Influence of work-induced martensite transformation by shot peening content on eddy current reaction

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Introduction

Shot peening (referred to as SP), which improves fuel efficiency by making product parts lightweight and high-strength, is used in the aerospace and automobile industries. [1]
SP is one type of surface modification method, and many studies have shown that the compressive residual stress distribution induced by SP greatly contributes to fatigue strength improvement. [2]-[4]
Therefore, it has become important to measure compressive residual stress.
X-ray residual stress analysis is generally used for steel, but X-ray permeation depth is several μm from most surfaces, and the only option is to scrape it in electro-polish to measure the depth distribution of stress. Therefore, it is performed only through a sampling check. A quick and non-destructive method to check the residual stress depth distribution introduced by SP is needed. [5]
Electromagnetic methods such as eddy current measurement can evaluate in principle the stress in SP processed steel caused by the reverse magnetostriction effect that changes magnetic properties when elastic strain or plastic strain is introduced to the ferromagnetic material by the skin effect of eddy currents. [6]-[8]

Objectives

The objective of this study is to evaluate internal stress by eddy current. This study is aimed at work-induced martensite transformation, which was one of the factors inducing compressive residual stress. The influence of work-induced martensite transformation content on the eddy current reaction and, by evaluation of work-induced martensite transformation by the eddy current, the estimate of the depth range of internal stress distribution were investigated.

Measurement principle and Evaluation

Evaluation principle of SP material by eddy current

Fig.1 shows a schematic diagram which explains how an eddy current is generated. An eddy current is a current in a conductor introduced by the magnetic field which varies with time, and it is possible to measure the change in anti-magnetic fields generated by eddy currents as a change in the coil impedance and phase. An eddy current is affected by the relative magnetic permeability and electric conductivity of the conductor, and its penetration depth can be changed by excitation frequency. Equation (1) shows the penetration depth of an eddy current and excitation frequency. [9],[10]

$$\delta = 1/\sqrt{(\pi f \sigma \mu)} \quad (1)$$

δ: Penetration depth of an eddy current (m),
f : Excitation frequency (Hz)
σ: Electric conductivity of a conductor (S / m)
μ: $=\mu_0 \times \mu_S$
[μ_0 : Magnetic permeability of a vacuum, μ_S : Relative magnetic permeability of a conductor] (H/m)

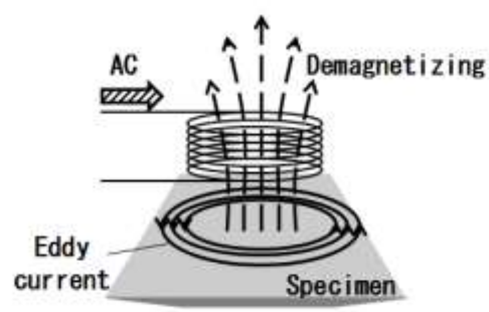

Fig.1 Schematic diagram of eddy current

Then, the inductive reactance (XL = ωL) component of the Y-axis direction as the vector component of the coil impedance (Z) and the pure resistance (R) component of the X-axis direction correspond to the relative magnetic permeability and the electric conductivity of a conductor respectively. It is possible to evaluate the properties of the conductor surface by comparing and evaluating them. Equations (2) and (3) show the relationship of the impedance and its components.

$$Z = R + j\omega L . \quad (2)$$
$$\theta = \tan^{-1}(\omega L / R) . \quad (3)$$

Z : Impedance (Ω), θ: Phase (rad), R : Resistance (Ω), L : Inductance (H), ω: Angular velocity (rad / s)

Relationship between residual stress introduction mechanism by SP and relative magnetic permeability

It is believed that there are two types of residual stress introduced mechanisms caused by SP. [1] One is the mechanism caused by a plastically deformed layer alone by SP. The other is that untransformed retained austenite generated by hardening of high-carbon steel, such as carburizing goods, undergoes deformation induced martensitic transformation by SP.

