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Influence of Retained Austenite, Strain-induced Martensite and Bending Stress upon Shot Peening-induced Residual Compressive Stresses

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1 Abstract

To introduce large residual compressive stresses by means of shot peening, the authors conducted an experiment using vacuum carburized and shot peened or stress peened test pieces. The influence of arc height (Ah), shot radius (R), retained austenite (γ_R), strain-induced martensite (M_Q) and bending stress (σ_{pre}) upon residual compressive stresses was investigated systematically. Residual compressive stresses were found to be quite dependent on Ah/R, only slightly influenced by γ_R and hardly affected by M_Q content. Approximately, 50 % of the applied σ_{pre} was introduced as residual compressive stress. Finally, the amount of induced residual compressive stresses linearly depended on Ah/R, γ_R and σ_{pre}.

2 Introduction

It is generally recognized that the introduction of large and deep residual compressive stresses is highly effective in improving the fatigue limit of mechanical parts which are subjected to cyclic loads at stress ratios $R = 0$ [1–3]. An economical method for inducing such beneficial residual stress distributions is to use shot peening which has been studied by various researchers [4-6]. For a given shot peening intensity, the following two conditions will help in inducing large and deep residual compressive stresses:

1) Decreasing the deformation resistance of a material during shot peening
2) Increasing the yield stress (hardness) of a material.

To achieve item 1) warm peening and stress peening were developed [7, 8]. There is carburizing and quenching for item 2) as a simple and easy to apply method. However, this method can lead to significant amounts of γ_R which will negatively affect hardness. On the other hand, it is known that this γ_R can transform to M_Q during shot peening. Further, the transformation from γ_R to M_Q involves volume expansion. Therefore, the authors assumed that by utilizing this phenomenon large and deep residual compressive stresses could be obtained. An experiment was conducted using vacuum carburized and shot peened or stress peened test pieces with various contents of γ_R. The influence of Ah, R, γ_R , M_Q and σ_{pre} on the residual compressive stress (σ_r) was analyzed systematically.

3 Experimental Methods

Material for the test pieces was JIS SCM822H with the following chemical composition in wt. %: 0.22 C, 0.25 Si, 0.86 Mn, 1.13 Cr, 0.36 Mo. Smooth rectangular test pieces were machined having the dimensions 30 × 90 × 5 mm. To investigate the influence of γ_R content on σ_r, the above test pieces were given three different vacuum carburizing or nitrocarburizing treatments. Hereafter, these test pieces are denoted as VC1, VC2 and VCN. The maximum residual stress (σ_{rmax}) among these test pieces was found to be only –412 MPa, while the maximum content of retained austenite of VC1, VC2 and VCN amounted to 15.2, 22.9 and 47.4 %, respectively. Shot peening was performed on the various test pieces being subjected to 4-point bending with σ_{pre} of –1000, 0, +1000 and +1400 MPa. Peening was done either by means of an impeller type (ISP) using Ø 0.8 mm shot of 560 HV hardness to 0.55 mmA intensity or by means of a direct pressure blast system using double peening (DSP). In primary shot peening (PSP), peening was performed with Ø 0.7 mm shot of 700 HV hardness to 0.30 mmC (conversion value of A strip: 1.05 mmA) intensity and in secondary shot peening (SSP), peening was done with Ø 0.08 mm shot of 700 HV hardness to 0.35 mmN (conversion value of A strip: 0.117 mmA) intensity.

Table 1 gives an overview of the various test piece conditions.

Table 1: Material and shot peening conditions

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI
Vacuum carburizing	VC1	VC2	VCN	VC1	VC2	VCN	Vc2	VC2	VC1	VC2	VCN
Shot peening	ISP	ISP	ISP	DSP	DSP	DSP	DSP	DSP	DSP	DSP	DSP
σ_{Pre} (MPa)	0	0	0	0	0	0	1000	–1000	1400	1400	1400

Measurements of γ_R contents and of σ_r values were performed by means of a micro X-ray stress analyzer using Cr-K_α radiation. Stresses were calculated by the $\sin^2\psi$-method.

4 Results and Analysis

4.1 σ_r-Depth Profiles and γ_R-Depth Profiles in Shot Peened Test Pieces

Among the 11 test piece conditions, characteristic differences in σ_r-depth profiles were evaluated as illustrated for test pieces III, IV, VIII and IX in Figure 1. Based on these experimental results, characteristic values within the σ_r-depth profiles and γ_R-depth profiles are defined in Figure 2.

