EFFECT OF SHOT PEENING ON SURFACE INTEGRITY

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ABSTRACT

This paper describes influences of factors such as size and velocity of particle, and thickness, hardness and crystal phase of work material on surface integrity. Hardness, residual stress and crystal transformation of zone affected by shot peening are examined for a medium carbon steel (C:0.45%, 180HV) and an austenitic stainless steel (SUS304, 210HV). The following results were showun in this paper: (1) Hardness distributions are divided into three types, which are work hadening, non-hardening and work softening ones. (2) Residual stress distributions are divided into two pypes, which are S-type and C-type. (3) As residual stress induced by the resistance of non affected layer, residual stress on the peened surface shows size effect of the thickness of work material. (4) The ratio of the critical thickness to the depth of workhadened layer is about 5. (5) Strain-induced transformation happens with shot peening. (6) The optimum affected-layer ratio (ratio of the depth of work-hardened layer to the thickness of material), which is called "sweet zone", is from 0.3 to 0.4.

SUBJECT INDEX

Surface integrity, hardness distribution, residual stress, critical thickness, strain induced transformation

INTRODUCTION

Shot peening is a cold working process improving the mechanical properties such as fatigue (Drechsler et al, 1999), stress corrosion cracking (Kirk, Render, 1999) and so on (Watanabe et al, 1999). Shot peening is, therefore, widely used in many industries such as aircraft, automobile, machine parts and chemical plants.

Surface integrity, which M. Field and J. Karles firstl brought forward in 1964, is the description and cintrol of the many possible alternations produced in a surface layer duting manufacturing including theie effects on the material performance of the surface in service (ANSI B211-1(1986). As shown in Fig.1 this concept includes hardness alternations, residual stresses, plastic deformations, heat-affected zone, recrystallization and so on. It influences strength of work materials for fatigue, stress corrosion cracking, wear and so on (Takazawa, 1989).

As mentioned above, shot peening including shot blasting techniques are widely used in many industries, but systematic studies on surface integrity are not very much.

In this paper, the influences of those factors, hardness, thickness and crystal phase of work material on surface integrity are shown.

SURFACE INTEGRITY

As illustrated in Fig. 1, this concept includes hardness alternations, residual stresses, plastic deformations, heat-affected zone, recrystallization and so on. They are closely related to the strength of work materials for fatigue, stress corrosion cracking, wear and so on (Takazawa, 1989).

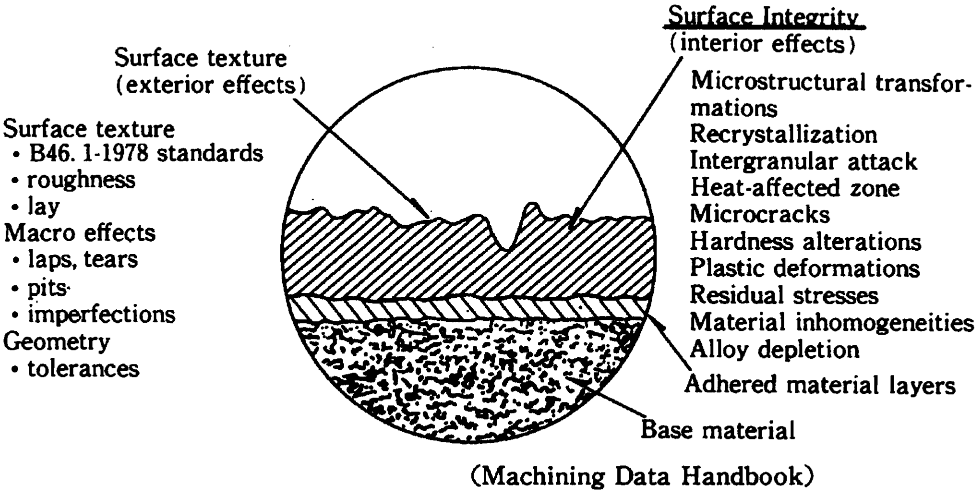


Fig.1 Surface integrity and surface texture

METHODS

Experimental conditions on shot peening (SP) treated in this paper are shown in Table1. Hardness was measured on the perpendicular section using a micro Vickers hardness tester. Hardness distributions were obtained from averaging data measured on the three positions in the same depth from the peened surface. Half-width values are the average obtained from six different inlet angle of X-ray on the residual stress measurement.

