RESIDUAL STRESS STATE DUE TO EXPLOSIVE HARDENING

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ABSTRACT

Residual surface stresses in high manganese steels explosively hardened have been reported recently. These results, however, were inconsistent as both tensile and compressive residual stresses were measured. A sufficient conclusion with respect of residual stress formation in the process of explosive hardening is not yet reached.

This paper reports two different types of explosive hardening procedures and residual surface stresses obtained. Samples were prepared from a plain carbon steel Ck45 to deprive of complicated phase transformation during explosive hardening process, making use of a tangential detonation process and a high velocity impact method. Residual surface stresses and the depth distributions of residual stress were measured by using an X-ray diffraction technique. As a result, residual surface stresses were obtained tensile of tensile character in the case of tangential detonation and of compressive character in the case of high velocity impact, respectively.

KURZFASSUNG

Über die Eigenspannungsausbildung in Metallen nach dem Explosivhärten wurde schon verschiedene Male berichtet. Es liegen allerdings widersprüchliche Befunde vor. sowohl Druckeigenspannungen als auch Zugeigenspannungen werden in den gehärteten Oberflächenschichten ermittelt. An einer Erklärung über die Entstehungsursachen der Eigenspannungsausbildung mangels es.

Der Zweck der geschilderten Untersuchungen ist die Analyse der aufgrund verschiedener Explosivhärteverfahren auftretenden Eigenspannungen. Die Untersuchungen werden mit dem Stahl Ck45durchgeführt., Zwei verschiedene Verfahren des Explosivhärtens kommen zum Einsatz, das der streifenden Detonation eines Explosivstoffes in Kontakt mit der zu härtenden Oberfläche und das der Hochgeschwindigkeitskollision. Die Eigenspannungen und deren Tiefenverteilung wurden mittels der röntgenographischen Eigenspannungsanalyse ermittelt. Eigenspannungen von Zugcharakter werden bei streifenden Einfall einer Detonationsfron erhalten, während Druckeigenspannungen sich ergeben bei einer Explosivhärtung mittels Hochgeschwindigkeitskollision.

INTRODUCTION

Residual surface stresses are of importance for service behavior of industrial parts. They can be of benefit of of detrimental effect, depending on their type, either of compressive or tensile nature, respectivley. Residual Stresses in explosively hardened steel have been reported recently. Investigations were made with high manganese austenitic steel. This material is of special interest because of its potential of good explosive hardenability. Hardness increase is more than 200% and is ranging several cm deep. Contradictory results, however, were reported about the residual stress state after explosive hardening. Both tensile and compressive residual stresses were measured by means of X-ray diffraction (1-3).

The purpose of this paper is to get more insight into the process of explosive hardening. As steel Ck45 has been widely investigated with respect of residual stress formation as a result of different conventional surface hardening procedures this steel was used also for the explosive hardening test, making use of different types of explosive hardening operations.

EXPLOSIVE HARDENING PROCEDURE

The explosive hardening of a metal surface is rather simple. A uniform layer of explosive is deposited onto the surface to be hardened. When detonated at one end, a detonation wave is striking the surface tangentially. A shock wave is penetrating the sample as indicated in Fig.1. The initial pressure *P* in the shock wave front is approximately given by the relation (1).

$$P = \frac{1}{4} r_E V_D{}^2$$

where r_E is the density of the explosive and *V*D is its detonation velocity. With this method pressures up to 30 GPa can be realized.

Higher pressures for explosive hardening are possible by high velocity impact. A metal plate is accelerated explosively to high velocity. At impact with a metal surface a plane shock wave with a pressure P of

$$P = U \cdot u \cdot r_p$$

is initiated, where U is shock wave velocity, u is particle velocity which in this case is *V*p/2. *rp* is the density of the impacting material. *V*p is velocity of the flyer plate. As a consequence of impact a shock wave is penetrating the sample and is attenuated during propagation. Figure 2 shows the set-up for this flyer plate impact.

