Relaxation behavior of laser-peening residual stress under tensile loading investigated by X-ray and neutron diffraction

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Abstract
Compressive residual stresses induced by peening techniques improve the strength properties of steels, such as fatigue and stress corrosion cracking. However, the compressive residual stress might be reduced owing to thermal and mechanical loading in-service. In this study, the behavior of surface and internal residual stresses of a laser-peened ferritic steel under quasi-static tensile loading was investigated by X-ray and neutron diffraction. The complementary use of these diffraction techniques provided decisive experimental evidence for elucidating the relaxation process. As the applied tensile stress increases, the inside of the sample yields before the surface yielding at the critical applied stress (the applied stress for the onset of relaxation of the surface residual stress). The internal yielding causes the redistribution of residual stress, resulting in the relaxation of the surface compressive residual stress. Therefore, the relaxation of the surface compressive residual stress under tensile loading starts before the surface yielding. The critical applied stress of peened samples subjected to a tensile loading can be estimated from the von Mises yield criterion with the maximum tensile residual stress inside the sample. The FWHM of X-ray diffraction profile of the sample surface was increased by laser-peening, and it was further increased by further plastic deformation after peening.

Key words: Laser-peening, Residual stress relaxation, Tensile loading, Neutron diffraction, X-ray stress measurement

1. Introduction

Compressive residual stresses in the surface layer of components prolong fatigue life and prevent stress corrosion cracking. Mechanical surface treatment techniques, such as shot peening and laser-peening, are available for inducing compressive residual stresses, and therefore, peening techniques have been widely used in mechanical components and structures. However, the benefits are reduced if the compressive residual stress relaxes due to thermal and/or mechanical loading during service. Therefore, it is important to evaluate the residual stress relaxation through the component’s service life in order to ensure its reliability. A number of papers have been published on residual stress relaxation under
mechanical loading (Holzapfel, et al., 1998), thermal loading (Feng, et al., 2009) and on their superimposed conditions (Nikitin, et al., 2004). In recent years, residual stress relaxation under mechanical loading has become more significant, not only for fundamental studies, but also for the evaluation of the structural integrity of important structures, such as nuclear power plants affected by earthquakes.

In almost all investigations, X-ray diffraction is used to measure the residual stresses, because it is a nondestructive stress measurement technique. Therefore, it works well for tracking relaxation processes of residual stresses. Conventional laboratory X-rays used for stress measurements penetrate the surface of engineering materials to less than about 20 μm depth. The residual stress in a component must be in an equilibrium state that balances the compressive residual stresses in the surface layer with tensile residual stresses beneath the surface. For a better understanding of the residual stress relaxation mechanism, stress states should be examined not only at the surface but also beneath the surface. The balancing tensile residual stress of the mechanically treated metals is located at a depth of about several hundred microns for shot peening and one millimeter or more for laser-peening under typical treatment conditions. The tensile residual stress beneath the surface may play an important role in the residual stress relaxation, especially under tensile loading, but as of yet, there is not sufficient experimental evidence. At these depths, non-destructive residual stress measurements are impossible by laboratory X-rays, because of their small penetration depth. On the other hand, neutrons have quite a large penetration depth (Withers and Bhadeshia, 2001, Woo, et al., 2011); therefore, the complementary use of neutron and X-ray diffraction can provide decisive evidence for understanding residual stress relaxation processes. In this study, the residual stress relaxation behavior under quasi-static tensile loading on laser-peened steel was investigated using neutron and X-ray diffraction and finite element analysis. The critical applied stress for the onset of surface compressive residual stress relaxation was also estimated.

