Dent and Affected Layer Produced by Shot Peening

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ABSTRACT

This paper presents several basic factors for shot peening. Shot peening consists of making of a dent, and the dent is formed by the impact of a steel ball. Laws of the dent formation as to the diameter and depth and volume for outside dent and inside dent which is yield zone of steel are obtained on the function of velocity and diameter of steel ball and hardness of material to be peened. Yield zone produced by shot peening makes affected layer which involves residual stress, change of hardness, and so on. The characteristics of formation of yield layer produced by shot peening are described. The hardness distribution in affected layer shows work hardening and work softening, then the distinction of both cases was cleared. Work softening phenomenon happens in cold workings of prestrained metals under certain combined strain. Residual stress in peened surface shows the size effect for thickness of specimen and decreases within the critical thickness related to peening conditions, and then, there is no residual stress in only affected layer made by etching from non-peened surface.

KEYWORDS

Dent; shot peening; yield zone; affected layer; work hardening; work softening; residual stress; size effect.

INTRODUCTION

Shot peening is a process by throwing many small hard balls at machine parts and producing many dents on them. A dent made by static pressure with various indenters had been researched as hardness, but by impact may be nothing. Then several experiments are carried out to obtain the data related the diameter and the depth of the dent with various conditions of impact on to diverse hardness steels. The dent is a result of plastic deformation accompanying with yield zone.

FORMATION OF DENT

It is interesting to compare the static and the impacted dent under various conditions. The static dent is produced by static compressive force as hardness test with diverse steel balls, and the impacted dent is produced to fall under gravity on to specimen. Experimental result as to relations of diameter of dent d and ball D, is shown in Fig.1 by parameters of the falling height H and static force P. Fig.1 shows the proportional relation between d and D to various falling heights. Steel ball at H impinges on target at a velocity v , and v is proportional to $H^{1/2}$. From the result of Fig.1 static force P is connected with D and v by the diameter of dent d as follows.

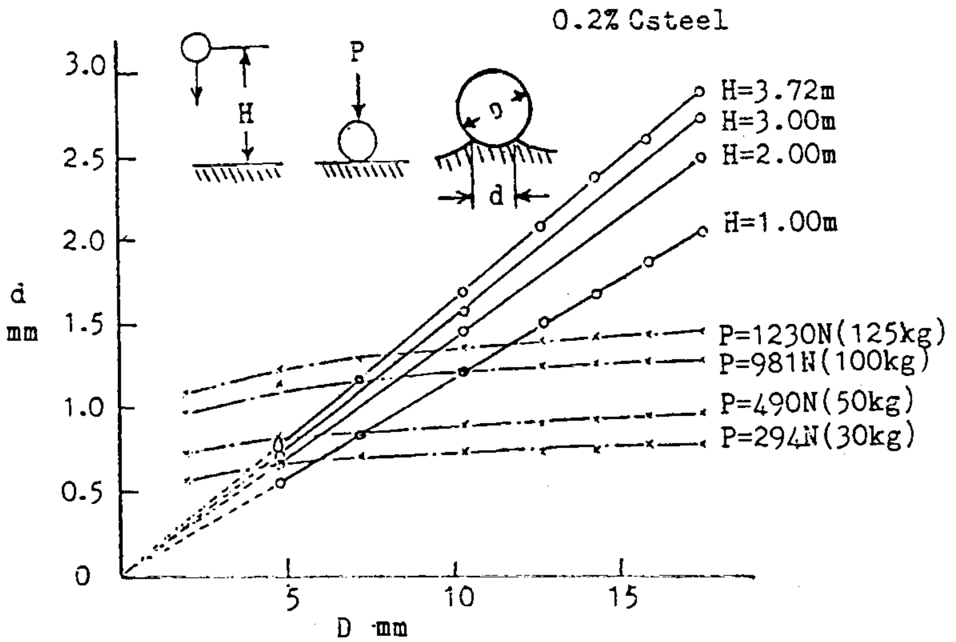


Fig.1. Comparison of the dent produced by static pressure to the dent by impact dropped from various heights.

$$P = Kp \cdot D^{1.97} \cdot v^{1.10}$$

where Kp is constant for material. Over wide range experimental conditions, $(d/D)^2$ is proportional to velocity of steel ball as shown in Fig.2. This implies following formula.