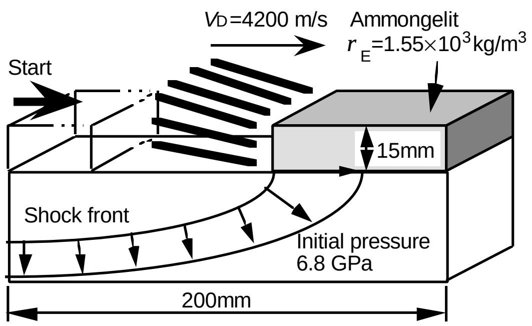


Fig.1 Explosive hardening by tangential detonation.

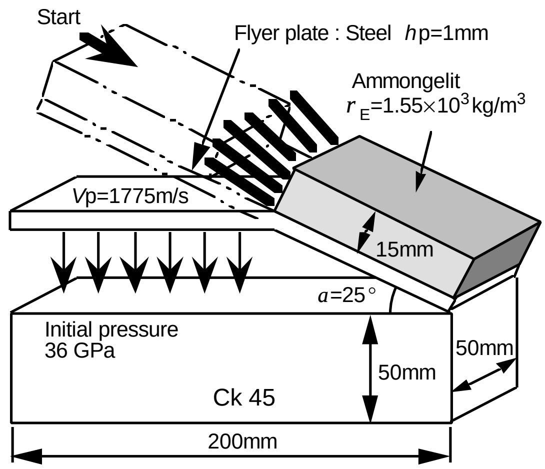


Fig.2 Explosive hardening by high velocity impact.

MATERIAL USED, METALLURGICAL AND HARDNESS INVESTIGATION

Samples consisting of steel Ck45 with compositions given in Table 1 and a size of 50mm x 50mm x 200 mm were used. Before shock hardening was performed they were normalized for 30 minutes at 1003K with subsequent furnace cooling. The surface to be hardened was electrolytically polished removing a layer of 200 µm.

Explosive hardening was performed with an explosive of type Ammongelit (detonation velocity V_D =4200 m/s, density r_E=1.55x10^3 kg/m^3).

Table 1 Chemical compositions of steel Ck45 (wt.%)

C	Si	Mn	P,S
0.45	0.25	0.65	Š0.035

The resulting data concerning impact velocity and shock pressure for both arrangements are given in Fig.1 and Fig.2. To calculate the flyer plate velocity Vp (Fig.2) the relations given by (4) were applied. It is obvious that the method shown in Fig.2 is leading to mich higher shock pressures. Sectioning of the sample was performed for metallographic, hardness and X-ray investigations as shown in Fig.3.

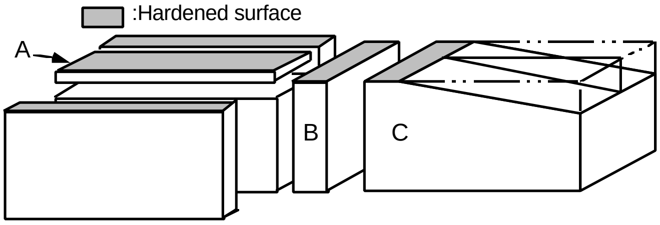
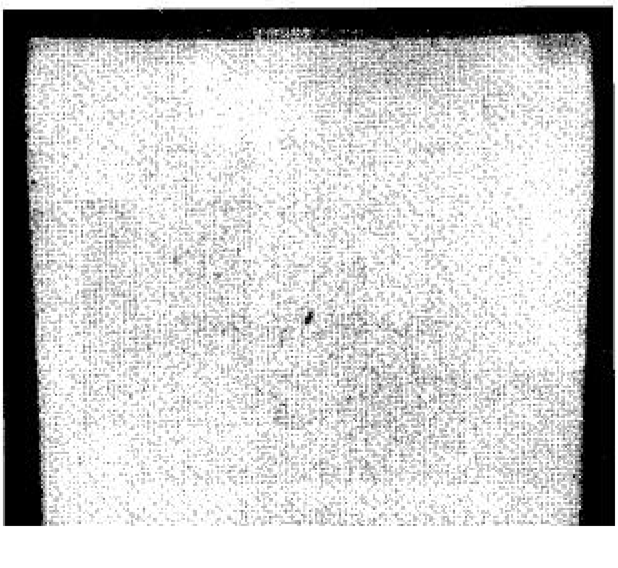


Fig.3 Scheme of sample preparation.

