The Influence of Peening Conditions on the Resulting Distribution of Residual Stress

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ABSTRACT

A concept is presented which is capable to explain numerous different residual stress distributions after shot peening. The concept is based on two competitive residual stress generating processes. The influence of shot peening conditions on the distribution of residual stresses is discussed in accordance with this concept.

KEYWORDS

Shot Peening, residual stress, plastic deformation, Hertzian pressure, strain hardening, surface roughness, hard shot, glass beads, steels, aluminium alloys, titanium alloys

INTRODUCTION

Numerous variables can be altered in peening processes, as for instance hardness and strain hardening behaviour of the peened material, material and hardness of the shot, shot size or shot velocity. Accordingly the variety of resulting residual stress states is large. The aim of this paper is to classify the numerous different residual stress distributions on which publications report and to describe a concept for a uniform explanation of the experimental results. Such a concept should be capable to predict which type of residual stress distribution has to be anticipated under distinct peening conditions and materials states. Consequently the concept should be helpful to find those peening conditions which result in optimum residual stress distributions for the different purposes shot peening is applied for.

CONCEPT FOR THE EXPLANATION OF DIFFERENT RESIDUAL STRESS DISTRIBUTIONS AFTER SHOT PEENING

Shot peening can produce compressive residual stress distributions with a maximum magnitude at the surface, often observed in soft materials, as well as with a maximum magnitude below the surface, mostly observed in materials of medium hardness and exclusively observed in hard materials. A concept which shall be able to explain both kinds of residual stress distributions must necessarily include two different processes of localized plastic deformation and consequently residual stress generation.

One of these processes is the direct plastic elongation of layers very close to the surface as a consequence of tangential forces due to numerous shot indentations (compare for instance Hornauer et al., 1981. Wohlfahrt, 1981/82). This process is comparable to hammering of the surface and is indicated in an increase of surface roughness or surface hardness. The elastic-plastic elongation of the surface layer results in compressive residual stresses with a maximum magnitude at the very surface, as illustrated schematically at the right side of fig. 1, if this effect is the only or predominant one. The degree of plastic deformation of surface layers is responsible for the magnitude of surface residual stresses. As a rough indicator of the degree of plastic deformation of surface layers the increment of surface roughness can be taken, if the original surface roughness before shot peening is sufficiently small. In soft material states the increment of surface roughness due to shot peening is relatively big. Consequently plastic deformation of surface layers should be the predominant process if a soft material is peened with a harder shot.

The second residual stress generating process can be Hertzian pressure which arises as a consequence of the vertical force F connected with the impact of each shot ball. The theory of Hertz describes the course of normal stresses below a surface on which for instance a ball is pressed statically. As shown at the left side of fig. 1 the resulting shear stress has a maximum value at a distict distance $z_{\tau,max}$ below surface which is

$$z_{\tau,max} = 0,47\ a \qquad (1)$$

when „a" is half the width of the contact zone. According to the theory the following relations exist between the Hertzian pressure p_o respectively the maximum shear stress τ_{max} and the vertical pressure force F and half width of the contact zone „a"

$$p_o = \frac{3}{2\pi} \cdot \frac{F}{a^2} \qquad (2)$$

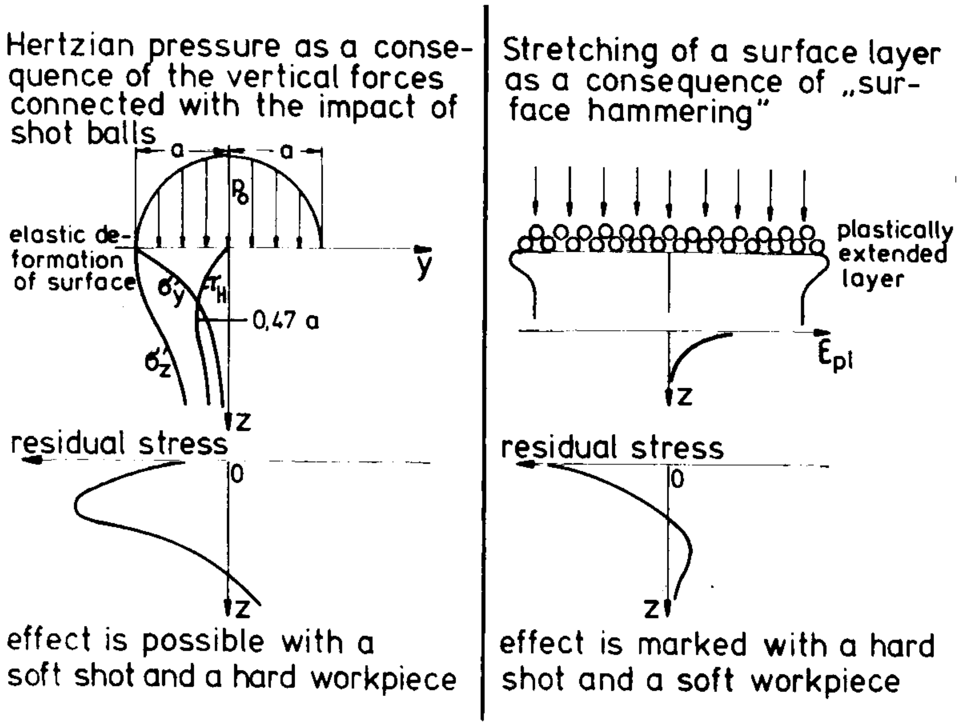

Fig. 1 Schematic illustration of the formation of residual stresses as a consequence of two competitive processes in shot peening: Hertzian pressure (left) and direct stretching of a surface layer (right).