$$d = Kd \cdot D \cdot v^{1/2}$$

where Kd is constant for hardness of material. Similarly, depth h of dent leaved in flat steel specimen is proportional to velocity v and diameter D of steel ball as shown in Fig.3. So that the formula of depth h is

$$h = Kh \cdot D \cdot v \ .$$

Where Kh is constant for hardness of material. Consequently from the formula of d and h, volume V of dent is

$$V = Kv \cdot D^3 \cdot v^2$$

$$= Kv' \cdot m \cdot v^2.$$

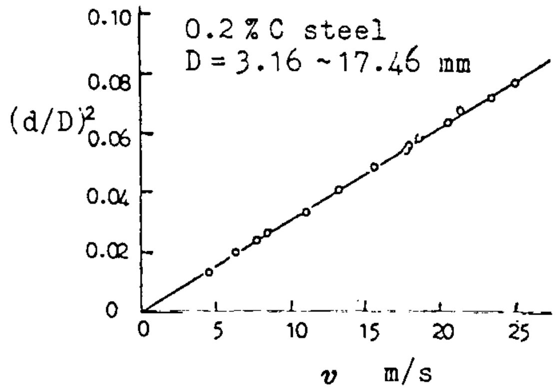


Fig.2. Relation between $(d/D)^2$ and velocity of steel ball.

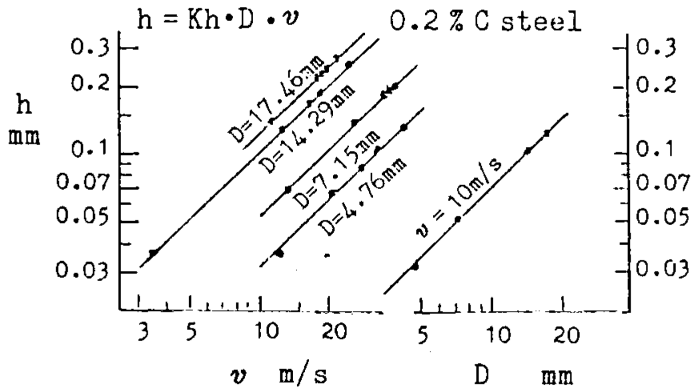


Fig.3. Depth of dent produced by impact.

Where Kv and Kv' are constants for hardness of material and m is mass of steel ball. From furthermore wide experiments such Vickers hardness of specimen as 100 ~ 400, values of Kd and Kh are obtained. Kd^2 and Kh are proportional to Vickers hardness of specimen as shown in fig.4, so that formulas of d, h and V may be widely available for shallow dents produced by hard balls as shot peening. The diameter of dent is a factor of area coverage and the depth of dent is a factor of surface roughness for shot peening. The effect of impact angle is that diameter and depth of dent produced by various impact angles are the same as produced by normal component of velocity on to the surface. Then the effective velocity of impact is $v \cos\alpha$, where α is the impact angle as shown in Fig.5. Fig.5 shows crosssections of dents produced by various impact angles and all sectional figures are almost symmetric, so that the increase of impact angle means the decrease of velocity of a steel ball. Thus, formulas described above are as follows

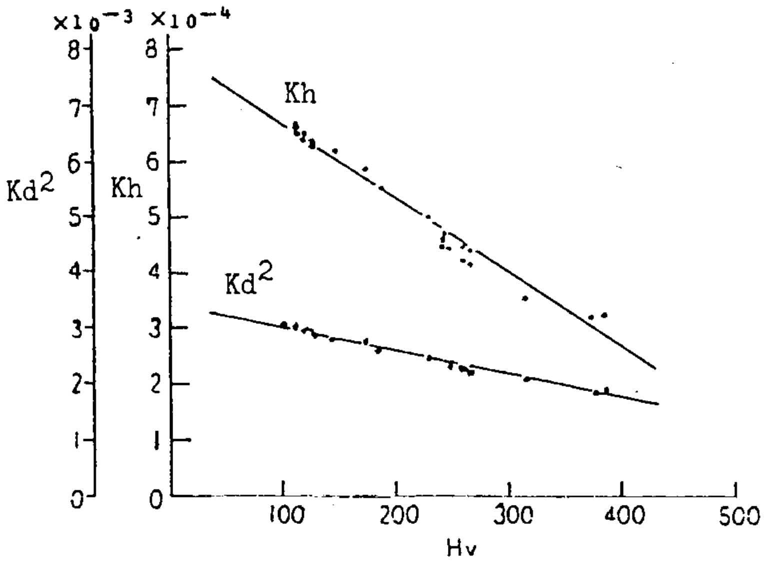


Fig.4. Relations between Kd^2, Kh and Vickers hardness of specimen.