Figure 4 and Fig.5 show the cross section of the hardened samples and their hardness distribution after hardened by both explosive procedures, respectively. In the case of high velocity impact, there are many internal cracks caused by interaction and reflection of shock waves. A typical spalling effect is observed at the lower part of the sample. Also the dark area is visible under the hardened surface with a depth of 12 mm. On the other hand, no internal crack and no dark area under the surface are observed for sample hardened by tangential detonation.



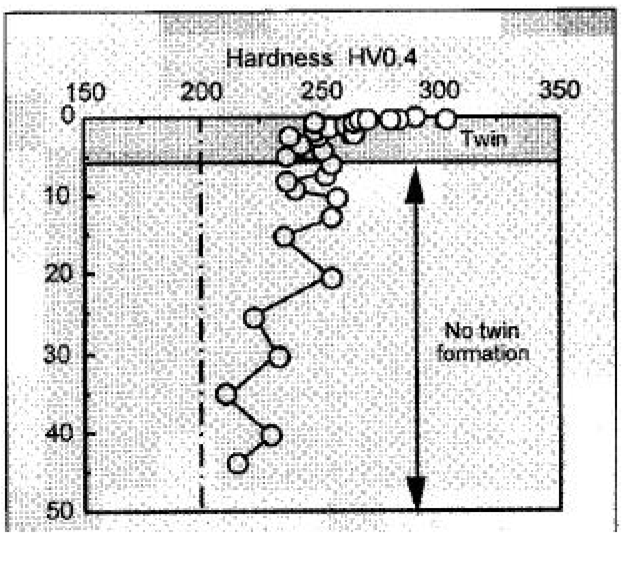
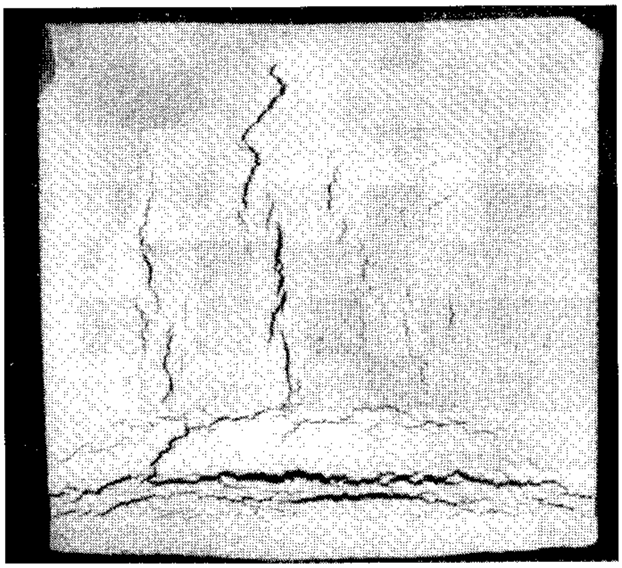


Fig.4 Cross section and hardness distribution vs. depth under surface of sample hardened by tangential detonation.



