RELAXATION OF SHOT PEENING RESIDUAL STRESSES OF THE STEEL 42 CrMo 4 BY TENSILE OR COMPRESSIVE DEFORMATION

H. Hanagarth, O. Vöhringer and E. Macherauch,
Institut für Werkstoffkunde I, Universität Karlsruhe, D-7500 Karlsruhe 1, FRG

ABSTRACT

The relaxation behaviour of shot peening residual stresses of the steel 42 CrMo 4 (AISI 4140) in a quenched and tempered state was investigated in uniaxial tension and compression tests, respectively. After deformation to given strain values, residual stresses were determined in the unloaded state by X-ray measurements. In compression tests, the relaxation of shot peening induced compressive residual stresses in the surface layers starts at the stress value $\sigma \approx -400\ N/mm^2$. On the other hand, the relaxation of shot peening induced tensile residual stresses in the core region starts at the relatively large tensile stress value $\sigma \approx 1150\ N/mm^2$. Thus, the relaxation behaviour of shot peening residual stresses is completely different at compressive and tensile loading. The combination of deformation tests and X-ray measurements allows the determination of the surface yield strength of shot peened specimens, thereby taking into account the fact that when superimposing the surface residual stress and a critical compressive loading stress, residual stress relaxation starts. A modelling of the relaxation behaviour caused by uniaxial and biaxial residual stress states, respectively, will be presented. In the shot peened state, a surface yield strength value results, which is 25 % smaller than that obtained in the unpeened condition. This finding will be analyzed and discussed, thereby considering results which were determined recently in analogous experiments with shot peened AlCuMg 2 and TiAl 6 V 4.

KEYWORDS

Residual stress-relaxation, tensile loading, compressive loading, surface yield strength, workhardening, worksoftening, half width, Bauschinger-effect.

INTRODUCTION

Shot peening of metallic materials induces characteristic changes of the surface state which may be described by compressive residual stress distributions and workhardening or worksoftening effects of the surface layers and by the roughness of the surface. The knowledge of the stability or relaxation behaviour of shot peening residual stresses under homogeneous tensile and compressive deformation, respectively, is of fundamental interest. As recently published in aluminium and titanium alloys, relaxation of these residual stresses occurs after the onset of plastic deformation in an anisotropic manner under tensile and compressive loading [1-4]. These investigations verify that a distinct combination of homogeneous deformation tests and X-ray residual stress measurements allows the determination of the surface yield strength of shot peened specimens. In the following, analogous results concerning the relaxation behaviour of shot peening residual stresses on the steel 42 CrMo 4 (AISI 4140) in a high-strength condition are presented and discussed.

EXPERIMENTAL DETAILS

The investigations were carried out with the low alloy steel 42 CrMo 4 (chemical composition in wt.-%: 0.44 C, 0.32 Si, 0.73 Mn, 0.01 P, 0.03 S, 1.11 Cr, 0.22 Mo, 0.11 Ni). Cylindrical specimens of 5 mm diameter and a gauge length of 50 mm for tensile tests and 10 mm for compression tests, respectively, were taken out from a round bar material.

The specimens were heat treated at 850 ^{o}C for 20 minutes, oil quenched, then tempered at 450 ^{o}C for 2 hours and then furnace cooled.

The shot peening treatments were conducted with an air-blast machine. A cast steel shot with a hardness of 44 to 48 HRC was used at a pressure of 1.6 bar and a coverage of 98 %.

In both the compression and the tensile tests, all specimens were deformed with a strain rate of $\dot{\varepsilon} = 4.2 \cdot 10^{-4}$ s^{-1}, using special equipments [5]. After deformation to given strain values, surface residual stresses were determined in the unloaded state with X-rays on {211}-interference planes according to the $\sin^2\psi$-method using CrKα-radiation [6]. Depth distributions of residual stresses and half width values of the X-ray interference lines were analysed by successive electrolytical surface removal.