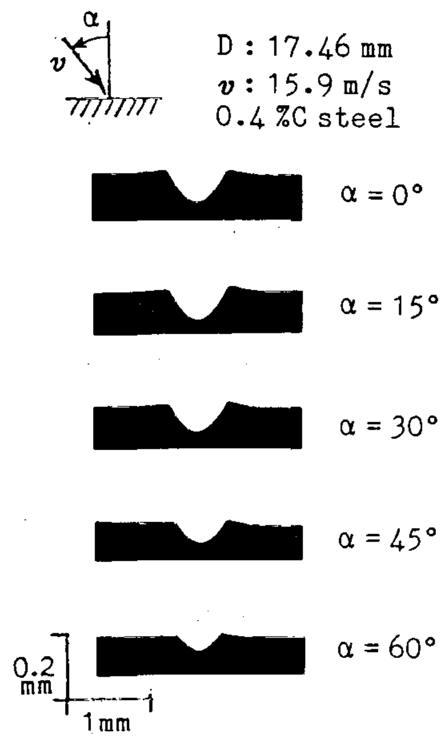


Fig.5. Effect of impact angle.

$$d = Kd \cdot D \cdot (v \cos\alpha)^{1/2}$$
$$h = Kh \cdot D \cdot v \cos\alpha$$
$$V = Kv \cdot D \cdot (v \cos\alpha)^2$$

or

$$= Kv' \cdot m \cdot (v \cos\alpha)^2 .$$

MATHEMATICAL APPROACH

Impinging a sphere on to the flat surface which is in the form of a massive anvil, the sphere makes a dent in the surface and rebounds. This impact may be devided mathematically into two types, such as entirely elastic and ideally plastic. Assuming several factors as elastic deformation, i.e. the mechanism involved in the dynamic dent is essentially the same as that which occurs under static conditions, and Young's moduli for sphere and elastic body are essentially the same as for static conditions. According to Hertz's equation

$$\lambda = \left\{ \frac{9}{8} \frac{P^2}{D} \left(\frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2} \right)^2 \right\}^{1/3}$$

where λ is the depth of contact, P is the force, as shown in Fig.6, E_1, E_2 are Young's moduli of sphere and elastic body respectively, ν_1 , ν_2 are corresponding Poisson's ratio.

Hence
$$P = 0.943 \left(\frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2} \right)^{-1} D^{1/2} \lambda^{3/2}.$$

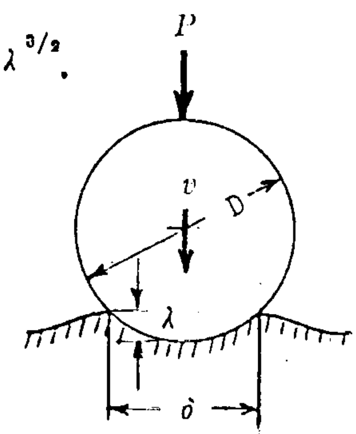


Fig.6. Elastic impact.

The equation of motion of the sphere is

$$m \frac{d^2\lambda}{dt^2} = -P$$

then

$$\int_v^0 m v\,dv = -\int_0^\lambda 0.943 \left(\frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2} \right)^{-1} D^{1/2} \lambda^{3/2} d\lambda$$

therefore

$$P = 0.757\ (\rho)^{3/5} \left(\frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2} \right)^{-2/5} D^2 v^{6/5}$$

and

$$\lambda = 0.864 \left\{ \rho \left(\frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2} \right) \right\}^{2/5} D v^{4/5}$$

where ρ is density of sphere, and from $\left(\frac{\delta}{2}\right)^2 \doteqdot \lambda \cdot D$, δ is the diameter of contacted circle

then

$$\delta = 1.728 \left\{ \rho \left(\frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2} \right) \right\}^{1/5} D v^{2/5}.$$

The volume V of dent of elastic deformation is

$$V = \frac{\pi}{6}\lambda\left(\frac{3}{4}\delta^2+\lambda^2\right)$$

$$\fallingdotseq \frac{\pi}{8}\delta^2\lambda$$

$$= 1.013\left\{\rho\left(\frac{1-\nu_1^2}{E_1}+\frac{1-\nu_2^2}{E_2}\right)\right\}^{4/5} D^3 v^{8/5}$$

$$= 1.935\left(\frac{1-\nu_1^2}{E_1}+\frac{1-\nu_2^2}{E_2}\right)^{4/5}\rho^{-1/5} m v^{8/5}$$

When rigid sphere impinges the massive ideally plastic body, plastic deformation is formed as shown in Fig.7. The resistance of deformation on area of annulus lying on the curved surface of dent equilibrates the impact force on it, i.e.

$$dp=\pi/2\cdot D^2\sin\theta\,(\sigma\cos\theta+\mu\sigma\sin\theta)\,d\theta .$$