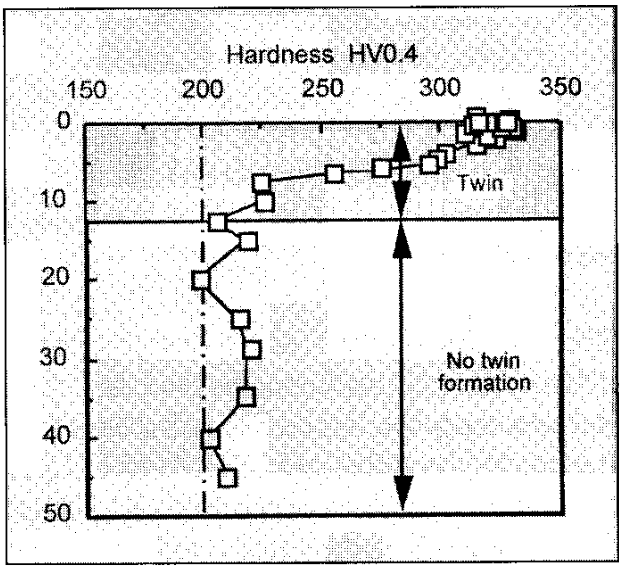


Fig.5 Cross section and hardness distribution vs. depth under surface of sample hardened by high velocity impact (flyer plate impact).

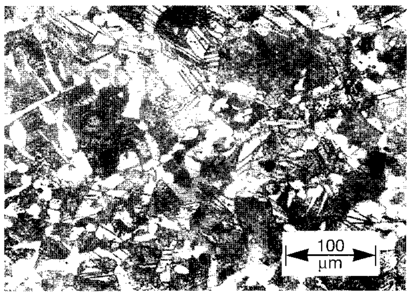


Fig.6 Microstructure of the explosively hardened sample. (Twins in the ferrite structure)

the shocked sample does not show remarkable macro-deformation, but a twin formation is observed in the ferrite structure. The number of twins is larger in the sample which was explosively hardened by the flyer plate impact technique (Fig. The hardness vs. depth-under-surface distribution shows the difference between the two samples. At the immediate surface the hardness values of HV305 and HV330 were obtained for the samples hardened by tangential detonation and by high velocity impact, respectively. In Fig.4, the main portion of the hardened layer is reaching to a depth of about 5 mm, followed by a less pronounced decay from HV250 to the initial hardness of HV200 up to a depth of about 40mm. Figure 5 showing the hardness of the sample hardened by flyer plate impact reveals a hardness decay to the initial hardness at a depth of about 12 mm under the surface. In both cases, the occurrence of twins which is shown in Fig.6 can be correlated with the range of the hardness. Typical for explosive hardening 2).

RESIDUAL STRESS INVESTIGATION

The X-ray diffraction technique by $\sin^2\psi$ method was used to determine the residual surface stresses due to two types of explosive hardening. The Siemens θ–θ-diffractometer D5000 with Ω geometry was employed. α–Fe (211)-diffraction profiles at $2\theta_0$ =156.4° by using CrKα radiation were measured at six different ψ

angles including positive and negative ψ directions. X-ray stress was calculated by the $\sin^2\psi$ method with X-ray elastic constant $1/2S2^X$ of 5.73×10^{-6} 1/MPa (5-6). Residual surface stress components σx, σy were determined parallel to a longitudinal and transverse direction of sample. In the tangential detonation hardening, the longitudinal direction of sample agreed with the direction of detonation. Initial residual stresses of all samples before explosive hardening also were measured. It was confirmed that initial residual stress state σx, σy is zero (the measured values ranged in between -20 MPa and +30 MPa).

