THE 7th INTERNATIONAL CONFERENCE ON SHOT PEENING
ICSP 7
INSTITUTE OF PRECISION MECHANICS WARSAW, POLAND

EFFECT OF SHOT PEENING PARAMETERS ON THE SURFACE CHARACTERISTICS OF DIFFERENTLY HEAT TREATED AISI 4140

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ABSTRACT

The effect of the technically important shot peening parameters peening pressure, mass flow, hardness and size of the shot particles on the surface layer properties were systematically studied. Samples of the differently heat treated steel AISI 4140 (German Grade 42CrMo4) with a hardness between HV 230 and HV 660 were shot peened. The surface layers were characterized the residual stresses and the half width values of interference lines using X-ray diffraction and by the surface roughness. With increasing workpiece hardness characteristic maxima of the compressive residual stresses beneath the surface are observed. An increasing peening intensity causes an increase of the depth where the residual stresses change their sign. During shot peening the half width values near the surface increase for softer material conditions due to a multiplication of dislocations, whereas these values decrease for harder material conditions, which is caused by a rearrangement of dislocations of high density to energetically more favourable positions.

KEYWORD

shot peening parameters, residual stresses, workpiece hardness

INTRODUCTION

Shot peening is an industrial process often used to improve the component properties, especially fatigue life and fatigue strength. In soft material conditions this is caused by work hardening of the regions close to the surface, which prevents or reduces the probability of crack initiation in this area. With increasing hardness of the material the amounts and the depth x_0 where the residual stresses change their sign become more substantial, thus preventing crack initiation and/or reduction of crack propagation [1,2].

For an optimization of the shot peening process it is necessary to know the effects of the shot peening parameters. The result of the shot peening treatment is influenced by the machining parameters, the shots used and the workpiece that is shot peened. The technically most important parameters are the shot velocity [3-8], the mass flow or exposure time [3,4,9,14], the hardness and size of the shots [3,4,6,9,15-22] and the workpiece hardness [23-25].

Although there are already some papers about the effects of these parameters, there does not exist any systematic study on the separated influence of these properties, especially on the induced residual stresses and the surface work hardening.

This paper reports on the influence of the parameters peening pressure, mass flow, hardness and size of the shots and workpiece hardness on the properties of the surface layers of AISI 4140 (German Grade 42CrMo4) steel samples in different heat treatment conditions (see also [26,27]). The surface layers are characterized by the distribution of residual stresses and half width values of the interference lines determined by X-ray measurement. In this context, the half width value is a measure of the microstructural work hardening or work softening of the material. Another property to characterize the surface is the surface roughness R_t.

MATERIAL AND HEAT TREATMENT

The investigations were carried out on the heat treatable AISI 4140 (German Grade 42CrMo4) with the chemical composition 0.44 C, 1.05 Cr, 0.21 Mo, 0.22 Si, 0.59 Mn, 0.06 Ni, 0.02 P, 0.01 S, bal Fe (in wt.-%). Flat samples with the dimensions 110 x 24 x 2 mm^3 were machined. The parameters of the heat treatments which were performed in a vacuum furnace (Fa. Degussa) are summarized in Tab. 1.

Designation	Heat treatment	Vickers-Hardness
normalized	930 °C / 3h, furnace cooling	HV 230
T 650	850 °C / 20 min → oil 25 °C + 650 °C / 2h, furnace cooling	HV 295
T 450	850 °C / 20 min → oil 25 °C + 450 °C / 2h, furnace cooling	HV 430
T 300	850 °C / 20 min → oil 25 °C + 300 °C / 2h, furnace cooling	HV 525
T 180	850 °C / 20 min → oil 25 °C + 180 °C / 2h, furnace cooling	HV 600
quenched	850 °C / 20 min → oil 25 °C	HV 660