$$\tau_{max} = 0,31 \cdot p_o = 0,31 \cdot \frac{3}{2\pi} \cdot \frac{F}{a^2} \qquad (3)$$

If the Hertzian pressure becomes high enough the maximum shear stress can exceed the flow stress in the depth of 0,47·a and the resulting plastic elongation will generate compressive residual stresses in this depth. The degree of plastic deformation in the depth of the maximum shear stress determines the maximum residual stress magnitude.

With equation (1) Schreiber (1976) estimated the depth of maximum shear stress for different peening and material conditions of a case hardening steel. It was assumed that the depth of the contact zone h is nearly equal to the measured surface roughness and thus the equation

$$a = \sqrt{2\,hr - h^2} \qquad (4)$$

could be applied to calculate half the width of the contact zone from known data (r = radius of the shot). The estimated depth of maximum shear stress was then compared with the measured depth of the maximum magnitude of residual stresses.

In any investigated material state (blank hardened 385 HV, case hardened and tempered 850 HV, case hardened 900 HV) the agreement between estimated and measured depth was very good if low shotvelocities were considered; the best agreement existed in the hardest material state. Obviously the Hertz equations are best adhered to in this case. But even with increasing peening energy the difference between the measured depth of maximum residual stress and the calculated depth of maximum shear stress remained within the accuracy of measurement or at least within the order of magnitude. Therefore the conclusion can be drawn that the Hertz equations remain valid at least approximately for shot peening conditions if plastic deformation of the surface and dynamic effects are not too predominant (Wohlfahrt 1981/82. Wohlfahrt 1983 . Compare Al-Hassani 1982).

The real distribution of compressive residual stresses after shot peening will result from the combined effect of both competing processes, direct plastic surface deformation and plastic deformation of deeper layers due to the Hertz pressure. If much energy is consumed for direct plastic deformation of the surface the effect of Hertzian pressure cannot be dominant. If plastic deformation of layers close to the surface is negligible and narrow contact zones exist, the effect of Hertz pressure will be dominant, resulting in high maximum magnitudes of residual stresses below surface. It depends upon the ratio of materials hardness and shot hardness, the shot diameter $\bar{d}$ and the kinetic energy $mv^2/2$ which of both stress generating processes will actually be dominant. This will be discussed in the following sections. It is assumed that the vertical pressure force F increases as the kinetic energy of the shot increases and that an increase of surface roughness is connected with an increase of the width of the contact zone $2\cdot a$. It shall be kept in mind that variations of peening conditions may alter the pressure force as well as the width of the contact zone.

APPLICATIONS OF THE DESCRIBED CONCEPT

Materials of low hardness ($HV\overline{<}300$)

If the hardness of the material is confined to 300 HV the hardness of the shot is usually higher. Much of the kinetic energy of the shot is consumed in this case for direct plastic deformation of surface layers and this will be the dominating process. The imprints of the shot have a relatively large depth and width and hence the Hertz pressure is relatively low.

Taking firstly into consideration very low shot energies, it is possible that the whole kinetic energy is consumed for plastic surface deformation - at least if extremely small shot diameters are excluded.A residual stress distribution with the maximum magnitude at the surface has to be anticipated then. In which way this type of residual stress distribution is altered if the peening energy is enhanced depends upon how the pressure force F and how the width of the contact zone are altered. This again depends on the strain hardening behaviour of the materials. As long as the increment of shot energy results in stresses and strains in the surface layer within the steeper part of the stress - strain curve, where pronounced strain hardening exists, the enlargement of the contact zone may remain relatively small. Then, with increasing shot energy the pressure force F may increase more than the square of the half width of the contact zone a^2. According to equation (2) and (3) the maximum shear stress may be raised sufficiently to produce a residual stress maximum below surface. Exactly this situation - relatively small increase of shot velocity when peening a steel with a hardness of 300 HV - is illustrated in results of Brodrick (1956/57). After peening with a shot of 0,6 mm/diameter and with low shot velocities of 20 m/sec and 25 m/sec the author found maximum magnitudes of compressive residual stresses at the surface (fig. 2). A relatively small increase of the shot velocity to 33 m/sec resulted in a maximum magnitude of residual stresses below surface. This maximum is relatively weak. The difference between the magnitude of surface stress and of maximum stress is 105 N/mm^2.