Table 2: σ_r and γ_R values in ISP test pieces

No.	σ_{rs} (MPa)	γ_{Rs} (%)	σ_{rmax} (MPa)	γ_{RD} (%)
I	–819	2,8	–1067	8,7
II	–757	6,8	–963	16,1
III	–628	22,2	–869	39,1

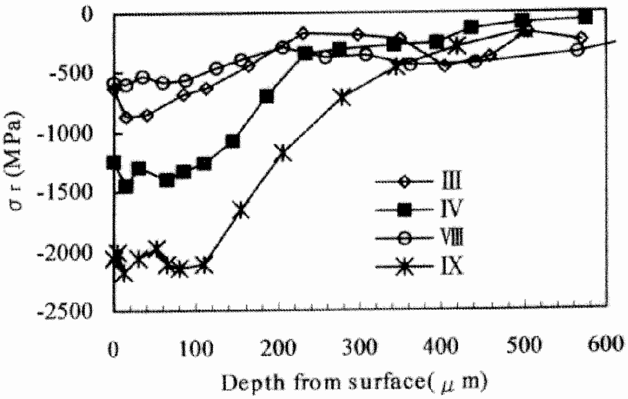

Figure 1: Typical examples of the σ_r-depth profiles

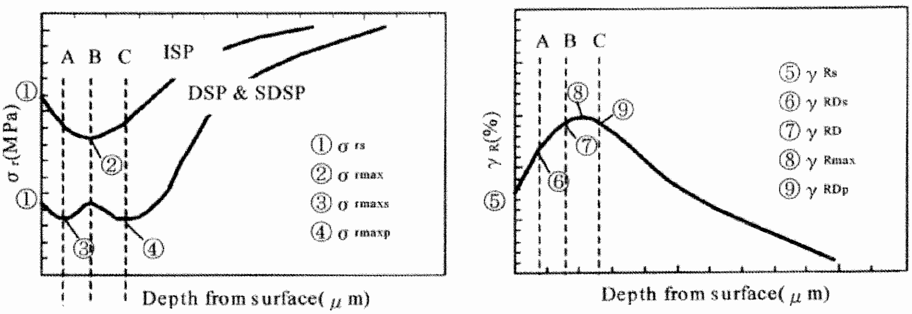

Figure 2: Characteristic values of σ_r- and γ_R-depth profiles (schematic)

These values as measured for the conditions ISP, DSP and SDSP are listed in tables 2, 3 and 4, respectively.

Table 3: σ_r and γ_R values in DSP test pieces

No.	σ_{rs} (MPa)	γ_{Rs} (%)	σ_{rmaxs} (Mpa)	γ_{RDS} (%)	σ_{rmaxp} (MPa)	γ_{RDp} (%)
IV	–1249	1,7	–1448	2,0	–1388	1,8
V	–1285	1,5	–1442	2,2	–1346	3,6
VI	–1192	10,5	–1325	22,8	–1232	25,6

Table 4: σ_r and γ_R values in SDSP test pieces

No.		σ_{rs} (MPa)	γ_{Rs} (%)	σ_{rmaxs} (MPa)	γ_{RDS} (%)	σ_{rmaxp} (MPa)	γ_{RDp} (%)
VII	Before[*1]	–1352	–	–1539	–	–1439	–
	After[*2]	–1819	1.2	–2038	1.3	–1907	7.4
VIII	Before	–1281	–	–1446	–	–1266	–
	After	–576	1.5	–589	2.5	–580	7.7
IX	Before	–1188	–	–1356	–	–1308	–
	After	–2049	1.1	–2180	0.8	–2109	3.0
X	After	–2032	0.8	–2224	1.9	–2071	5.8
XI	Before	–1223	–	–1125	–	–1119	–
	After	–2092	14.1	–2140	29.9	–1871	30.4

[*1] before removing bending stress, [*2] after removing bending stress

In addition, the effect of σ_{pre} on σ_r values can be seen in table 4. "Before" means under bending stress, "after" means bending stress removed. The surface residual stress σ_{rs} and the maximum residual stress values σ_{rmax}, σ_{rmaxp} and σ_{rmaxs} varied considerably from –576 up to –2092 MPa and from –580 up to –2224 MPa, respectively. Furthermore, the γ_R content which is one of the objects of this analysis varied extensively from 0.8 % up to 30.4 %.