Tab. 1: Heat treatment conditions and Vickers-hardness

EXPERIMENTAL DETAILS

All shot peening treatments were carried out simultaneously from both sides using an air blast machine (Fa. Baiker). The nozzles had a diameter of 8 mm. The distance z between nozzle and sample was always z = 80 mm and the peening angle was 90°. For the parameter variation, the peening pressure p was adjusted between 1.6 and 8 bar and the mass $\dot{m}$ flow between 1.5 and 10 kg/min. For the variation of the shot type, S110 46HRC, S170 46HRC, S170 56HRC and S330 56HRC were used. The average diameter of the shots is 0.28 mm for S110, 0.43 mm for S170 and 0.84 mm for S330. In order to reduce the shot deformation and wear, S170 56HRC was used for the peening pressure and mass flow variation for the quenched and quenched and tempered conditions with tempering temperatures 180 °C and 300 °C (T180, T300). For the larger mass flows, a peening pressure of 3 bar was chosen, in order to prevent the hoses from plugging. The residual stresses were determined using the $\sin^2$-ψ-method [28] with a CrKα-radiation on the {211}-interference plane. The residual stress and half width measurements at the subsurface layers were carried out after removing thin layers with an electrolytical polishing technique, in steps of 0.025 mm up to a depth of 0.4 mm. The measured residual stress distributions were corrected for the surface removal applying the method according to [29].

RESULTS

Influence of workpiece hardness

The influence of the workpiece hardness on the surface properties after shot peening at constant peening parameters - S170 46 HRC, peening pressure p = 1.6 bar, mass flow $\dot{m}$ = 1.5 kg/min and Almen intensity = 0.3 mmA - was studied at all six different heat treatment conditions.

Fig. 1 presents the surface roughness R_t after shot peening as a function of workpiece hardness. For the normalized condition R_t increases by a factor of 10. For the quenched condition the surface roughness is almost the same for both the peened and the unpeened samples.

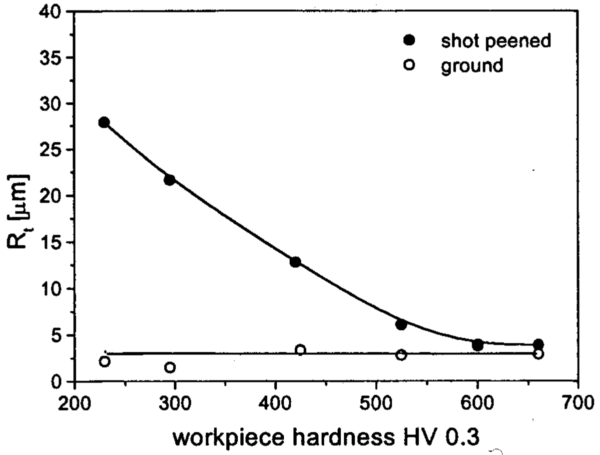

Fig.1: **Surface roughness before and after shot peening vs. workpiece hardness (S170 46HRC, p = 1.6 bar, $\dot{m}$ = 1.5 kg/min)**

The residual stress distribution of the shot peened samples can be seen from Fig. 2a, which show an increasing amount of residual stresses at the direct surface layer for the normalized condition up to the tempered condition T450. With increasing sample hardness the residual stresses at the surface decrease. The depth x_0, where the residual stresses change their sign decreases with increasing workpiece hardness. Only the T180 condition (600 HV) shows a smaller x_0 than the quenched condition (660 HV). For increasing sample hardness a characteristic maximum of compressive residual stresses can be found below the surface, in a depth of 0.05 mm. Its value amounts to σ^{rs} = -800 N/mm^2.

In Fig. 2b the half width distributions after shot peening can be seen as a function of the distance from surface for the different heat treated samples. The curves for the normalized and the quenched and tempered samples T650 are similar. However, the half width values for the normalized condition are somewhat smaller than those for T650. Both curves show increasing values at the surface. The half width values for T450 are constant. After shot peening, in the case of T180, T300 and the quenched conditions half widths in the area close to the surface are smaller than those measured in deeper regions of the sample. There exists a minimum beneath the surface nearby 0.05 mm and a relative maximum at the surface, respectively.