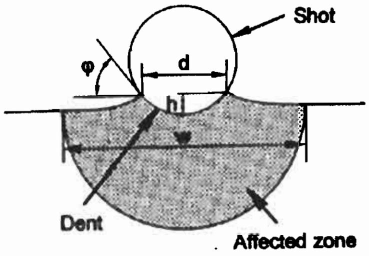
Table 1 Experimental conditions

Equipment	Centrifugal type: 15 - 35 [m/s]
Shot : Material, size	Steel : 0.55, 0.92, 1.1, 1.6, 2.2 [mm] Hardness: 650 - 800 [HV]
Peening time	1 [s] -T_f, T_f: Full coverage time
Peening angle	0, 30, 45, 60, 90 [deg] *) *)90[deg]: Normal to the peening surface
Work: Material	Medium carbon steel (0.45%C) Hardness: 180 [HV] Size: 25,25,t, t: 1 - 11.5 [mm]
	Austenitic stainless steel (SUS304) Hardness: 210 HV Size: Dia.20, H20 [mm]
X-Ray diffraction	Cr-kα, (2 1 1) plane
Residual stress measurement	FWHM middle point method

RESULTS

1. Affected zone

As illustrated in Fig.2, a blasted shot impacts on the surface, and produce a dent and an affected zone. The volume ratio of affected zone to dent is apromaxitly from 250 to 300 as shown in Fig.3.



d : w ≒ 1 : 3

d : h ≒ 10 : 1

φ < 10°

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

Fig.2 Shape of dent

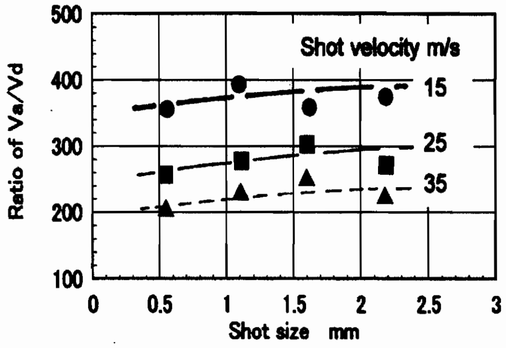


Fig.3 Ratio of affected zone to dent volumes

2. Hardness distribution

Although hardness distribution produced by shot peening for an annealed steel is work hardening type, the distributions for pre-strained steel shift to other types as shown in Fig.4.

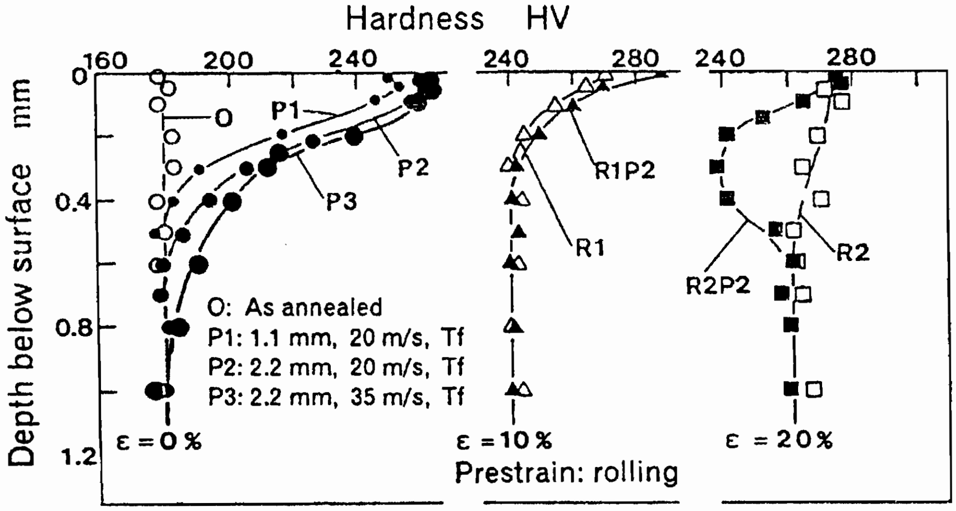


Fig.4 Hardness distributions produced by SP

Hardness distribution produced by shot peening changes from hardening type to non-hardening and then to softening one with increase of pre-strain, and depth of work hardened layer decreases with the increase of pre-strain. This, therefore, is not sufficient to judge the depth of affected layer using only hardness distribution.

