Characteristics of Shot Peened Surfaces and Surface Layers

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ABSTRACT

This paper describes the influence of the shot size, the shot velocity and the work hardness on the characteristics of peened surfaces and surface layers. In order to clarify the clear influences of those factors, a medium carbon steel (S45C) was peened by a centrifugal type peening machine using 4 different cast steel shots. Following results are obtained; (1) The diameter of dent is in proportion to the shot size and the square root of the shot velocity, and in inverse proportion to the fourth root of the work hardness. (2) The contact angle of dent is in proportion to 2/3 power of the shot velocity, and the values were varied from 11 to 18°. (3) The surface roughness is in proportion to the shot size and the shot velocity, and in inverse proportion to the square root of the work hardness. (4) The depth of work hardened layer increases proportionally to the fourth root of the kinetic energy of a shot. (5) Residual stresses in the surface layer induced by shot peening are compressive, and the maximum value in this experiment was about -390 MPa.

KEY WORDS

Shot peening, shape of dent, surface roughness, hardness distribution, half width, residual stress, affected layer.

1. INTRODUCTION

Shot peening is a cold working process impacting the work material using spherical particles, and producing many spherical dents on the surface and the affected layer below the surface. As the working device of shot peening is uncountable spherical particles, the surface roughness has non-directional quality, and the blasted particles can strengthen work materials having various shapes and narrow parts such as the inside of a pipe or the bottom of a gear.

As the results, shot peening improves the mechanical properties on fatigue [1, 2], stress corrosion cracking [3, 4], wear [5], and also produces additional effects on the flow resistance coefficient of the peened surface[6] and on the heat transfer characteristics [7]. Shot peening techniques are, therefore, widely used in many industries.

Peening variables which influence the characteristics of the surfaces and surface layers are the type of equipment, the material, size and velocity of shot, the peening angle, the peening time and so on. In addition, mechanical properties and the size of work material also influence the characteristics.

In this paper, in order to clarify the clear influences of the shot size, the shot velocity and the work hardness on the characteristics of the peened surfaces and the surface layers, a medium carbon steel (S45C) was peened by a centrifugal type peening machine using 4 different cast steel shots. The shape of dent, the surface roughness, the hardness distribution, the half width and the residual stress were measured, and their influences on the characteristics were studied.

2. EXPERIMENTAL PROCEDURES

Experimental conditions on shot peening, the work material and the residual stress measurement are listed in Table 1. All work materials are annealed at 820 ° C for 2 hours before shot peening to study the clear influences by shot peening.

Table 1 Experimental conditions

Shot peening	Equipment	Centrifugal type
	Shot material, size	Steel (800HV): 0.55, 1.1, 1.6, 2.2 mm
	Shot velocity	15, 20, 25, 30, 35 m/s
	peening time	Full coverage time
	Peening angle	Normal to the peening surface
Specimen	Materials	Medium carbon steel (0.45%C)
	Size	25 × 25 × 11.5 mm
Residual stress measurement	X-ray, Diffraction plane	Cr-k_α, (211) plane
	Diffraction angle	FWHM middle point method
	Calculation	$\sin^2\psi$ method

The diameters of a dent were measured crosswise with a tool microscope whose magnification was 30 times and 20 individual data were averaged. The hardness was measured on the perpendicular section using a micro Vickers hardness tester. Three surface profiles of a specimen were recorded with a profile recorder, and the surface roughness values, Ry, were obtained from averaging their three data. Half width values are the average of 6 different ψ angles.

As listed in Table 1, X-ray diffractometer were used for the residual stress measurements and residual stress values were calculated from the following formula,

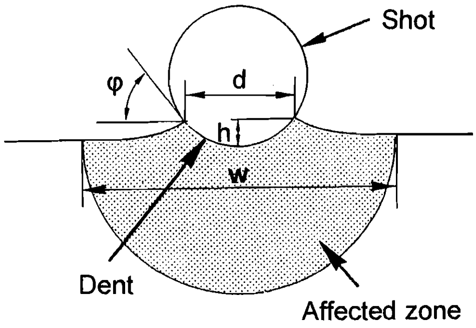
$$\sigma_R = -\frac{E}{2(1+\nu)} \cot\theta_0 \frac{\partial 2\theta}{\partial \sin^2\psi}$$

where E: 206 GPa, v: 0.28, θ_0: standard Brag angle, 2θ: diffraction angle of specimen, ψ: inlet angle of X-ray.