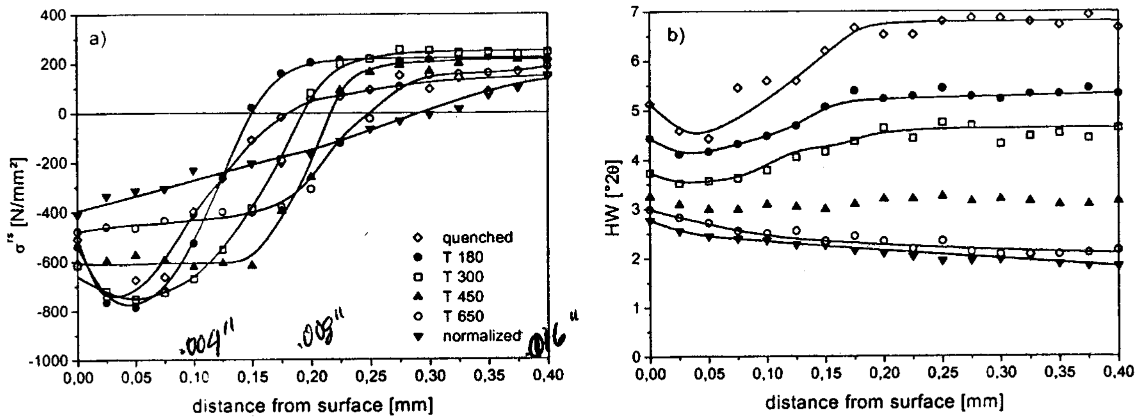

Fig 2: **Residual stresses (a) and half widths (b) vs. distance from surface for different heat treatment conditions (S170 46HRC, p = 1.6 bar, ṁ = 1.5 kg/min)**

Influence of shot type

The influence of the shot type was also studied at all six different heat treatment conditions. Four different shots were used. The other peening parameters, which are summerized in Tab. 2, were held constant.

Shot type	Peening pressure [bar]	Mass flow [kg/min]	Almen intensity [mmA] [illegible] A
S110 46HRC	1.6	1.5	0.20 4
S170 46HRC			0.30 12
S170 56HRC			0.31 12
S330 56HRC			0.50 20

Tab. 2: **Peening parameters used in order to investigate the influence of the shot type on the surface properties**

Fig. 3 presents the surface roughness R_t of the samples after shot peening, which increases with decreasing sample hardness for all shot types. If shot size or shot hardness increase, the surface roughness rises for all heat treatment conditions. The softer the workpiece conditions, the more obvious the differences are.

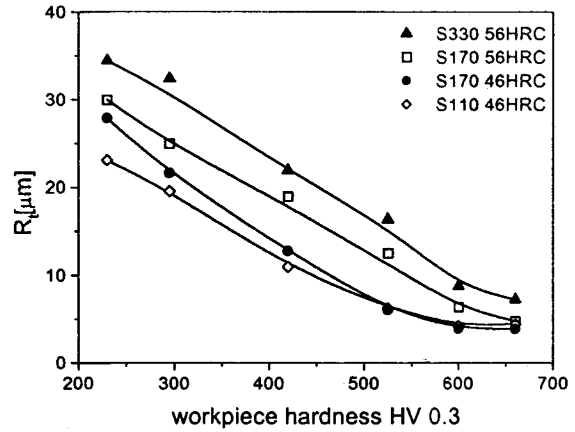

Fig. 3: **Surface roughness vs. workpiece hardness for different shot types (p = 1.6 bar, ṁ = 1.5 kg/min)**

The influence of the shot type on the residual stress distribution can be seen for the quenched and tempered condition T450 in Fig. 4. The depth where the residual stresses change their sign increases with the shot diameter, whereas the residual stresses up to a depth of 0.1 mm beneath the surface are not affected. For a constant shot size, the hardness of the shots has no influence on the residual stress distribution.

