THE SIGNIFICANCE OF ALMEN INTENSITY FOR THE GENERATION OF SHOT PEENING RESIDUAL STRESSES

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ABSTRACT

Basic peening parameters of shot peening processes are mean shot velocity , mass flow and peening time as well as material, geometry, dimension and hardness of the shots and the parts to be treated resp. Nevertheless in practice, besides specifications of type and hardness of the material and the shot peening medium resp., peening operations are pragmatically characterized by Almen intensity and coverage. Whereas reproducibility of shot peening processes can be obtained in this way, it is not unambiguous with respect to the resulting shot peening residual stress distributions. In this paper, this aspect is investigated using quenched and tempered shot peened steel of the German grade X 35 CrMo 17 and aluminium base alloy Al 7020 as examples. Characteristic residual stress depth profiles are shown, realized using a variation of Almen intensities and shot diameters. The resulting residual stress distributions are discussed taking into account the amounts of compressive residual stresses as well as thicknesses of affected surface layers..

KEYWORDS

Almen intensity; residual stress; coverage; shot diameter; stress analysis

INTRODUCTION

Shot peening is a mechanical surface treatment to improve properties of components under fatigue loading, in corrosive environments or during fretting fatigue. This is due to the resulting near surface materials states as a consequence of inhomogeneous plastic deformations and , in case, phase transformations. Residual stresses and strain hardening effects have to be mentioned first of all.

Process parameters for appropriate shot peening operations are determined empirically in most cases, because theoretical modelling is not sufficiently reliable. For that purpose experimental work is necessary or experiences already gained have to be used. In all cases, it is necessary, to describe peening processes by such parameters, which unambiguously specify consequences of the shot peening process on near surface materials properties. In the case of fundamental research about shot peening (see e. g. /1 - 11/), consequences of elementary peening parameters mean shot velocity or peening pressure, mass flow and peening time (related to area) as well as properties of peening media and materials to be treated (type and state of the material, geometry, volume and hardness) are analysed. In Fig. 1. influence of these parameters on resulting residual stress distributions is schematically shown / 11, 12/. In practice, however, peening processes are not described by the above mentioned process parameters, but by Almen intensity, coverage and type of the peening medium used /13, 14/. Shot peening processes can be reproduced if these parameters are known. However, there is no clear correlation with resulting residual stress distributions. Therefore the consequences of such shot peening treatments in individual cases are difficult to assess. This paper deals with this problem using examples of differently shot peened quenched and tempered steel as well as aluminium base alloy.

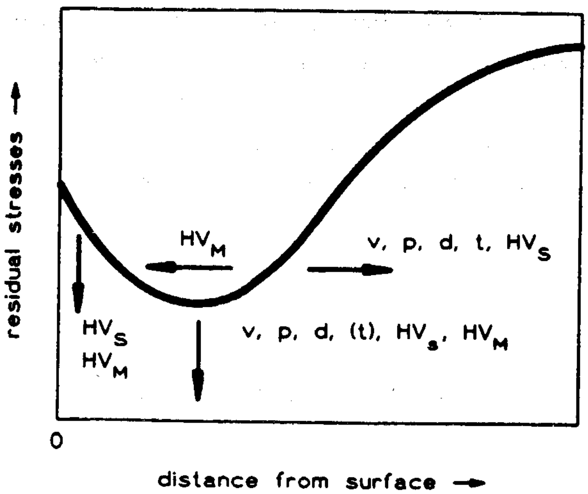

Fig. 1: Consequences of elementary peening parameters on residual stress development /10, 11/

hardness of material	HV_M
hardness of shots	HV_S
shot diameter	d
mass flow	$\dot{m}$
shot velocity	v
pressure	p
peening time	t

MATERIALS AND EXPERIMENTAL PROCEDURES

Materials investigated were the quenched and tempered steel X 35 CrMo 17 with 0.32 C, 15.18 Cr, 0.91 Mo, 0.8 Ni, 0.55 Si, 0.59 Mn, 0.0355 P, 0.005 S, rest Fe (wt.-%)and the age hardened aluminium base alloy Al 7020 with 0.17 Si, 0.35 Fe, 0.11 Cu, 0.29 Mn,

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1.24 Mg, 0.16 Cr, 4.66 Zn, 0.16 Ti + Zr, rest Al (wt.-%). Flat specimens of steel were heat treated (950^{0}C, 20 min -> oil + 700^{0}C, 60 min -> air) and ground prior to shot peening to a thickness of 3 mm. 6 mm thick Al 7020 - specimens were peened as delivered. Mechanical properties of the materials investigated are listed in Tab. 1.