3. EXPERIMENTAL RESULTS

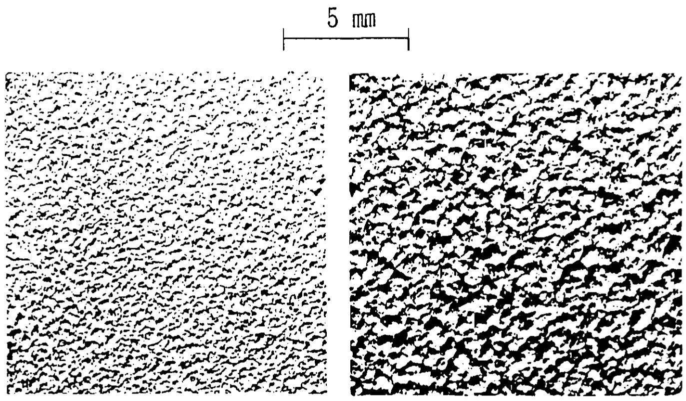
3.1 Shape of dent

The profile of a dent and symbols are illustrated in Fig. 1, and the shot peened surfaces at full coverage are shown in Fig. 2. The characteristics of the surface is influenced basically by the shape of single dent.



d: Diameter of dent
h: Depth of dent
φ: Contact angle of dent
w: Width of affected zone

Fig. 1 Shape of dent and symbols



(a) D: 1.1 mm
v: 35 m/s

(b) D: 2.2 mm
v: 35 m/s

Fig. 2 Shot peened surfaces

3.1.1 Diameter of dent (d)

Figure 3 shows the influences of the shot size (D), the shot velocity (V) and the work hardness (H) on the diameter of dent (d), and the following formula is obtained.

$$d = k_d \cdot D \cdot V^{1/2} \cdot H^{-1/4} \qquad (1)$$

where k_d is the coefficient of the formula.
The maximum influence factor in these three ones is, therefore, the shot size.

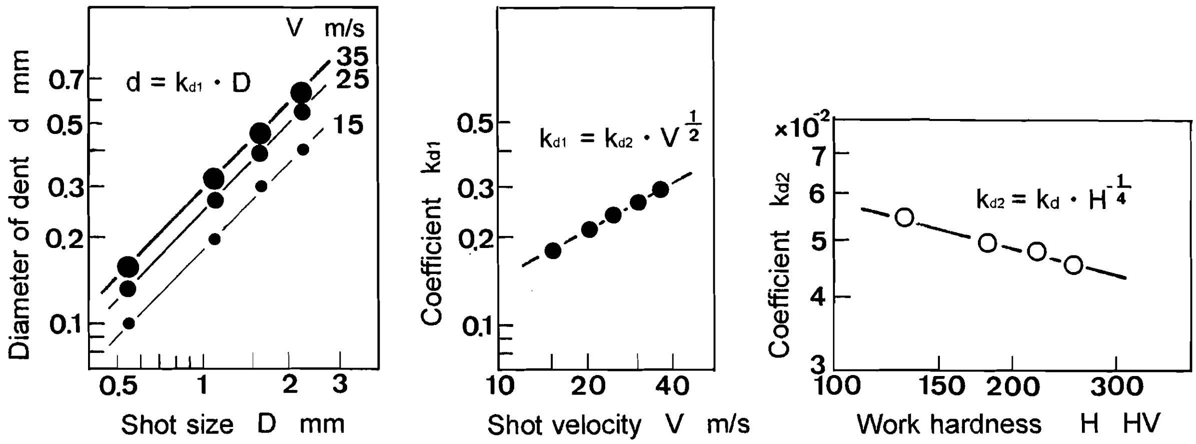


Fig. 3 Influence of shot size (D), shot velocity (V) and work hardness (H) on diameter of dent (d)

As shown in Fig. 4, d/D is in proportion to the square root of the shot velocity, and the values were varied from 0.2 to 0.3. Namely, the diameters of dent formed by shot peening in this experiment ranged about from 1/4 to 1/3 times as large as the shot size, and the width of affected layer (w) illustrated in Fig. 2 ranged about 3 times as large as the diameter of dent.