Hence

$$P=\int_0^{\phi}\pi/2\cdot D^2\sigma\sin\theta\,(\cos\theta+\mu\sin\theta)\,d\theta$$

$$=\pi/2\cdot D^2\sigma\,\left(1/2\cdot\sin^2\phi\;+\mu/2\,(\phi-\sin\phi\cos\phi)\right)$$

$$=\frac{\pi}{4}\sigma d\left[d+\mu\left\{\frac{D^2\phi}{d}-(D-h)\right\}\right]$$

$$=\frac{\pi}{4}\sigma d^2\left\{1+\mu\frac{d}{4D}\right\}.$$

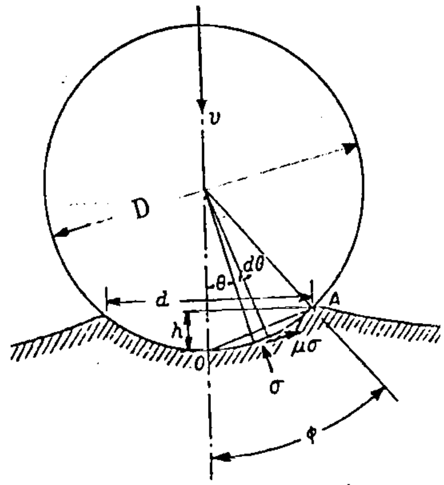


Fig.7. Plastic impact.

where μ is the coefficient of friction between sphere and plastic body, σ is deformation resistance per unit area, P is impact force. Equation of motion of sphere is

$$m\frac{dv}{dt}=-P .$$

Hence

$$mv^2=2\int_0^d\frac{\pi}{4}\sigma d^2\left\{1+\mu\frac{d}{4D}\right\}\frac{d}{2D}dd$$

$$=\frac{\pi\sigma}{16D}d^4\left(1+\mu\frac{d}{5D}\right)$$

$$=2\sigma V\left(1+\frac{\mu d}{5D}\right).$$

From several experiments it is found that volume of the dent produced by steel balls for 0.2 %C steel is proportional to the kinetic energy of a ball as shown in Fig.8, therefore the second term in the above formula is negligible in practice.

Hence

$$\mu\approx 0 .$$

Then, results are as follows.

$$P = \pi \left(\frac{\rho\sigma}{6}\right)^{1/2} D^2 v$$

$$d = 2\left(\frac{\rho}{6\sigma}\right)^{1/4} D v^{1/2}$$

$$h = \left(\frac{\rho}{6\sigma}\right)^{1/2} D v$$

$$V = \frac{\pi}{8} d^2 h$$

$$= \frac{\pi\rho}{12\sigma} D^3 v^2$$

$$= \frac{1}{2}\sigma^{-1} m v^2$$

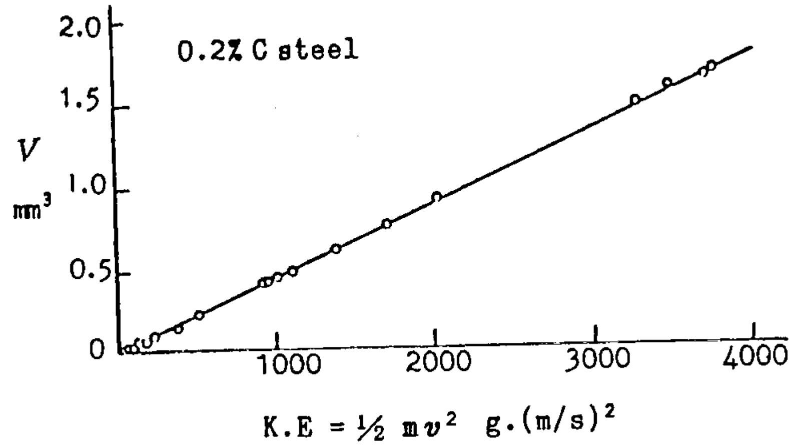


Fig.8. Relation between volume of a dent and kinetic energy of a steel ball.

Formulas of impact obtained from experimental results and mathematical are very similar to each other as to the exponents of D and v as shown in Table 1. These are available for fundamentals of the impact by hard steel balls.

impact		exponent							
		force (P)		dent					
				diameter(d)		depth (h)		volume (V)	
		D*	v**	D	v	D	v	D	v
mathematical result	elastic	2	1.2	1	0.4	1	0.8	3	1.6
	plastic	2	1.0	1	0.5	1	1	3	2
experimental result		1.97	1.10	1	0.5	1	1	3	2

* ball diameter, ** impact velocity

Tab.1. Comparison of exponents obtained from experiment to mathematical analysis.

