FATIGUE STRENGTH AND RESIDUAL STRESS DISTRIBUTION OF THE WORK-SOFTENED STEEL BY SHOT PEENING

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ABSTRACT

Work-softening and work-nonhardening phenomena generally happen under combined cold deformation, and these phenomena also appear under shot peening. This paper describes on the results of the relation between the residual stress distribution and fatigue strength of work-hardened, work-softened and work-nonhardened steels produced by shot peening. Shot peening was performed for carbon steel (0.45%C) with steel shot and a centrifugal blasting machine. Test specimen was rolled as prestrain before shot peening for work-softening and work-nonhardening on the hardness distributions, and ratio of rolling reduction estimated 10 % and 20 %. Obtained factors are hardness distribution, half width, residual stress distribution and S-N curves. Residual stress distribution was measured by window method with X-ray diffraction. The depth of work-softened layer is similar to the depth of work-hardened one. Half width decreased in the work-softened layer and then this suggests the recover of the prestrain by shot peening. The fatigue strength of work-softened specimens increased 53 % and 44 % compared with to prestrained and annealed respectively, and of the specimens which disclosed at surface the maximum work-softened zone by etching were also increased 20 % and 13 % respectively. Generally, the more the surface residual stress, the more the fatigue strength under the same shot peening condition.

KEYWORDS

Shot peening, work-hardening, work-nonhardening, work-softening, half width, residual stress, stress distribution, hardness distribution, fatigue strength.

INTRODUCTION

Work-softening is produced by combined cold working [1][2]. The hardness distribution in the affected layer by shot peening also shows work-softening [3]. The relation between the hardness distribution and the fatigue strength already reported in the previous conference, wherein fatigue strength of the material involved the work-softened layer produced by shot peening has increased. Generally, in work-softening zone not only the hardness distribution, but also half width and residual stress distributions are different from work-hardening zone.

This paper described experimental study on the distribution of residual stress and fatigue strength of work-hardened, work-nonhardened and work-softened materials. Work materials are carbon steels (0.45 %C) annealed and prestrained by rolling. Shot peening is performed on these materials and the distributions of hardness, half width and residual stress were measured. Fatigue tests were run in order to clear the influence of distribution of residual stress.

EXPERIMENTAL CONDITIONS AND PROCEDURE

Experimental conditions are shown on shot peening, specimen, prestrain, fatigue test, residual stress measurement and chemical etching in Table 1. Nomenclature and combined working conditions used in this experiment are shown in Table 2. In order to expose the work-softening and work-nonhardening zones on the surface, the thicknesses of specimen R1P2E and R2P2E were prestrained at the thickness 4.6 mm, after etching these became 4.0 mm. R1P2G and R2P2G were prestrained in order to clear the influence of surface roughness on the fatigue strength of work-softened and work-nonhardened materials, and these thicknesses were 4.06 mm, after polishing these became 4.0 mm.

Table 1 Experimental conditions

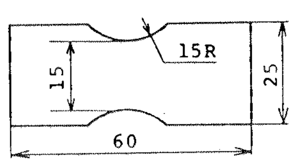
Shot peening	Equipment: centrifugal type Shot: cast steel (HV 800), Shot size mm: 1.1, 2.2, Shot velocity m/s: 20, 35 Peening time: Tf (full coverage time)
Specimen	Material: annealed carbon steel (0.45 %C), HV 180
	 Thickness: 4 mm
Prestrain	Rolling reduction ε % : 10, 20
Fatigue test	Alternate bending cpm: 2000
Residual stress measurement	X-ray Diffraction: (211)plane, Iso-inclination method 2θ - $\sin^2\psi$ method, ψ deg: 0, 30, 45, 60 Target: Cr, Tube voltage: 30 kV, Tube current: 35 mA Window: 5 mm x 5 mm
Chemical etching	HNO_3 30% solution

Table 2 Nomenclature and combined working conditions

Nomenclature	Specimen
O	Annealed
P1	Shot peened, shot size: 1.1 mm, velocity: 20 m/s, Tf
P2	Shot peened, shot size: 2.2 mm, velocity: 20 m/s, Tf
P3	Shot peened, shot size: 2.2 mm, velocity: 35 m/s, Tf
R1	Rolled: reduction ε = 10 %
R2	Rolled: reduction ε = 20 %
R1P2	P2 shot peening after R1 rolling
R1P2G	Polished after R1P2
R1P2E	0.3 mm chemically etched after R1P2
R2P2	P2 shot peening after R2 rolling
R2P2G	Polished after R2P2
R2P2E	0.3 mm chemically etched after R2P2

Hardness distribution was obtained from perpendicular section to peened surface with vickers hardness tester, and averaged from the same depth data on three positions.