2. Experimental procedure
2.1 Specimen and surface treatment

The material used in this study is a ferritic steel, JIS SM41, which is commonly used in welded structures. The chemical composition of the material is shown in Table 1. The tensile strength and the yield stress of the material are 400 MPa and 286 MPa, respectively. Tensile specimens, as shown in Fig. 1, were cutout from the material. A rectangular plate specimen with a size of 20 × 20 × 5 mm$^3$ was also cut from the material, and used for the measurement of the depth profile of the initial peening residual stress. For removing workhardened layers by milling, both surfaces of all specimens were polished by emery paper before laser-peening. Laser-peening without sacrificial coatings (LPwC) (Sano, et al., 1997) was applied to both polished surfaces according to a typical laser-peening condition shown in Table 2. The fundamental wave of a Q-switched Nd:YAG laser was frequency-doubled to a water penetrable wave (λ = 532 nm) by a second harmonic generator with a nonlinear optical crystal. The pulse duration was 8 ns in FWHM. The specimen was fixed on a sample holder and driven to x- and y-directions in a water jacket during irradiation. The laser scanning pattern is shown in Fig. 1. The coverage, $C_v$, is defined by Eq. (1),

$$C_v = \frac{\pi \cdot d^2}{4} \cdot N_d$$

where $d$ is the laser spot diameter and $N_d$ is the irradiation density (number of pulses per unit area).

<table>
<thead>
<tr>
<th>C</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤0.23</td>
<td>≥2.5×C</td>
<td>≤0.035</td>
<td>≤0.035</td>
</tr>
</tbody>
</table>

Table 1 Chemical composition of the SM41 steel (wt. %).

<table>
<thead>
<tr>
<th>Sacrificial coating</th>
<th>Pulse energy $E_P$, mJ</th>
<th>Laser spot diameter $d$, mm</th>
<th>Power density $I_0$, TW/m$^2$</th>
<th>Irradiation density $N_d$, pulse/mm$^2$</th>
<th>Coverage $C_v$, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>non</td>
<td>200</td>
<td>0.8</td>
<td>50</td>
<td>36</td>
<td>1810</td>
</tr>
</tbody>
</table>

Table 2 Condition of laser peening.
Fig. 1 Tensile specimen. Laser-peening was applied on both L-T surfaces.

![Fig. 1 Tensile specimen. Laser-peening was applied on both L-T surfaces.](image)

Fig. 2 Setup for neutron stress measurement. A loading device was set on the sample stage of engineering diffractometer RESA-1 in JRR-3 of the Japan Atomic Energy Agency as shown in (a). The gage volume was 0.5 × 0.5 × 10 mm³ which was defined by incident slits and a receiving radial collimator. Elastic strains in the loading direction were measured as shown in (b). The sample was scanned step by step to obtain through-thickness distributions of elastic strain at each applied stress.

2.2 Stress measurements

Surface residual stresses were measured by X-ray diffraction according to the sin²Ψ method (JSMS Committee on X-Ray Study on Mechanical Behavior of Materials, 2005). A small loading device (max. 20 kN) was set on the laboratory X-ray diffractometer for measuring surface residual stresses under tensile loading. Tensile stresses were applied in a quasi-static operation to the tensile specimen by turning the nut of the loading device manually. Surface residual stresses at the center of the specimen were measured in the loading direction. The Cr-Kα characteristic X-ray and the α-Fe (211) diffraction peak at the diffraction angle 2θ of about 156.4° (scattering vector Q = 53.7 nm⁻¹) were used to determine lattice strains. The X-ray irradiated area was about 3 mm in diameter. The depth profile of the initial residual stress induced by the LPwC was measured by a successive layer removal technique with repeated electrolytic polishing and X-ray stress measurement up to a depth of about 1 mm. The electrolytic polished area was about 8 mm in diameter at the center of the plate specimen.

