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

STABILITY OF RESIDUAL STRESSES IN SHOT PEENED AND HIGH PRESSURE WATER PEENED STAINLESS STEELS AT ELEVATED TEMPERATURES

P. Krull, Th. Nitschke-Pagel, H. Wohlfahrt

Welding Institute, Langer Kamp 8, D-38106 Braunschweig, Germany
Tel.: +49 531 391 7845 Fax: +49 531 391 5834 e-mail: ifs-bs@tu-bs.de

ABSTRACT

In water surrounded areas many failures of stainless steels are caused by stress corrosion cracking. If the surface of these materials is changed by peening processes, compressive residual stresses will be induced and stress corrosion cracking may not occur. For this reason stainless steel of type 316 Ti (1.4571) was shot peened and also high pressure water peened to induce compressive residual stresses in surface layers. During normal service conditions the strain hardened surface layers have been exposed to elevated temperatures. The influence of time and different temperatures on the stability of residual stresses in surface layers were investigated. The relaxation of the residual stresses at the surface and in near surface areas was measured by means of X-ray diffraction. With the presented experimental results the effects of peening processes can be evaluated with respect to typical thermal loading effects.

KEY WORDS

shot peening, high pressure water peening, residual stresses, thermal loading, relaxation behaviour, stainless steels

Introduction

The surface strength and hardness of steels can be increased by the induction of near surface plastic deformations due to shot peening or high pressure water peening processes. The aim of these processes is to produce components with an unchanged geometry, but with an improved fatigue strength in order to be able to use smaller cross-sections or to reduce costs. The susceptibility to stress corrosion cracking is reduced as well. The beneficial effects of the induced compressive residual stresses depend strongly on their stability under various service conditions like thermal loading or different load stresses. Consequently in the following not only the magnitude of compressive residual stresses as a result of shot peening and high pressure water peening will be investigated and compared, but also especially the stability of the residual stresses under thermal loading.

Experimental Work

The experiments were carried out with a stainless steel of type AISI 316 Ti (German No. 1.4571). The chemical composition and the mechanical properties are given in Table 1 and 2. The outer dimensions of the specimens are described in figure 1.

Table 1 Chemical composition of 316 Ti (in %)

C	Cr	Ni	Mo	Ti	Si	S	P	Mn	Nb	Cu	Fe
0,024	18,3	11,3	2,47	0,352	0,602	0,006	0,027	1,12	0,017	0,189	65,6

Table 2 Mechanical properties of examined 316 Ti (3 mm sheet-metal)

0,2 % YS [MPa]	UTS [MPa]	ductile yield [%]	reduction of area [%]
346	609	65,1	69,5

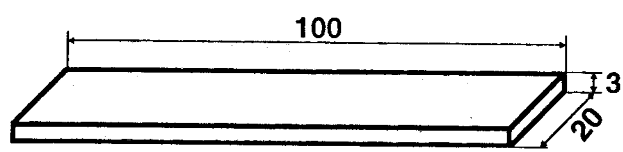


Fig. 1 Outer dimensions of the specimens (shot peened or high pressure water peened)

The shot peening and high pressure water peening processes were carried out with following parameters:

Shot peening

Shot:	AISI 304 rounded off
Size:	0,8 mm
Intensity:	0,010 – 0,012´´ A
Coverage:	125 %
Specification:	MIL-S-13165 C

High pressure water peening

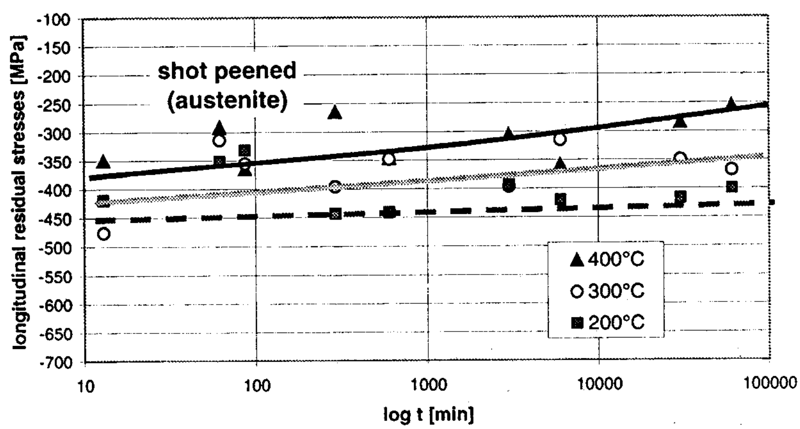
Shot:	Water
Jet pressure:	100 MPa
Distance from nozzle:	45 mm
Peening time:	1 sec

Experiments with thermal loading were performed in an oven at temperature levels of 200°C, 300°C and 400°C. Up to times of 300 min the specimens were kept in air. At elevated exposure times the specimens were annealed in evacuated tubes of glass to avoid thick layers of oxides which may influence the measurements of residual stresses at the surface.