4.2 σ_r-Depth Profiles in SDSP Test Pieces

Figure 3 shows σ_r-depth profiles in SDSP test pieces before and after removing σ_{pre} amounting to +1000 and –1000 MPa for test pieces VII and VIII, respectively.

Comparing the data of these test pieces under bending stress, little differences were found in σ_r-depth profiles up to the depth of 150 ìm while in greater depths, differences were quite marked. However, after removing σ_{pre}, both σ_r-depth profiles differed considerably. For example, σ_{rs} and σ_{rmax} of test piece VII were –1819 and –2038 MPa, respectively while those of test piece VIII were σ_{rs} = –576 MPa and σ_{rmax} = –580 MPa. This indicates that for introducing high values of residual compressive stresses, stress peening under tensile stresses should be done.

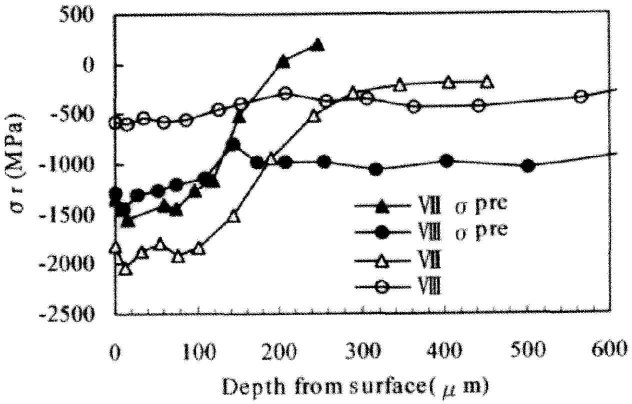

Figure 3: σ_r--depth profiles in SDSP test pieces

4.3 Influence of γ_R Content on Shot Peening-Induced Residual Compressive Stresses

The amount of shot peening-induced residual compressive stresses in carburized, quenched and tempered test pieces increases by

1) Plastic deformation of tempered martensite (M_t) before shot peening
2) Volume expansion by transformation of γ_R to M_Q during shot peening
3) Plastic deformation of M_Q
4) Plastic deformation of γ_R

The effect of γ_R content as determined after shot peening on σ_{rmax} values of the test pieces I–VI (no bending stress applied) is shown in Figure 4.

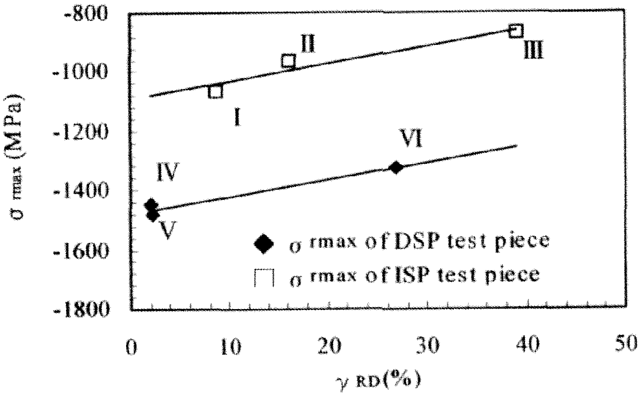

Figure 4: σ_{rmax} vs. γ_{RD} content (no bending stress applied)

As γ_R content increases, σ_{rmax} values decrease. Presumably, this is caused by the the yield stress of γ_R being lower than that of M_t and M_Q. While the dependency of σ_{rmax} values on γ_R content is similar for ISP and DSP test pieces, DSP resulted in residual compressive stresses about 400 MPa higher than those in ISP. This 400 MPa difference is attributed to plastic deformation of different quantities of M_t and M_Q caused by the differences in shot peening intensity between ISP and DSP.

4.4 Influence of Ah on Residual Stresses

Although Ah values were widely varied, σ_{rmax} values stayed almost the same while the corresponding depths of these values differed considerably. For example, these depths were 55–65 μm for PSP and only 8–16 μm for SSP. Thus, σ_{rmax} can not be evaluated quantitatively by *Ah* only. Obviously, this is due to the fact that *Ah* is an integral value of the residual compressive stress field (unit: MPa mm).