EXPERIMENTAL RESULTS

The depth distributions of the residual stresses and the half width values are plotted in Fig. 1. The amount of shot peening induced compressive residual stress directly in the surface is approximately 540 N/mm^2. In a distance from surface of 0.08 mm, the residual stress amount assumes a maximum value ($\sigma_{RS} \approx -585$ N/mm^2). The penetration depth of the compressive residual stresses is 0.23 mm. With decreasing distance from surface x ($x < 0.4$ mm), the half width values increase from a plateau value $HW^c = 180$ min to a maximum value on the direct surface $HW^s = 200$ min. Obviously, shot peening induces only a relatively small microstructural workhardening effect in the surface region of this quenched and tempered steel condition.

Shot peening residual stress states under tensile or compressive loading are unstable, and relaxation occurs when critical loading stresses are exceeded. Corresponding results of surface residual stresses are presented in Fig. 2 as a function of loading stress and in Fig. 3 as a function of total deformation. The compressive residual stresses in the surface of about -540 N/mm^2 are reduced by about 95 % of the yield strength of

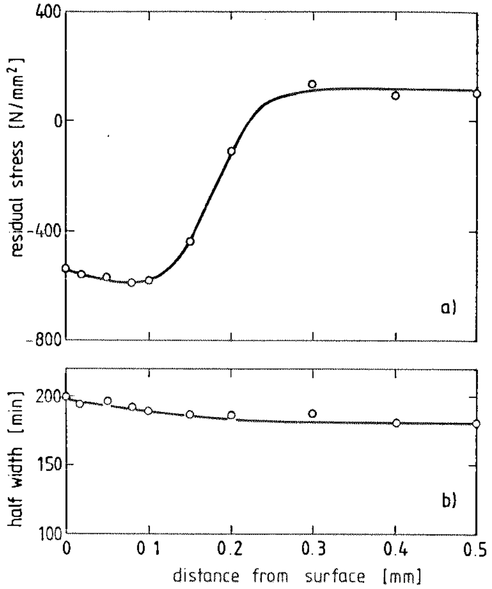

Fig. 1 Residual stress (a) and half width of X-ray interference lines (b) as a function of distance from surface of shot peened 42CrMo4 in a quenched and tempered (450 °C / 2 h) condition

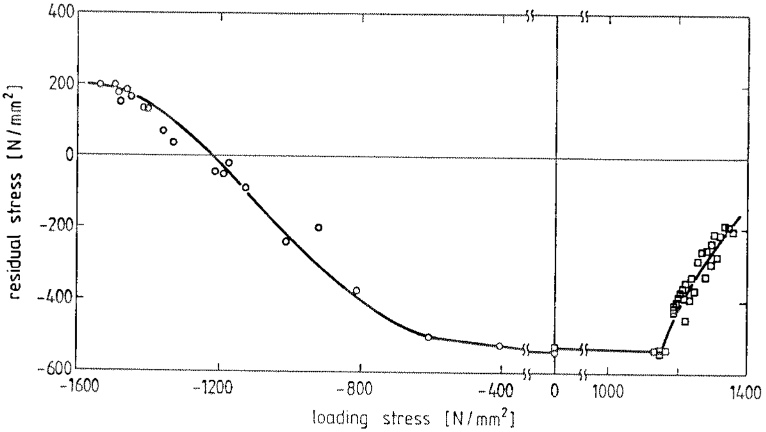

Fig. 2 Residual stress as a function of loading stress in tension and compression, respectively, of shot peened 42 CrMo 4

unpeened material, $R_{e(t)} \approx R_{p0.01(t)} \approx 1210$ N/mm², by a tensile load ($\sigma \approx 1150$ N/mm²; $\varepsilon_t \approx 0.55$ %), and by about 30 % of the yield strength of unpeened material, $R_{e(c)} \approx R_{p0.01(c)} \approx 1330$ N/mm², by a compressive load ($\sigma \approx -400$ N/mm²;