Residual stress distribution was measured with small window method on the specimens worked by shot peening and rolling. The area of window is 5mm × 5 mm. Residual stress was 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, ν : 0.28, θ_0 : standard Brag angle, 2θ : diffracted angle, ψ: inlet angle of X-ray.

EXPERIMENTAL RESULTS

Hardness Distribution

Materials prestrained 0, 10 and 20 %, and shot peened involve three patterns of hardness distribution; work-hardening, work-nonhardening and work-softening, as shown in Fig.1. Hardness distribution of annealed specimen shows work-hardening. The maximum work-hardening ratio is 47 % and the maximum depth of work-hardened layer is 1 mm (P3). The hardness distribution of shot peened specimen after 10 % prestrained R1P2 shows work-nonhardening and the depth of work hardened layer is 0.3 mm shallower 50 % than the annealed specimen. The hardness distribution of shot peened after 20 % prestrained R2P2 shows work-softening. The maximum work-softening ratio is 8 % and the maximum depth of work softened layer R2P3 is 1 mm.

As shown in Fig.2, the surface layer of specimens were etched chemically 0.3 mm, but the hardness distributions is the same as before. After etching the surface hardness of R1P2E became the same as matrix and the maximum work-softened zone of R2P2E was exposed on the surface. The hardness distribution of specimens R1P2G and R2P2G polished after shot peening were the same as those of before polishing.

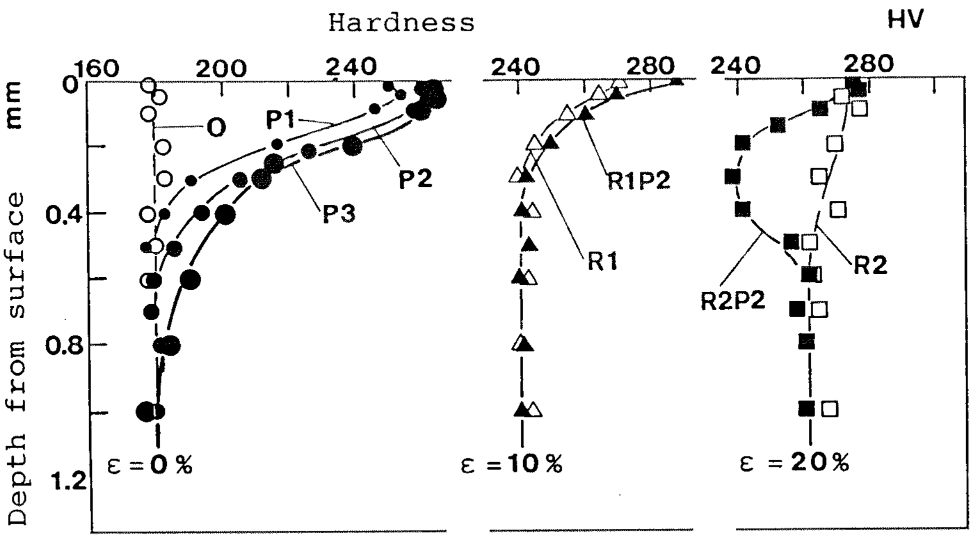


Fig.1 Hardness distributions produced by rolling and shot peening.