YIELD ZONE UNDER DENT

Producing a dent by impact of a hard ball on to the steel, the zone under the dent may be affected by plastic flow on it. If steel specimen is stressed beyond yield stress, we can detect the yield zone in the specimen by using Fry's reagent. The yield zone detected under a dent produced in 0.2 %C steel is shown in Fig.9. Yield zone has about eighty times the volume of dent. The yield zone of repeated impact on the dent is shown in Fig.10. Repeating impact does not so increase the volume, but slightly increases it.

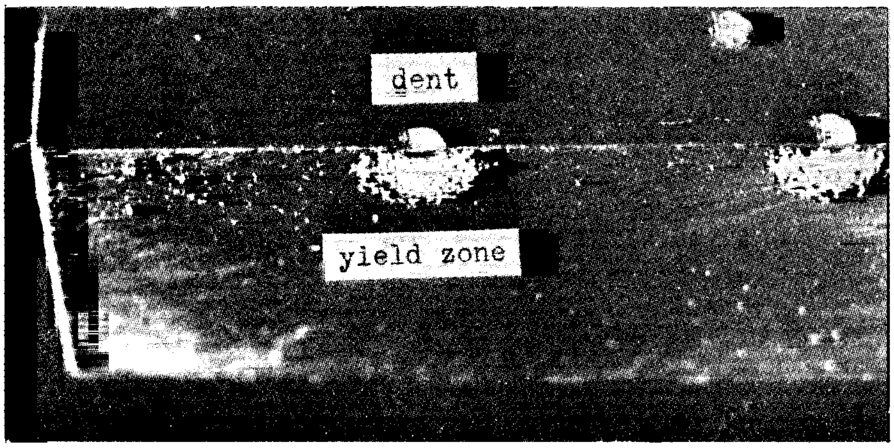
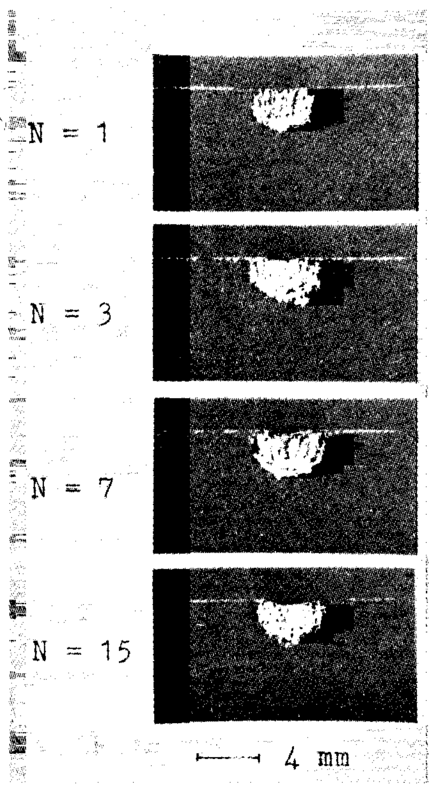


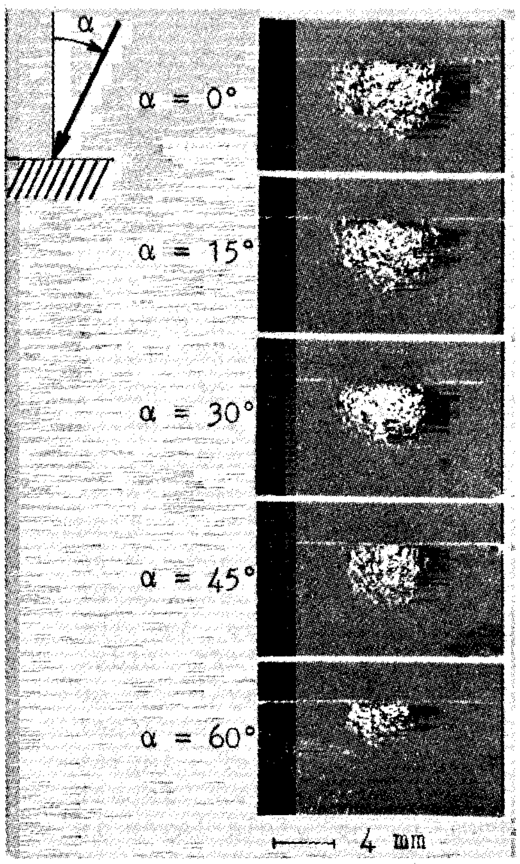
Fig.9. Bird's eye view of a crosssection of two dents and yield zones.

