Thermal Relaxation of Shot Peening Residual Stresses in the Differently Heat Treated Plain Carbon Steel Ck 45

J. Hoffmann*, B. Scholtes, O. Vöhringer and E. Macherauch
Institut für Werkstoffkunde I, Universität Karlsruhe (TH), FRG

*now with Daimler Benz AG, Mannheim, FRG

Introduction

Shot peening residual stresses are of considerable interest because of their consequences on the mechanical and/or corrosion behaviour of the material treated. Therefore, special attention has to be paid to the stability of existing shot peening residual stress states during service. In this paper, the thermal relaxation of shot peening residual stresses of the plain carbon steel Ck 45 is investigated and discussed. The influence of annealing time and temperature is quantitatively evaluated using a Zener-Wert-Avrami function, which has successfully been applied in other cases (see e. g. (1-3)).

Materials under investigation and experimental details

Flat specimens of the German steel grade Ck 45 (plain carbon steel with 0.45 wt.-% C) were investigated in a normalized, a quenched and tempered and in a quenched (hardened) state. Details about the different heat treatments and the resulting mechanical properties are summarized in Tab. 1. After heat treatment, the specimens were shot peened using the parameters also indicated in Tab. 1.

Residual stresses were determined by X-ray diffraction using macroscopic elastic constants to calculate stresses from the measured lattice strains. Depth distributions were analysed by successive electrolytical surface removal.

Thermal stress relaxation in the temperature range $150^{\circ}C \leq T_a \leq 250^{\circ}C$ was carried out in a temperature controlled oil bath. For annealing at temperatures $T_a > 250^{\circ}C$ a fluidized bed furnace was used with nitrogen as circulation gas (1).

Experimental results

Fig. 1 shows depth distributions of residual stresses and half-width values after shot peening of the differently heat treated materials states. In the normalized condition, maximum residual stresses occur immediately at the surface whereas for the quenched and tempered state maximum stress values are shifted below the surface. For the hardened material, surface compressive residual stresses are relatively small, but a pronounced stress maximum at a surface distance of about 0.1 mm is observed. Half-width values of the normalized state decrease continuously from ≈ 3° at the surface to ≈ 2° in the interior of the material.

Heat Treatment	Mech. Properties	Shot Peening Parameters
normalized: 850°C/1h furnace cooling	200 HV 0.05 R_{eS} = 340 N/mm² R_m = 600 N/mm²	S170 (Ø 0.45 mm) p = 0.45 bar coverage: 1×98 %
quenched and tempered: 800°C/15 min → oil +400°C/2h → air	500 HV 0.1 R_{eS} = 1375 N/mm² R_m = 1450 N/mm²	S230 (Ø 0.6 mm) v = 53 m/s coverage: 3×98 %
quenched: 800°C/15 min → oil	700 HV 0.1 $R_{p0.2}$ = 1840 N/mm² R_m = 2010 N/mm²	S230 (Ø 0.6 mm) v = 81 m/s coverage: 3×98 %

Tab. 1: Heat treatments, mechanical properties and shot peening parameters of the materials states investigated.

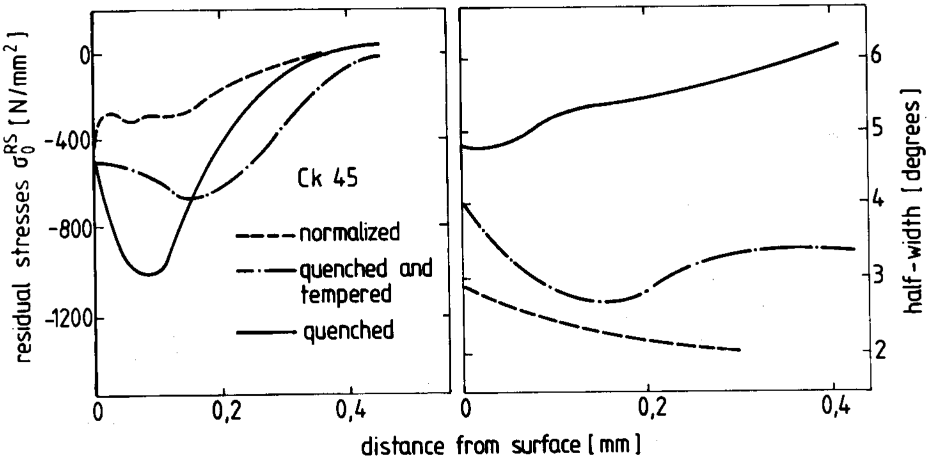

Fig. 1: Residual stresses and half-width values of the shot peened materials under investigation

In the quenched and tempered state, also maximum half-width values are observed at the surface and a minimum ≈0.15 mm below the surface exists. As for the hardened state, a continuous increase of the half-width values with its minimum at the surface is measured.