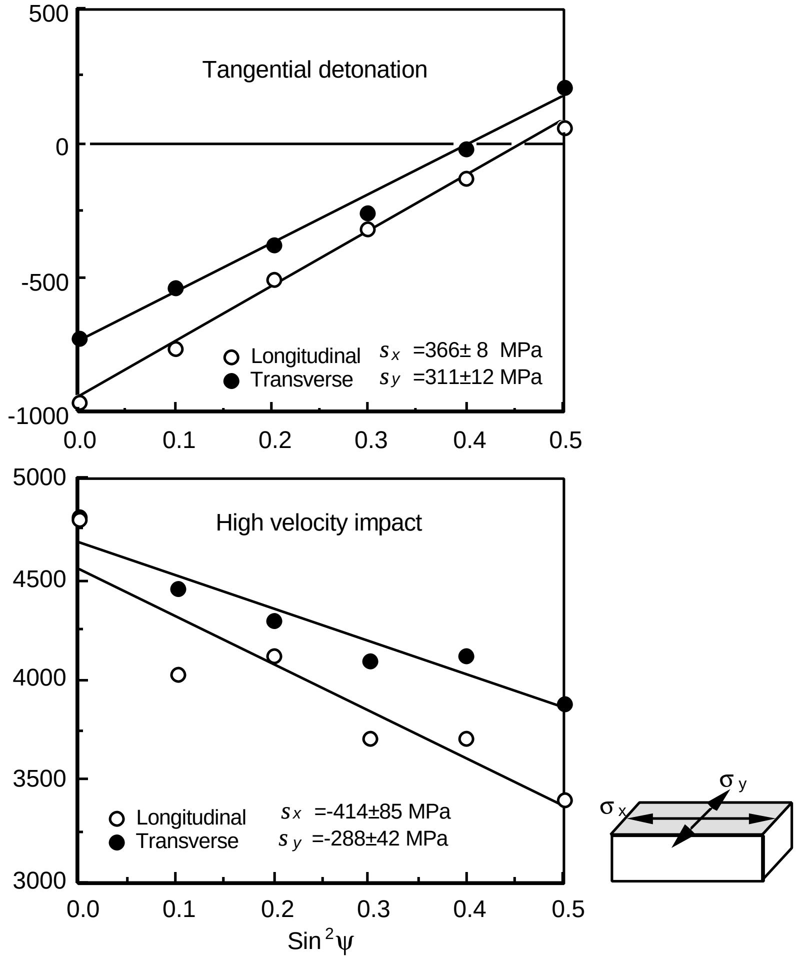


Fig.7 ε-$\sin^2\psi$ diagrams obtained at explosively hardened surface.

Figure 7 shows the ε-$\sin^2\psi$ diagrams at surfaces obtained by both methods of explosive hardening. The negative slopes of the mean square line at the surface hardened by high velocity impact give compressive residual stresses.

The surface reveals a longitudinal residual stress σx of -414±85 MPa and a transverse stress σy of -288±42 MPa. On the other hand, the $\sin^2\psi$ diagrams in the case of tangential detonation have positive slopes in both directions. Residual tensile stresses σx of 366±8 MPa and σy of 311±12 MPa were obtained at a surface hardened by tangential detonation. It is interesting to note, that standard deviations are much better in the latter case. In both cases of explosive hardening method the absolute value of residual stress in longitudinal direction is larger in amount than in transverse direction.

X-ray stress measurements at some depths under explosive surface were carried out to obtain the depth distributions of residual stress components σx, σy . Conditions of X-ray stress measurement were the same as these of measurement of residual surface stress. Samples were cut off with oblique angle of 8° vs. the surface. The cutting surface was electropolished to remove the machining layer. A possible effect of the oblique cutting on the released residual stresses can be neglected.