The hardness number is influenced by the practical stress. For example, hardness number decreases in the tensile stress field and increases in the compressive stress field as shown in Fig.5.

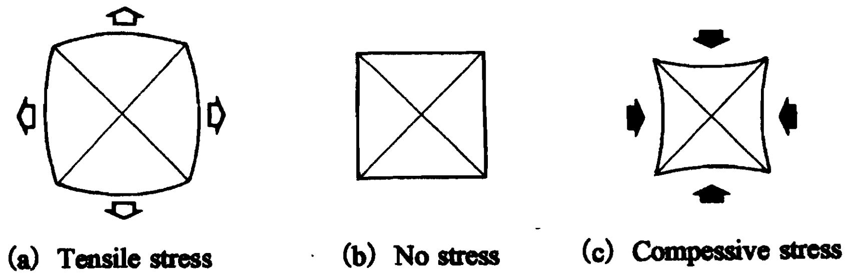


Fig.5 Influence of residual stress on hardness number

As mentioned above, when shot peening variables are the same but the thickness of specimen are not the same each other, residual stresses induced by shot peening and their hardness distributions are not the same. Figure 6 shows the hardness distributions produced by shot peening under the same conditions for two specimens with the different thickness. The hardness near the surface in the thinner specimen is lower than that in the thicker specimen, but hardness in the deeper layer is higher on the contrary. This difference is owing to the change of residual stresses.

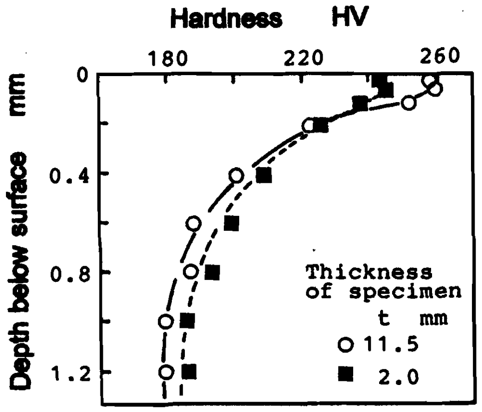


Fig.6 Influence of residual stress on hardness number

3. Half width

The broadening of half width means the increase of the scatter of the micro strain in crystal, and its change is similar to the hardness one. Figure 7 shows the influence of shot peening for a rolled steel on half width. Influence of shot peening is larger than that of rolling.

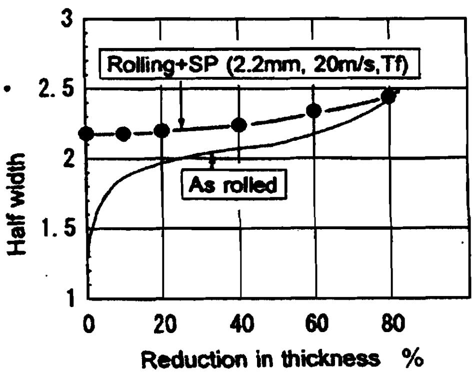


Fig.7 Half width of shot peened material

4. Residual stresses

4.1 Influence of peening time, size and velocity of shot

Figure 8 shows the influence of peening time on area coverage and surface residual stresses induced by shot peening. In early stage, they increase rapidly, and then they approach saturated values when over 80 % of area is peened. Therefore, in the surturated case as shown in Fig. 9, surface residual stress is not sensitive with peening conditions,or the influences of both factors are negligible.