Through-thickness distributions of residual stress were measured nondestructively by neutron diffraction on the neutron engineering diffractometer RESA-1 in JRR-3 of the Japan Atomic Energy Agency as shown in Fig. 2. The neutron diffraction technique is based on the Bragg equation shown in Eq. (2). From Eq. (2), the elastic lattice strain, ε, is obtained as shown in Eq. (3).

\[ \lambda = 2d \sin \theta \]  
\[ \varepsilon = \frac{\Delta d}{d_0} = -\cot \theta \cdot \Delta \theta \]

where \( \lambda \) is the wavelength, \( d \) is the lattice spacing, \( \theta \) is the Bragg scattering angle, and \( E \) is Young’s modulus. In this study, a wavelength of 0.166 nm, gauge volume of 0.5 × 0.5 × 10 mm³, and α-Fe (211) reflection at 2θ of about 90° were
chosen to determine lattice strains. The (211) reflection is suitable for residual stress measurements in bcc-Fe materials, because it shows low sensitivity to intergranular strain (ISO/TS 21432:2005). The stress in the loading direction was determined by multiplying the measured strain, $\varepsilon$, in the loading direction with Young’s modulus, $E$, of the (211) reflection ($E_{211} = 225$ GPa) of the material, under the assumption of a uniaxial stress state. The loading device used in the X-ray stress measurement was set on the sample stage of RESA-1. In both the neutron and the X-ray diffraction measurements, stresses were measured in the loading state as well as unloading state.

3. Finite element analysis

Non-linear structural analyses were performed using a commercial finite element (FE) code ANSYS10 for the simulation of the residual stress relaxation behavior during tensile loading. Figure 3 shows the three-dimensional rectangular finite element model used in the analyses. Three dimensional eight-node solid elements, the von Mises yielding criterion, and the isotropic hardening rule were used in the analyses. In this study, applied load is monotonic tension, therefore the Bauschinger effect is unnecessary to be considered, and hence the isotropic hardening rule can be utilized. The stress-strain (SS) curve for the FE analysis was determined from the experimental result of a tensile test using the tensile specimen without laser-peening. The true SS curve was calculated from the measured nominal SS curve using following equations, 

$$
\varepsilon_t = \ln(1 + \varepsilon_n) \\
\sigma_t = \sigma_n(1 + \varepsilon_n)
$$

We have especially focused on the critical applied stress at the onset of residual stress relaxation on the peened sample. In this case, the most important material property is the yield strength of as-received material as described later. Therefore, the true SS curve was approximated for the FE analysis by multi-linear line, as shown in Fig. 4, ignoring Lüders strain region for simplification.

The depth distribution of initial peening residual stress following the experimentally measured distribution was introduced to the model by applying the peen-forming simulation technique (Yamada, et al., 2002) as follows. At first, a depth distribution of the linear expansion coefficient, which was smaller approaching the surface, was set near both surfaces of the FE model. Subsequently, the FE model was subjected to a heat cycle in order to obtain a realistic stress distribution comparable to peening. When the temperature exceeded a certain value, the surface layer deformed plastically, because the surface layer was stretched from deeper layers that had a larger thermal coefficient. Next, the temperature was lowered to room temperature, resulting in the generation of compressive residual stresses in the surface layer by the elastic restriction from the region beneath the plastically stretched surface layer. The depth distribution of the linear expansion coefficient and the maximum temperature in the heat cycle were adjusted for creating an initial peening residual stress distribution which was similar with the experimentally measured distribution. After that, the external tensile loading was applied step by step on the FE model that contained the initial peening residual stress, and the change in residual stresses, as well as plastic strains, were analyzed.

4. Experiment results

4.1 Initial residual stress distribution

Depth distributions of residual stress obtained by X-ray and neutron diffraction are shown in Fig. 5. Compressive residual stresses are introduced by the LPwC in both surface layers up to a depth of about 1 mm. Tensile residual stresses of about 100 MPa are observed in the center region of the specimen. It is generated as a counterbalance to the surface compressive residual stress. The black line in Fig. 5 shows the simulated result from the FE model. Both the experimental
4.2 Changes in surface residual stress