Table 1: Mechanical properties of materials investigated

		X 35 CrMo 17	Al 7020
R_m	[N/mm^2]	940	394
$R_{po,2}$	[N/mm^2]	775	344
A	[%]	15,5	13,3
HV 5		330	105

In all cases, cast - steel shot as peening medium was used with a hardness of 450 - 550 HV and a constant coverage of $2 * t_{98\%}$ was maintained. Shot diameter and Almen intensity were varied. In Tab. 2 all peening variations investigated are summarized. Residual stress analyses were carried out using a computerized ψ - diffractometer following the $\sin^2\psi$ - technique of X - ray stress analysis /15/. In the case of steel {211} - planes of ferrite with Cr Kα - radiation, in the case of aluminium base alloy {511/333} - planes with Cu Kα - radiation were measured. To calculate stresses experimentally determined X - ray elastic constants were used. Depth distributions of residual stresses were analysed by successive electrolytical layer removal.

Table 2: Parameter of the shot peening treatments

Variant	Material	Shot diameter	Almen intensity
1	X 35 CrMo 17	0,58 mm (S 230)	0,1 mmA
2	X 35 CrMo 17	0,58 mm (S 230)	0,2 mmA
3	X 35 CrMo 17	0,84 mm (S 330)	0,2 mmA
4	X 35 CrMo 17	0,84 mm (S 330)	0,3 mmA
5	X 35 CrMo 17	1,40 mm (S550)	0,3 mmA
6	X 35 CrMo 17	1,40 mm (S550)	0,4 mmA
7	Al 7020	0,58 mm (S 230)	0,2 mmA
8	Al 7020	0,58 mm (S 230)	0,3 mmA
9	Al 7020	0,84 mm (S 330)	0,2 mmA
10	Al 7020	0,84 mm (S 330)	0,3 mmA

in all cases: Coverage: $2 * t_{98\%}$; Hardness of shots: 450 - 550 HV

RESULTS AND DISCUSSION

For all shot peened variants of steel X 35 CrMo 17, despite different peening parameters, nearly the same surface residual stress values were measured (see Figs. 2 - 4). Maximum shot peening residual stresses were detected immediately at or below the surface. Also the amount of maximum compressive residual stresses was only slightly influenced by the process parameters used. Distinct differences, however, were detected regarding the depth distributions and the thicknesses of the layers with compressive residual stresses. This is additionaly confirmed by depth distributions of interference line half - width values not presented here.

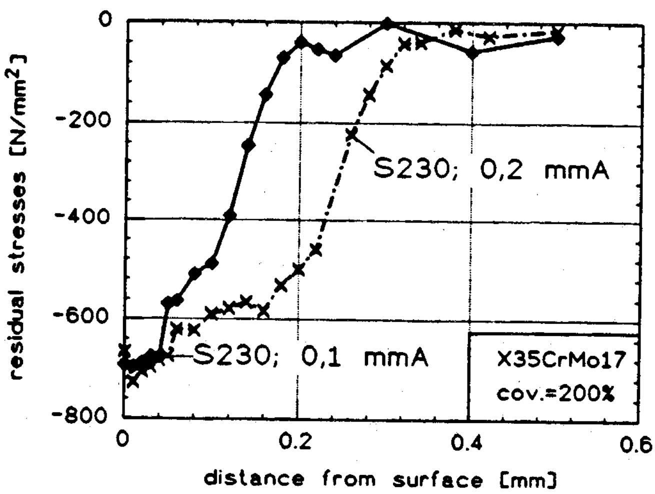

Fig. 2: Residual stress, depth distribution of variant 1 (S230; cov. = 200%; i = 0,1 mmA) and variant 2 (S230; cov. = 200%; i = 0,2 mmA)