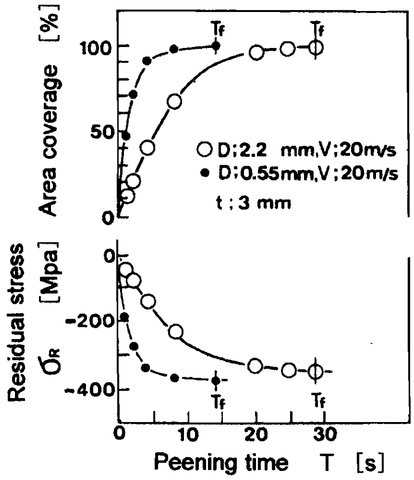


Fig.8 Influence of peening time on area coverage and surface residual stress

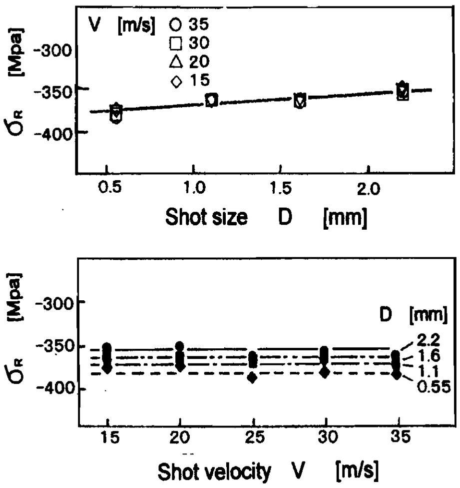


Fig.9 Influence of shot size and shot velocity on surface residual stress

4.2 Influence of thickness of specimen

Figure 10 shows the effect of the thickness of specimen on the surface residual stresses. Critical thickness (t_c) means the minimum thickness for efficient introduction of compressive residual stresses. Surface residual stresses fall to zero wherever the thickness of work material and those depths of work hardened layer are overlapped. Figure 11 shows the relation between the critical thickness and the depth of work hardened layer, and it's ratio is 5.

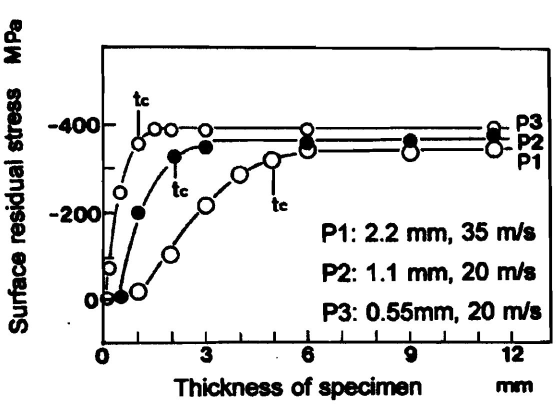


Fig.10 Influence of thickness of specimen on surface residual stresses

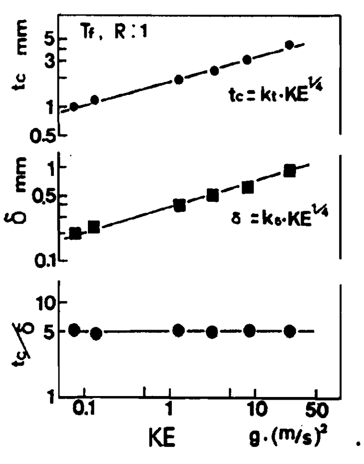


Fig.11 Relation between critical thickness and the depth of work hardened layer(δ)

4.3 Influence of compressive stress on the hardness number

Surface residual stresses, however, change after etching the reverse side layer by layer as shown in Fig.12. , in which "A" and "B" are the results on the peened surface and on the reverse side respectively. As the ratio of the depth of affected layer to the thickness of specimen change, the curvature of specimen increases once and then decreases gradually. Residual stresses on the both surfaces turn from compressive to tensile with the progress of the etching. Surface residual stresses fall to zero wherever the thickness of specimen and the depth of the work-hardened layer are overlapped.

Figure 13 shows the relation between the strain and the residual stresses on the peened surface after etching layer by layer, and they are completely proportional to each other. The non-affected layer, therefore, induces compressive residual stresses on the peened surface and the surface layer.

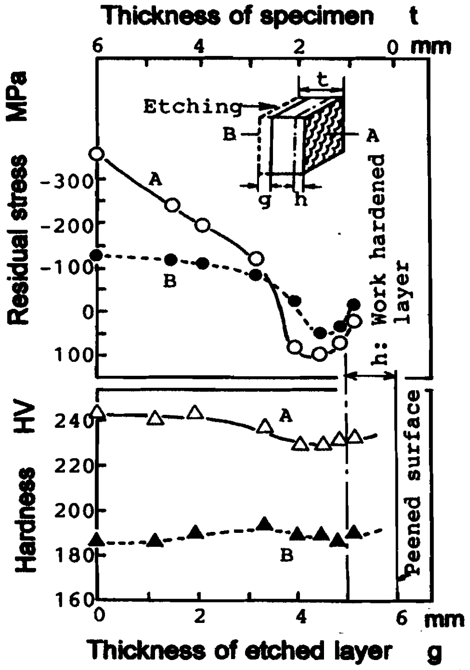


Fig.12 Change of residual stresses and hardness on the peened surface during etching the reverse side