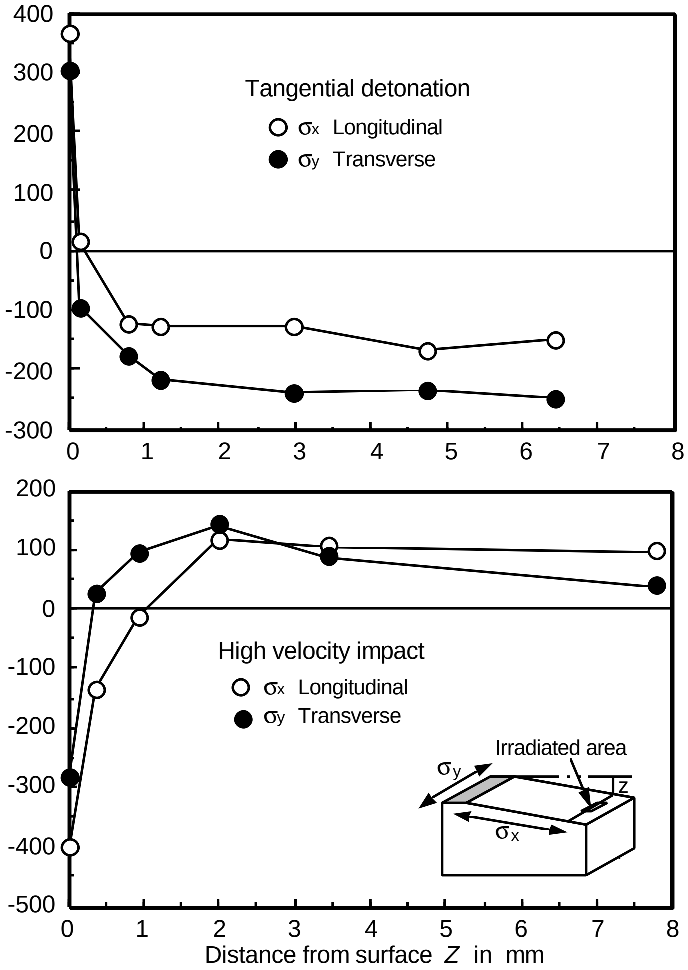


Fig.8 The depth distributions of residual stresses.

Figure 8 illustrates the depth distributions of residual stress components σx, σy in longitudinal and transverse direction. The tangential detonation produces a tensile surface stress in both directions acting in a thin layer to a depth of about 150µm, and then changing to compressive residual stresses at larger depth.

In the case of high velocity impact, however, the compressive stress in both directions existed in deeper layers. The stresses in the transverse direction were decaying to zero at a depth of 350µm whereas the stresses in the longitudinal direction were decaying to zero at a depth of about 1mm, and in deeper layers changing to tensile stresses.