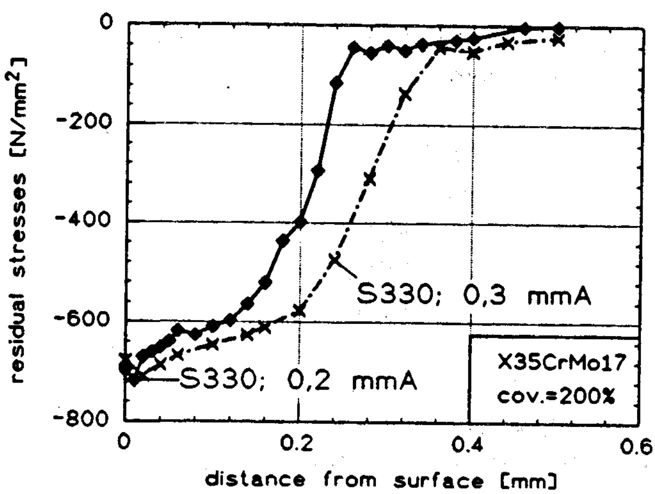

Fig. 3: Residual stress, depth distribution of variant 3 (S330; cov. = 200%; i = 0,2 mmA) and variant 4 (S330; cov. = 200%; i = 0,3 mmA)

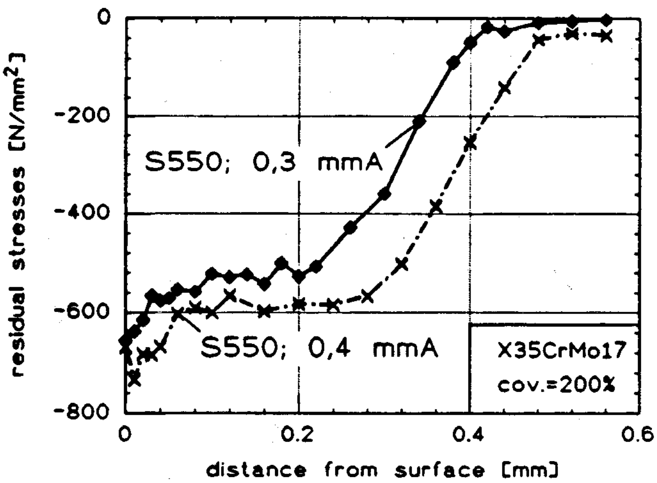

Fig. 4: Residual stress, depth distribution of variant 5 (S550; cov. = 200%; i = 0,3 mmA) and variant 6 (S550; cov. = 200%; i = 0,4 mmA)

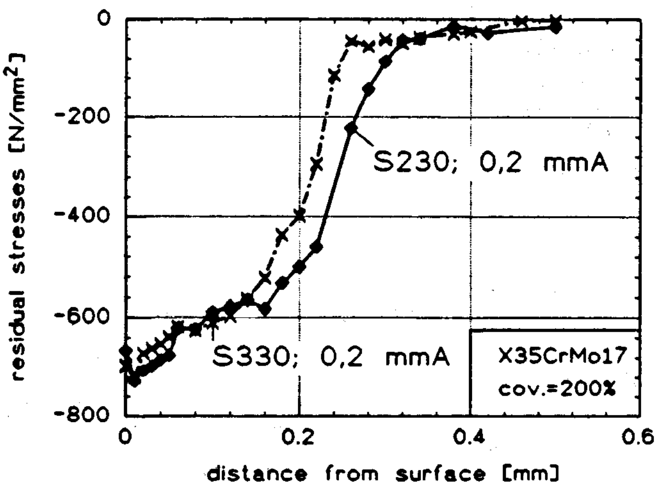

Fig. 5: Consequences of shot diameter on residual stress development of steel X 35 CrMo 17 using a peening intensity of 0.2 mmA