3.1.2 Depth of dent (h)

The depth of dent is closely related to the surface roughness and the above mentioned characteristics, and were calculated assuming the shape of dent is spherical. As shown in Fig. 5, the values were varied from 5 to 50 μm, which ranged from 1/100 to 3/100 times as large as the shot size.

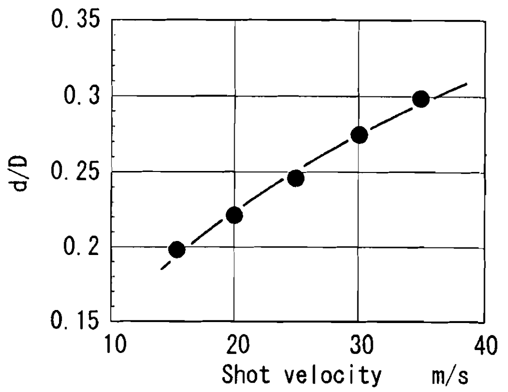


Fig.4 Influence of shot velocity on the ratio d/D

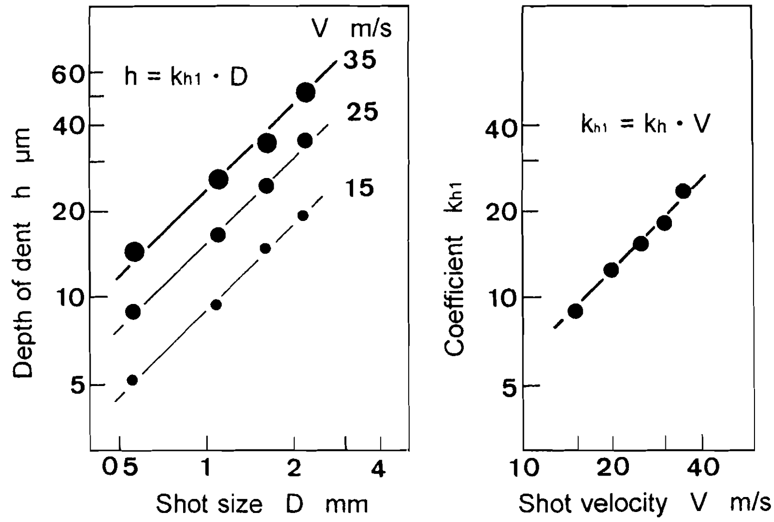


Fig. 5 Influences of shot size and velocity on the depth of dent

3.1.3 Contact angle of dent (φ)

The properties on tribology of the peened surface are influenced by the affected layer and the contact angle of dent (φ) illustrated in Fig. 2.

Figure 6 shows the influences of the shot size and velocity on the contact angle of dent. The contact angle is in proportion to 2/3 power of the shot velocity and independent to the shot size. Namely, when shot velocities are the same, the similar figures of dent are formed regardless of the shot size.

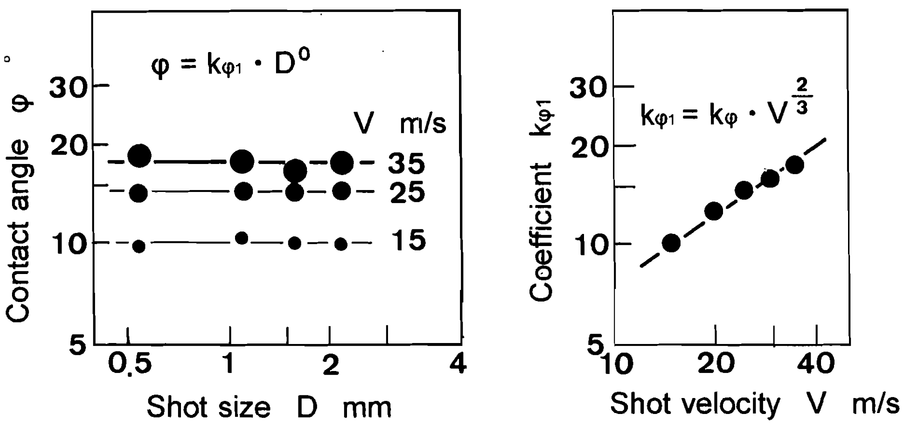


Fig. 6 Influence of shot size and velocity on contact angle of dent

3.2 Surface roughness

The surface roughness is the very important factor relating to the fatigue strength, the abrasiveness and the heat transfer characteristics.