For evaluating the compressive residual stress quantitatively, relations given by Al-Hassani et al. [9, 10] are used which show that the maximum size of the plastic zone of an indentation is proportional to *R*. Thus, by using the ratio *Ah*/*R*, the influence of R becomes nil. *Ah*/*R* is thought to include factors a) to d) of section 3).

4.5 Influence of *Ah*/*R* on γ_R and Residual Stresses

The effect of *Ah*/*R* on γ_R and σ_{rmax} is illustrated for test piece VC2 in Figure 5.

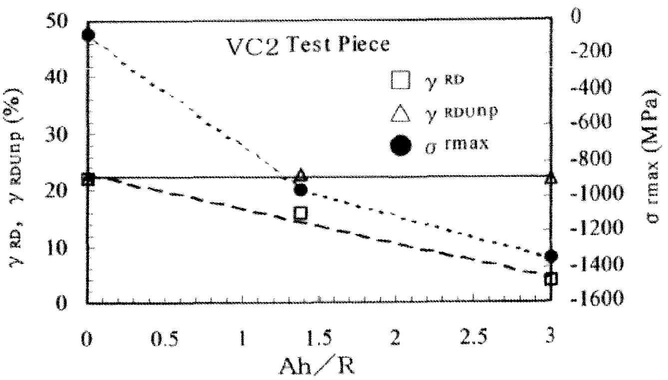

Figure 5: γ_{RD}, γ_{Rdump} and σ_{rmax} vs. Ah/R of VC2 test piece

The γ_R values shown were determined before and after shot peening at depths where σ_{rmax} values (after shot peening) were found. The difference between γ_R contents before and after shot peening (Figure 5) corresponds to the amount of M_Q. From Figure 5, the following can be stated:

a) Increasing *Ah*/*R* leads to higher σ_{rmax}.
b) Increasing *Ah*/*R* decreases γ_R and thus, increases M_Q.

4.6 Influence of M_Q on Residual Stresses

The relation between M_Q and σ_{rmax} for a given ratio $Ah/R = 3.0$ is shown in Figure 6.

Obviously, there is no simple correlation between M_Q and σ_{rmax} which is attributed to the fact that in shot peening both transformation-induced and plasticity-induced stresses interfere.

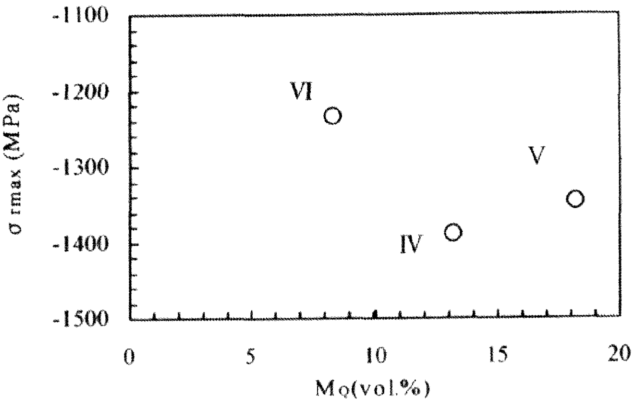

Figure 6: σ_{rmax} vs. M_Q (Ah/R = 3.0)

4.7 Influence of σ_{pre} in Stress Peening on γ_R and Residual Stresses

The influence of σ_{pre} in stress peening on γ_R as well as on σ_r is illustrated for test piece VC2 in Figure 7. From these results, the following can be concluded:

a) σ_r is directly proportional to σ_{pre}
b) γ_R content or M_Q content are independent of σ_{pre}