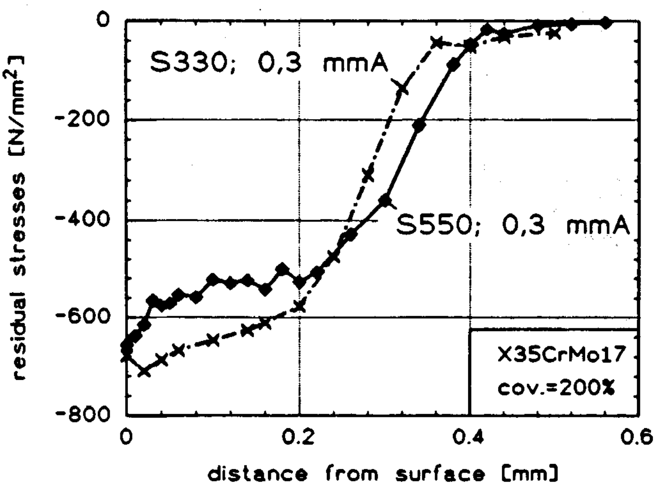

Fig. 6: Consequences of shot diameter on residual stress development of steel X 35 CrMo 17 using a peening intensity of 0.3 mmA

Also for Al 7020 different shot peening treatments used yield almost identical residual stresses near the surface, but surface layers with compressive residual stresses of different thickness (see Figs. 7 and 8).

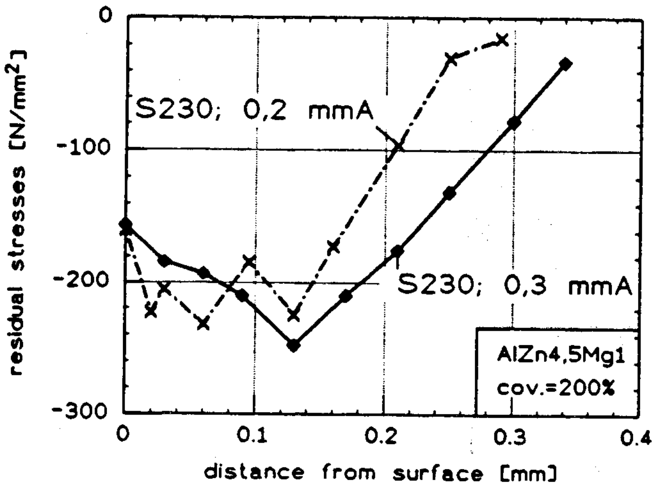

Fig. 7: Residual stress, depth distribution of variant 7 (S230; cov. = 200%; i = 0,2 mmA) and variant 8 (S230; cov. = 200%; i = 0,3 mmA)

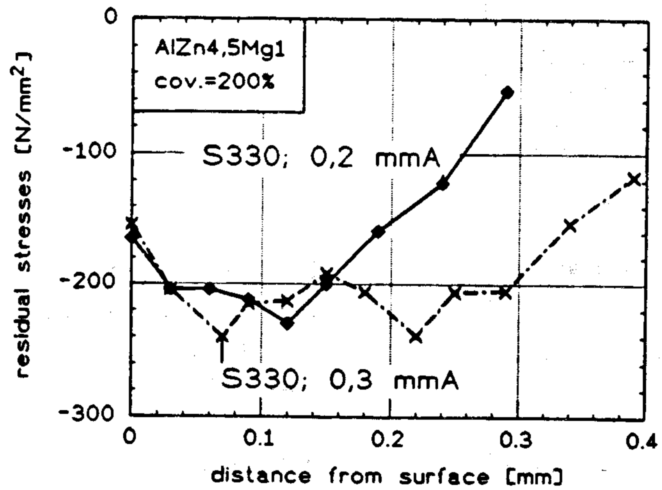

Fig. 8: Residual stress, depth distribution of variant 9 (S330; cov. = 200%; i = 0,2 mmA) and variant 10 (S330; cov. = 200%; i = 0,3 mmA)