The changes in the surface residual stress and the full width at half maximum (FWHM) of the X-ray diffraction profile on the surface during tensile loading are shown in Fig. 6. The FWHM can be regarded as an indicator of plastic deformation. Actually, the FWHM increased from about 1.30° to about 2.02° by plastic deformation caused by the laser-peening. The total stress, \( \sigma_{\text{tot}} \), measured in the loading state, linearly increases with increasing applied stress, \( \sigma_{\text{ap}} \), up to about 220 MPa, while the residual stress, \( \sigma_{\text{res}} \), measured in the unloading state, retains the initial residual stress (Stage I). The FWHM keeps its initial value in this stage. In Stage I, only elastic deformation must occur in the specimen, therefore \( \sigma_{\text{tot}} \) shows the sum of \( \sigma_{\text{res}} \) and \( \sigma_{\text{ap}} \). Following an increase in the applied stress, \( \sigma_{\text{tot}} \) and \( \sigma_{\text{res}} \) start to decrease from compression towards zero at \( \sigma_{\text{ap}} \approx 220 \) MPa (= critical applied stress, \( \sigma_{\text{ap(c)}} \)), while the FWHM still retains the initial value until \( \sigma_{\text{ap}} \approx 250 \) MPa (Stage II). From this we follow that surface residual stresses start to relax without surface plastic deformation in Stage II. The residual stress, \( \sigma_{\text{res}} \), rapidly decreases from its initial value around -300 MPa to almost zero as the applied stress increases to 30 MPa from \( \sigma_{\text{ap(c)}} = 220 \) MPa. From \( \sigma_{\text{ap}} = 250 \) MPa, the FWHM increases with increasing applied stress due to the plastic deformation of the surface (Stage III). In the case of a shot-peened steel, the FWHM on the surface was not further increased by plastic deformation after peening (Hanagarth et al., 1990). Additionally, the increase of FWHM by shot-peening was clearly larger than that by laser-peening (Kumagai et al., 2013).
From these facts, it is considered that the plastic deformation caused by laser-peening is relatively smaller, and therefore the FWHM on the laser-peened surface can be further increased by further plastic deformation after peening. The whole section of the specimen deforms plastically in Stage III.

4.3 Change in the internal residual stress

Figures 7 (a) and (b) show the through-thickness distribution of total stress, $\sigma_{\text{tot}}$, and residual stress, $\sigma_{\text{res}}$, respectively, as measured by neutron diffraction. As shown in Fig. 7 (a), the distribution of $\sigma_{\text{tot}}$ shifts to the upper side on the figure with increasing applied stress up to 187 MPa, while no change in $\sigma_{\text{res}}$ can be seen in Fig. 7 (b). When the applied stress reaches 227 MPa, $\sigma_{\text{tot}}$ inside of the specimen exceeds the yield stress (Fig. 7 (a)) and the distribution of $\sigma_{\text{res}}$ slightly changes (Fig. 7 (b)). The redistribution of $\sigma_{\text{res}}$ must be caused by the internal yielding, resulting in the onset of the surface stress relaxation. Therefore, it is reasonable that $\sigma_{\text{ap(c)}} (=220$ MPa), which is determined in Fig. 6, lies between 187 and 227 MPa. At $\sigma_{\text{ap}} = 313$ MPa in Fig. 7 (a), the distribution of $\sigma_{\text{tot}}$ is almost flat, because the whole section of the specimen deformed plastically, but slightly higher tensile stresses are observed near both surfaces. As the yield strength of the surface layer is higher than that of the interior region, owing to work-hardening by the LPwC (Maawad, et al., 2012), the stress in the surface layer can be higher than that of the interior region.

5. FE results and discussion

To confirm the validity of the interpretations of the experimental results mentioned above, finite element analyses were performed as outlined in the Section 3. FE results of stresses and equivalent plastic strains during tensile loading are shown in Fig. 8 (a)–(c). Figures 8 (a) and (b) show $\sigma_{\text{tot}}$ and $\sigma_{\text{res}}$, respectively. The FE results show the same tendencies with those observed in the experimental results (Fig. 7 (a) and (b)). The distribution of $\sigma_{\text{tot}}$ shifts up in the figure with the same shape as the initial state (Stage I) and the relaxation starts when the interior region reaches the yield stress (Stages II). Fig. 8 (c) shows the FE results of the changes in the plastic strain distribution during tensile loading. Plastic strains exist on both surface layers of the sample at the initial state. They were introduced when the residual stress distribution was created for simulating the peening residual stress. As the applied stress increases, no change in the plastic strain distribution is observed at $\sigma_{\text{ap}} = 170$ MPa. Plastic strain in the interior region increases at $\sigma_{\text{ap}} = 280$ MPa, while that of the surface retains the initial value. Finally, plastic deformation occurs across the whole section of the specimen. Comparison of the FE and experimental results on the inside and surface stresses is shown in Fig. 9. Both results agree well to each other and $\sigma_{\text{ap(c)}}$ is about 220 MPa for both the experimental and FE results.