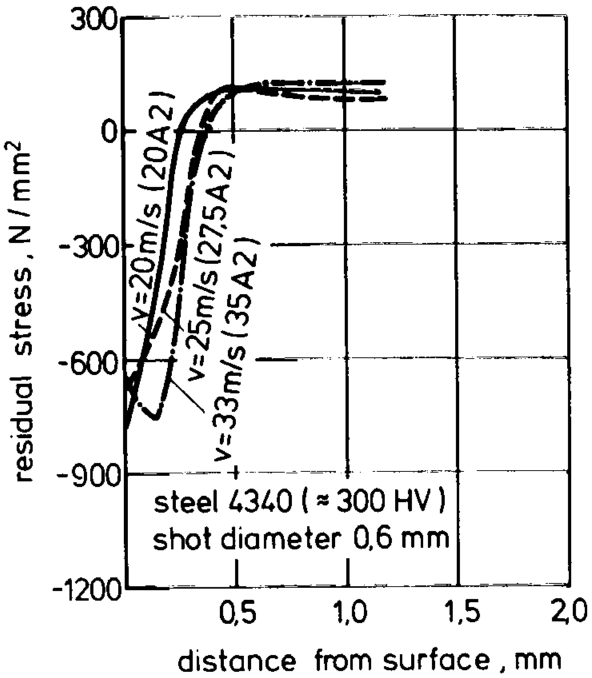

Fig.2 Residual stress distribution in steel of 300 HV after shot peening with different low shot velocities. Brodrick (1956/57).

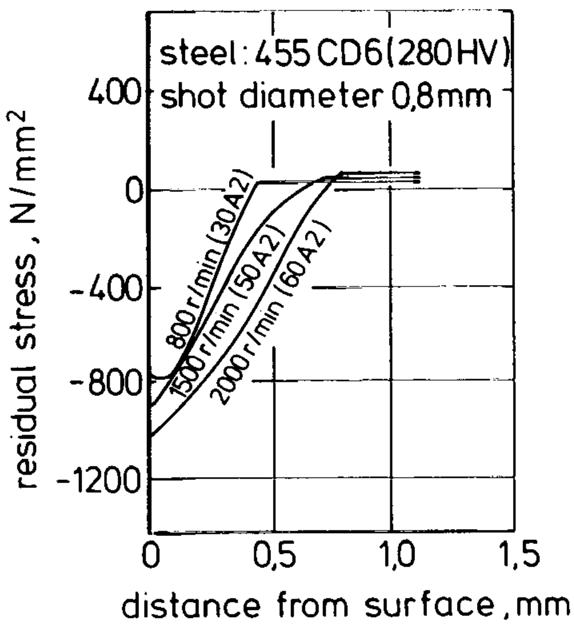

Fig. 3 Residual stress distribution in steel of 280 HV after shot peening with different high shot velocities. Niku-Lari (1981/82).

It is of special interest that Niku-Lari (1981/82) has practically continued the work of Brodrick to very high shot velocities. Steel specimens (French specification 45 5 CD) with a hardness of 280 HV were peened with a shot of 0,8 mm diameter and different shot velocities. The lowest shot velocity was not very different from the highest shot velocity of Brodrick and resulted in a residual stress distribution with the maximum magnitude below surface very similar to the corresponding one of Brodrick. Fig. 3 illustrates, that with increasing shot velocities residual stress distributions were originated with an increasing maximum magnitude at the surface. Obviously the maximum residual stress can reach values within the order of magnitude of ultimate strength. The depth of the layer containing compressive residual stresses increased as well with the shot energy.The measured enlargement of surface roughness indicates a pronounced broadening of the contact zone and with that again a favouring of direct plastic deformation of the surface. Thus the magnitude of surface residual stress can become higher than the residual stress due to the Hertzian pressure which is still present. It is obvious to assume that this occurs as with very high shot velocities the flattened part of the stress - strain curve is reached, where any increment of stress, produced with an increase of shot energy, results in a relatively high increment of strain.

Sequences of residual stress distributions versus shot energy similar to the presented one were observed from other authors, for instance Brodrick (1956/57) and Hirsch et al. (1982) on aluminium alloys. Schreiber (1966, 1977 a) reports on residual stress distributions in a soft steel (175 HV) fitting into the sequence. Taking together the results on different materials the following generalized summary is possible.

Shot peening of soft materials (HV $\lessapprox$ 300) with a markedly harder shot can result in a maximum magnitude of residual stress at the surface if low shot energies are applied. A maximum residual stress magnitude below surface is possible in connection with low shot energies, but is favoured if medium shot energies are used. Compared with harder states of the same material the residual stress maximum below surface is less pronounced in the soft state. Very high shot energies - especially if realized with a shot of a large diameter - can produce residual stress distributions with a maximum magnitude at the surface and relatively thick layers containing compressive stresses due to the effect of the Hertzian pressure. In all cases a shot with a smaller diameter favours the Hertzian pressure effect, that is to say a maximum magnitude of residual stress below surface.