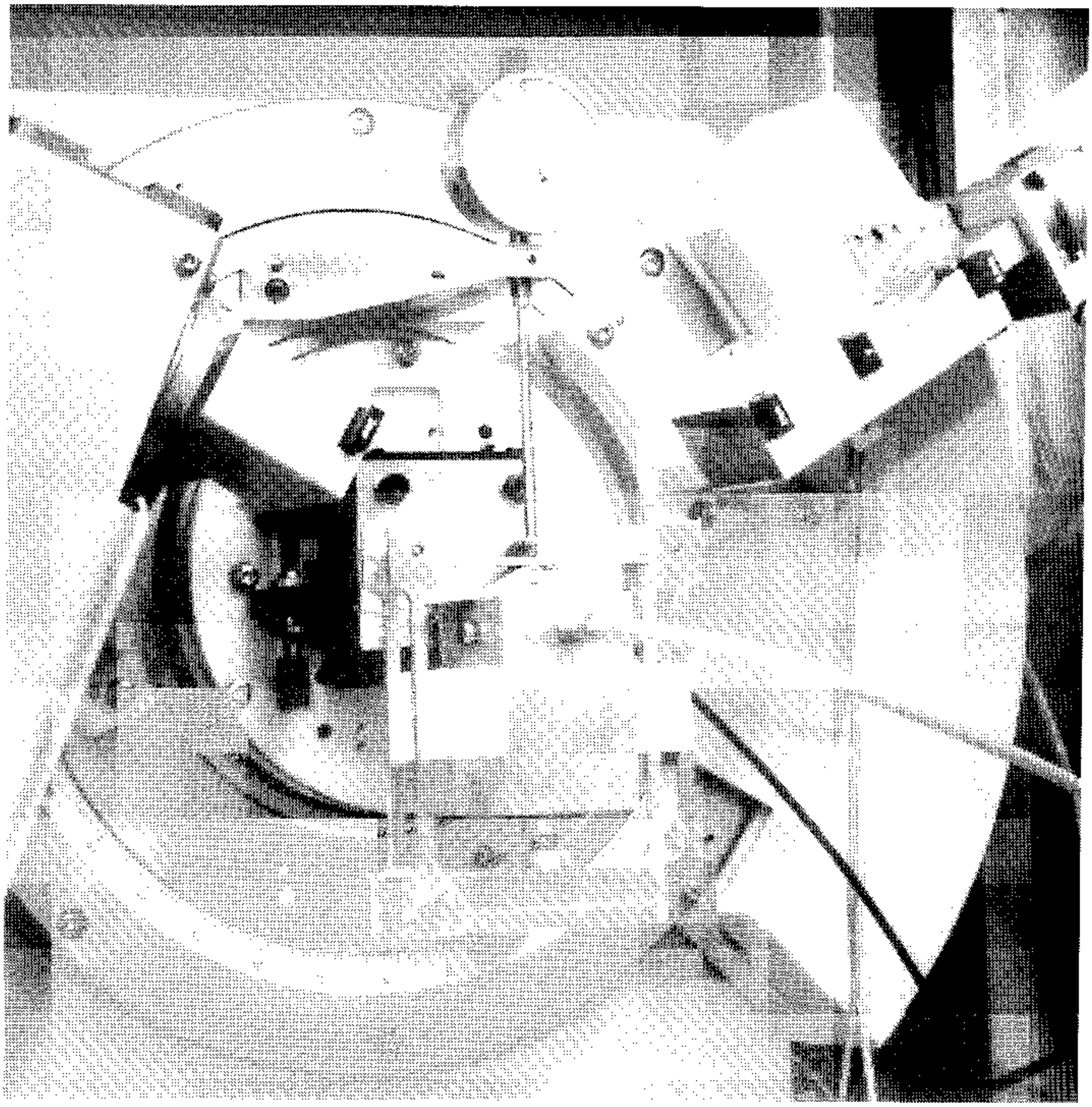


Fig.9 Four-point bending apparatus developed.

The X-ray elastic constants at explosive hardened surfaces were determined. A special four-point bending apparatus actuated by air pressure was designed for this purpose, which is shown Fig.9. This apparatus has an inner span length of 10 mm and an outer one of 100 mm. The displacement of the surface of sample is quite small and therefore a realignment of the diffractometer with changing applied stress is not necessary.

Specimen size was 20mm x 110mm x 3mm. To measure the applied stress, a strain gage on back side of the sample was used. The X-ray elastic constants $s1^X$, $1/2s2^X$ of explosively hardened surfaces and annealed Ck45 samples were determined by using ε-$\sin^2\psi$ diagrams including eleven ψ-angles of the positive direction obtained under five or six stress levels.

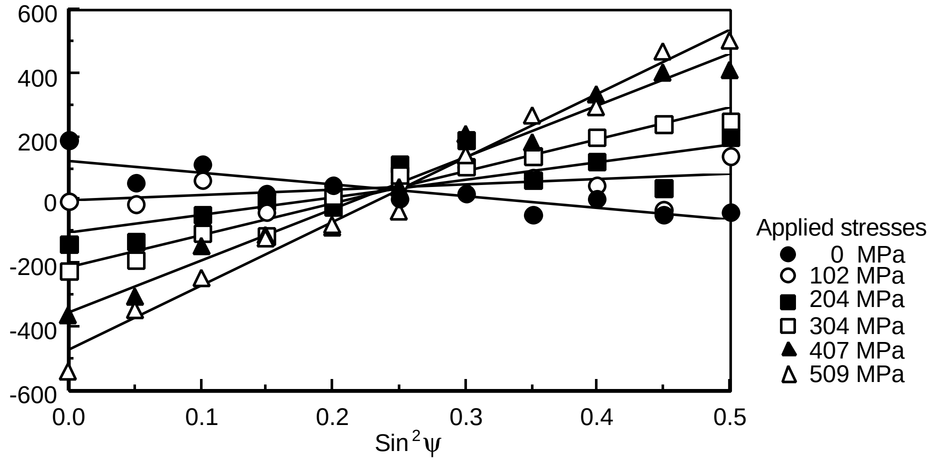


Fig.10 ε-$\sin^2\psi$ plots measured under six applied stress levels.