The effect of impact angle was already described as to the dent. The volume of dent and yield zone is proportional. Fig.11 shows the yield zone impinged by various angles. Yield zone is symmetric and decreases with increase of impact angle as dent. Values of yield zone obtained from experiments for depth h' and width w' shown in Fig.12 and volume V' induce following formulas



N:numbers of repeat
D:7.15mm, v:29.2m/s, 0.2 %C steel

Fig.10. Yield zone of repeated impact.



D:17.46mm, v:15.9m/s, 0.2 %C steel

Fig.11. Yield zone impinged by various angles.

$$h' = K_1 \cdot D \cdot (v \cos\alpha)^{2/3} \cdot N^{1/40}$$

$$w' = K_2 \cdot D \cdot (v \cos\alpha)^{2/3} \cdot N^{1/20}$$

$$V' = K_3 \cdot D^3 \cdot (v \cos\alpha)^2 \cdot N^{3/40}.$$

Where N is the number of repeat and K_1, K_2, K_3 are constant for material. Yield zone becomes affected layer for shot peening.

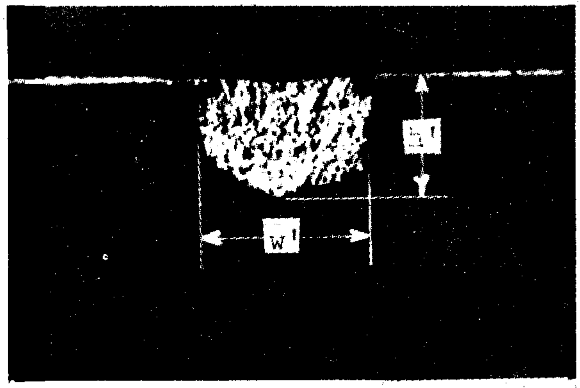
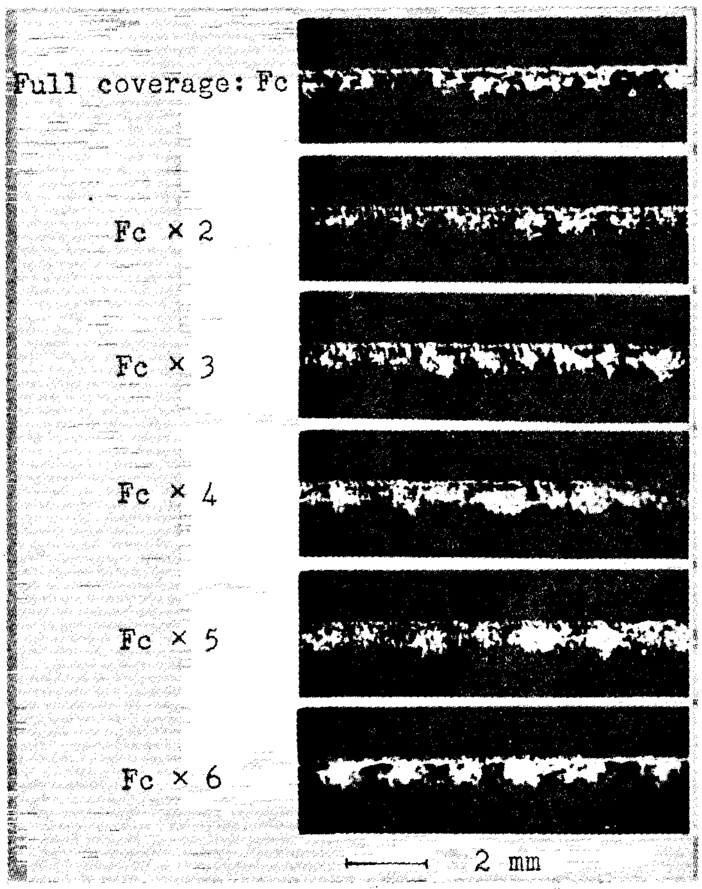


Fig.12. Dimension of yield zone.