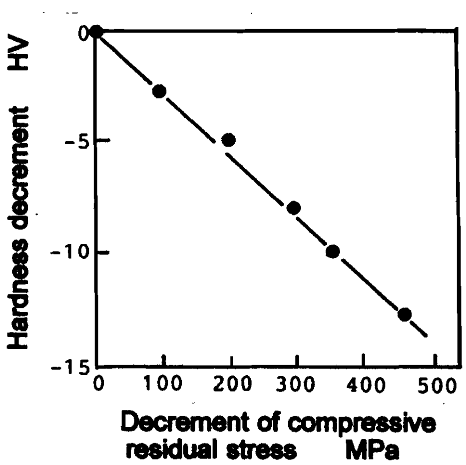


Fig. 13 Influence of residual stresses on the hardness numbers

4.4 Residual stress distribution

Stress distribution is also significant to the fatigue strength of material. Figure 14 shows residual stress distributions induced by shot peening for a medium carbon steel (S45C) and a carburized steel (SCM415). In the case of softer material, the distribution is “C type” which the maximum compressive stress exist on the surface. The both distributions are “S type” where the maximum compressive stresses exist below the surface.

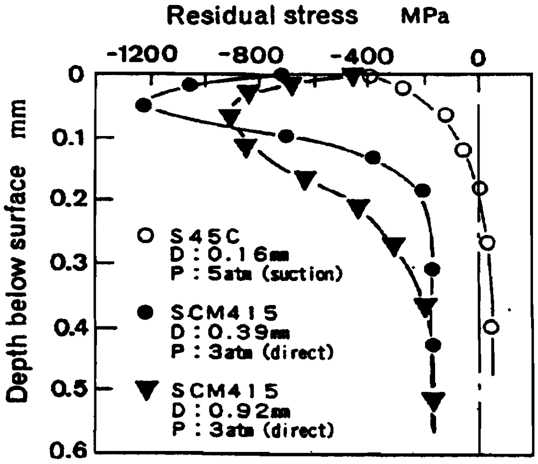


Fig. 14 Residual stress distributions

4.5.1 Influence of tensile strain induce by simple bending

Tensile stresses were induced on the convex surface by bending as shown in Fig. 15(a). The influence of the tensile strain on the stress is shown in Fig. 15(a). During on-load, the tensile stress increases remarkably in the low strain and approaches a saturated value about 200 MPa over about 0.5 % tensile strain. The stresses after off-load turn to the compressive residual stresses and also approach a saturated value about -200 MPa. The difference between off-load and on-load stresses is 150 MPa during the elastic deformation and is from 150 to 460 MPa during the plastic deformation. The hardness during on-load shows 3 different stages as shown in Fig. 15(b). Namely, the hardness decreases remarkably in the first stage, the decrement is saturated in the second stage, and then the hardness increases proportionally with the increase of tensile strain in the third stage.

In the first stage where the tensile strain is under 0.2 %, the hardness after off-load return to the same value before the bending. In the second stage where the tensile strain is from 0.2 to 1 %, when the load is released, the hardness that shows work-hardening is in proportion to the residual strain. In the third stage where the tensile strain is over 1 %, as the value of hardness increment with work-hardening is larger than the hardness decrement by tensile stresses, the hardness during on-load increases. After all, when tensile strain is about 1 %, the hardness number reaches the lowest value and the maximum softening ratio is 7 %. When the tensile strain is 4 %, the hardness number is offset by the influences of the tensile strain and the work-hardening. The work-hardening after off-load is in proportion to the residual strain. The difference between off-load and on-load hardness is under 5 HV within the elastic limit, and 20 HV exceed the elastic limit.

The hardness decrement by the tensile stress is linear in the low stress level by about 150 MPa, and the work-softening ratio is up to 3 % in this stage. The influence of stress over about 150 MPa on the hardness number increases. The relation between the tensile stress decrement and the hardness increment is linear.