In Fig. 2 a survey is given about thermally induced changes of shot peening residual stresses and half-width values. Experimentally determined data before and after annealing are plotted as a function of the distance from surface. In the normalized condition, annealing at 400°C/30 min considerably diminishes the residual stresses at the surface to about 50 % of the initial

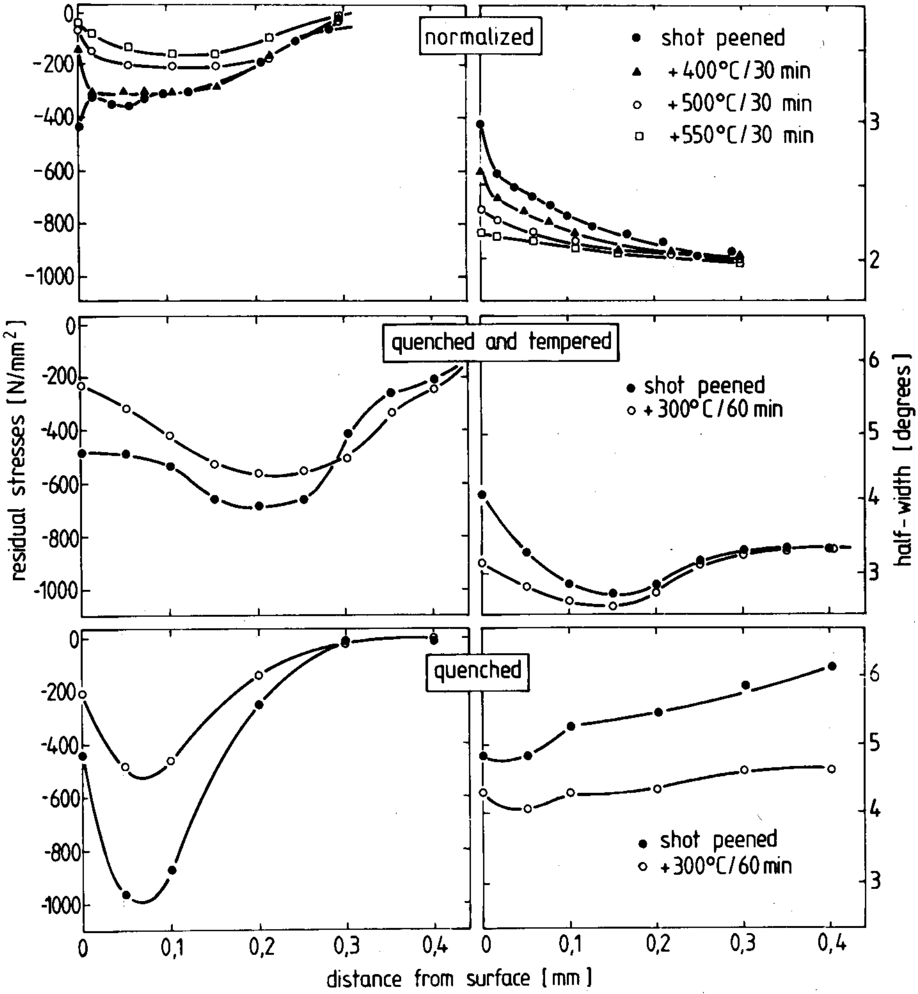

Fig. 2: Residual stresses and half-width values of the shot peened materials states before and after annealing

value. Below the surface, however, almost no changes of the residual stress state are observed. At 500°C/30 min and 550°C/30 min, the residual stress level is generally diminished, but the most pronounced residual stress relaxation still occurs immediately at the surface. Concerning the half-width values, a continuous decrease with increasing annealing temperature is observed. In the quenched and tempered state, too, the relaxation of residual stresses and half-width values is more pronounced for the surface than for the interior of the specimen. However, this is not as pronounced as in the normalized state.