In shot peening, kinetic energy of the shots striking with high velocity against the materials surface is partly used for plastic deformations of near surface layers. Kinetic energy of a particle with mass m and velocity v is given by

$$E_{kin} = 0.5\, m\, v^2. \tag{1}$$

Therefore, kinetic energy of the shots taking part in the shot peening process can be described by

$$E_{kin} = 0.5\, \dot{m}\, t\, \bar{v}^2 \tag{2}$$

with $\dot{m}$: mass flow, $\bar{v}$: mean shot velocity and t: peening time. Energy transfer from the shots to the material happens by a partly elastic impact, and loss of kinetic energy of the shots is described by

$$\Delta E_{kin} = E_{kin}(1 - \varepsilon^2) \tag{3}$$

with ε depending on the properties of impact partners, describing consequences of plastic deformations, friction, fracture processes and heat production. Finally using eq. (2)

$$\Delta E_{kin} = 0.5\, \dot{m}\, t\, \bar{v}^2 (1 - \varepsilon^2) \tag{4}$$

is valid, which describes energy exchange during impact process in a general way. Taking into account, that heat production as a consequence of friction and plastic deformation processes is small and neglecting fracture processes, ΔE_{kin} is entirely used for plastic deformation of shots and the material treated. Energy fraction used for plastic deformation of shots or material resp. is, as it is the case for ε, determined by the deformation behaviour of the impact partners.

Today, it is accepted that plastic deformation of materials during spot peening operations is based on two mutually interacting processes /2/. Plastic straining of surface layers occurs, and as a consequense of the deformation distribution connected, maximum compressive residual stresses at the surface result. On the other hand, due to Hertzian pressure between shots and materials surface, maximum shear stresses at a surface distance

$$z_{\tau max} = 0.47\, a \tag{5}$$

occur with 2a: diameter of contact area. The superposition of both partial processes yields residual stress distributions characteristic for shot peened surfaces. Obviously not only kinetic energy of the shots is of importance, but also contact geometry determines amount and depth distribution of plastic deformation.

A qualitative assessment of the influence of process parameters on resulting residual stress distributions is shown in Fig. 1. Quite a number of experimental investigations have essentially confirmed this schematic diagram. The above mentioned considerations about energy exchanges are fully in agreement with Fig.1, taking into account that, in general, hardness of shots and material can be correlated with ε and, hence, with plastic deformations.

Up to now, elementary independent shot peening process parameters have been used to discuss consequences of the process. If, however, practically used parameters Almen intensity and coverage are taken into consideration, problems arise in explaining resulting residual stress distributions. This is due to the fact that Almen intensity as well as coverage depend on several of the elementary process parameters. Coverage e. g. is controlled by elastic plastic deformation behaviour of impact partners, but also by contact geometry and, hence, by geometry of shots and material to be treated as well as by mass flow, peening time and peening velocity. If. e. g. equal peening intensities and coverages with shots of different geometries have to be realized, at least one further elementary peening parameter has to be adapted. One can clearly see that given values of Almen intensity or coverage resp. can be achieved as a consequence of quite different elementary processes. Consequently, the same values of Almen intensity or coverage can be connected with quite different distributions of plastic deformations and hence residual stresses in near surface layers. This is verified by the results presented in this paper. If. e. g. residual stress depth distributions, realized by peening with equal values of Almen intensity and coverage, but different shot diameters, are compared, a clear influence of the diameter of the peening medium used can be seen. Shot peening treatments of Al 7020 with small (0.2 mmA, see Fig. 9) as well as with high intensities (0.3 mmA, see Fig. 10) yield thicker surface layers with compressive residual stresses, if larger shot diameters are used. Amounts of maximum compressive residual stress, however, remain almost unchanged. For steel X 35 CrMo 17, however, a different influence of shot geometry is observed. For a peening intensity of 0.2 mmA, smaller diameters lead to thicker affected surface layers, but do also not influence the amount of maximum compressive residual stresses (see Fig. 5). For 0.3 mmA, however, in the case of shots S330 and S550 resp. the larger diameter increases thickness of the affected surface layer. Here, only at the very surface, identical amounts of compressive residual stresses are observed (see Fig. 6). Distributions of half - width valus of interference lines agree well with characteristic features of residual stress depth distributions.