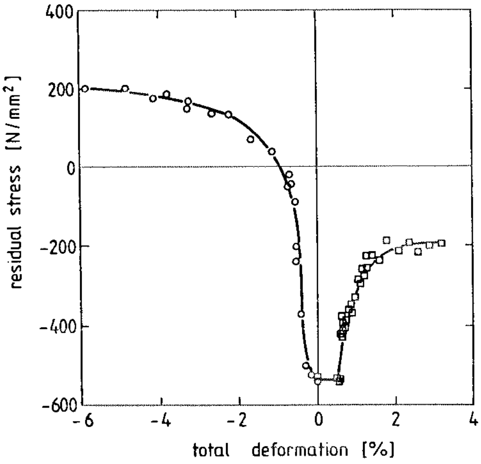

Fig. 3 Residual stress as a function of total deformation in tension and compression, respectively, of shot peened 42 CrMo 4

$\varepsilon_t \approx -0.19$ %. In the quenched and tempered condition of this material a typical strength-differential effect of $R_{e(c)} - R_{e(t)} \approx 120$ N/mm^2 exists [7]).

Residual stress-relaxation occurs much more rapidly during compression than during tension. After a total strain $\varepsilon_t \approx -1$ %, the surface residual stresses σ_{RS}^{S} are completely removed (see Fig. 3). If $\varepsilon_t < -1$ %, the sign of σ_{RS}^{S} changes. In the case of tensile loading, the residual stress-relaxation, however, is incomplete. Combined with residual stress-relaxation, only a relatively small decrease of the half width values - as a measure of the microresidual stresses - is observed. Fig. 4 illustrates this behaviour as a function of total strain.

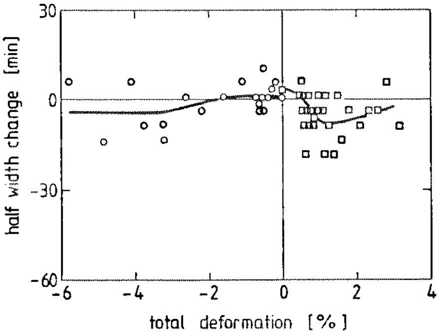

Fig. 4 Half width change as a function of total deformation in tension and compression, respectively, of shot peened 42 CrMo 4

DISCUSSION

An assessment of these findings is made possible by taking into account a composite model in which a slender shot peened specimen is ideally divided into surface and core regions. The surface region is characterized by shot peening induced compressive residual stresses σ^{s}_{RS} and by the surface yield strength R^{s}_{e}. The unpeened core region holds tensile residual stresses σ^{c}_{RS} and the yield strength R^{c}_{e} [3]. In this model, the real multiaxial residual stress distribution will be substituted by longitudinal residual stresses with a rectangular profile. For the purpose of selecting σ^{s}_{RS}, it seems to be significant to take the maximum amount of shot peening residual stresses $\sigma^{s}_{RS,max}$ in a distance from surface of 0.08 mm instead of the smaller surface value [4]. During tensile loading, the onset of plastic deformation in the composite occurs at the composite yield strength [3]

$$\overline{R}_{e(t)} = R^{c}_{e(t)} - \sigma^{c}_{RS} \, . \qquad (1)$$

During compressive loading, plastic deformation starts in an analogous manner at the composite yield strength

$$\overline{R}_{e(c)} = R^{s}_{e(c)} - |\sigma^{s}_{RS}| \, . \qquad (2)$$

In this case σ^{s}_{RS} and σ^{c}_{RS} have the meaning of the residual stresses which occur after shot peening in surface and core, respectively, and from which only σ^{s}_{RS} can be determined nondestructively. The stress values $\overline{R}_{e(t)}$ and $\overline{R}_{e(c)}$ can be taken directly from Fig. 2 as loading stresses at the onset of residual stress relaxation in tension and compression, respectively. Then, the surface yield strength $R^{s}_{e(c)}$ can be estimated by eq. (2). As shown in Tab. 1 under the condition $\sigma^{s}_{RS} = \sigma^{s}_{RS,max}$, the surface yield