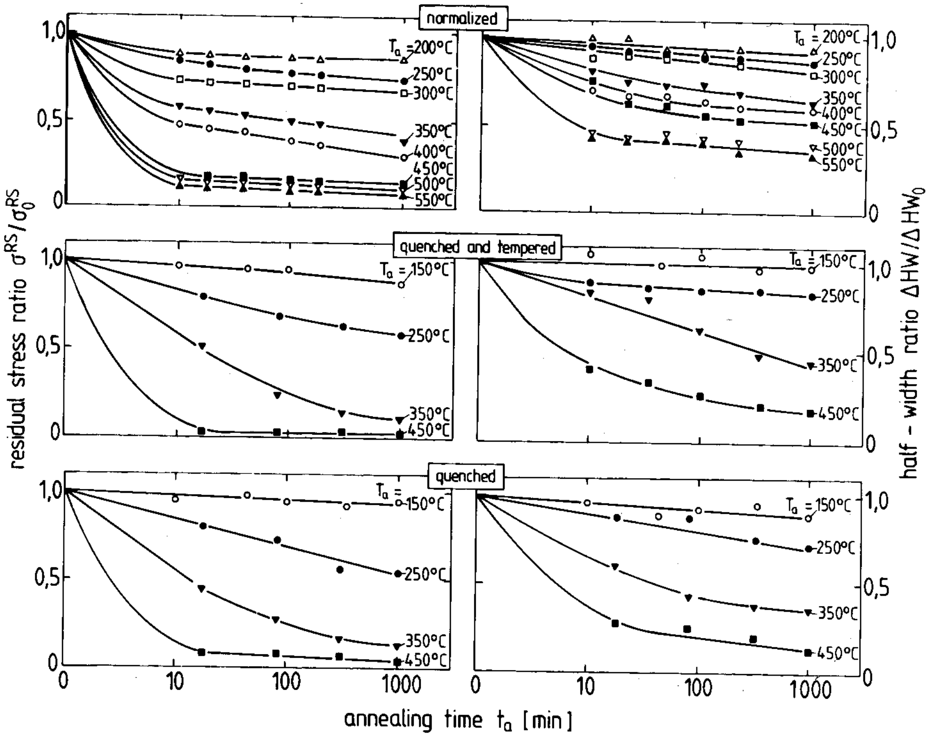

Fig. 3: Influence of annealing time t_a and annealing temperature T_a on the relaxation of residual stresses and half-width values at the surface of normalized, quenched and tempered, and quenched specimens

Regarding quenched specimens, the percentage residual stress relaxation is nearly constant as a function of the distance from the surface. For this heat treatment, the changes of the half-width values are more pronounced for the interior than for the near surface regions of the specimens.

For the direct surface of the specimens, the complete relaxation behaviour of residual stresses and half-width values is summarized in Fig. 3. In the left part, residual stress ratios $\sigma^{RS}/\sigma_o^{RS}$ (σ_o^{RS}: surface residual stress before annealing) are plotted for different annealing temperatures T_a as a function of annealing time t_a. Characteristic differences between the individual materials conditions can be stated. In the normalized state, stress relaxation is clearly less pronounced than in the quenched and tempered or in the quenched state. In particular, this can be seen for T_a = 250°C and 350°C. A similar behaviour is observed for the referred half-width values $\Delta HW/\Delta HW_o$ (ΔHW: half-width relaxation; ΔHW_o: difference between half-width before annealing and half-width of normalized state).

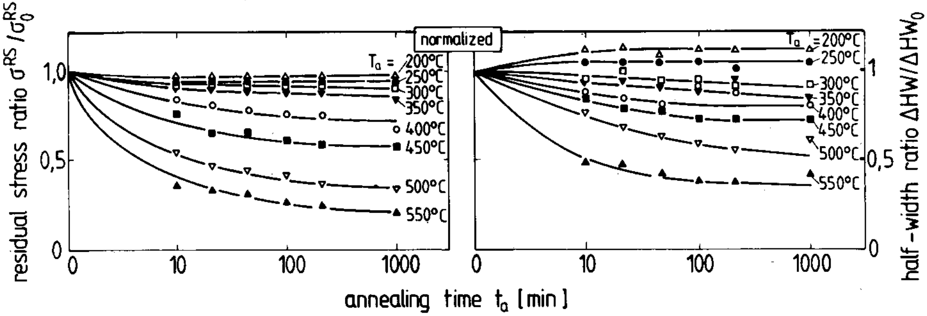

Fig. 4: Influence of annealing time t_a and annealing temperature T_a on the relaxation of residual stresses and half-width values 0.08 mm below the surface of normalized specimens

To analyse more in detail the subsurface relaxation behaviour of normalized materials, a batch of specimens had been electropolished to a depth of 0.08 mm after shot peening. As already indicated in Fig. 2, in this distance from the surface, the relaxation of residual stresses is considerably less pronounced than immediately at the surface. This can clearly be seen in Fig. 4 where all measured data for specimens electropolished by 0.08 mm are compiled. Up to 300°C only a very small stress relaxation occurs. In general, to reach a stress relaxation of 50 % in 1 h, the relaxation temperature has to be increased by about 120°C compared to the surface of the material. The half-width values, too, show characteristic differences of their relaxation behaviour, if surface values in Fig. 3 and subsurface values in Fig. 4 are compared. For the lowest annealing temperatures, even a small increase compared to the shot peened state is measured.