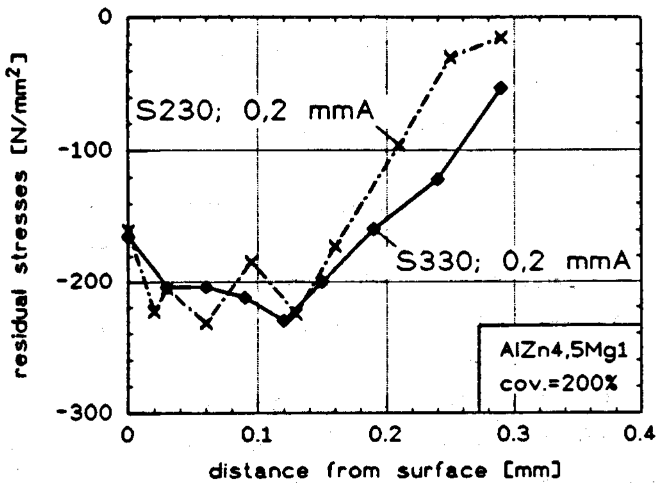

Fig. 9: Consequences of shot diameter on residual stress development of aluminium alloy Al 7020 using a peening intensity of 0.2 mmA

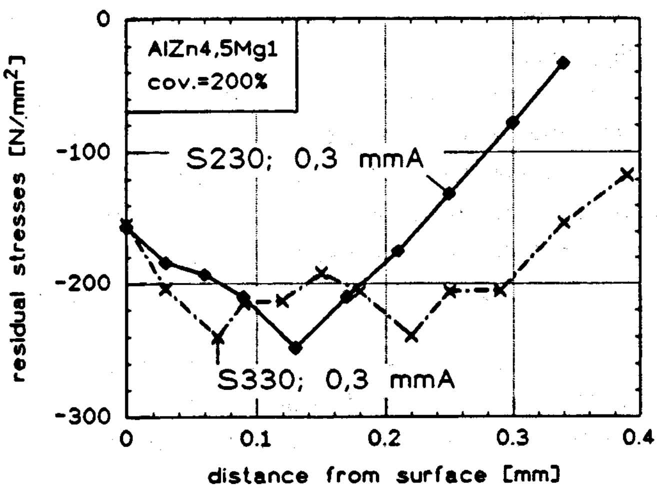

Fig. 10: Consequences of shot diameter on residual stress development of aluminium alloy Al 7020 using a peening intensity of 0.3 mmA

These experimental observations can be understood if it is taken into account that peening with equal Almen intensity, but different shot diameters means that besides shot geometry at least one further basic peening parameter has to be changed. Consequently residual stress depth distributions presented are not only influenced by variations of shot diameter, but are consequences of characteristic combinations of shot peening process parameters.

Increasing peening intensity, keeping shot diameter and coverage constant, yields in all cases investigated here a lager effective depth of compressive residual stresses (see Figs. 2 - 4, 7 and 8). However, this observation cannot be generalized in all cases.

Hardness of shots as well as of materials treated are looked upon as elemetary shot peening process parameters. From Fig. 1 follows, that increasing materials hardness leads to higher amounts of compressive residual stresses, but smaller penetration depths. With respect to the residual stress depth distributions presented in this paper, it turns out that consequences of hardness, peening intensity and shot diameter are correlated. As expected, for Al 7020 smaller amounts of shot peening residual stresses are produced than for steel X 35 CrMo 17. If, however, affected surface layer thickness is taken into consideration (see Figs. 11 - 13), no clear tendency of the effect of workpiece hardness can be stated. Only for the shot peening variant "S330/0.3 mmA" (see Fig. 13), as expected, a thicker layer with compressive residual stresses was observed for Al 7020 compared with steel. For "S330/0.2 mmA" (see Fig. 12) thickness of affected surface layer is nearly equal for both materials and for "S230/0.2 mmA" (see Fig. 11) surface layer of Al 7020 is smaller than for steel X 35 CrMo 17. This is also due to the fact that residual stresses are, finally, controlled by the amount and distribution of shot peening induced plastic deformations. For comparable material states, e.g. for quenched and tempered steels of different tempering temperature, specification of hardness may correlate with elastic plastic deformation behaviour of the materials. But for completely different materials as it is the case here, from hardness values alone no clear conclusions can be drawn about amount and distribution of residual stresses to be expected. Moreover, elastic - plastic and cyclic deformation behaviour is of importance.