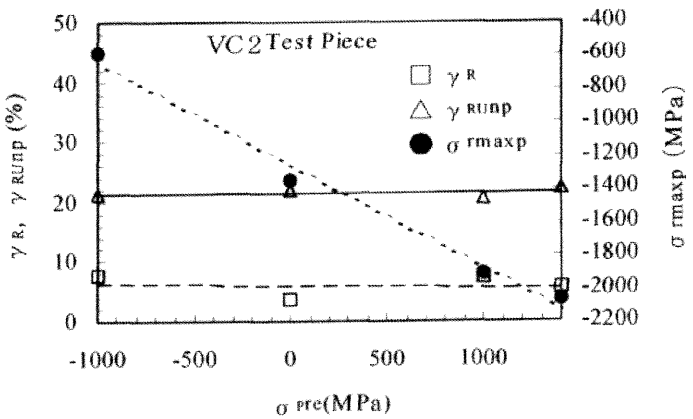

Figure 7: γ_R, γ_{Runp}, and σ_{rmaxp} vs. σ_{pre} of VC2 test piece

4.8 Influence of Ah/R, γ_R and σ_{pre} on Residual Stresses

Although an assessment of the individual contributions of the various parameters in shot peening to the development of residual compressive stresses is quite difficult mainly because of the complex nature and interference of transformation-induced and plasticity-induced residual compressive stresses, from Figures 4–7, the following conclusions can be made:

1) With an increase in γ_R content, σ_r decreases.
2) As Ah/R increases, γ_R content decreases and thus, M_Q content increases.
3) No correlation exists between M_Q and σ_{rmax}.
4) σ_r is directly proportional to σ_{pre}.

Based on the conclusions a) to d) and the data from tables 2–4, a regression analysis was performed leading to the following equations I and II (Figure 8):

$$\sigma_{rs} = -276\ Ah/R + 7.1\ \gamma_R - 0.59\ \sigma_{pre} - 451 \tag{I}$$

$$\sigma_{rmax} = -172\ Ah/R + 7.1\ \gamma_{RD} - 0.54\ \sigma_{pre} - 822 \tag{II}$$

where the experimental values Ah/R = 1.4 – 3.0, γ_R (after shot peening) = 0.8 – 29.9 % and σ_{pre} = –1000 – +1400 MPa were used.

From the above equations it is seen that increasing Ah/R and σ_{pre} increase the residual compressive stresses σ_r while increasing γ_R decreases σ_r. Again, this is attributed to the yield stress of γ_R being lower than that of both M_t (before shot peening) and M_Q (after shot peening).

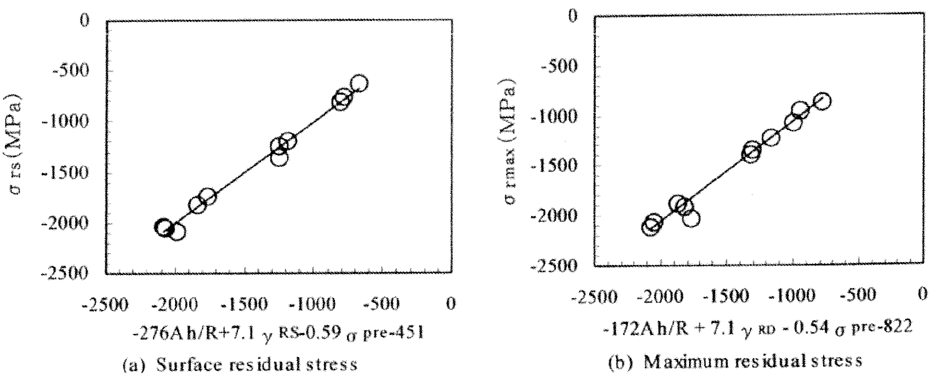

Figure 8: σ_r vs. Ah/R, γ_R and σ_{pre}

5 Conclusions

The authors conducted an experiment using JIS SCM8222H test pieces and investigated the influence of shot peening and material parameters on residual compressive stress formation.

Arc height Ah, shot radius R, retained austenite content γ_R, strain-induced martensite M_Q and bending tensile stress σ_{pre} were varied systematically. The following conclusions can be drawn:

1. Both the surface and maximum residual stress after shot peening are proportional to the new parameter Ah/R.
2. The higher the retained austenite content as present after shot peening, the smaller the surface and maximum residual stresses. However, there was little influence of retained austenite content as determined before shot peening. This is attributed to the low yield stress of retained austenite.
3. Strain-induced martensite as formed during shot peening does not influence the surface and maximum residual compressive stresses. This is attributed to the interference of transformation-induced and plasticity-induced residual compressive stresses.
4. Approximately 50 % of the amount of the tensile bending stress during stress peening is effective in increasing the surface and maximum residual compressive stresses.
5. From the above results, equations I and II were obtained where residual compressive stresses are seen to increase with increasing arc height/shot radius and amount of tensile bending stress and to decrease with increasing amounts of retained austenite measured after shot peening.

6 References

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