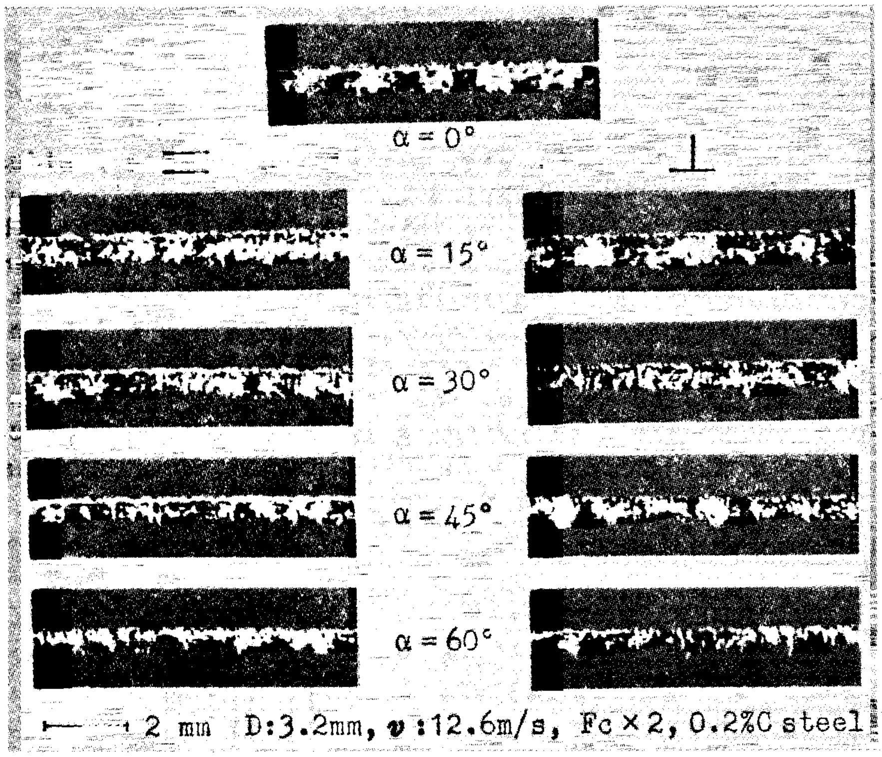
YIELD ZONE PRODUCED BY SHOT PEENING

It is evident that the yield layer produced by shot peening, as shown in Fig.13, will not depend essentially on exposure time of shot, but on diameter and velocity of shot, and consists of discontinuous yield zone. The effect of angle is also shown in Fig.14, and it is clear that the yield layer of the right side is the same as the left side. Therefore yield layer is no directional, and decreases with increase of impact angle. Effective impact velocity for yield layer is normal component similar to dent and yield zone.



D:3.2mm, v:12.6m/s, 0.2%C steel

Fig.13. Yield layer produced by shot peening.



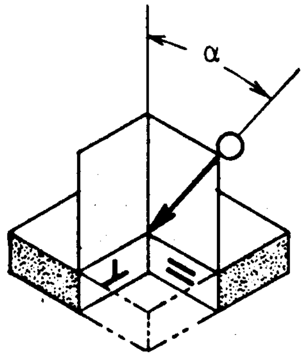
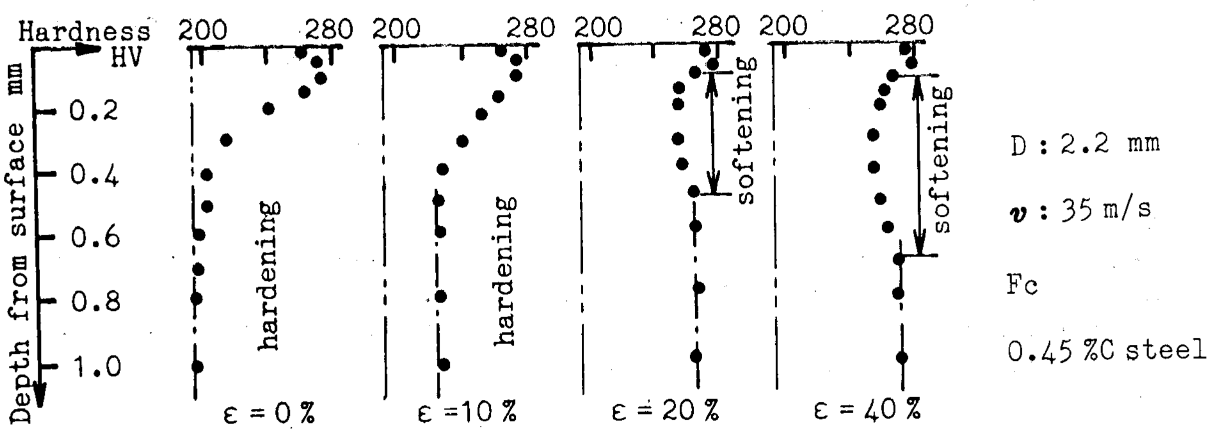


Fig.14. Yield layer produced by shot peening with various angles.