The next focus is the magnetic property of metal. It is said that the magnetic property of metal depends on the distance between transition metal atoms. Fig.2 shows the Bethe-Slater curve representing the relationship of the exchange interaction to the ratio between the inter-atomic distance (R) and atomic radius (d). Jeff (exchange interaction), which aligns with the magnetic moment between atoms mutually, varies with inter-atomic distance along the Bethe-Slater curve in which ferromagnetic is magnetic at room temperature and anti-ferromagnetic is not magnetic at room temperature.[11]

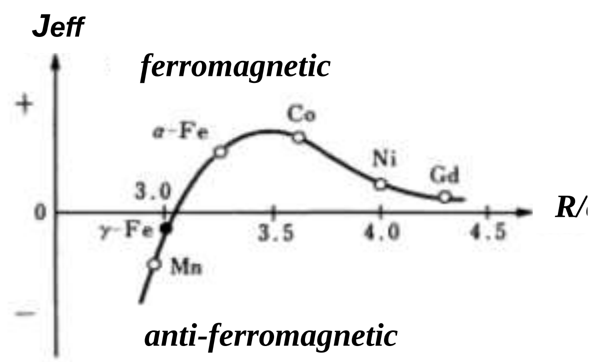

Fig.2 Bethe-Slater curve [11]

Jeff of γ-Fe: austenite is positioned (-), Jeff of α-Fe: ferrite is positioned (+) on the curve, and Jeff of martensite: paramagnetic body-centered tetragonal of α-Fe is considered to be located between the two points. Therefore, it is estimated from this curve that relative magnetic permeability increases in deformation induced martensite transformation.

From these, it is considered that work-induced martensite transformation is by shot peening content on eddy current reaction in principle. Thus, keeping track of the changes in retained austenite is considered to be an evaluation of the internal stress caused by SP.

Methodology

Test material

For the test material used in this study, we prepared materials of the chromium-molybdenum steel SCM420 and machined them into a shape which is shown in Fig.3. The chemical composition of the materials is shown in Table 1. The heat treatment before SP was vacuum carburizing. Additionally, the effective hardened layer depth is prepared to be 0.5mm, and quenching conditions and the outermost surface hardness are prepared to be 760HV. Fig.4 shows the retained austenite distribution of the test material.

Table.1 Chemical composition of used materials [Mass %]

C	Si	Mn	P	S	Ni	Cr	Mo	Cu
0.2	0.33	0.83	0.015	0.011	0.11	1.01	0.15	0.08

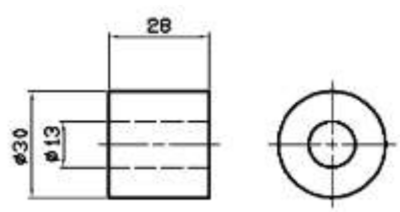

Fig.3 Shape and dimension of specimen

SP conditions

In this study, SP was carried out in 4 types of conditions as shown in Table 2. For processing conditions, so as to change peak depth and peak value of residual stress distribution introduced into the specimen, only shot particle size was changed in the same material. SP①~③ are shot peening conditions.

Material evaluation method of the specimen

For the material evaluation of the specimen, I measured residual stress (σR) and retained austenite (γR) by X-ray diffraction method, which is generally used. The residual stress was calculated from changes in the space of (211) planes of α-Fe with the characteristic X-ray Cr-Kα line. The retained austenite was calculated from the ratio of the X-ray integrated intensities of (220) plane of γ-Fe to that of (211) planes of α-Fe with the characteristic X-ray Cr-Kα line.

For the measurement of the depth distribution of the steel material, the retained austenite and residual stress were measured while the specimen surface was removed by electrolytic polishing.

Eddy current measuring method and evaluation

In this study, I produced a resin-made bobbin to match the shape and size of the specimen, a bundle of weaving copper wire having a diameter of 0.1mm, and wound it on the bobbin into coils.

Fig.5 shows a schematic diagram of the experimental apparatus used in this study. As the detection method of eddy currents, I used the single system of a penetration type self-induction coil and a commercially available impedance analyzer for the measurement. The test frequency was decided so that the penetration depth of eddy currents became 5μm ~ 150μm. I recorded the impedance and phase angle of the coil at the time of placing the specimen into the coil in these conditions.

The Y-axis component of the eddy current (XL) was calculated from impedance and phase angle, and the change in the relative permeability was evaluated by the ratio of inductive reactance before and after SP. Further, using equation (1), the test frequency was converted to penetration depth of the eddy current and compared to eddy current measurement results with X-ray diffraction measurement results for the spread of distribution and the peak depth of distribution. Also, using the change of relative magnetic permeability on the Bethe-Slater curve, eddy current measurement results were inspected.