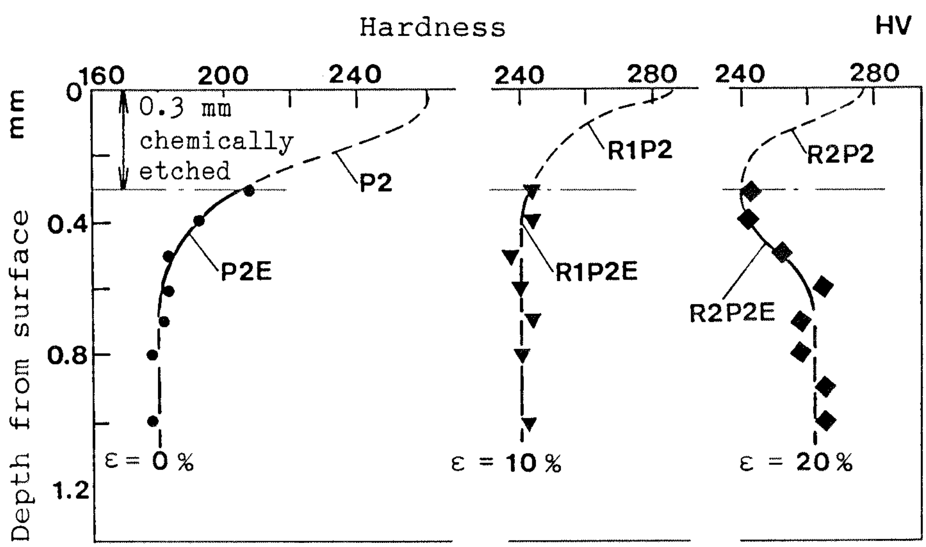


Fig.2 Hardness distributions after etching from peened surface.

Half Width distribution

The change of half width means the change of micro crystal deformation, therefore, half width distribution is similar to the hardness distribution as shown in Fig.3. The half width decreases at the work-softened zone, then this suggests that the work-softening means the decrease of plastic strain induced by rolling. Half width distribution also doesn't change with chemical etching as shown in Fig.4.

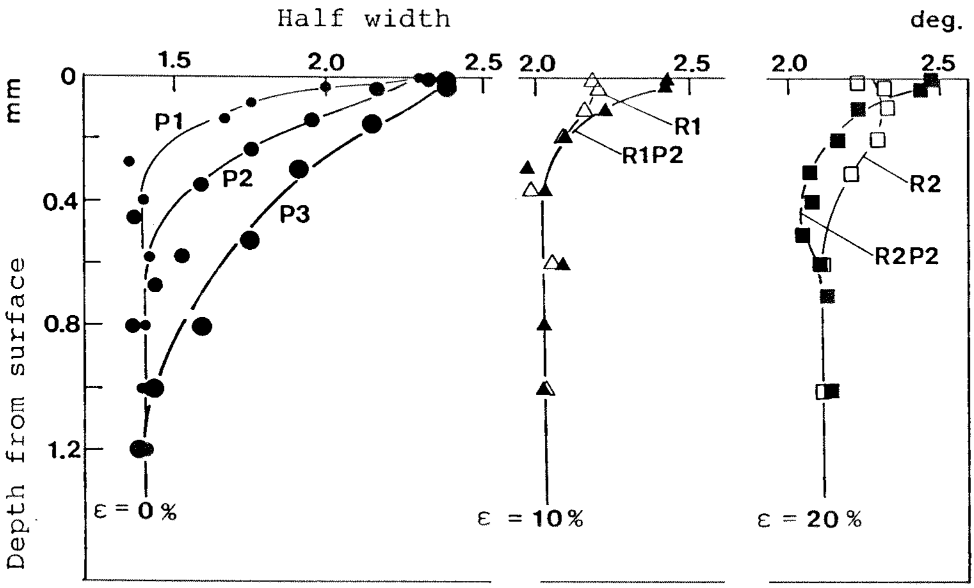


Fig.3 Half width distributions produced by rolling and shot peening.