Figure 7 shows the influences of the shot size (D), the shot velocity (V) and the work hardness (H) on the surface roughness (R_y), and the following formula is obtained.

$$R_y = k_R \cdot D \cdot V \cdot H^{-1/2} \qquad (2)$$

where k_R is the coefficient of the formula.
The maximum influencing factors in these three factors are, therefore, the shot size and the shot velocity.

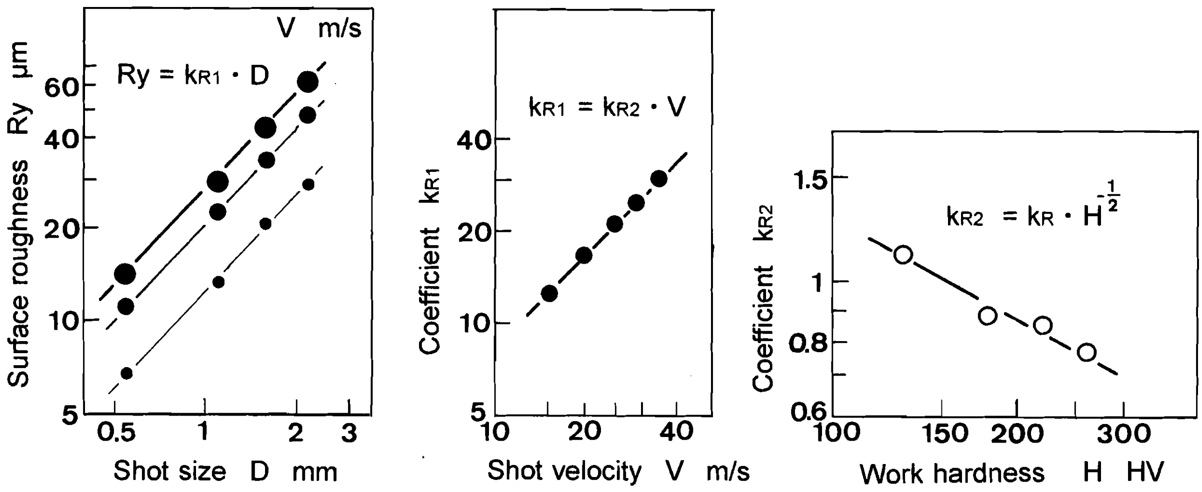


Fig. 7 Influences of shot size (D), shot velocity (V) and work hardness (H) on surface roughness (R_y)

The ratios of surface roughness to the depth of dent are presented in Table 2, and the surface roughness is about 40 % larger than the depth of dent.

There are some cases that the surface characteristics are different from each other even if their surface roughness values are the same. For example, as shown in Fig. 8, the surface characteristics produced by shot peening and grit blasting are much different from each other at the similar surface roughness.

Table 2 The ratios of the surface roughness to the depth of dent

D (mm) \ V (m/s)	17	35
2.2	1.53	1.20
1.6	1.32	1.36
1.1	1.44	1.30
0.55	1.75	1.26

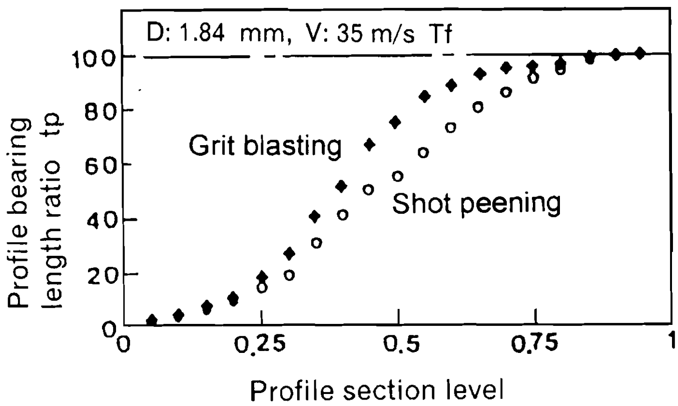


Fig. 8 Bearing area curves

3.3 Hardness distribution

The work hardened layer is also one of the most important factors relating to the fatigue strength, the stress corrosion cracking and the heat transfer characteristics.

