Delta X_a$ and $\sigma_{y_{uni}} - \sigma_{x_{uni}}$ in Fig. 4. The first terms of horizontal axes in Figs. 3 and 4 is the applied stress which is in the same direction as the coil winding, and $\sigma_{x_{uni}} - \sigma_{y_{uni}}$ or $\sigma_{y_{uni}} - \sigma_{x_{uni}}$ show the differential applied stress. The gradient shown in Fig. 3 is $310 \pm 110 \, \Omega/TPa$, and that in Fig. 4 is $380 \pm 120 \, \Omega/TPa$. From this, the errors of the gradient are 35% and 32%, respectively, which relate the measuring accuracy. These two gradients have almost the same value. Thus, the applied stress and the stress difference can be evaluated using the tangential-rectangular coil. The electrical conductivity increases with the introduction of compressive stress due to the piezoresistive effect. In using a tangential coil, the direction in which the coil reactance is reduced is the same as that in which the electrical conductivity is increased. From the relationships between the applied stress and the eddy current results, the variations in the coil reactance shown in Figs. 3 and 4 are derived from the variation in applied stress. The reduction in $\Delta X_a$ with electrical conductivity is similar to that in previous reports. Thus, it can be concluded that a tangential-rectangular coil can be used to evaluate uniaxial stress, and also to evaluate the stress anisotropy.

![Fig. 3](image_url)  Variation of the differential reactance with differential applied stress with the direction of the coil the same as that of the applied compressive stress

![Fig. 4](image_url)  Variation of the differential reactance with differential applied stress with the direction of the coil perpendicular to that of the applied compressive stress
3.2 Stress Measurement by an X-ray Diffraction Method

To confirm the stress states of the specimens, they were evaluated using an X-ray diffraction method. Table 2 shows the stress measured by the X-ray diffraction method at \( \phi_R = 0 \) deg, \( \sigma_{n0} \), at \( \phi_R = 60 \) deg, \( \sigma_{n60} \), at \( \phi_R = 120 \) deg, \( \sigma_{n120} \), the maximum normal stress, \( \sigma_{nmax} \), the minimum normal stress, \( \sigma_{nmin} \), and the maximum shearing stress, \( \tau_{max} \). The normal stresses \( \sigma_{n0} \), \( \sigma_{n60} \) and \( \sigma_{n120} \) were calculated from \( \sigma_n \) for pairs of measuring angles \( \phi_R = 0, 180 \) deg, \( \phi_R = 60, 240 \) deg, and \( \phi_R = 120, 300 \) deg, respectively. In the case of the GW (NP) specimen shown in Table 2, the highest residual stress among the 3 angles is \( \sigma_{n0} \). In the case of the GW (CP) specimens, the differences between \( \sigma_{n0} \), \( \sigma_{n60} \) and \( \sigma_{n120} \) are smaller than those for the NP specimen. In addition, from the results shown in Table 2, all the stress parameters decrease with CP processing time due to the introduction of the compressive residual stress. In particular, the difference between \( \sigma_{nmax} \) and \( \sigma_{nmin} \), and \( \tau_{max} \) both decrease with processing time. The peening introduces an equibiaxial compressive stress. Thus, the difference between \( \sigma_{nmax} \) and \( \sigma_{nmin} \), and \( \tau_{max} \) decrease with the introduction of the equibiaxial compressive residual stress by CP. The stress states for the others processes shown in Table 2 show the same tendency as the GW (NP) specimen. It can be concluded that surface processes such as GW, CNS, SB and Flap give an anisotropic stress state.

3.3 Eddy Current Signal Varied with Coil Winding Direction

Figures 5 and 6 shows the eddy current results for the NP specimen and the CP specimen at \( t_p = 5 \) s/mm varying with \( \phi_R \), respectively. Both are GW specimens. To compare Figs. 5 and 6 with Table 2, the lines are drawn at \( \phi_R = 60, 120, 180, 240 \) and 300 deg in Figs. 5 and 6. The eddy current signal was used to obtain the differential reactance, \( \Delta X \), which is the difference between the reactance at \( \phi_R \), \( X_{\phi R} \), and that at \( \phi_R = 0 \) deg, \( X_{\phi 0} \), as follows:

Table 2  Stresses measured by an X-ray diffraction method and the calculated maximum and minimum normal stress and maximum shearing stress (MPa)