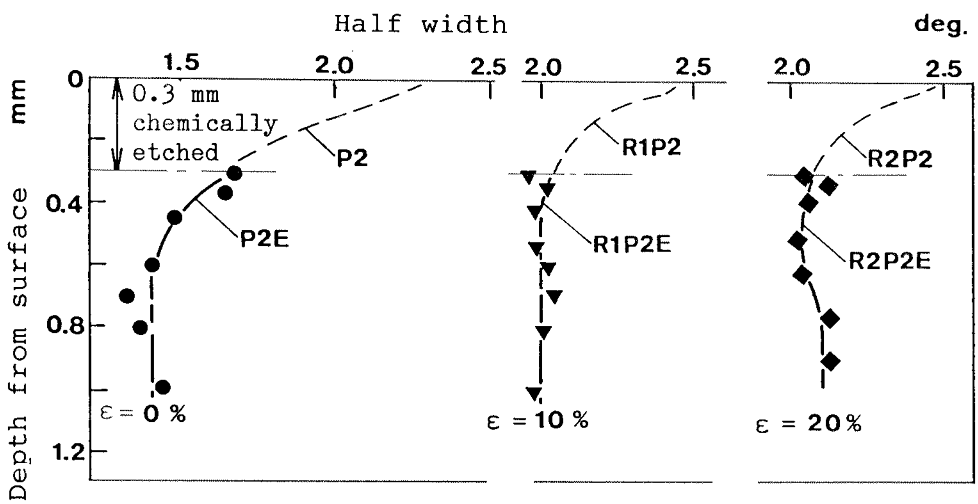


Fig.4 Half width distributions after etching from peened surface.

Residual Stress Distribution

There are two types, (C type and S type), in the residual stress distribution induced by shot peening. Fig.5 shows the residual stress distributions induced by shot peening for the annealed and prestrained specimens and the distribution of the annealed shows two types, i.e. P1,P2 and P3 correspond C and S type respectively. The surface residual stress increases with the decrease of the kinetic energy of a shot. The residual stress distributions on the shot peened specimen after prestrained are similar with each other.

As shown in Fig.6, after etching 0.3 mm, the distributions of shot peened specimens don't change before etching. Generally, though high surface residual stress is removed by etching, the residual stress distribution didn't change with etching and also in the case of polishing the distribution of R2P2G was the same as R2P2.

Fatigue Test

Results of the fatigue tests are shown in Fig.7 and Fig.8 on annealed,(O), on rolled (R1, R2), on shot peened (P2, R1P2, R2P2), on etched (R1P2E, R2P2E) and on polished (R1P2G, R2P2G).

The peening effect on the fatigue strength are clear for not only the work-hardened specimen but also the work-nonhardened and the work-softened specimens as shown in Fig.8. The fatigue strength of R1P2E smaller than R1P2 but larger than rolled and annealed. The maximum fatigue strength is obtained from R2P2G and the maximum increasing ratio is 52 % and 43 % compared with annealed and the prestrained respectively. The increasing ratio of R2P2E is 20 % and 13 % compared with them.

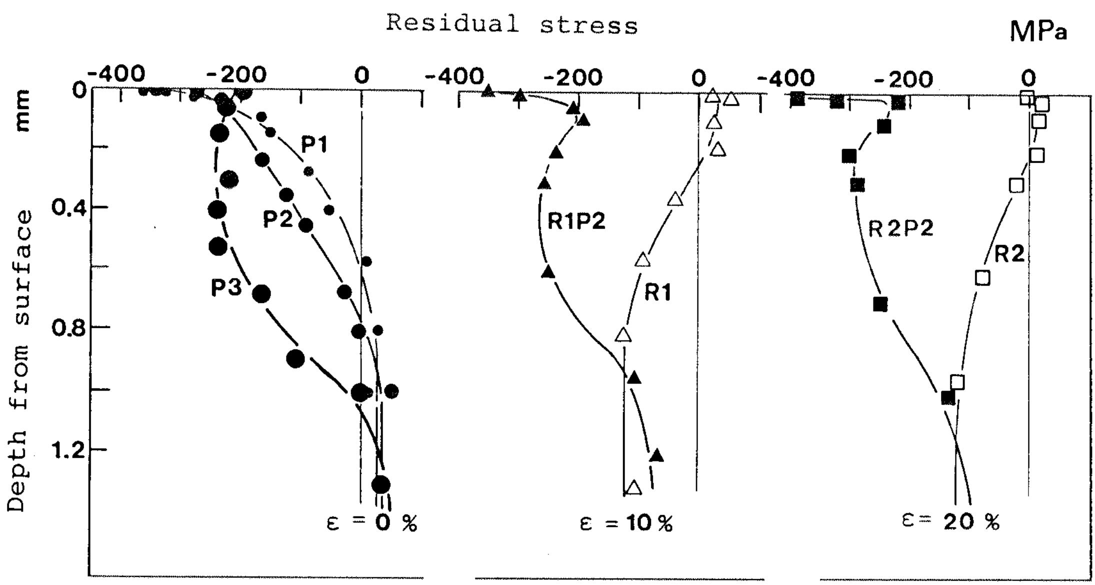


Fig.5 Residual stress distributions induced by rolling and shot peening.