WORK HARDENING AND WORK SOFTENING UNDER PEENED SURFACE

Several experiments were run to obtain distributions of hardness from peened surface into inside of specimen which was annealed, cold rolled, compressed, elongated, etc. It is of interest to note that according to experiments, the distribution of hardness of affected layer produced by shot peening is divided into three types. The first type shows work hardening for annealed or a little prestrained metals, the second type shows work non-hardening for medium prestrained metals and the final type shows work softening for much prestrained metals. Typical results are shown in Fig.15. These prestrain must be cold working and amount of work softening depends on ratio of strain. The phenomenon of work softening happens not only in shot peening but also in general cold working process. Work softening does not weaken such mechanical properties as tensile strength or fatigue limit.



ε : compressive strain before shot peening

Fig.15. Hardness distribution produced by shot peening.

RESIDUAL STRESS

It is clear from experiments as shown in Fig.16 that the surface residual stress produced by shot peening is not so varied by peening conditions such as shot size, velocity or peening time, but by thickness of specimen to be peened. The surface residual stress decreases steeply for thin specimen. The thickness at breaking point Tc as shown in Fig.16 is varied by kinetic energy of a shot and the more the energy increases, the more the thickness. Then there is the size effect of the thickness of specimen for residual stress produced by shot peening. The critical thickness Tc is proportional to the depth of yield zone under the dent. Etching from non-peened surface, the residual stress of peened surface decreases with increasing thickness of etching and goes to zero at the thickness f as shown in Fig.17.

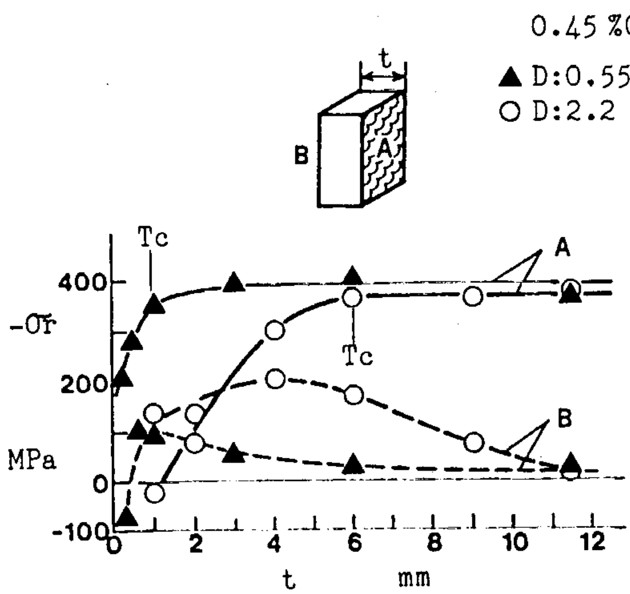


Fig.16. Size effect of surface residual stress σ_r for the thickness of specimen t. Tc : critical thickness, A : peened, B : non-peened.

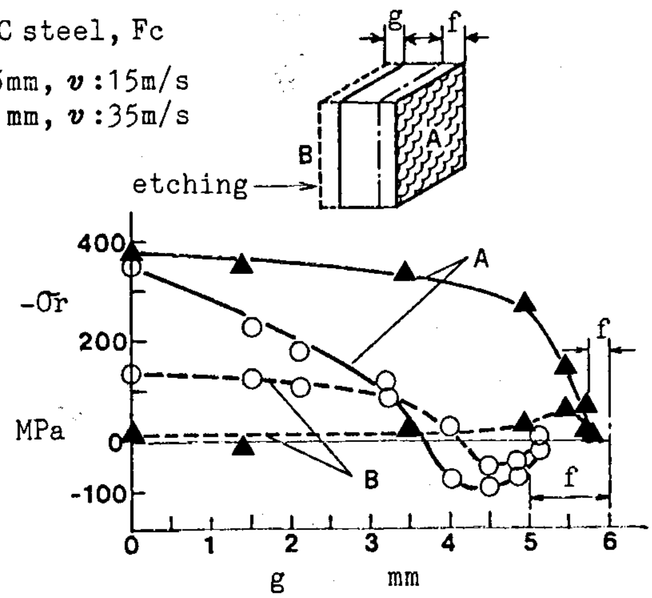


Fig.17. Change of surface residual stress σ_r on A and B for the thickness of etching g. f : affected layer, A : peened, B : non-peened.

CONCLUSION

1. Formulas of dent produced by impact of sphere were obtained in relation to velocity and diameter of sphere and other.
2. The yield zone under the dent produced by impact of sphere was detected and its characteristic was cleared.
3. The distribution of hardness into peened surface has three types such as work hardening, work non-hardening and work softening.
4. Surface residual stress produced by shot peening has the size effect for the thickness of specimen to be peened and falls to zero where the thickness of specimen and affected layer are equals.