<table>
<thead>
<tr>
<th></th>
<th>( \sigma_{n0} )</th>
<th>( \sigma_{n60} )</th>
<th>( \sigma_{n120} )</th>
<th>( \sigma_{nmax} )</th>
<th>( \sigma_{nmin} )</th>
<th>( \tau_{max} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>GW (NP)</td>
<td>890 ± 40</td>
<td>460 ± 30</td>
<td>350 ± 40</td>
<td>890 ± 60</td>
<td>240 ± 60</td>
<td>330 ± 60</td>
</tr>
<tr>
<td>GW (CP 0.25 s/mm)</td>
<td>150 ± 20</td>
<td>0 ± 30</td>
<td>-80 ± 20</td>
<td>160 ± 40</td>
<td>-120 ± 40</td>
<td>140 ± 40</td>
</tr>
<tr>
<td>GW (CP 0.5 s/mm)</td>
<td>-130 ± 30</td>
<td>-120 ± 30</td>
<td>-160 ± 20</td>
<td>-110 ± 40</td>
<td>-160 ± 40</td>
<td>20 ± 40</td>
</tr>
<tr>
<td>GW (CP 1 s/mm)</td>
<td>-180 ± 30</td>
<td>-190 ± 20</td>
<td>-240 ± 20</td>
<td>-170 ± 50</td>
<td>-240 ± 50</td>
<td>40 ± 50</td>
</tr>
<tr>
<td>GW (CP 2 s/mm)</td>
<td>-370 ± 20</td>
<td>-310 ± 20</td>
<td>-370 ± 20</td>
<td>-310 ± 30</td>
<td>-390 ± 30</td>
<td>40 ± 30</td>
</tr>
<tr>
<td>GW (CP 5 s/mm)</td>
<td>-500 ± 20</td>
<td>-460 ± 20</td>
<td>-440 ± 40</td>
<td>-440 ± 50</td>
<td>-500 ± 50</td>
<td>30 ± 50</td>
</tr>
<tr>
<td>CNS</td>
<td>-180 ± 20</td>
<td>-350 ± 20</td>
<td>-480 ± 20</td>
<td>-170 ± 30</td>
<td>-510 ± 30</td>
<td>170 ± 30</td>
</tr>
<tr>
<td>SB</td>
<td>-200 ± 20</td>
<td>-330 ± 20</td>
<td>-440 ± 20</td>
<td>-180 ± 30</td>
<td>-460 ± 30</td>
<td>140 ± 30</td>
</tr>
<tr>
<td>Flap</td>
<td>110 ± 20</td>
<td>-20 ± 30</td>
<td>-250 ± 20</td>
<td>160 ± 40</td>
<td>-260 ± 40</td>
<td>210 ± 40</td>
</tr>
</tbody>
</table>

Fig. 5  Variation of the differential reactance of the GW and NP specimen with the coil winding direction
From Figs. 5 and 6, $\Delta X$ for the NP specimen varies with $\phi_R$, and $\Delta X$ for the CP specimen has a constant value. It has been reported that the electrical conductivity increases with compressive stress \(^{(14)}\). The electrical conductivity of the peened materials also increases because of the introduction of the compressive residual stress \(^{(10)}\). In using the tangential coil, the reduction in coil reactance signifies an increase in the electrical conductivity \(^{(16)}\). In addition, the NP specimen contains anisotropic stress as shown in Table 2. The variation in coil reactance shown in Fig. 5 is derived from the stress anisotropy. Comparing the relationship between $\Delta X$ and $\phi_R$ shown in Fig. 5 with $\sigma_{n0}$, $\sigma_{n60}$ and $\sigma_{n120}$ given in Table 2, the higher $\sigma_n$ is at the same angle, $\phi_R = 0$ deg. In addition, it was revealed that the maximum normal stress in the GW (NP) specimen is with both $\phi_R = 0$ and $\phi_R = 180$ deg, and the direction of minimum normal stress is with both $\phi_R = 90$ and $\phi_R = 270$ deg calculated from the results in Table 2. The reduction in $\Delta X$ with the electrical conductivity shows the same tendency as in previous reports \(^{(16)}\). This may be affected by the conductivity difference caused by the piezoresistive effect \(^{(15)}\). Table 3 shows the arithmetical average roughness, $R_a$, of the NP specimen and the CP specimen at $t_p = 5$ s/mm for $\phi_R = 0$ and 90 deg. GW specimens were used for the roughness measurements. From Table 3, $R_a$ with $\phi_R = 90$ deg is significantly larger than that with $\phi_R = 0$ deg in the case of the CP specimen at $t_p = 5$ s/mm. In addition, $R_a$ of non-ground SUS316L specimen treated after peening is the same level of or less than $R_a$ described in Table 3. If the surface roughness affects the eddy current signal, the eddy current results of the CP specimen are also affected by the surface roughness. From Fig. 6, $\Delta X$ is constant and the effect of the surface roughness is not evident. In addition, from the stress stated of the GW (NP) and GW (CP 5 s/mm) specimen shown in Table 2, CP reduces the stress anisotropy, and the biaxial compressive stress is induced into GW (CP 5 s/mm). From $R_a$ in Table 3 and the reactance variations shown in Figs. 5 and 6, the effect of the surface roughness on the eddy current signal is small, and the stress state can be measured by the eddy current method considering the stress state after CP described in Table 2. The large deviation as shown in Fig. 6 may be derived from the stress measurement accuracy and surface roughness. However, the number of measurement may reduce the large deviation as shown in Fig. 6.