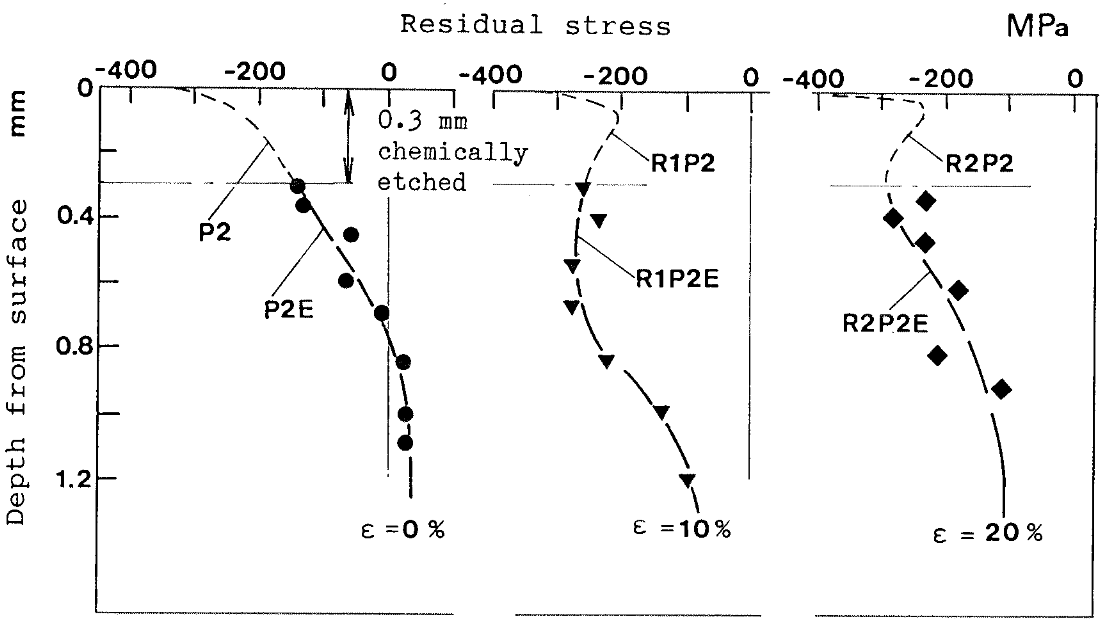


Fig.6 Residual stress distributions after etching from peened surface.

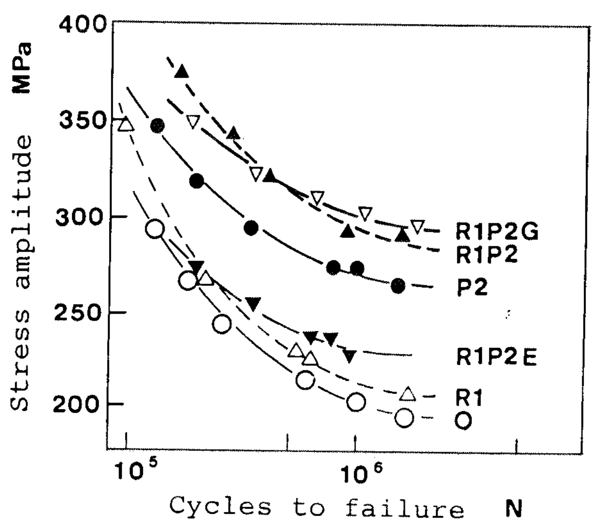


Fig.7 S-N curves for work-nonhardening type. (prestrain: 10 %)