Materials of a medium hardness (350 - 600 HV)

On a medium level the hardness of the usual shot may be higher than the hardness of the material to be peened or may be nearly the same.

At first residual stress distributions shall be discussed which result from peening of steels with a hardness of ca. 400 HV with shot of the usual hardness (470 - 520 HV). In this case plastic surface deformation is lower than in the case of shot peening soft materials under the same conditions. Smaller surface roughness values confirm this. More energy is available for Hertzian pressure and this effect will be favoured. Therefore a clear residual stress maximum below the surface is normal. The difference between the magnitude of surface residual stress and maximum residual stress is for instance ≈ 50 N/mm^2 if a shot diameter of 0,8 mm is used (Niku-Lari 1981/82) or can become as big as 300 N/mm^2 if shot of lower diameters (o.6 or o.3 mm) is used (Schreiber 1976, 1977 b). Only Brodrick (1956/57) reports on a few examples of residual stress distributions with the maximum magnitude at the surface if low shot energies are used.

The influence of shot velocity and shot size on magnitude and depth of the residual stress maximum can be explained in agreement with equations (3) and (4). Fig. 4 illustrates residual stress distributions in steel specimens with a hardness of 385 HV (case hardening steel containing 0.15 % C, 1.23 % Mn, 1.08 % Cr - blank hardened) after peening with shot of different diameters and with different shot velocities (Schreiber et al. 1977 b). If one compares the residual stress distributions after peening with a shot of 0.6 mm diameter and different velocities one can see, that an increase of the shot velocity shifts the depth of the residual stress maximum to deeper layers. This is in agreement with equation (1), as in this state of the steel surface roughness increases markedly from 13µm to 25µm with the used shot velocities and therefore the width of the contact zone increases correspondingly. The maximum magnitude of compressive residual stresses increases from 780 N/mm^2 to 840 N/mm^2 (respectively to 870 N/mm^2 for a shot velocity of 81 m/sec not represented in the figure). The increase of the maximum magnitude with increasing shot velocity is marked but not as big as observed in hard materials under usual peening conditions. This results can be explained as follows. In connection with an enhanced shot velocity the width of the contact zone increases as well as the pressure force F. Corresponding to the above cited surface roughness values the increment of the width of the contact zone is larger in a state of medium hardness than in a very hard state (compare next chapter). Therefore according to equation (3) the increase of the maximum shear stress and consequently the increase of the maximum residual stress magnitude below surface remain smaller in the state of medium hardness than in a hard state.

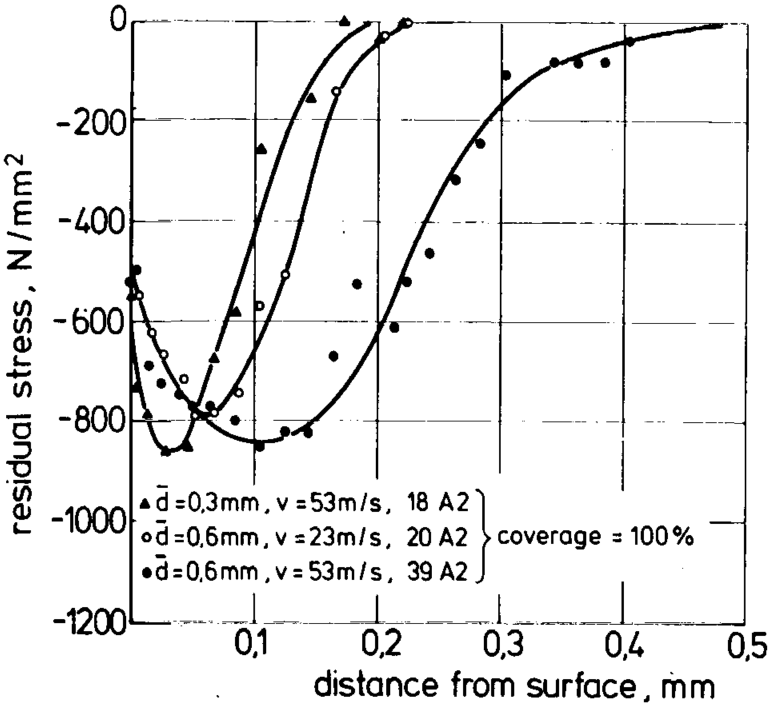

Fig.4 Residual stress distribution in a blank hardened steel (German specification 16 MnCr5, 385 HV) after peening with shot of different diameters $\bar{d}$ and with different shot velocities v. (Schreiber et al. 1977 b).