Figure 10 shows the ε-$\sin^2\psi$ plots of the sample explosively hardened by high velocity impact for six different applied loading stresses. The initial residual stress of -65±28 MPa in longitudinal direction is much smaller than the original residual surface stress in the bulk sample. This stress relief is due to the cutting of the four-point bending sample with 3 mm thickness. The X-ray elastic constants were taken from the slopes and intersections at ψ=0° of the ε-$\sin^2\psi$ diagrams as a function of applied stress. Table 2 summarizes the measured X-ray elastic constants. It is evident that the X-ray elastic constant $1/2S2^X$ for the sample hardened by tangential detonation is the same as for the annealed sample. However, there is a severe deviation to a smaller value of $1/2S2^X$ for the sample hardened by high velocity impact. Using this value of $1/2S2^X$ to calculate the residual surface stress of the sample hardened by high velocity impact, a value of -505±104 MPa and -351±51 MPa is obtained for stress in the longitudinal and transverse direction, respectively.

X-ray elastic constants	$1/2S_2{}^X$x10^{-6} 1/MPa	$S_1{}^X$x10^{-6} 1/MPa	E^X (GPa)	ν^X
Steel Ck45 annealed	5.60± 0.28	-1.16± 0.06	225	0.262
Tangential detonation	5.75± 0.37	-1.09± 0.06	214	0.233
High velocity impact	4.72± 0.14	-1.10± 0.05	277	0.305

E^X: Young's modulus ν^X: Poisson ratio

Table 2 X-ray elastic constants of explosively hardened and annealed Ck45

DISCUSSION OF RESULTS

The investigations clearly show that depending on explosive hardening method both residual surface stresses of tensile and compressive character can arise. At the first glance this seems to be due to the different pressures once acting in the tangential detonation with 6.8 GPa and on the other hand in the flyer plate impact technique with 36 GPa.

It is well known, that pressures larger than 13 GPa in iron cause a transformation to ε–Fe (3,7). This transformation from *bcc* structure to hexagonal structure is associated with a volume contraction. So, as upon shock release a volume expansion will occur, compressive stresses are formed in surface layers.

On the other hand in both processes, tangential detonation and flyer impact hardening, heat is generated at the immediate contact surface. Subsequent cooling would account for tensile residual stresses. There are two kinds of heating. One due to shock wave loading (increase of internal specific energy of material) and the other due to inhomogeneous plastic deformation of the surface layers and heating due to heat transfer from the detonation products. The latter one is especially applicable to the hardening by tangential detonation. Indeed in this case tensile residual stresses are observed. As a consequence of high temperature and rapid cooling one would expect some retained austenite in thin surface layers of the sample hardened by tangential detonation. However, such is only found in the sample hardened by flyer plate impact. It is interesting to note that the X-ray elastic constant $1/2s2^{X}$ of the shocked sample varies in the case of the sample hardened by flyer plate impact. It is smaller than the corresponding value of the annealed sample. This fact is consistent with earlier findings (8) that after plastic deformation or after hardening of steel the X-ray elastic constants $s1^{X}$, $1/2s2^{X}$ decrease in amount.

CONCLUSION

The investigations clearly show that residual surface stress states depended on explosive hardening method. Residual surface stress formation is associated with the phase transformation caused by shock wave pressure and the rapid cooling at the surface during the explosive hardening process. It is a matter of further investigations to investigate quantitative measures of the two individual effects on the resulting residual stress state. Further examinations are necessary in order to allow clearer predictions of residual stress states, especially varying shock intensity and shock duration as well. It is interesting to note, that very weak shock pressures in the range slighly higher than the yield strength of the material allow the relief of existing residual stress states (9).

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