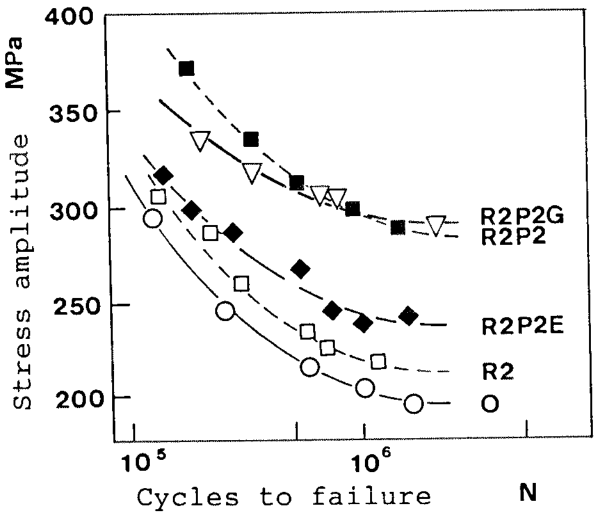


Fig.8 S-N curves for work-softening type.
(prestrain: 20 %)

The relations between the maximum hardness in hardness distribution and fatigue strength are shown in Fig.9, the results of rolled specimen are dislocated from a line. On the same way, the relations between the surface residual stress and the fatigue strength are shown in Fig.10. The more the compressive surface residual stress, the more the fatigue strength. On the other hand, as shown in Fig.11, the difference of fatigue strength under the same prestrain between only prestrained and after shot peened (R2P2G vs R2) increases with the kinetic energy of a shot. As mentioned above, The increase of the kinetic energy of a shot increases the compressive stress into deep zone but decreases the surface residual stress.

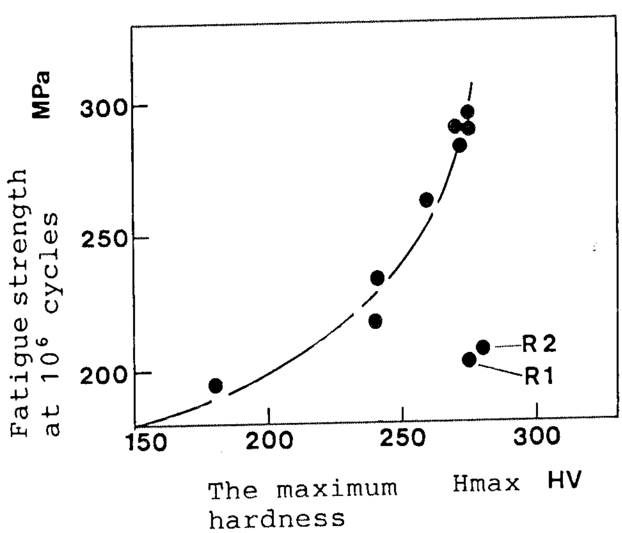


Fig.9 The maximum hardness in the affected layer versus fatigue strength at 10^6 cycles.

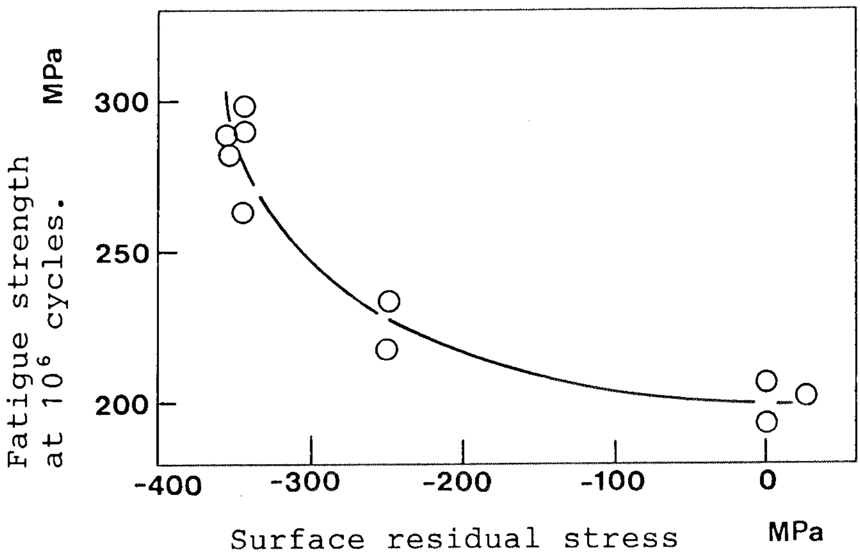


Fig.10 Residual stress on the shot peened surface versus fatigue strength at 10^6 cycles.