Although hardness distributions produced by shot peening are the work hardening type for all annealed specimens as shown in Fig. 9, the hardness distributions after shot peening for the prestrained materials shift from the hardening type to the non-hardening and then to the softening types with increasing the prestrain. Estimating the depth of affected layer from only the hardness distribution is, therefore, not always sufficient.

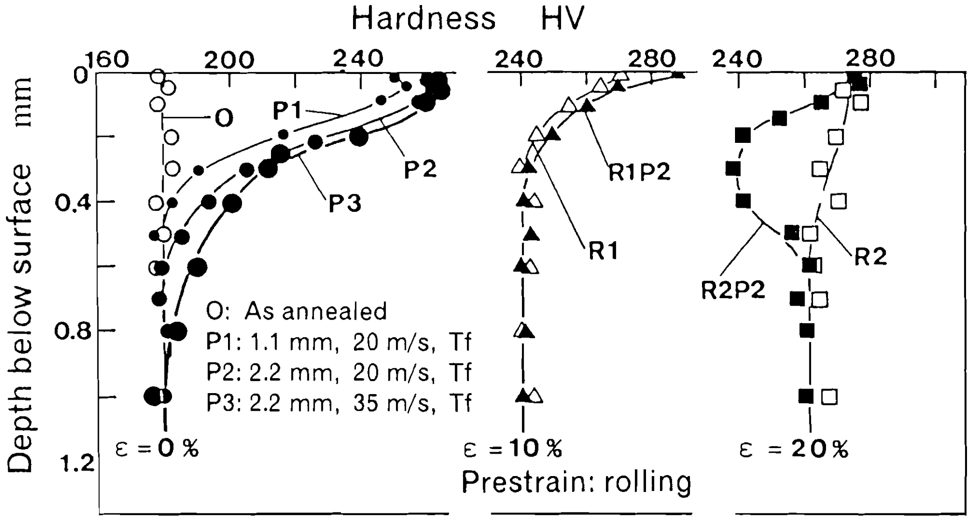


Fig. 9 Hardness distributions

3.4 Half width

The half width is a factor relating to the micro deformation of crystal grain. Figure 10 shows the influence of shot peening on the half width for the rolled materials which were deformed uniformly comparing with shot peening. The strains of the peened surface are similar to the case of about 70 % reduction in thickness by rolling process.

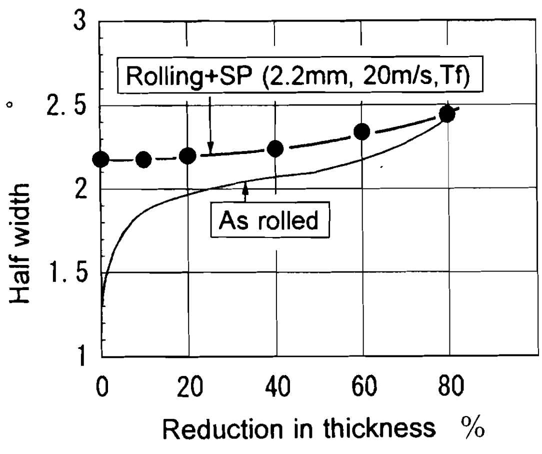


Fig. 10 Influences of shot peening on half width

3.5 Surface residual stress

The surface residual stress is also one of the most important factors relating to the fatigue strength, the stress corrosion cracking and the abrasiveness characteristics.

3.5.1 Shot peening

Surface residual stresses after shot peening are induced by the non-affected layer below the surface [8]. As shown in Fig. 11, surface residual stresses induced by shot peening and grit blasting are influenced by the work thickness. The minimum thickness that surface residual stresses are induced sufficiently is defined as the critical thickness [9], and the surface residual stress falls to zero wherever the thickness of work material and the depth of work hardened layer are overlapped.

Figure 12 shows the influences of the kinetic energy of a shot on the critical thickness and on the depth of work hardened layer. Both factors are in proportion to the fourth root of the kinetic energy of a shot, and the ratio of the critical thickness to the depth of work hardened layer is constant, whose value is 5. In order to induce sufficient surface residual stresses by shot peening, the work thickness should be, therefore, over the critical thickness or over 5 times of the depth of work hardened layer.