The longitudinal (parallel to the long axis of the specimens) and the transverse residual stresses after peening were measured in a thin surface layer of the specimens with an X-ray diffractometer using Cr-K_α-radiation. Only the longitudinal residual stresses are presented in this paper, because the transverse residual stresses turned out to equal the longitudinal residual stresses. Depth profiles of the residual stresses were taken by sequential electrochemical polishing layer by layer. The {220}-diffraction-lines of the austenite were detected by a scintillation counter and the macro residual stresses were evaluated using the $\sin^2\psi$-method [1]. Due to plastic deformations of the surface layers martensite may occur in these zones [7]. To determine the content of the martensite and the residual stresses in it the {211}-diffraction lines of the martensite were also detected. Above 5 % martensite it was possible to calculate the residual stresses of this phase with a reliable accuracy.

Results and Discussion

Figures 2 and 3 reveal the longitudinal residual stresses and figures 4 and 5 the corresponding half widths of the diffraction lines after shot peening or high pressure water peening and after exposure to different temperatures for different times. Selected residual stress and half width depth profiles are shown in figures 6 – 9. The essential features of the curves are as follows:



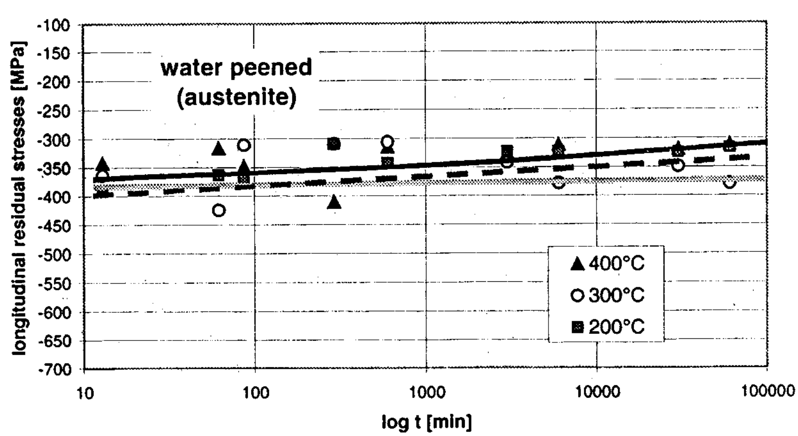


Fig. 2 Longitudinal residual stresses in the austenite of shot peened and high pressure water peened specimens versus time of exposure to different temperatures