Tab. 1 Properties of various material states after shot peening (R and σ in N/mm^2)

material	$R_{P0.01(c)}$ $\approx R^{c}_{e(c)}$	$\sigma^{s}_{RS,max}$	$\overline{R}^{c}_{e(c)}$	$R^{s}_{e(c)}$	$R^{s,m}_{e(c)}$	$\frac{R^{s,m}_{e(c)}}{R^{c}_{e(c)}}$	$\frac{HW^{s}}{HW^{c}}$
42 CrMo 4 (quenched and tempered)	1330	-585	400	985	860	0.65	1.11
AlCu5Mg2 (as received)	375	-340	175	515	454	1.21	1.53
AlCu5Mg2 (under-aged)	275	-360	75	435	403	1.47	1.90
AlCu5Mg2 (peak-aged)	350	-185	75	260	232	0.66	1.34
TiAl6V4 (as received)	860	-830	250	1080	980	1.14	1.87

strength is given by

$$R^{s}_{e(c)} \approx 985 \text{ N/mm}^2 .$$

As the yield strength of the core $R^{c}_{e(c)}$ is not influenced by shot peening, this property can be substituted approximately by the 0.01-proof stress during compression loading, $R_{p0.01(c)}$. Then, the comparison of the yield strengths of surface and core results in

$$R^{s}_{e(c)} < R^{c}_{e(c)} .$$

Consequently, the determination of the surface yield strength by the combination of compression tests with the onset of residual stress relaxation yields to the finding that shot peening worksoftens the surface region. Until now, the determination of surface yield strength $R^{s}_{e(c)}$ was carried out and discussed under the condition of uniaxiality of residual stresses and of their parallelism to the loading stresses. However, in reality, in shot peened surfaces, biaxial residual stress states exist, which have to be taken into account in order to estimate the surface yield strength. For materials without texture it can be assumed in a good approximation that the biaxial surface residual stress state is isotropic [4,8]. In the case of a multiaxial residual stress state, residual stress-relaxation during compression loading starts when the local value of the equivalent stress σ_{eq} reaches the surface yield strength $R^{s,m}_{e(c)}$ [3]. Based on the van Mises hypothesis, the relationship

$$R^{s,m}_{e(c)} = \sigma_{eq} = \sqrt{(\bar{R}_{e(c)})^2 + (\sigma^{s}_{RS})^2 + |\bar{R}_{e(c)} \cdot \sigma^{s}_{RS}|} \qquad (3)$$

is valid [3,4]. If the same "compression stress" $\bar{R}_{e(c)}$ is applied the application of eq. (3) results in a smaller surface yield strength value $R^{s,m}_{e(c)} \approx 860 \text{ N/mm}^2$ (see Tab. 1) than in the uniaxial case (c.f. eq. 2) due to inhibition of slip. The previously drawn conclusion that the quenched and tempered condition of this shot peened steel is characterized by a worksoftened surface state is not changed by this correction.

The worksoftening effect of 35 % (see Tab. 1) determined with the aid of the surface yield strength is incompatible with the measured distribution of the half width values in Fig. 1. The half width as a measure of the microresidual stresses shows a relatively small, but nevertheless significant workhardening effect with decreasing distance from surface. The ratio of surface half width to core half width is given by $HW^s/HW^c = 1{,}11$ (see Tab. 1). A similar worksoftening effect measured by the surface yield strength was reported earlier for an aluminium alloy AlCu5Mg2 (2024) in a peak-aged condition [1,4]. Some properties of this alloy are presented in Tab. 1. In this case, the half widths show also workhardening effects ($HW^s/HW^c = 1{,}34$; Tab. 1). Other materials and material states, for example AlCu5Mg2 (as received and under-aged) and TiAl6V4 (Tab. 1), are characterized by workhardening effects with regard to both properties, the surface yield strength and the half width values [2,4].