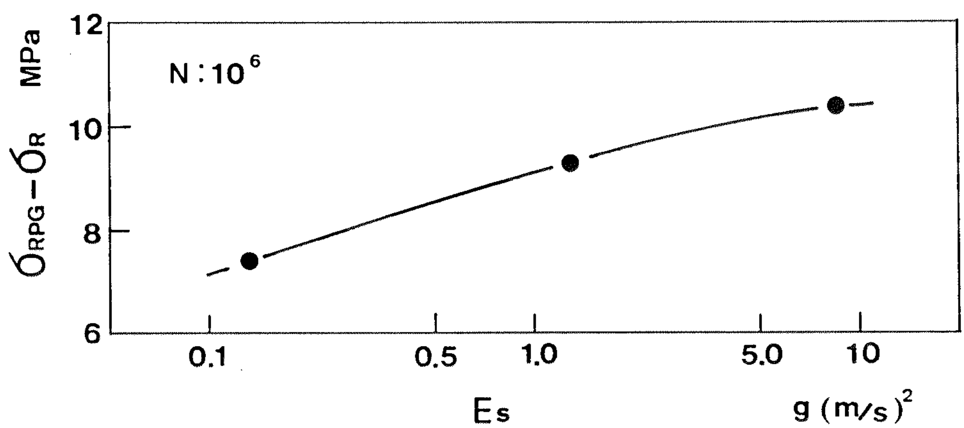


Fig.11 Influence of kinetic energy of a shot on fatigue strength between shot peened after prestrained specimens and only prestrained.

The relations between the residual stress in the work-softened zone and the fatigue strength are shown in Fig.12. The more the compressive residual stress, the more the fatigue strength. Therefore, the fatigue strength of the peened specimen is closely connected with the surface residual stress, the residual stress distribution and the surface hardness.

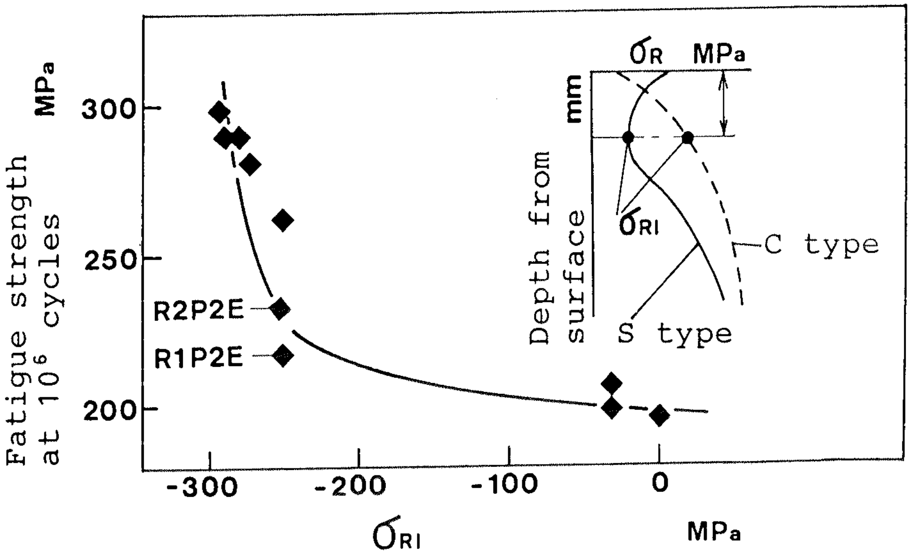


Fig.12 Residual stress under the surface versus fatigue strength at 10^6 cycles

CONCLUSIONS

1)The half width distribution is similar with the hardness distribution in the work-softened zone.
2)Residual stress induced by shot peening onto the prestrained steel is larger than that onto the annealed.
3)The more the kinetic energy of a shot, the more the fatigue strength.
4)The maximum increasing ratio of fatigue strength of the work-softened material produced by shot peening was 52 % compared with the annealed and 43 % with the prestrained in this experiment.
5)The increasing ratio of fatigue strength of the specimen which exposed the maximum work-softened zone on the surface by chemical etching after shot peening was 20 % and 13 % compared with the annealed and the prestrained steels respectively in this experiment.

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