It has been shown that the thermal relaxation of residual stresses and half-width values in dependence on time and temperature can be described by a Zener-Wert-Avrami-equation (2)

$$\sigma^{RS} / \sigma_o^{RS} = \exp [- (At_a)^m] \qquad \text{Equ. 1}$$

with

$$A = B \exp [-Q/kT_a] \qquad \text{Equ. 2}$$

and

m = value depending on the corresponding relaxation mechanism
B = const.
Q = activation energy for stress relaxation
k = Boltzman's constant

and

T_a = absolute annealing temperature

In this case, for distinct stress relaxation values σ^{RS} / σ_o^{RS}, linear log t_a - $1/kT_a$ relations are valid. Fig. 5 shows that for the materials states investigated including data from (1) eqs. (1) and (2) give an accurate quantitative description of thermal stress relaxation, and the mean values for Q and m compiled in Tab. 2 can be derived.

	Q [eV]	m
normalized		
• surface	2,5	0,12
• surface layer removed	4,5	0,14
quenched and tempered	1,3	0,24
quenched	1,3	0,27

Tab. 2: Mean values Q and m of the materials states investigated

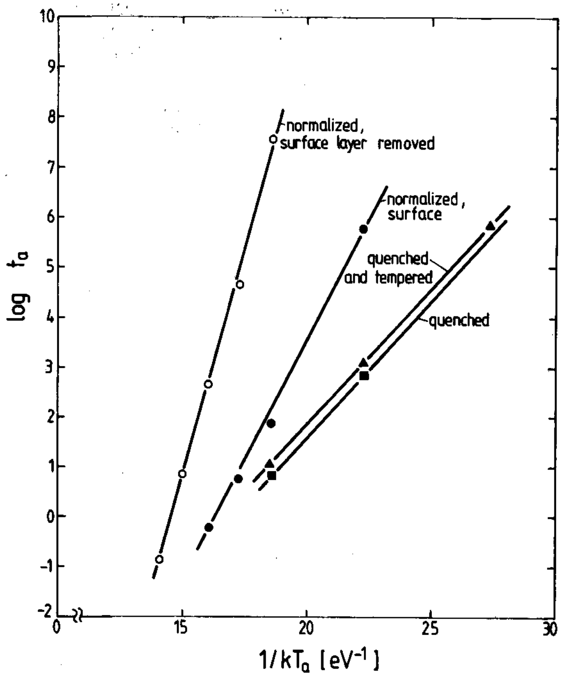

Fig. 5: log t_a - $1/kT_a$ diagram for a residual stress relaxation of 50 %

Discussion

Thermal residual stress relaxation is a consequence of microplastic deformation processes thus converting elastic strains associated with residual stresses into plastic ones. Thereby, different thermally activated processes can be distinguished. Besides time t_a and temperature T_a the materials microstructure which itself is a consequence of the plastic deformations associated with the development of residual stresses is of importance. The different distributions of half- width values as a function of the distance from the surface measured after shot peening already indicate the development of different microstructures in each case. If normalized Ck 45 is shot peened, maximum plastic deformations occur at the surface continuously decreasing to the interior. This is associated with the formation of dislocation cells and tangles at the surface and randomly distributed dislocations in the interior (4). In general, a decreasing dislocation density and a characteristic decrease of the half-width values as a function of the distance from the surface is observed. The different thermal relaxation behaviour of residual stresses and half-width values nearest to the surface and below the surface of normalized Ck 45 is a direct consequence of this inhomogeneous microstructure in the shot peened surface layer. This also becomes obvious by the different activation energies measured for the relaxation processes. In the case of hardened and shot peened Ck 45, as a consequence of the hardening process, already before the mechanical surface treatment extremely high dislocation densities in the order of 10^{12} - 10^{13} cm^{-2} exist. In addition, the concentration of interstitially dissolved carbon atoms is higher than the equilibrium condition. Up to now, there exist no direct observations of microstructural changings, especially of dislocation rearrangements in the surface layers of hardened materials during shot peening. However, the decrease of half-width values in comparison with the unpeened materials state (see Fig. 2) clearly indicates that processes occur which are different from those in normalized materials. It is reasonable to suppose that characteristic dislocation rearrangements take place which do not considerably change the dislocation density already existing before the shot peening process. Obviously, this high dislocation density in the whole surface layer affected by shot peening is responsible for the uniform residual stress relaxation independent of the distance from the surface. Of course, the relaxation behaviour of the hardened and tempered materials state is also controlled by the microstructure, which itself is determined by the tempering temperature. For the case investigated, as can be seen from the half-width distributions in Fig. 2, the surface layer is work-hardened by the peening process and stress relaxation is more pronounced at the surface than in the interior.