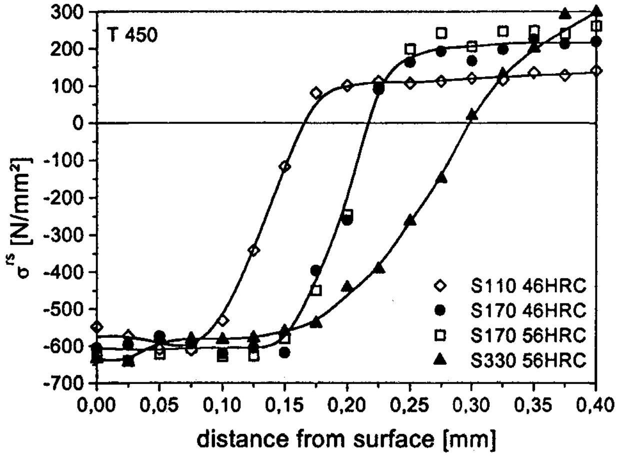

Fig 4: **Residual stresses vs. distance from surface for different shot types at the quenched and tempered T 450 (p = 1.6 bar, ṁ = 1.5 kg/min)**

Influence of the peening pressure

Tab. 3 represents the peening parameters for the variation of peening pressure. The shot S170 46HRC was used for the normalized as well as for the T650 and the T450 condition. The harder workpiece conditions were peened with the shot S170 56HRC in order to avoid shot deformation and wear.

Heat treatment	Shot type	Peening pressure [bar]	Mass flow [kg/min]	Almen intensity [mmA]
normalized	S170 46HRC	1.6	1.5	0.3
T 650		5		0.59
T 450		8		0.68
T 300	S170 56HRC	1.6	1.5	0.31
T 180		5		0.61
quenched		8		0.70

Tab. 3: Peening parameters used to investigate the influence of the peening pressure on the surface properties

The influence of the peening pressure on the surface roughness R_t is described in Fig. 5 for the different heat treatment conditions. For the normalized and the T650 conditions the surface roughness increases up to the maximum peening pressure p = 8 bar. The surface roughness for the T450 and T300 conditions first of all increases with p and R_t is constant for peening pressures above p = 5 bar. The surface roughness of the T180 and the quenched conditions is not significantly affected by the peening pressure.

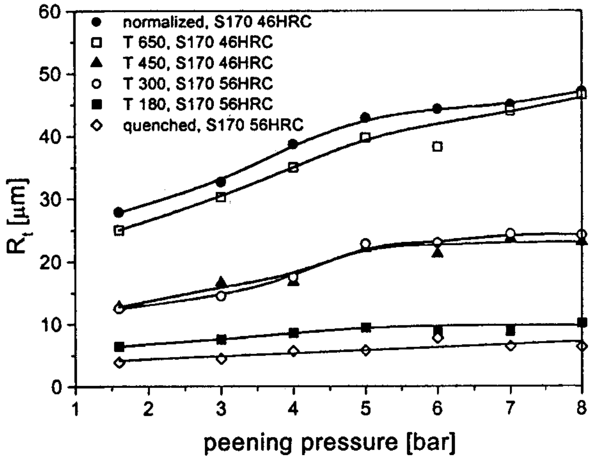

Fig. 5: Surface roughness vs. peening pressure at different heat treatment conditions (S 170 46HRC or S 170 56HRC, $\dot{m}$ = 1,5 kg/min)

The residual stress distributions for different peening pressures were measured for the quenched conditions (Fig. 6a).The residual stresses are independent of the peening pressure. The distance from the surface of the maximum compressive residual stresses and the depth, where the residual stresses change their sign increase with increasing peening pressure, however, the value of the maximum remains almost constant.

The distributions of the half widths are illustrated in Fig. 6b and show that an increase of the peening pressure leads to a decrease of the half widths for the quenched condition up to a distance from surface of 0.275 mm. A peening pressure of 8 bar affects a further decrease of the half widths compared to the curve for p = 5 bar.