A smaller shot ($\bar{d}$ = 0,3 mm) with a narrower contact zone (see equation (4)) results in a distinctly bigger magnitude of compressive residual stresses than the somewhat larger shot ($\bar{d}$ = 0,6 mm). The difference is evident even if one compares the results of the smaller and the larger shot after peening with equal shot velocities (v = 53 m/sec) and hence unequal Almen intensities. The difference is quite pronounced if peening conditions are compared which result in nearly the same Almen intensity (v = 53 m/sec, 18 A2 for $\bar{d}$ = 0,3 mm and v = 23 m/sec, 20 A2 for $\bar{d}$ = 0,6 mm).

The residual stress distributions with a distinct maximum below surface discussed so far in this passage are typical for peening with usual steel shot - the hardness of which is 470 - 520 HV and thus not much higher than the hardness of the material or even equal to that hardness, especially if one takes into account strain hardening of the material. If materials of medium hardness are peened with special shot of higher hardness - either steel shot or glass beads - direct plastic deformation of the surface is favoured. As an example fig. 5 represents residual stress distributions in titanium alloys (ultimate strength 1140 respectively 1050 N/mm^2) after peening with glass beads (Braski and Royster, 1967). If the glass beads are small a maximum below surface is still present as a consequence of the very narrow contact zone, however, surface stresses can reach a relatively high magnitude as well. For comparison, Brodrick (1956/57) reports on residual surface stress magnitudes of only 385 N/mm^2 to 525 N/mm^2 in a titanium alloy of an ultimate strength of 1165 N/mm^2 which was peened with the usual steel shot.

If peening is performed with glass beads of the extraordinary diameter of 0,425 mm plastic surface deformation of the titanium alloy becomes predominating and the maximum magnitude of compressive residual stresses moves to the surface (fig.5). The effect of Hertzian pressure, of course still present, is expressed in the extreme thickness of the layer containing compressive stresses. Other authors have also published examples of residual stress distributions with a relatively high maximum magnitude at the surface (Wohlfahrt 1981/82) and with an extremely thick layer containing compressive residual stresses (Franz 1979) after peening of titanium alloys with glass beads.

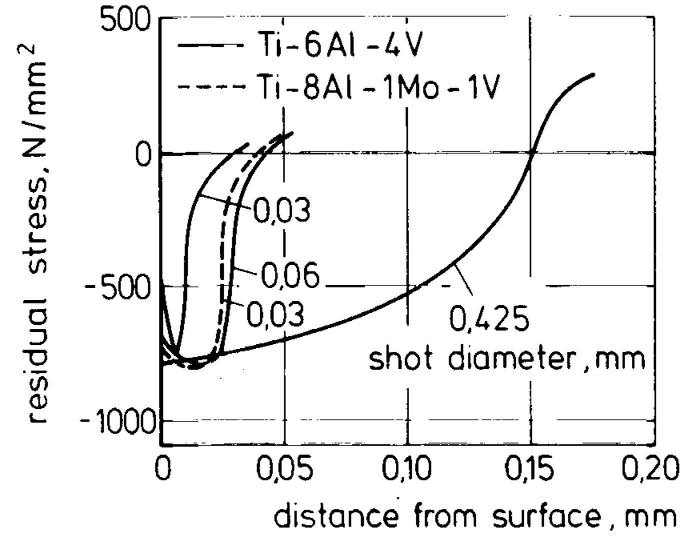

Fig.5 Residual stress distributions in different titanium alloys after peening with glass beads of a different diameter. Braski and Royster (1967).

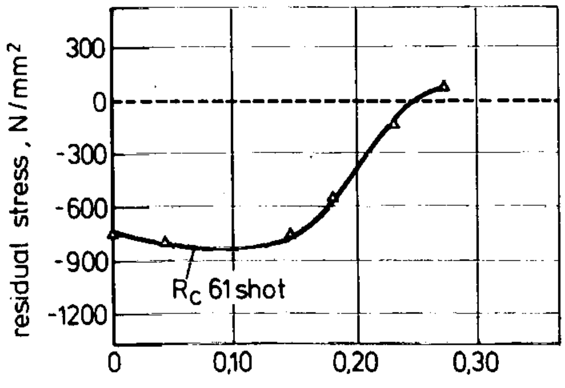

Fig.6 Residual stress distribution in a quenched and tempered steel (U.S. specification 1045, 485 HV) after peening with a very hard shot (720 HV, $\bar{d}$ = 0,8 mm). Lauchner (1974).

A residual stress distribution of the same type as the last discussed one is generated if steel of a medium hardness (485 HV) is peened with a shot ($\bar{d}$ = 0,8 mm) of the extraordinary hardness of 720 HV (Lauchner, 1974). As can be seen in fig. 6 surface residual stress and maximum residual stress are nearly equal and the layer containing compressive residual stresses is relatively thick.