The results presented clearly indicate, that, using Almen intensity as process parameter alone, residual stress distributions cannot be reproduced in an unambiguous way. Only the use of elementary process parameters allows to predict shot peening residual stresses.

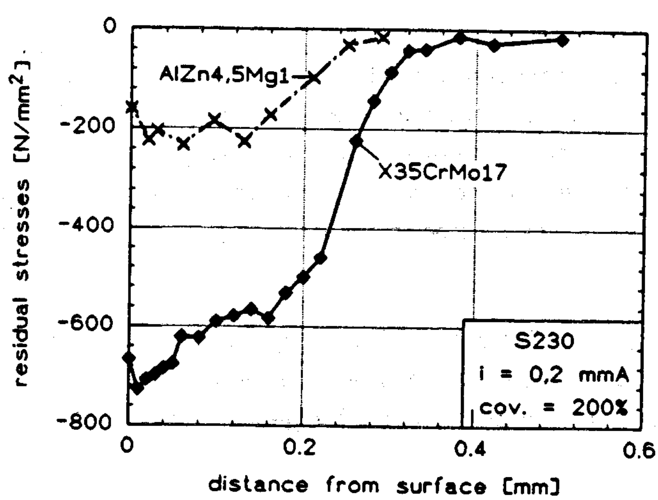

Fig. 11: Depth distribution of residual stress after identical shot peening treatment (S230; i = 0,2 mmA; cov. = 200%) of X 35 CrMo 17 and Al 7020

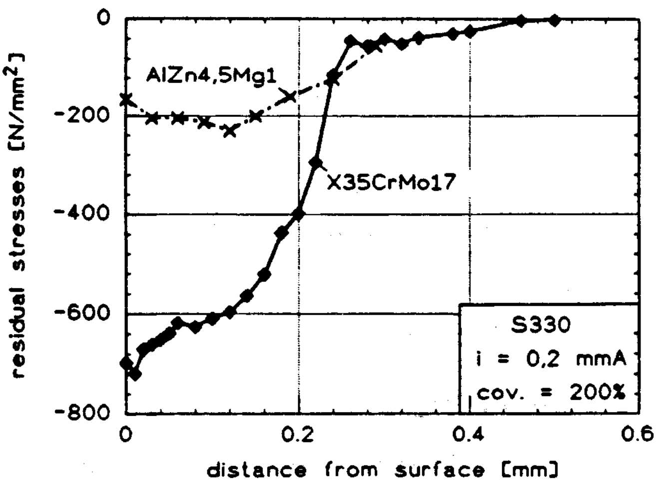

Fig. 12: Depth distribution of residual stress after identical shot peening treatment (S330; i = 0,2 mmA; cov. = 200%) of X 35 CrMo 17 and Al 7020

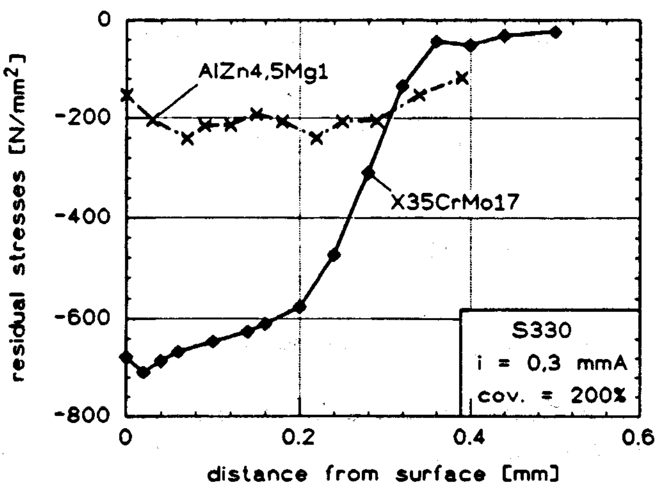

Fig. 13: Depth distribution of residual stress after identical shot peening treatment (S330; i = 0,3 mmA; cov. = 200%) of X 35 CrMo 17 and Al 7020

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