Table.2 Conditions of shot peening

	SP①	SP②	SP③
Shot method	Direct pressure		
Diameter [mm]	0.05	0.3	0.6
Hardness [Hv]	700	700	700
Air pressure [MPa]	0.3	0.3	0.3
Coverage [%]	300	300	300
Arc height	0.275 [mmN]	0.240 [mmA]	0.497 [mmA]

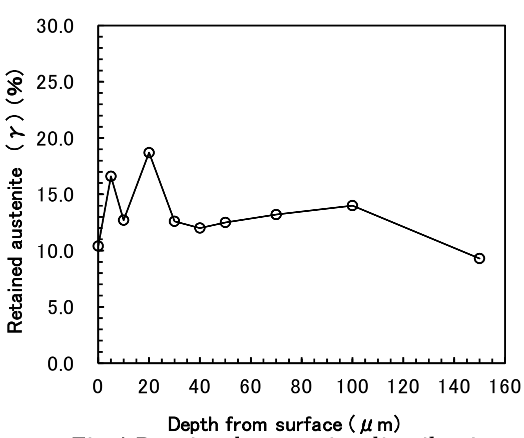

Fig.4 Retained austenite distribution

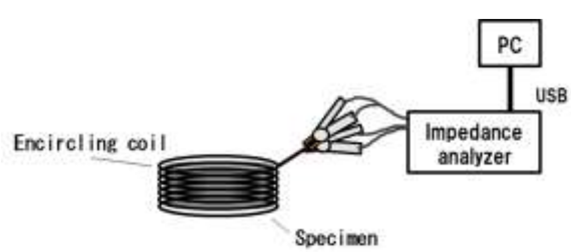

Fig.5 Experimental setup

Results and analysis

Comparing the residual stress distribution and work-induced martensite transformation distribution

Fig.6 shows the residual stress distribution measurement results of the specimens. Fig.6 shows that the maximum compressive residual stress is -1715MPa in SP① (particle diameter 0.05mm), with almost the same maximum compressive residual stress value of -1300MPa in the other two conditions. The depth of maximum compressive residual stress is 5 ~ 10μm in SP①, and 20μm in both SP② and SP③.

The amount of change in retained austenite before and after SP, namely the amount of deformation induced martensitic transformation measured by X-ray ([γ0-γ1]) was calculated, and the relationship between the results and the depth is shown in Fig.7. γ0 is the amount of retained austenite in the raw material, and γ1 is the amount in the SP material. The depth of maximum [γ0-γ1] is 5μm in SP①, and 20μm in SP②,③. The range from the outermost surface to the depth where [γ0-γ1] becomes 0% has a tendency to spread deeper as the shot particle size increases.

Comparing the residual stress distribution and [γ0-γ1] distribution, the depth range of the residual stress distribution and [γ0-γ1] distribution is about the same, but there is not a correlating relationship between the amount of [γ0-γ1] and the residual stress value.

With these results, it is difficult to estimate a residual stress value from an amount of [γ0-γ1]. On the other hand, by evaluation of [γ0-γ1] distribution, it is thought that it can estimate the depth range of residual stress distribution.

Eddy current measurement results

Fig.8 shows the relationship between the ratio of inductive reactance change of SP material to one of the raw materials (XL1 / XL0) and the penetration depth. XL0 is the inductive reactance of the untreated material and XL1 is that of the SP material. Fig.8 shows that XL1 / XL0 of all specimens is larger than 1 in all penetration depths of 0~150μm, so the inductive reactance component has increased. This indicates that the relative magnetic