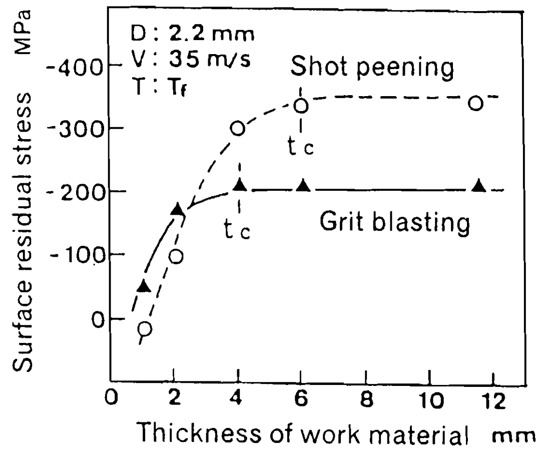


Fig. 11 Size effects of thickness of work material on surface residual stresses

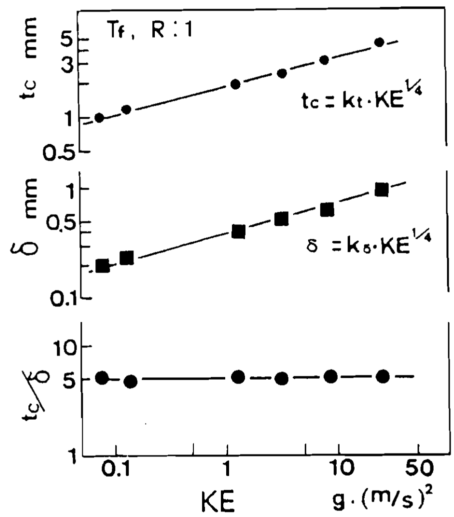


Fig. 12 Influence of the kinetic energy of a shot on t_c, the depth of work hardened layer and their ratio

3.5.2 Sheet bending

Figure 13 shows surface stresses during "on load" and after "off load". As shown in Fig. 13(a), during the tensile stresses are applying to the sheet, tensile stress appears, but after the applied stress removed, stresses on the surface shift to compressive residual stresses which reach a saturated value about -200 MPa with increasing the applied stress. In the case that the applied stresses are compressive as shown in Fig. 13(b), the phenomenon is completely contrary to the case of the tensile stresses, and the saturated value is about 200 MPa which is tensile.

Those residual stresses don't increase like as shot peening, because the deformed material is not strengthened by a simple bending process.

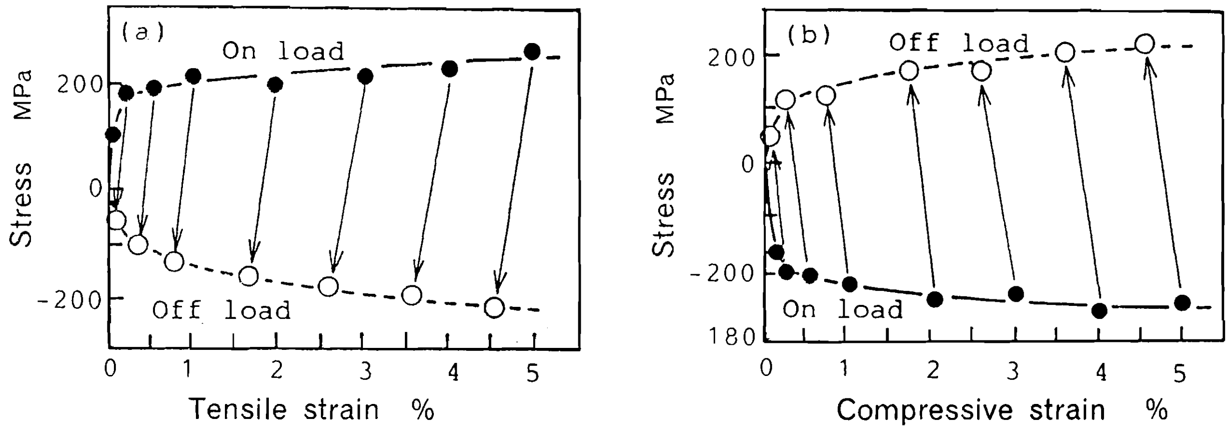


Fig. 13 Influence of applied strain on surface stress and residual stress

3.5.3 Ball peening

In order to clarify the reason why high compressive residual stresses are produced by shot peening, as an additional experiment, a ball whose diameter is 8 mm was thrown to the specimen and a large dent was formed. Figure 14 shows surface residual stresses on the inside and the circumference of dent with a collimator of 0.5 mm in diameter.