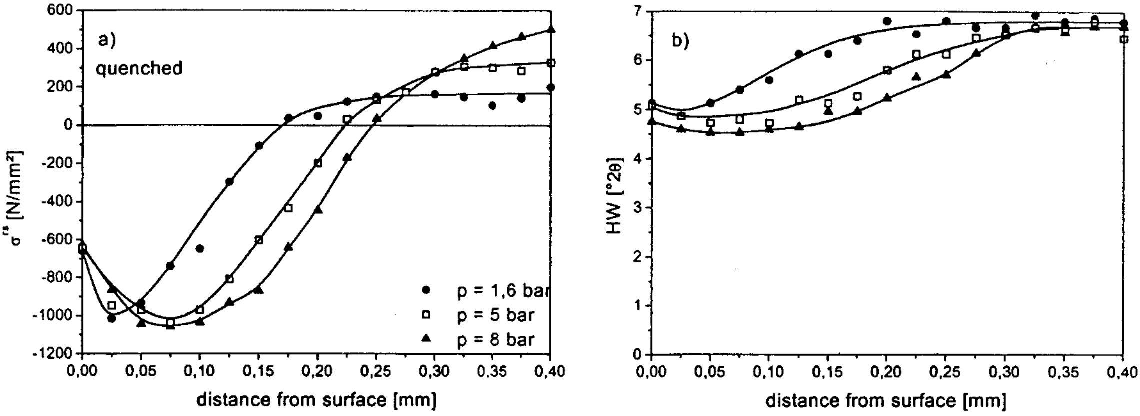

Fig. 6: Residual stresses (a) and half widths (b) vs. distance from the surface for different peening pressures at the quenched condition (S 170 56HRC, $\dot{m}$ = 1.5 kg/min)

Influence of the mass flow

The mass flow variation was carried out for the investigations using the peening parameters shown in Tab. 4. As before, the harder material conditions (T300, T180, quenched) were peened with the shot S170 56HRC.

Heat treatment	Shot type	Mass flow [kg/min]	Peening pressure [bar]	Almen intensity [mmA]
normalized	S170 46HRC	1.5	3	0.44
T 650		6		0.35
T 450		10		0.35
T 300	S170 56HRC	1.5	3	0.47
T 180		6		0.38
quenched		10		0.36

Tab. 4: Peening parameters used to investigate the influence of the mass flow on the surface properties

In Fig. 7 the surface roughness values for the different material conditions are shown as a function of the mass flow $\dot{m}$. For the normalized and the T650 conditions the surface roughness decreases with increasing mass flow. For harder workpiece conditions the decrease of the surface roughness diminishes. For all conditions, however, the surface roughness for $\dot{m}$ = 10 kg/min is smaller than the one for $\dot{m}$ = 1.5 kg/min.

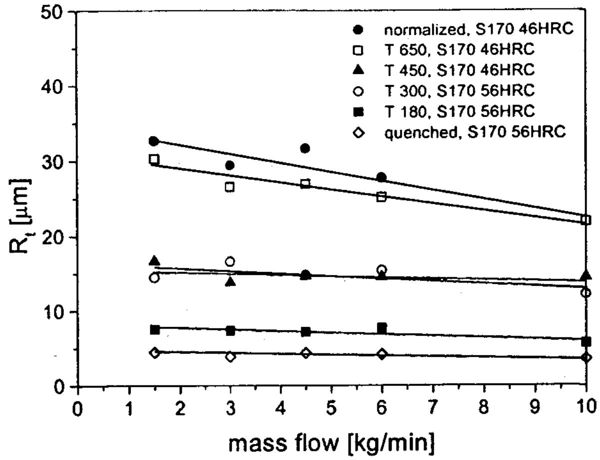

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Fig. 7: Surface roughness vs. mass flow at different heat treatment conditions (S 170 46HRC or S 170 56HRC, p = 3 bar)

The effect of the mass flow variation on the residual stress distribution is shown in Fig. 8 for the T450 condition. The mass flow has no significant influence on the compressive residual stresses up to a distance from the surface of 0.1 mm. At larger distances from the surface the compressive residual stresses decrease with increasing mass flow, combined with a reduction of the depth x_0 where the residual stresses change their sign.