The reason for this different behaviour is given by the deformation processes occurring during shot peening and by the following uniaxial compression test. The deformation processes induced by shot peening are, on the one hand, the plastic stretching of the near surface layer with maximum forces and workhardening at the surface itself and, on the other hand, the Hertzian pressure with maximum values of the forces below the surfaces [9]. In order to determine the surface yield strength, it is necessary to subsequently deform the shot peened specimen in compression test. Thus, the surface will locally be deformed in the opposite direction as in the shot peening process; this yields to the appearance of the Bauschinger-effect combined with worksoftening in the surface region. It is well-known that the Bauschinger-effect is particularly pronounced in predeformed materials with *incoherent precipitations (for example, in AlCu5Mg2* (peak-aged) and quenched and tempered steels [10,11]), which are responsible for large back stresses and pronounced worksoftening effects during deformation in the opposite direction. Now, the surface yield strength is influenced on the one hand by the shot peening induced work hardening effect characterized by the half width ratio HW^s/HW^c (see Tab. 1) and on the other hand by the Bauschinger worksoftening effect. Obviously, the condition $R^{s,m}_{e(c)}/R^{c}_{e(c)} > 1$ for the yield strength ratio is valid if the shot peening induced workhardening is larger than the Bauschinger worksoftening. In the other case, $R^{s,m}_{e(c)}/R^{c}_{e(c)} < 1$, the Bauschinger worksoftening is predominant.

The relaxation behaviour of shot peening residual stresses by increasing total deformation can also be discussed qualitatively under the assumption of an uniaxial residual stress state [3,4]. The deformation of a composite specimen may be characterized for surface, core and composite by stress - total deformation curves, as schematically sketched in Fig. 5. Then, an additional simplification will be assumed by a

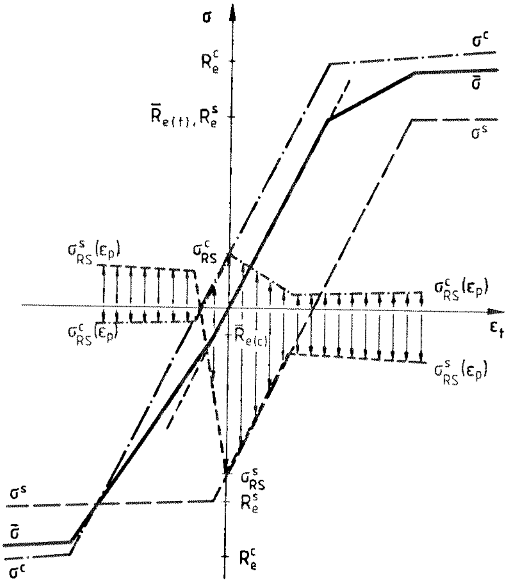

Fig. 5 Description of the stress-deformation behaviour and residual stress behaviour due to uniaxial loading in tension and compression, respectively, of a composite material consisting of surface region s and core region c with different yield strengths $R_e^c > R_e^s$, and linear workhardening

deformation behaviour with constant workhardening rates which are larger in the core than in the "predeformed" surface. Dependent on the extent of plastic deformation during tension and compression, respectively, relaxation or rearrangement of the residual stresses occurs. As a result, the amount of residual stress changes is determined by the deformation inhomogeneity between surface and core. The deformation behaviour of the residual stresses represented in Fig. 5 qualitatively agrees with the experimental findings (see Figs. 2 and 3).

The comparison between the workhardening curves of shot peened and unpeened states enables the calculation of the surface residual stresses σ_{RS}^{S}, taking as a basis the above-mentioned composite modell with uniaxial loading stress and residual stress states. On condition that ε_t = const., in the composite the following mixture rule for the applied "composite" stress is valid

$$\bar{\sigma} = \sigma^S \cdot \frac{A^S}{A} + \sigma^C \cdot \frac{A^C}{A} \quad . \qquad (4)$$

A^S/A and A^C/A are the area fractions of surface and core, respectively. After unloading, the surface residual stress is given by the difference

$$\sigma_{RS}^{S} = \bar{\sigma} - \sigma^S \; . \qquad (5)$$

Both relationships yield to

$$\sigma_{RS}^{S} = (\sigma^C - \bar{\sigma}) \cdot \frac{A^C}{A^S} \; . \qquad (6)$$

The flow stresses of unpeened and shot peened states, σ^C and $\bar{\sigma}$, respectively, are measurable properties. Therefore, exact determinations of stress-deformation curves during tension and compression were carried out on both states with the aid of strain gauges. The ratio $A^C/A^S \approx 6.4$ was approximately estimated with reference to the residual stress distribution illustrated in Fig. 2. [5]. σ_{RS}^{S}-values calculated with eq. (6) are given in Fig. 6 as a continuous line. These values qualitatively agree with the experimental data