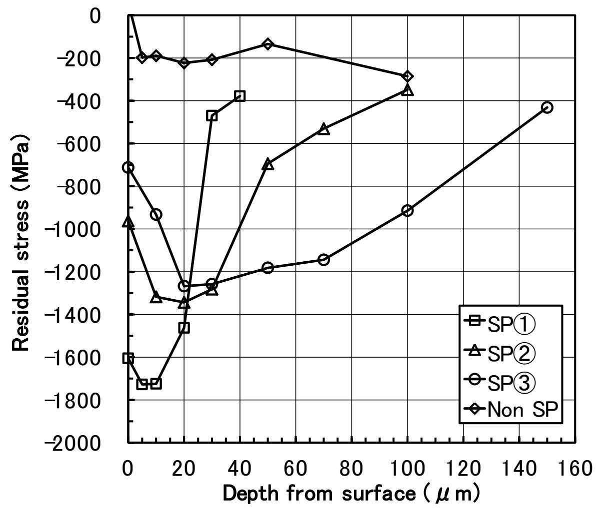

Fig.6 Residual stress distribution

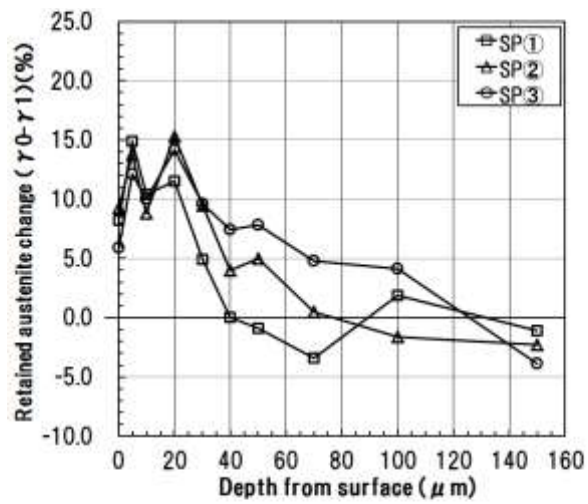

Fig.7 Retained austenite change distribution

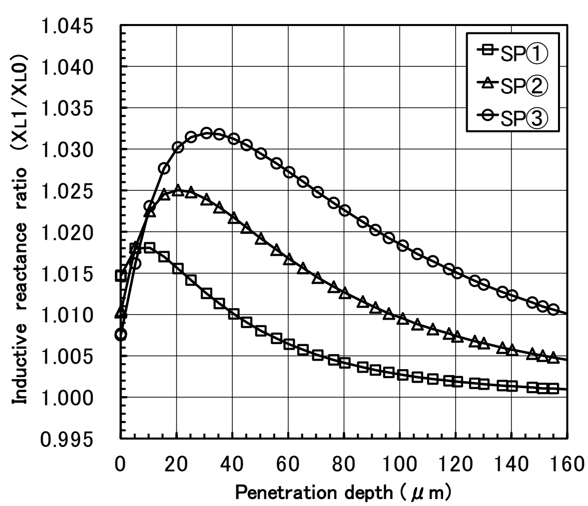

Fig.8 Inductive reactance ratio of penetration depth

permeability of the specimen has been increased by SP.
The highest peak value of XL1 / XL0 is in SP③. The peak value of XL1 / XL0 has a tendency to increase as the shot particle diameter becomes larger. And peak depth of XL1 / XL0 is 5μm in SP①, 20μm in SP②, and 30μm in SP③. The range from the outermost surface to the depth where XL1 / XL0 becomes 1 has a tendency to spread deeper as the shot particle size increases.

Comparison of work-induced martensite transformation distribution and eddy current measurement results

Comparing XL1 / XL0 and [γ0-γ1] distributions, both of the values are in the order of SP① < SP② < SP③ in the depth of 30 ~ 70μm. Furthermore XL1 / XL0 > 1 in all penetration depths of 0 ~ 150μm, so the relative magnetic permeability is increasing. This is because of the change in crystal structure during deformation induced martensitic transformation by the SP. Since the increase in the relative magnetic permeability due to the transformation from anti-ferromagnetic material austenite to paramagnetic material martensite is also considered to be on the Bethe-Slater curve in Fig.2, the variation along the measurement principle was confirmed.
Peak depth of XL1 / XL0 is almost the same as that of [γ0-γ1] in SP① and SP②. When the retained austenite amount of the specimen inside is measured by X-ray, it is necessary to cut in electrolytic polishing. Polishing precision at this time is about ± 5μm. The difference between peak depth of the XL1 / XL0 and that of [γ0-γ1] in SP① and SP② is within ± 5μm, and it is considered that the evaluation of the depth of the [γ0-γ1] peak value is precise. Meanwhile, since the difference is 10μm or more in SP③ because martensitic transformation extended to inside more than with other specimens, it is considered as the result that an eddy current reacted to the inside more. From this, it may be difficult to estimate a peak of the stress because the eddy current reaction is affected by the martensitic transformation.
Finally, the value of [γ0-γ1] obtained by integrating up to each depth was compared with the value of XL1 / XL0. Fig.9 shows the results. From Fig.9, it can be seen that there is a correlation with a correlation coefficient R2 >= 0.997 of the integrated value of [γ0-γ1] with XL1 / XL0 up to 20μm of [γ0-γ1] around in SP② and ③. This is because the eddy current reaction depends on the relative magnetic permeability changes from the outermost surface to a depth of penetration. Meanwhile, the relationship loses linearity in the [γ0-γ1] in the region deeper than peak depth and XL1 / XL0 is saturated. It is supposed that XL1 / XL0 will continue increasing without being saturated if the eddy current reacts to only the change in austenite. However, it is saturated.
As a supplementary test, for a material that has almost no austenite, we prepared nitride treated spring steel (SUP10). Fig.10 shows the results that were measured by eddy current of a specimen treated with SP. Table.3 shows SP conditions. Other test conditions remained the same. Fig.10 shows