As a conclusion of this paragraph one can say in accordance with the assumption of the proposed concept: Shot peening of materials of medium hardness normally results in residual stress distributions with a maximum magnitude below surface. The difference between the magnitude of surface residual stress and maximum residual stress depends upon peening conditions or peening energy. The depth of the maximum magnitude and of the layer containing compressive residual stresses increases as shot energy increases. Only if the shot is extremely hard, compared with the hardness of the material, an increasing shot energy finally results in the same type of residual stress distribution - with the maximum magnitude at the surface - as for soft materials. That is to say, in principle the same sequence of residual stress distributions can be generated in materials of medium hardness as in soft materials.

Materials of high hardness (> 600 HV)

On a very high hardness level above 600 HV the hardness of the usual shot is lower than the hardness of the material. Only the hardness of special shot may be equal to materials hardness or a bit higher.

If a hard material is peened with the usual shot of somewhat lower hardness only little direct plastic surface deformation occurs. The very low surface roughness confirms this. Hence the magnitude of surface residual stress can be rather low. As a consequence of the narrow contact zone the Hertzian pressure effect is dominating clearly. The magnitude of the residual stress maximum below surface can become very big, absolutely as well as compared to the value of the residual surface stress. According to equation (1) the depth of the maximum residual stress magnitude is small.

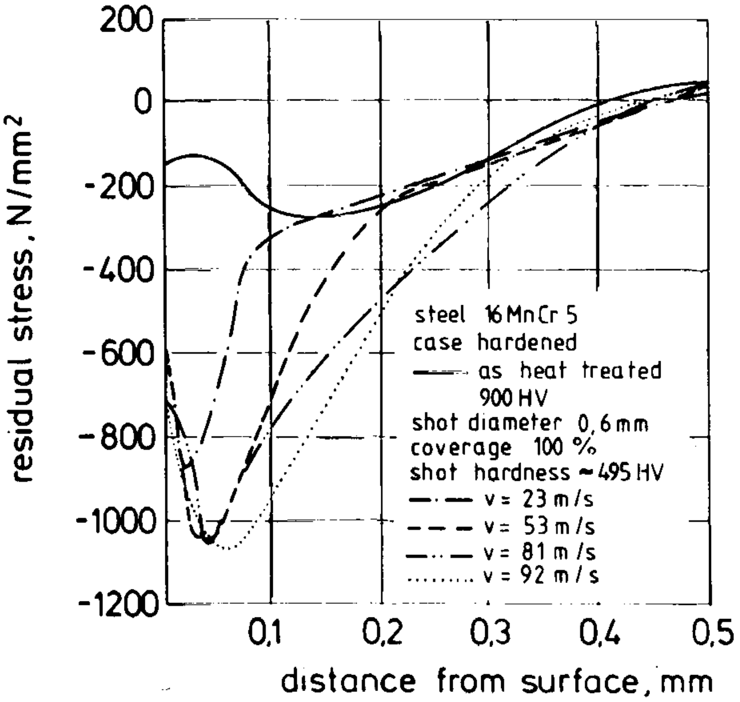

Fig.7 Residual stress distributions in a steel which was case hardened and cooled in liquid air (900 HV, German specification 16 MnCr5) after shot peening with different shot velocities v. Schreiber et al. (1978 a).

As illustrated in fig. 7 an increasing shot velocity results in an increase of the magnitude of the residual stress maximum as well. An increment from 880 N/mm^2 to 1080 N/mm^2, twice as big as for blank hardened steel specimens (385 HV) was observed as a case hardened steel (900 HV) was peened with shot of usual hardness (470 - 520 HV) and the shot velocity was enhanced from 23 m/sec to 81 m/sec (Schreiber et al. 1978 a). The rather low depth of the stress maxima increased as well as the shot velocity was enhanced. According to equation (1), (3) and (4) these results are reasonable as the increment of surface roughness from 2,1 µm (v = 23 m/sec) to 3,0 µm (v = 81 m/sec) remains extremely small, and hence the maximum shear stress will increase considerably as shot velocity increases. As shot hardness is lower than materials hardness plastic deformation of the shot increases rather than plastic deformation of the material surface if the shot velocity is enhanced. Accordingly surface residual stresses remain practically unaltered if the shot velocity changes.

Results from Brodrick (1956/57) show the influence of the shot diameter on residual stresses in a hardened and peened steel (AISI 4340; 52 HRc). The magnitudes of the maximum residual stresses as well as of the surface residual stresses decrease with increasing shot diameters up to 2 mm. According to equation (3) this is possible if the increment of the square of the half width of the contact zone exceeds the increment of the pressure force and the maximum shear stress decreases. One can conclude that these conditions have been fulfilled in the experiments of Brodrick since the increase of the Almen intensity with shot diameter was relatively small.