$\sigma_{\text{ap(c)}}$ can be estimated based on the von Mises yield criterion under an in-plane stress state (Holzapfel, et al., 1998):

$$\sigma_y = \sigma_{\text{eq}} = \sqrt{(\sigma_{\text{res, L}} + \sigma_{\text{ap(c)}})^2 + (\sigma_{\text{res, T}})^2 - (\sigma_{\text{res, L}} + \sigma_{\text{ap(c)}}) \cdot \sigma_{\text{res, T}}} \quad (4)$$

where $\sigma_y$ is the yield strength of the material, $\sigma_{\text{eq}}$ is equivalent stress, and $\sigma_{\text{res, L}}$ and $\sigma_{\text{res, T}}$ are initial residual stresses in the longitudinal and transverse direction, respectively. Since the applied stress is tensile in this study, we estimate $\sigma_{\text{ap(c)}}$ by assigning the condition at the time
when the equivalent stress inside of the specimen reaches the yield strength in Eq. (4). The yield strength inside the specimen is supposed to be the same as that of the as-received material (= 286 MPa), because the interior region is not deformed plastically by the LPwC. \( \sigma_{res,L} \) inside of the specimen is equal to about 100 MPa as shown in Fig. 5. Generally, residual stresses introduced by LPwC are almost biaxially equivalent inside the specimen (Sano, et al., 2006). Therefore, we assumed that the degree of \( \sigma_{res,T} \) inside the specimen is equal to \( \sigma_{res,L} \) inside (= 100 MPa). The \( \sigma_{ap(c)} \) calculated from the above condition is 223 MPa. This is very close to \( \sigma_{ap(c)} = 220 \) MPa observed in Fig. 6. From this observation, it is clear that the relaxation of surface residual stress starts when the interior region yields.

From the above results, it has been confirmed that the relaxation of the surface compressive residual stress under tensile loading starts when the inside stress reaches the yield stress. Therefore, the surface compressive residual stress relaxation can start prior to the plastic deformation of the surface and the through-thickness residual stress distribution should be known in order to estimate the critical applied stress.

\[
\sigma_{ap(c)} = 220 \text{ MPa}
\]

Fig. 9 Comparison of the experimental and FE results of residual stress on the surface and the inside of the specimen.

6. Conclusion

The relaxation behavior of laser-peening induced residual stress during tensile loading was investigated on a ferritic steel, JIS SM41, using X-ray and neutron diffraction and FE analysis. The complementary use of neutron and X-ray diffraction provided decisive experimental evidence for elucidating the relaxation process. The deformation behavior of the laser-peened sample during tensile loading can be classified into three stages: fully elastic deformation (Stage I), internal plastic deformation (Stage II), and fully plastic deformation (Stage III). The yielding of the interior region at the beginning of Stage II causes the redistribution and relaxation of residual stress. Therefore, the relaxation of the surface compressive residual stress under tensile loading starts before the surface yields. The critical applied stress of peened samples subjected to a tensile loading can be estimated from the von Mises yield criterion with the maximum tensile residual stress inside the sample. The surface compressive residual stress rapidly decreases from its initial value to zero by a relatively small increase of the applied stress from the critical applied stress (at only 30 MPa from \( \sigma_{ap(c)} \) (= 220 MPa) in this study). The FWHM of X-ray diffraction profile of the sample surface was increased by laser-peening, and it was further increased by further plastic deformation after peening.

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