Figures 7 and 8 show the relationships between $\Delta X$ and $\sigma_n$, and $\Delta X$ and the shearing stress, $\tau_s$, of the GW (NP) specimen, respectively. From Fig. 7, there is a linear relationship between $\Delta X$ and $\sigma_n$ because of the piezoresistivity. On the other hand, the relationship between $\Delta X$ and $\tau_s$ shown in Fig. 8 is nonlinear. From the relationship between $\Delta X$ and $\tau_s$ in
Fig. 8, it can be concluded that an ellipsoidal line can be drawn through the points. From Figs. 2 ~ 4, the eddy current signals using a tangential-rectangular coil are affected by stress. The reduction in coil reactance in the direction of induced compressive stress shown in Fig. 7 is the same as the tendency in Figs. 2 ~ 4 because of the piezoresistive effect. However, further analysis based on the ellipsoidal relationship between $\Delta X$ and $\tau_s$ shown in Fig. 8 may show that the shearing stress can be obtained from the eddy current signal results. From, the relationships between $\sigma_n$ or $\phi_R$ and $\Delta X$ shown in Figs. 5, 7 and 8, it is revealed that the stress anisotropy and the stress state can be evaluated by an eddy current method with a tangential-rectangular coil.

3.4 Evaluation of the Shearing Stress

To evaluate the shearing stress using the eddy current method with a tangential-rectangular coil, the eddy current signals from other CP specimens were

Table 3  Arithmetical surface roughness of the NP specimen and the CP specimen with $t_p = 5$ s/mm at $\phi_R = 0$ and 90 deg

<table>
<thead>
<tr>
<th>Specimen</th>
<th>$\phi_R$ (deg)</th>
<th>$R_a$ (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GW (NP)</td>
<td>0</td>
<td>0.8 ± 0.2</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>1.1 ± 0.2</td>
</tr>
<tr>
<td>GW (CP 5 s/mm)</td>
<td>0</td>
<td>1.2 ± 0.3</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>1.7 ± 0.2</td>
</tr>
</tbody>
</table>

Fig. 7  Variation of the differential reactance of the GW and NP specimen with the normal stress

Fig. 8  Variation of the differential reactance of the GW (NP) specimen with the shearing stress
measured. Table 4 shows the variation of $\Delta X$ with $t_p$ for various surface finishes. $\Delta X$ was measured with $\phi_R = 0, 45$ and 90 deg considering the stress states shown in Table 2. In this paper, $\Delta X$ at $\phi_R = 45$ deg is designated as $\Delta X_{45}$, and that at $\phi_R = 90$ deg is designated as $\Delta X_{90}$. From Table 4, $\Delta X$ shows an asymptotic behavior with $t_p$ because of the introduction of the equibiaxial compressive stress. On the other hand, from the results of $\Delta X_{45}$ and $\Delta X_{90}$ of the surface finished specimens such as GW, CNS, SB and Flap which were not peened, $X$ at $\phi_R = 45, 90$ deg have different values compared to $X$ at $\phi_R = 0$ deg because of the anisotropic stress state shown in Table 2. Figure 9 shows the relationship between the radius of the differential reactance circle, $r_{\Delta X}$, and the maximum shearing stress calculated from Table 4 and $\tau_{\max}$ shown in Table 2. The same method is used to obtain $r_{\Delta X}$ as to draw Mohr’s stress circle. From Fig. 9, $r_{\Delta X}$ increases with $\tau_{\max}$, and there is a linear relationship between them. From Fig. 9, it can be concluded that $\tau_{\max}$ can be obtained using an eddy current method using a tangential-rectangular coil. The gradient shown in Fig. 9 is $390 \pm 70 \, \Omega/\text{TPa}$. From this, the error of the gradient is 18%. By varying the coil winding direction, the peening intensity can also be evaluated by the eddy current method using a tangential-rectangular coil. From Figs. 5–9, it can be concluded that the direction of the principal stress can be determined by the eddy current method. The principal stress direction reveals the direction in which the fracture propagates. The merit of using the eddy current method is measuring time. To obtain the shearing stress with an X-ray diffraction method, it takes 180 minutes in the present condition and 6 directions measurement. On the contrary, it takes a few minutes to obtain the shearing stress in the eddy current method. In addition, the value of the normal stress can be determined using a combination of the X-ray diffraction and eddy current