Residual stresses of zone A are compressive but not so high, residual stresses on the piled-up zone B are tensile under about 200 MPa, and residual stresses of the zone C turn to compressive, which are also not so high.

Shot peening, therefore, induce high compressive residual stress owing to the strengthening process by countless spherical shots.

3.6 Residual stress distribution

The residual stress distribution is also significant to the fatigue strength of material. Figure 15 shows residual stress distributions after shot peening for a medium carbon steel (S45C) and a carburized steel (SCM415). The distribution on S45C is "C type" which the maximum stress exists on the surface, and both distributions on SCM415 are "S type"

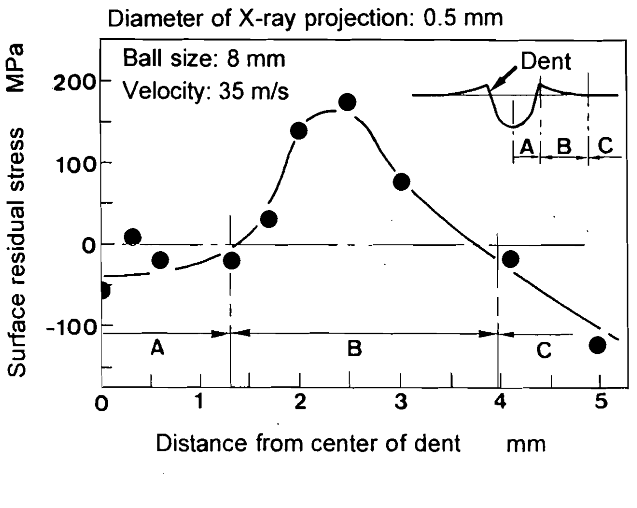


Fig. 14 Residual stresses on the dent and its circumference

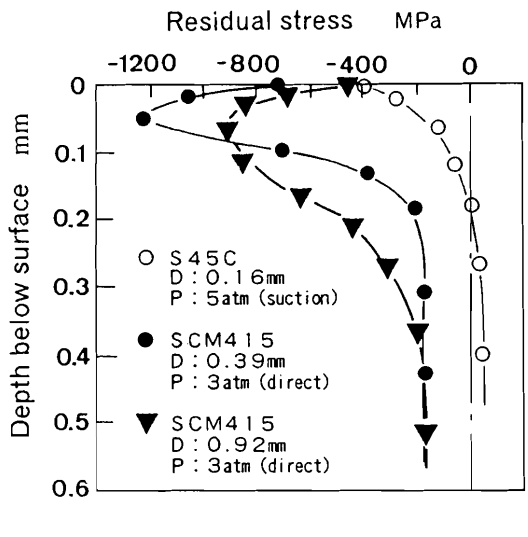


Fig. 15 Residual stress distributions

which the maximum stresses exist below the surface.

C type stress distribution is effective for the case which the fracture starts from the surface, and S type stress distributions is effective for the case which the fracture starts from the subsurface layer.

4. CONCLUSIONS

In order to clarify the clear Influence of the shot size, the shot velocity and the work hardness on the characteristics of the peened surfaces and the surface layers. Following results are obtained.

(1) The diameter of dent is in proportion to the shot size and the square root of the shot velocity, and in inverse proportion to the fourth root of the work hardness.

(2) The contact angle of dent is in proportion to 2/3 power of the shot velocity, and the values were varied from 11 to 18 ° .

(3) The surface roughness is in proportion to the shot size and the shot velocity, and in inverse proportion to the square root of the work hardness.

(4) The depth of work hardened layer increases proportionally to the fourth root of the kinetic energy of a shot.

(5) Residual stresses in the surface layer induced by shot peening are compressive, and the maximum value in this experiment was about -390 MPa.

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