Evaluation of residual stress distribution of shot-peened spring by positron annihilation spectroscopy
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Introduction
Shot peening is widely used for surface-treating of spring parts as a powerful method to enhance the fatigue durability. The effect of shot peening is usually evaluated by the X-ray diffraction, but the repeatable electrochemical polishing should be required to measure the inner surface of shot peened parts. In order to increase the reliability of the treatment, a completely non-destructive inspection method is strongly required. Positron annihilation spectroscopy (PAS) has been used for probing lattice defects. By using PAS, it is possible to evaluate lattice defects, which is dislocation, induced by shot peening in the inner surface of a peened part non-destructively. In this study, we investigated the validity of PAS as a non-destructive inspection for shot peening for a coil spring specimens.

Objectives
The objective is to predict the residual stress distribution of the inner surface of a spring specimens by using the relationship between the thickness of plastic deformation ($h_p$) and S-parameter from non-destructive Positron annihilation method.

Methodology
Figure 1 shows the schematic illustration of the constructed positron annihilation spectrometer for Doppler broadening measurements. As shown in this figure, the main constituent is a gamma ray detector and a $^{22}$Na radioisotope positron source with an activity of 1 MBq. High energy positrons are emitted from $^{22}$Na and are implanted into the material with several tens micrometers in depth (< 200 µm in case of steel). The positrons are thermalized and annihilate with surrounding electrons, followed by the emission of annihilation gamma rays of around 511 keV. At this study, emitted gamma ray (inner side of coil spring) could be detected at the other side which is outer side due to itself high penetrating power.

Figure 2 shows the principle of the Doppler broadening method. Positron annihilation spectroscopy is sensitive to the variation of open spaces in materials at the atomic scale. Positrons thermalized in a material are easily trapped by defects such as vacancies, dislocations, microvoids etc. Positrons in the defect-free region have a higher possibility of annihilation with core electrons with higher velocity, leading to the considerable Doppler broadening of the energy distribution due to the annihilation gamma rays centered at 511 keV. On the other hand positrons trapped in defects have a lower probability of annihilation with core electrons, which causes “narrowing” of the 511-keV annihilation photo peak. The extent of this “narrowing” is usually quantified by using the S parameter. The S parameter is defined as a fraction of gamma-ray counts in the central window (dS) to those in the whole 511 keV peak (dA) as shown in Fig 3 as following formula (1).

$$S \text{ parameter} = \frac{dS}{dA} \quad (1)$$
Several spring parts were prepared with different coverage, 20-50%, 50-80%, 80-100% and 100% over. Shot peening treatment was conducted by conditioned cut wire shot with 0.87 mm diameter and HV640 hardness. Centrifugal peening machine was used with 70m/s wheel speed. The residual stresses were determined by using an X-ray diffractometer with the sin²Ψ - method. The residual stress distribution was obtained by repeated X-ray measurements and electrochemical polishing.

**Results and analysis**

Figure 4 shows the residual stress distribution of above different coverage rate. The stress profile with over 80% coverage were almost same shape. Positron annihilation gamma ray spectra for the inner surface of the X-ray measured spring specimens were measured without any electrochemical polishing the spring specimen. The shape of the gamma ray spectra was analyzed as the S – parameter by above analysis. Figure 5 shows the relation between the S - parameter and shot peening treatment time (Coverage). The measured relationship was very close to the saturation curves and S-parameter with over 100% coverage was saturated as shown in this figure. This tendency should be very close to compressive residual stress profile characteristic.
Here, the equation for the relationship between plastic deformation and residual stress distribution has been proposed by Y. F. Al. Obaid (1) as following (2).

\[ \sigma_R(\chi) = \frac{E\varepsilon_m}{1-\nu^2} \left[ -6\frac{\lambda}{h} \left( \frac{h}{2} - x \right) c_1 + \frac{1}{2} c_2 - \frac{1}{2} \cos \left( \frac{\chi - \alpha h_p}{(1-\alpha)h_p} \pi \right) + 1 \right] \]  

(2)

\[ \lambda = \frac{h_p}{h} \]

\[ c_1 = \frac{(1-\alpha)^2}{\pi^2} \lambda \left( 1 + \cos \frac{\alpha}{1-\alpha} \pi \right) + \frac{1}{2} c_2 - \frac{1}{2} \lambda \]

\[ c_2 = 1 + \frac{1-\lambda}{\pi} \sin \frac{\alpha}{1-\alpha} \pi \]

\[ h_p \]: Plastic zone depth, \( E \): Young’s modulus, \( \nu \): Poisson ratio, \( h \): Thickness of specimen, \( \varepsilon_m \): Maximum strain, \( \alpha \): coefficient of peak depth

Watanabe et al. showed the prediction of residual stress distribution which could match precisely the actual measured stress value, based on above eq. (2) with analysis value of \((h_p)\) calculated by shot media diameter and shot injecting speed \([2]\). Generally speaking, it is considered that S-parameter could detect the plastic deformation at the surface. Further the prediction of residual stress distribution at the peened surface could be possible if plastic zone depth \((h_p)\) was determined for S-parameter.

Here, Eq.(2) has two unknown value, \( \varepsilon_m \) and \( \alpha \) except \((h_p)\). In order to predict the stress profile from S-parameter, we assumed the below two unknown value could represent as the power function of \((h_p)\).

\[ \alpha = a \cdot h_p^i \] 

(3)

\[ \varepsilon_m = b \cdot h_p^i \] 

(4)

Hereafter, the equation that substituted Eq. 3, Eq. 4 for Eq. 2 was indicated as estimated equation.
Firstly, in order to make a correlation between S-parameter and \((h_p)\), least square fitting is applied to measured residual stress value in Figure 4 to estimate \((h_p)\) value, a, b, i and j at Eq. 3 and Eq. 4. Figure 6 shows the relationship between S-parameter and estimated square of plastic zone depth \((h_p^2)\). As results good linear relationship was confirmed. Therefore, it is considered that this method could predict the peened residual stress distribution.

In order to evaluate this hypothesis for the prediction of residual stress distribution by positron analysis, we prepared the coil spring specimens with two types of coverage, 80% and 100%. Shot peening were conducted by 0.87mm conditioned cut wire shot with HV640 hardness, and 70m/s injecting speed. Figure 7 shows the results of S-parameter at this trial for peened coil spring specimens. Clear difference was observed among different specimens, i.e. not peened specimen, 80% and 100% coverage specimen.

![Fig.6 Relation between (Plastic zone depth)² and S-parameter](image1)

![Fig.7 S-parameter at each conditions](image2)

![Fig.8 The comparison between the predicted residual stress profile and actual measured stress value](image3)
Figure 8 shows the comparison between the predicted residual stress profile by S-parameter from this positron annihilation analysis and actual measured residual stress value by X-ray diffraction. Predicted stress could show the actual stress value very well. In conclusion, positron annihilation spectroscopy could predict the residual stress distribution of shot peened spring material with completely non-destructive measurement. This result is very useful for daily inspection after shot peening at industrial facilities.

Summary
In this study, we investigated the validity of PAS as a non-destructive inspection for shot peening for a coil spring specimen. The objective is to predict the residual stress distribution of the inner surface of a spring specimens by using the relationship between the thickness of plastic deformation (h_p) and S-parameter from non-destructive Positron annihilation method.

Following is a summary of the results obtained;
There is a good correlation between S-parameter and plastic zone depth estimated from residual stress distribution. Further, it was suggested the prediction of residual stress distribution of the inner surface without polishing was possible from S-parameter.

References