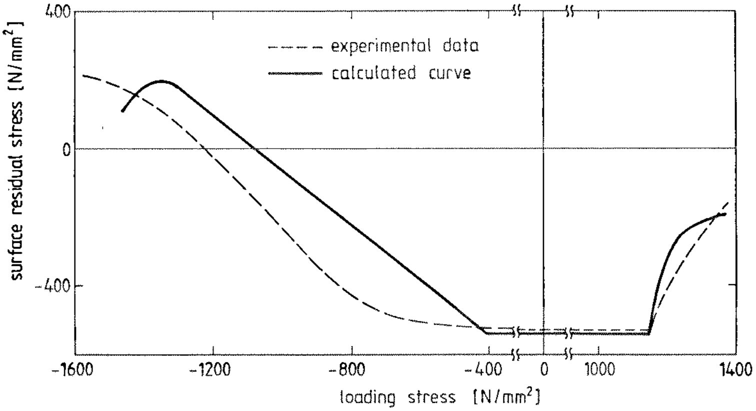

Fig. 6 Comparison of experimentally determined and by modelling calculated residual stresses as a function of the loading stress of shot peened 42 CrMo 4

(dotted curve with data from Fig. 2). However, the calculated relaxation rates are larger than the measured ones. It may be possible that this difference is caused by triaxial loading stress states occurring between surface and core in the real case.

SUMMARY

The deformation behaviour of a shot peened specimen can be discussed on the basis of a simple composite model. The combination of mechanical and X-ray investigations enables the determination of the composite yield strength and the surface yield strength, respectively. The yield strength ratio of surface and core shows that shot peening yields to a worksoftening of the surface of the investigated steel 42 CrMo 4 in the quenched and tempered state. This finding seems to be in contradiction with the behaviour of the half width values of the X-ray interference lines. A solution of this problem will be offered if the Bauschinger-effect is taken into account in the discussion. The relaxation behaviour of shot peening residual stresses is completely different during compressive and tensile loading. This anisotropic behaviour was modelled and discussed.

REFERENCES

[1] Hirsch, T.; Vöhringer, O.; Macherauch, E.: In "Proc. 2nd Int. Conf. Shot Peening". Am. Shot Peening Soc., Paramus, N. J. (1984), 90/101

[2] Vöhringer, O.; Hirsch, T.; Macherauch, E.: In "Proc. 5th Int. Conf. Titanium". DGM-Informationsgesellschaft, Oberursel (1985), Vol. 4, 2203/2211

[3] Vöhringer, O,: In "Advances in Surface Treatments" (Ed. A. Niku-Lari) Vol. 4: Int. Guidebook on Residual Stresses, Pergamon Press, London (1987), 367/396

[4] Hirsch, T.; Vöhringer, O.; Macherauch, E.: Härterei-Techn. Mitt. 43 (1988), 16/20

[5] Hanagarth, H.: Dr.-Ing. Dissertation, Universität Karlsruhe (1989).

[6] Macherauch, E.; Müller, P.: Z. Angew. Physik 13 (1961), 305/312

[7] Macherauch, E.; Vöhringer, O.: Härterei-Techn. Mitt. 41 (1986), 71/91

[8] Ebenau, A.; Vöhringer, O.; Macherauch, E.: In "Proc. 3rd Int. Conf. Shot Peening". DGM-Informationsgesellschaft, Oberursel (1987), 253/260

[9] Wohlfahrt, H.: In "Residual Stresses and Stress Relaxation", Sagamore Army Materials Res. Conf. Proc. (Ed. E. Kula, V. Weiss). Plenum Press, New York, Vol. 28 (1982), 71/92

[10] Deffner, B.; Vöhringer, O.; Macherauch, E.: In "Proc. 5th Int. Conf. Titanium". DGM-Informationsgesellschaft, Oberursel (1985), Vol. 3, 1915/1921

[11] Scholtes, B.; Vöhringer, O.: Härterei-Techn. Mitt. 41 (1986), 347/354