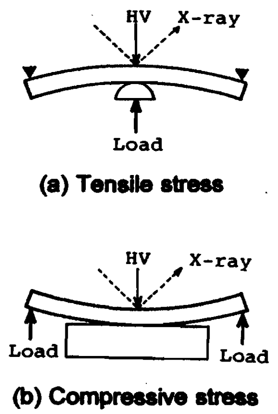


Fig.15 Bending strain, hardness and stress measurements

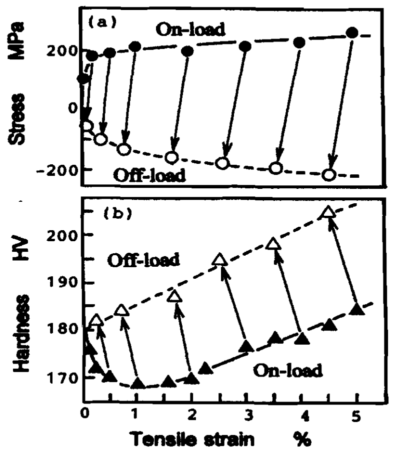


Fig.16 Influence of strain on hardness and residual stress

4.5.2 Influence of compressive stress

Compressive stresses were induced on the concave surface as shown in Fig. 17(b), and the influences of the compressive strain on the stress and on the hardness are shown in Fig. 18. Compressive stresses during on-load increase remarkably in the low compressive strain and approaches a saturated value -260 MPa over 2 % compressive strain. The stresses after off-load turn to the tensile and the saturated value is about 200 MPa. The difference of stresses during on-load and after off-load increases with the increase of the compressive strain, and when the strain is over about 3 %, the difference of their stresses reaches a saturated values about 460 MPa.

During on-load, the hardness is increased by the compressive strain as shown in Fig. 17(b). The hardness after off-load decreases and the work-hardening appears in proportion to the compressive strain. The difference between the hardness during on-load and after off-load increases with the increase of the compressive strain and approaches a saturated value 13 HV.

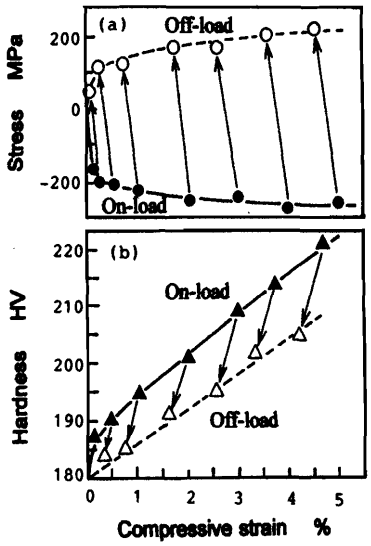


Fig.17 Influence of compressive strain on stress and hardness

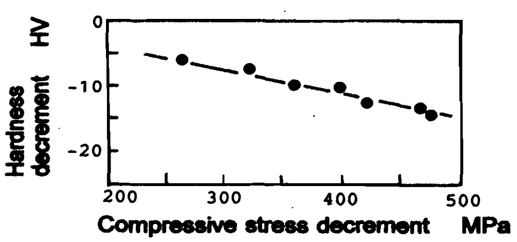


Fig.18 Relation between stress and hardness decrements

The influence of compressive stress on the hardness is shown in Fig. 18. The hardness increases with the compressive stress in the elastic strain and increases rapidly after the compressive stress is over 150 MPa,. The influence of compressive stress on the hardness number is about 2 % in the elastic stress field. The relation between the compressive stress decrement and the hardness decrement is shown in Fig. 16. When the difference between compressive stresses and the tensile stresses is 460 MPa, the difference of the hardness become about 13 HV. These influence of compressive stresses on the hardness values in this bending are very similar to the case of shot peening.

5. Transformation of crystal

Figure 19 shows the X-ray diffraction patterns on as-annealed, grit blasted and shot peened. The peak neighbored on 149 degree shows that the structure of the annealed material is clearly austenite. After blasting, the height of the peak decreases and another peak arises neighbored on 156 degree, which is the peak of (211) plain of alpha-Fe. This result suggests that strain-induced transformation happened due to blasting. Figure 20 shows the austenite volume distribution changed by shot peening, and also the volume in the affected layer decrease owing to the strain-induced transformation.