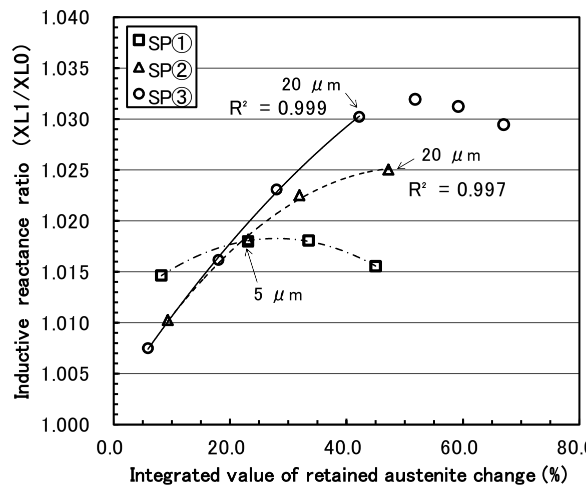

Fig.9 Relation between Inductive reactance ratio and integrated value of retained austenite change

Table 3 Conditions of shot peening

	SP④	SP⑤
Shot method	Direct pressure	
Diameter [mm]	0.05	0.3
Hardness [Hv]	700	700
Air pressure [MPa]	0.2	0.2
Coverage [%]	100	100
Arc height	0.250 [mmN]	0.220 [mmA]

that XL1 / XL0 of all specimens was smaller than 1 in all penetration depths of 0~150μm, so the inductive reactance component has decreased. With this result, it is thought that the relative magnetic permeability decreased under the influence of the elastic strain or the plastic strain (or the both) by SP. Also, for the change after peak depth of XL1 / XL0 shown in Fig.8, it is supposed that an eddy current reacted in the same factor.

With these results, by evaluation of [γ0-γ1] distribution by eddy current, it is thought that it can estimate the depth range of stress distribution. Also, the decrease of the relative magnetic permeability after peak depth of XL1 / XL0 will be inspected more in the future.

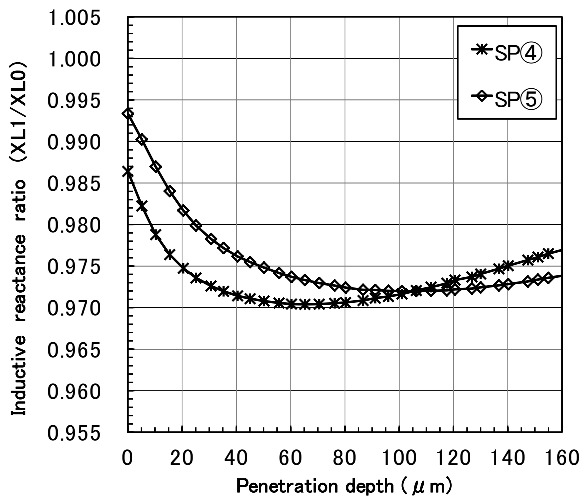

Fig.10 Inductive reactance ratio of penetration depth

Conclusions

The results obtained by this study are as follows.

(1) On the basis of the Bethe-Slater curve, this experiment has shown that the relative magnetic permeability of the test strip indicates a change depending on the distance between atoms which is caused by deformation induced martensitic transformation.

(2) For the material induced martensite transformation by shot peening, by evaluation of [γ0-γ1] distribution by eddy current, it is thought that it can estimate the depth range of the stress distribution.

(3) It was confirmed that there is a correlation with a correlation coefficient R2 >= 0.997 of the integrated value of [γ0-γ1] with XL1 / XL0 in depth of 0μm -20μm.

References

[1] JSSP, Metal Fatigue and Shot Peening, edited by Gendaikougakusya, (2004).
[2] K. Matsui, Y. Eto, K. Yukitake, Y. Misaka, K. Ando, JSME, 66-650, (2000), 1878-1885.
[3] A. Tange, T. Akutu, N. Takamura, JSSE, 36, (1991), 47-53.
[4] Y. Kobayashi, T. Tsuji, R. Ishikura, K. Inoue, JSSE, 57, (2012), 9-15.
[5] Y. Watanabe, K. Hattori, M. Yamawaki, Y. Kobayashi, K. Ito, ICSP-12, (2014).
[6] A. Akio, JSTRA, 17-1, (1980), 1-80.
[7] A. Akio, C. Takizawa, MTRAJ, 18-1, (1973), 351-360.
[8] N. Ishikawa, Shimizu Research Report, 37, (1983), 71-77.
[9] JSNDI, Eddy Current Testing Ⅰ, edited by JSNDI, 17, (1995).
[10] R. Ito, T. Azuma, S. Soma, S. Murakami, T. Kuriyagawa, JSAT, 56-8, (2012), 26-31.
[11] K. Sato, Applied Material Science, edited by Ohmsha (1991-2).