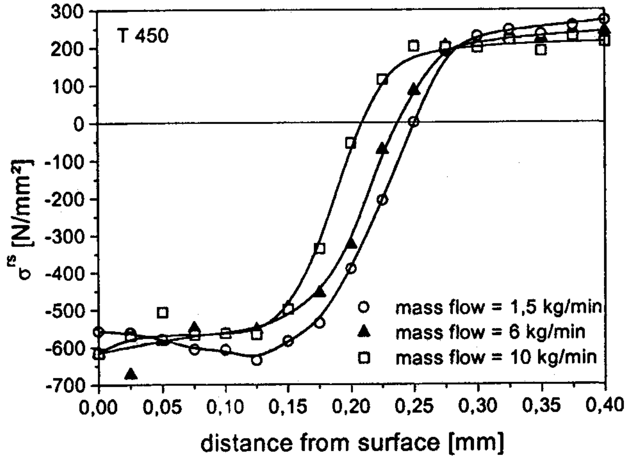

Fig. 8: Residual stresses vs. distance from surface for different mass flows at the quenched and tempered condition T450 (S 170 46HRC, p = 3 bar)

DISCUSSION

The results which are presented for different heat treatment conditions at constant peening parameters confirm the model [23], which describes the residual stress formation during shot peening. The maximum value of the compressive residual stresses of the normalized condition, which shows the smallest hardness (230 HV) of the materials investigated, exists directly at the surface. This finding is explained in [23] by the dominating hammering effect of the shots, which causes the highest amount of plastic deformation on the surface. The location of the maximum compressive residual stress, however, is beneath the surface for the T300, T180 and the quenched conditions, which can be explained by the dominating effect of the Hertzian stress, which has its maximum below the surface. For the T450 and the T300 conditions, which have a hardness of 430 HV and 525 HV, the values of the compressive residual stresses show a plateau like region with almost constant residual stresses which starts at the surface. After this plateau the amount of the residual stresses decreases. The maximum value of the compressive residual stresses increases with increasing workpiece hardness up to the T180 condition (600 HV) but slightly decreases for the quenched condition (660 HV). This behaviour can be explained in this connection with the course of the depth x_0, where the residual stresses change their sign. x_0 decreases with increasing workpiece hardness in agreement with the model of [23] or, more exactly, with increasing material resistance against the onset of plasticity. However, an exception in this case is the T180 condition which shows the minimum value of x_0 but has a hardness which is smaller than that of the quenched condition. This is caused by the fact that the 0.01-proof stress is larger in the T180 condition than in the quenched condition due to the pinning of dislocations by the solute carbon atoms and by fine carbide precipitations [30].This work hardening effect cannot be detected in hardness measurements, because the plastic deformation caused by the hardness pyramid is so large that all moveable dislocations are broken away from their pinning points.

The half widths are a measure of the microstructural work hardening or softening in the surface layers. In Fig. 2a it can be recognized that the half widths for conditions with HV < 300 increases in the surface layers compared to the values in deeper regions of the sample. This behaviour indicates microstructural work hardening effects due to the peening induced multiplication of dislocations [24]. In contrast to this behaviour, the half widths decrease in the surface layers in the case of harder workpiece conditions (HV > 500), i.e. that in conditions with very high dislocation densities before peening a microstructural softening process occurs. This is caused by a rearrangement of dislocations in energetically more favourable positions combined with reduced mean microstrains as well as by annihilation of dislocations. Furthermore, in quenched conditions stress induced rearrangements of soluted carbon atoms can occur during peening into octahedral sites due to the Snoek-effect. This reduces lattice distortions and can contribute also to the decrease of the half width values [27]. In case of the T450 condition the half widths do not change by shot peening. This indicates that the work hardening effect due to dislocation generation and the work softening effect due to dislocation annihilation and rearrangement balance each other.

With increasing shot size the depth x_0, where the residual stresses change their sign, is increasing for all heat treatment conditions at constant shot hardness. The increase of the depth x_0 and of the distance from surface of the maximum residual stress can be explained by the larger mass of each shot, which increases its impulse. This enlargement of the shot impulse also causes a larger plastification of the direct surface layer and increases the thickness of the penetrated layer.