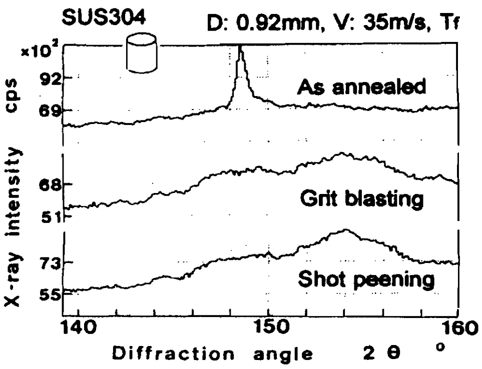


Fig. 19 X-ray diffraction patterns

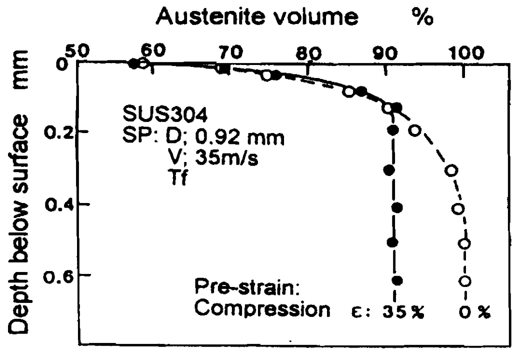


Fig.20 Austenite volume distributions after shot peening

5. Fatigue strength of shot peened material

The important factors closely relating to the fatigue strength are residual stresses, work hardening or forging effect and surface roughness. Figure 21 shows the effect of thickness of specimen and peening effect for 3 different thickness of specimen. The fatigue strengths increases while the thickness decreases with the exception of one result.

Figure 22 shows the influence of affected-layer ratio (ratio of the depth of work-hardened layer to the thickness of material) on the increase of fatigue strength. The sweet zone is from 0.3 to 0.4 of the ratio.

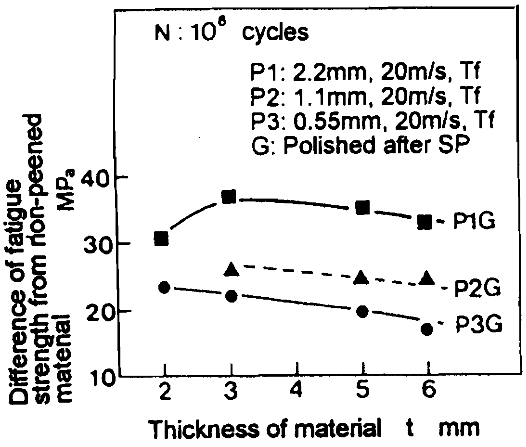


Fig. 21 Influence of thickness of specimen on fatigue strength

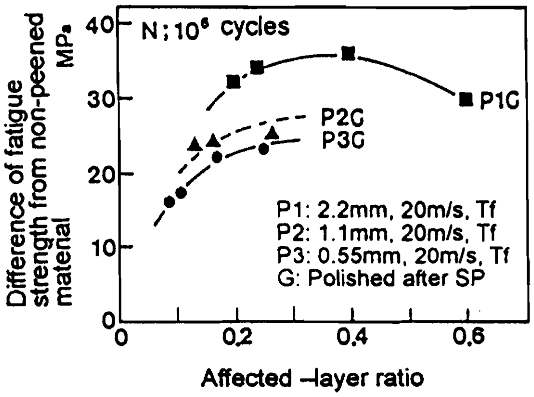


Fig.22 Influence of affected-layer ratio on fatigue strength

CONCLUSIONS

(1) Hardness distributions are divided into three types, which are work hadening type, non-hardening type and work softening type.
(2) Residual stress distributions are divided into two pypes, which are S-type and C-type.
(3) As residual stress induced by the resistance of non affected layer, residual stress on the peened surface shows size effect of the thickness of work material.
(4) The ratio of the depth of workhadened layer to critical thickness is about 5.Critical thickness of shot peening is about 50% thicker than that of grit blasting.
(5) Strain-induced transformation happens with shot peening.
(6) The optimum affected-layer ratio (ratio of the depth of work-hardened layer to the thickness of material), which is called "sweet zone", is from 0.3 to 0.4.

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