Very instructive results about the competitive character of plastic surface deformation and effect of Hertzian pressure exist on peening hard materials with shot of different hardness (Schreiber et al. 1977 c). A case hardened steel with a hardness of ≈ 820 HV and a case hardened and tempered steel with a hardness of ≈ 700 HV were peened as well with a usual shot (hardness 470 - 520 HV, $\bar{d}$ = 0,6 mm), as with a harder shot (590 - 670 HV, $\bar{d}$ = 0,5 mm). The shot velocity was 81 m/sec in both cases. Fig. 8 compares the characteristic residual stress values. In the case hardened and tempered state (700 HV) the substitution of the somewhat softer shot by the harder shot enhances exclusively surface residual stresses. In the case hardened state (820 HV) the harder shot enhances surface residual stress modestly and the magnitude of maximum residual stress considerably. The explanation for these results is, that with an increase of shot hardness direct plastic deformation of surface layers of the material to be peened increases at most slightly as long as the shot hardness remains clearly below the hardness of the material, but increases markedly as shot hardness reaches values close to the material hardness. The surplus of

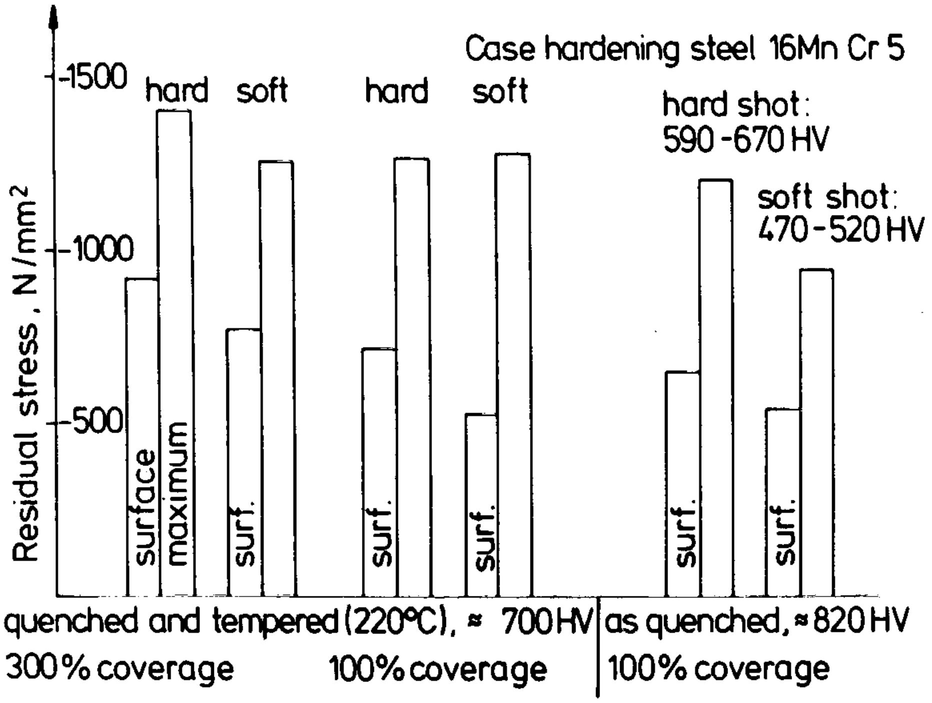

Fig. 8 Magnitudes of surface residual stress (surf.) and maximum magnitudes of residual stress after peening with a hard and a soft shot. Case hardened steel (16MnCr5) in two different conditions. Schreiber et al (1977 c).

energy due to a reduction of plastic deformation of the shot is consumed fully for plastic surface deformation in the somewhat softer tempered state (700 HV), whereas in the case hardened state of the material (820 HV) a part of this energy surplus is available for plastic deformation of deeper layers as a consequence of Hertzian pressure. Nevertheless the maximum magnitude of residual stress in the case hardened state does not reach the maximum magnitude in the tempered state. Is has to be assumed that in the tempered state (700 HV) a somewhat lower shear stress is necessary for plastic deformation than in the extremely hard state (820 HV) and hence a distinct shot energy respectively shear stress results in a higher degree of plastic deformation.

Results of Lauchner (1974) indicate that an extremely hard shot (720 HV, $\bar{d}$ = 0,8 mm) is able to generate extremely high magnitudes of residual stresses even in a very hard steel (745 HV). At the surface a residual stress magnitude of 1070 N/mm^2 and below the surface a maximum magnitude of 1450 N/mm^2 was observed.

Another typical example of the competitive character of direct plastic deformation of surface layers and of plastic deformation in deeper layers due to the Hertzian pressure are residual stress distributions after shot peening in notches. As fig. 9 illustrates one finds higher maximum magnitudes