In all the material conditions an increasing peening pressure causes a larger depth x_0 which is in agreement with the results in [3-8]. Thereby the surface residual stresses are constant, while other investigations report as well an increase [6] as a decrease due to overpeening by multiple coverage. The constant residual stresses at the surface can be explained by the same effect mentioned for the variation of the shot size. At the harder workpiece conditions the shift of the maximum value of the compressive residual stresses is caused by the location of the maximum Hertzian shear stress. When the peening pressure is increased, the surface roughness increases as a sign of larger shot impacts. This behaviour is combined with an increase of the location of the maximum shear stress.

Higher peening pressures effect an increase of the half widths in the surface layers due to larger plastifications in the surface layers and an enlargement of the dislocation density in this region. However, for the harder workpiece conditions the half widths in the layer close to the surface are decreasing with increasing peening pressure. In this case the dislocations which were generated with high density by quenching can rearrange during peening into energetically more stable configurations with reduced mean microstrains.

An enlargement of the mass flow for all material conditions yields a decrease of x_0. This is due to the fact that the probability of mutual pushes of the shots in the nozzles and the hoses increases with the mass flow. Thereby a decrease of the kinetic energy stored in the shots occurs which causes smaller x_0. For the softer material conditions the mass flow has no influence on the surface residual stresses. At first sight, these results are contradictory to other investigations [4,9,16], where an increase of the mass flow is considered to be equivalent to an increasing coverage. An increase of the coverage, however, can be reached not only by an increasing mass flow but also due to a prolongation of the exposure time which can be realized for an air blast system with a decreasing nozzle velocity. A comparison of the residual stress distribution after shot peening with different mass flow the same coverage for normalized samples can be seen in Fig. 9. One sample was shot peened with a mass flow of 10 kg/min and an exposure time of t = 16 s. The other was peened with a mass flow of 1.5 kg/min and an exposure time of t = 106 s, which was theoretically determined in order to get the same coverage. Under the latter conditions the depth x_0 becomes larger. Therefore, an increase of the coverage via the mass flow can cause other residual stress distributions than an increase via the exposure time. A comparison of these findings and the results of other investigations is problematic because there the coverage was determined by the exposure time.

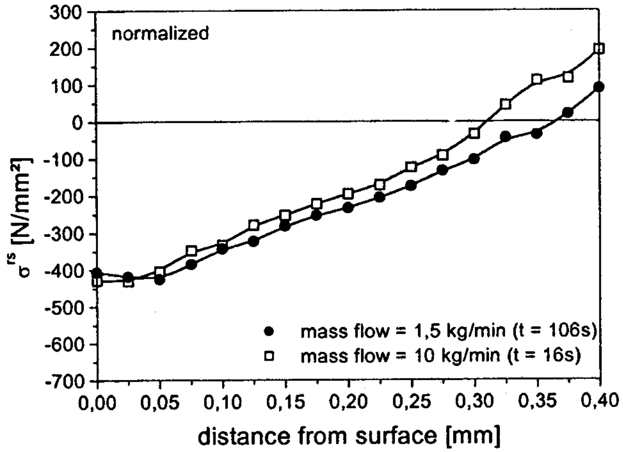

Fig. 9: **Residual stresses vs. surface distance for different mass flows and exposure times at the normalized condition and coverage (S170 46HRC, p = 3 bar)**

The depth x_0 where the residual stresses change their sign and the depth where the half widths reach the values of an unpeened sample do not always correspond to each other. Obviously, different processes are responsible for the change of the residual stresses and the half widths. The compressive residual stresses result from a plastification of the surface layers balancing the residual stresses over the entire cross section of a sample. Therefore, x_0 does not necessarily correspond to the depth of the plastification. The half width value on the other hand is affected by microstructural processes (dislocation multiplication or dislocation rearrangement in energetically more stable positions combined with annihilation processes) and shows the true depth of the influenced material layer by shot peening.