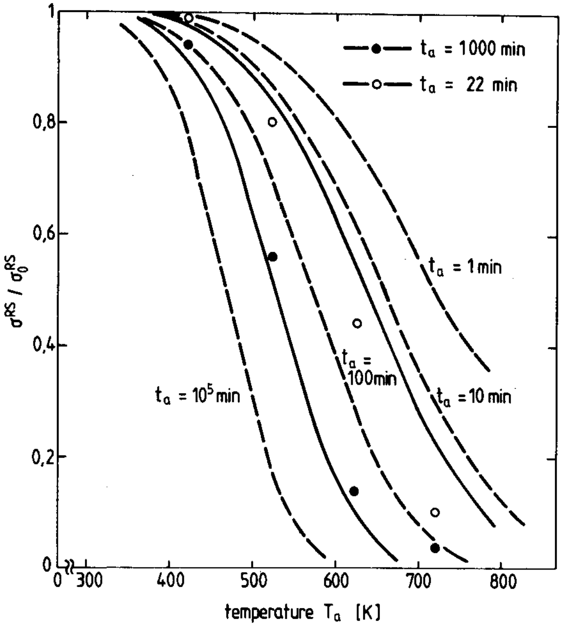

Fig. 6: Residual stress relaxation of hardened and shot peened Ck 45 calculated with mean values $m = 0,27$, $B = 7,4 \times 10^8$ min^{-1} and $Q = 1,3 eV$ in comparison with experimentally determined data.

The activation energies measured supply useful information about the mechanisms controlling the relaxation process. For the normalized material, at the surface, $Q = 2,5$ eV is in the order of $Q_0 = 2,6$ eV, which is attributed to self diffusion or high temperature creep. The value of $Q = 4,5$ eV, which has been determined for subsurface layers cannot be explained by a structural process. The activation energy of $Q = 1,3$ eV measured for the quenched and tempered as well as for the quenched state is consistent with the diffusion process of matrix atoms along the core of edge dislocations. In both cases, for normalized as well as for hardened materials, thermally activated climb of edge dislocations is the rate determining relaxation process.

For practical purposes, it is important to note that as a consequence of the different thermally activated processes in normalized and hardened steels, relaxation of shot peening residual stresses for a given t_a, T_a-combination is more pronounced in quenched or quenched and tempered materials, respectively, than in the normalized state. This can clearly be seen when comparing the isothermal curves of the different materials states in Fig. 3. Using eqs. (1) and (2) with values for m and Q given in Tab. 2 and appropriate B-values, the relaxation behaviour of residual stresses for those time, temperature combinations can be assessed where experimenally determined data are not available. This is exemplarily shown in Fig. 6. For t_a = 22 min and 1000 min calculated curves are compared with measured values. Despite the scattering of the measuring points a satisfying agreement between calculation and measurement can be stated which can be improved if more experimental data are available. In this way, by tabulating appropriate Q-, m- and B-values for interesting materials and materials states, a quantitative description of the stress relaxation behaviour seems possible.

References

(1) J. Hoffmann, Dr.-Ing. Diss, Univ. Karlsruhe (1985)

(2) O. Vöhringer, in: Advances in Surface Treatments, Vol. 4, ed. A. Niku-Lari, Pergamon Press (1987), 367

(3) J. Hoffmann, B. Scholtes, O. Vöhringer and E. Macherauch, in: Residual Stresses in Science and Technology, DGM (1987), in press

(4) D. Hakimi, C. Servant and L. Castex, in: Second Int. Conf. on Shot Peening, Chicago. The American Shot Peening Society, Paramus, N. J. (1984), 249