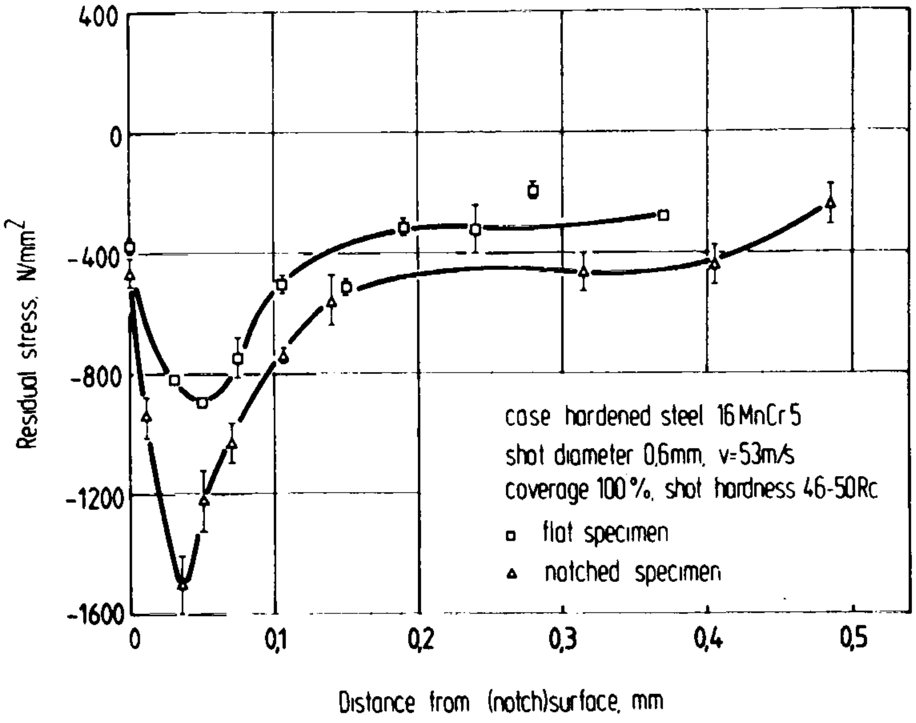

Fig. 9 Residual stress distribution below the surface of a flat sample and below the surface of a notch. Case hardened steel (16 MnCr5, 820 HV). Schreiber et al. (1978 b). Compare Todd et al. (1971).

of compressive residual stresses can originate below a notch than in layers below the smooth surface of flat samples of the same material peened with the same peening parameters (Schreiber et al. 1978 b). Obviously this is a consequence of the hindered plastic deformation in the notch due to the multiaxial state of stress. A limited plastic deformation near the surface should favour the effect of maximum shear stress in deeper layers and should lower the magnitude of surface residual stress. In fact in 3 of 4 investigated cases the surface residual stresses were lower in the notch than at the smooth surface or at the surface of a completely even sample.

Important facts of this chapter can be summarized as follows: residual stress distributions observed up to now after shot peening of hard materials show always a maximum magnitude below the surface. The maximum magnitude can become as high as ≈ 1500 N/mm^2, whereas the magnitude of surface residual stress can be rather low. A sufficiently hard shot is necessary to get the highest possible maximum magnitudes in unnotched samples. An especially hard shot favours direct plastic deformation of surface layers as well, but the observed surface stress remains nevertheless well below the maximum stress.

SUMMARY

A concept is presented which is capable to explain and to predict the different residual stress distribution after shot peening of materials with low, medium and high hardness and to describe the influence of peening conditions as shot hardness, size and velocity correctly. The concept distinguishes between two competitive residual stress generating processes:

- direct plastic elongation of layers very close to the surface, and
- plastic deformation in deeper layers, where the shear stress τ connected with the pressure force F of shots has a maximum.

The degree of plastic deformation of surface layers is responsible for the magnitude of surface residual stresses, the degree of plastic deformation in the depth of the maximum shear stress determines the maximum residual stress magnitude.

Plastic deformation of surface layers is the predominant process if a soft material (HV<300) is peened with a harder shot. Then a residual stress maximum below surface - which is often hardly pronounced - arises only if distinct peening conditions, favouring strain hardening effects, as for in- instance medium shot energies, are applied. In connection with very high shot energies residual stress distributions are observed with the maximum magnitude at the surface and with a relatively thick layer containing residual stresses.

With increasing hardness of the peened material depth and diameter of shot indentations become smaller and thus the pressure due to the impact of the shot as well as the maximum shear stress become higher. In other words, as with increasing hardness less energy is consumed for plastic deformation of surface layers of the peened material more energy is available for plastic deformation in deeper layers. Therefore extended plastic deformation can occur in deeper layers and a higher maximum magnitude of compressive residual stresses can be produced - even with a somewhat softer shot.

In materials of medium hardness (350<HV<600) a marked residual stress maximum below surface is normal. Lower shot diameters and higher shot velocities generally enhance the magnitude of the residual stress maximum below surface. If an especially hard shot is applied, high shot energies in connection with relatively large shot diameters can produce residual stress distributions with the maximum magnitude at the surface and with a relatively thick layer containing residual stresses.

After shot peening of hard materials (HV>600) exclusively residual stress distributions with a maximum magnitude below the surface are observed. Lower shot diameters and higher shot velocities can cause a pronounced increase of the maximum magnitude of residual stress. Even more effective is an especially hard shot, which is able to enhance the magnitude of the maximum stress as well as of the surface stress considerably.

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