The results presented here allow to judge how far the Almen intensity enables conclusions concerning stress distribution. In principle three properties are of interest in this context, the residual stress value at the surface, the depth and the value of the maximum compressive residual stress and the depth x_0 where the residual stresses change their sign. A correlation of the Almen intensity with the surface value of the residual stresses does not appear to be useful because the surface value of the residual stresses is not significantly affected by the peening parameters in many cases. The depth and the value of the maximum compressive residual stress are certainly not useful, because they are directly on the surface for softer workpiece conditions. The depth x_0 drawn as a function of the Almen intensity in Fig. 10, leads to reasonable correlations. Here the x_0 and the corresponding Almen intensity can be seen for the normalized, the T450 and the quenched material conditions showing linear relationships, with x_0 increasing with increasing Almen intensity.

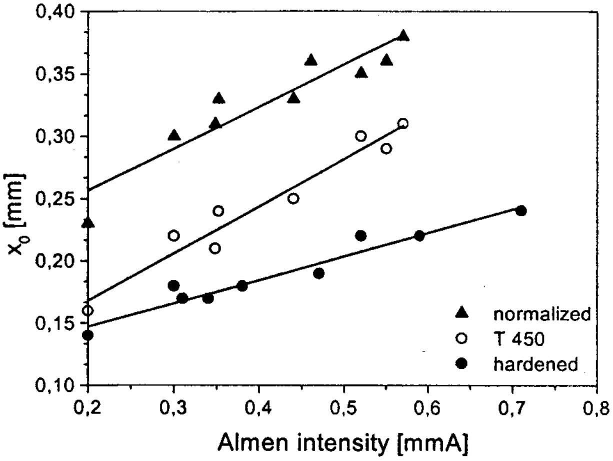

Fig. 10: **Depth x_0 where the residual stresses change their sign vs. Almen intensity for different heat treatment conditions**

SUMMARY

Fig. 11 summarizes schematically the influence of the peening parameters on the residual stress distribution. The arrows show the shift direction of the residual stress distribution when the indicated parameter increases.

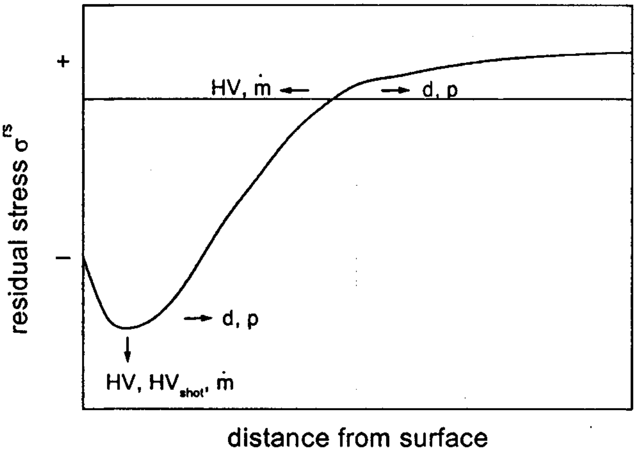

Fig. 11: **Influence of the peening parameters on the residual stress distribution (schematically)**

It can be seen that an increase of the workpiece hardness HV results in a decrease of the depth x_0 where the residual stresses change their sign and in a formation of a maximum compressive residual stress value below the surface which also increases with increasing hardness. An increase of the shot hardness HV$_{shot}$ effects an increase of the maximum compressive residual stress only for harder material conditions. A growth of the mass flow $\dot{m}$ results in a smaller x_0 and, for a coverage below 100%, in an increase of the maximum compressive residual stress. Furthermore a higher peening pressure p and a larger shot size d cause an

increasing x_0 and an enlargement of the surface distance of the maximum value of the compressive residual stresses.
Finally it remains to be mentioned that with increasing workpiece hardness the half width values of the surface layers show a transition from microstructural hardening to softening. The peening pressure is not the only parameter which has an decisive effect on the half widths.

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