Table 4 Variation of the differential reactance with CP processing time and various surface finishing methods for determination of the maximum shearing stress

<table>
<thead>
<tr>
<th></th>
<th>$\Delta X_{45} (\Omega)$</th>
<th>$\Delta X_{90} (\Omega)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>GW (NP)</td>
<td>-0.12 ± 0.04</td>
<td>-0.23 ± 0.04</td>
</tr>
<tr>
<td>GW (CP 0.25 s/mm)</td>
<td>-0.18 ± 0.03</td>
<td>-0.20 ± 0.03</td>
</tr>
<tr>
<td>GW (CP 0.5 s/mm)</td>
<td>0.02 ± 0.02</td>
<td>0.04 ± 0.04</td>
</tr>
<tr>
<td>GW (CP 1 s/mm)</td>
<td>0.02 ± 0.03</td>
<td>0.04 ± 0.05</td>
</tr>
<tr>
<td>GW (CP 2 s/mm)</td>
<td>0.02 ± 0.04</td>
<td>0.01 ± 0.06</td>
</tr>
<tr>
<td>GW (CP 5 s/mm)</td>
<td>0.00 ± 0.04</td>
<td>0.02 ± 0.03</td>
</tr>
<tr>
<td>CNS</td>
<td>-0.07 ± 0.04</td>
<td>-0.12 ± 0.03</td>
</tr>
<tr>
<td>SB</td>
<td>-0.02 ± 0.06</td>
<td>-0.13 ± 0.04</td>
</tr>
<tr>
<td>Flap</td>
<td>-0.11 ± 0.06</td>
<td>-0.19 ± 0.06</td>
</tr>
</tbody>
</table>

Fig. 9 Variation of the radius of the differential reactance circle with the maximum shearing stress
methods. The merit of this combination is that it takes a shorter time to evaluate the stress state.

4. Conclusions

In this study, to establish a practical method to evaluate the peening intensity and the residual stress in metallic materials containing anisotropic stress, non-peened and cavitation peened austenitic stainless steel samples of Japanese Industrial Standard (JIS) SUS316L, whose surfaces had previously been ground by an angle grinder to introduce anisotropic stress, were evaluated by an eddy current method with a tangential-rectangular coil. The results obtained by the eddy current method were compared with the residual stress measured by an X-ray diffraction method. In addition, to investigate the behavior of the tangential-rectangular coil for measuring stress, the variation of the eddy current signal with a mechanically induced uniaxial compressive stress was measured. The results obtained are summarized below.

(1) The stress anisotropy can be evaluated by an eddy current method with a tangential-rectangular coil by varying the coil winding direction. The peening intensity of metallic materials with anisotropic stress can be evaluated by the eddy current method.

(2) The eddy current signal using the tangential-rectangular coil is affected by anisotropic stress. It is affected by the stress state, but not by uniaxial stress. The eddy current signal using a tangential-rectangular coil detects the difference in stress between that in the same direction as the coil winding and that perpendicular to it. The reactance decreases and the electrical conductivity increases with applied compressive stress.

(3) The shearing stress is related to the radius of the differential reactance circle. Therefore, it can be concluded that the shearing stress can be evaluated by the eddy current method using a tangential-rectangular coil.

(4) From the stress measurement results obtained from the X-ray diffraction method, the specimens which were ground or polished but not peened have anisotropic stress. The direction of maximum tensile stress is the same as the rotating direction of the angle grinder. After cavitation peening, a compressive residual stress is introduced and the level of anisotropy decreases.

(5) The maximum shearing stress decreases with the processing time of cavitation peening due to the introduction of equibiaxial compressive stress.

Acknowledgements

This work was partly supported by a Grant-in-Aid for JSPS Fellow 21·3334 from the Japanese Society for the Promotion of Science (JSPS).

References