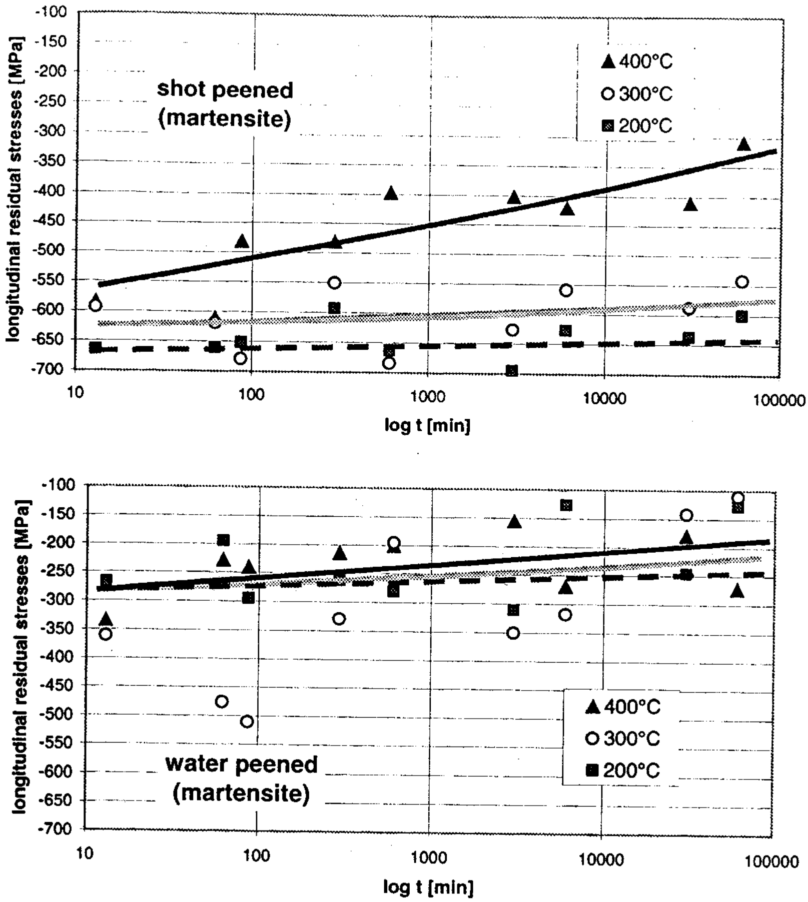
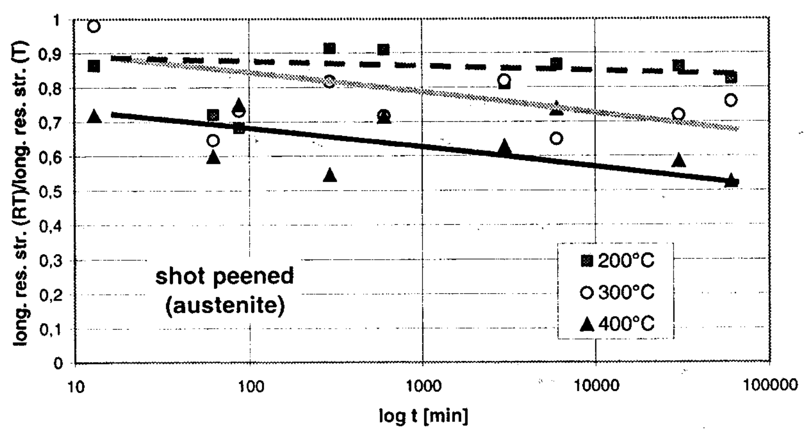


Fig. 3 Longitudinal residual stresses in the martensite of shot peened and high pressure water peened specimens versus time of exposure to different temperatures

Shot peening induced higher magnitudes of compressive residual stresses in the martensite than in the austenite, whereas water peening resulted in residual stresses with the same magnitude in both phases or even in a somewhat lower magnitude in the martensite. These results reflect clearly the higher yield strength of the martensite. Already after short annealing times reductions of the residual stresses could be observed. As can be seen in figure 2 or figure 3 after an annealing time of 13 min the residual stress values are lower for the higher annealing temperatures. In all investigated cases the decrease of the residual stresses can be represented by a linear relationship in a plot with a logarithmic time scale and the slope of the regression lines rises with increasing temperature. The maximum percentage of the decrease at 400 °C/ 60 000 min is 48 % in the austenite and 60 % in the martensite (fig. 4). At the annealing temperature of 300 °C the high magnitudes of compressive residual stresses in the martensite after shot peening remain relatively stable, whereas the residual stresses in the austenite are reduced somewhat stronger. At 200 °C only minimal changes could be detected. The lower initial residual stresses after high pressure water peening show a moderate reduction with the annealing time at 400 °C – in the austenite as well as in the martensite – and nearly no reduction at 300 °C (fig. 3).

The half widths corresponding to figure 2 are shown in figure 5. A small continous decrease of approximately 0.2 ° can be seen in the shot peened condition up to annealing times of 60 000 min. The average curves at 200 °C and 300 °C are nearly equal, the curve at 400 °C runs about 0.25 ° lower. The half widths of the high pressure water peened specimens show nearly no decrease with increasing time independant of the temperature. The reported results indicate that differences of the dislocation densities of the shot peened and of the high pressure water peened austenite and martensite have to be seen as the reason for the different reductions of residual stresses and half widths of the diffraction lines with temperature and time. Detailed investigations by transmission electron microscopy [4] revealed for instance a different near surface microstructure of shot peened and of high pressure water peened specimens. The dislocation density was observed to be very high in the shot peened specimens and quite low in the high pressure water peened specimens. Due to these initial states the activation of dislocation rearrangements by elevated temperatures appears easier in the shot peened specimens as in the high pressure water peened specimens. Consequently the reduction of the residual stresses and of the half widths is stronger or faster after shot peening than after high pressure water peening. A higher dislocation density can also be asumed in the shot peened or high pressure water peened martensite compared with the austenite, if the initial values of the half widths are taken as an indicator for the dislocation density. Therefore the stronger decrease of the residual stresses and half widths in the martensite compared with the austenite may also be a consequence of a more pronounced rearrangement of dislocations in the martensitic structure with a higher dislocation density.



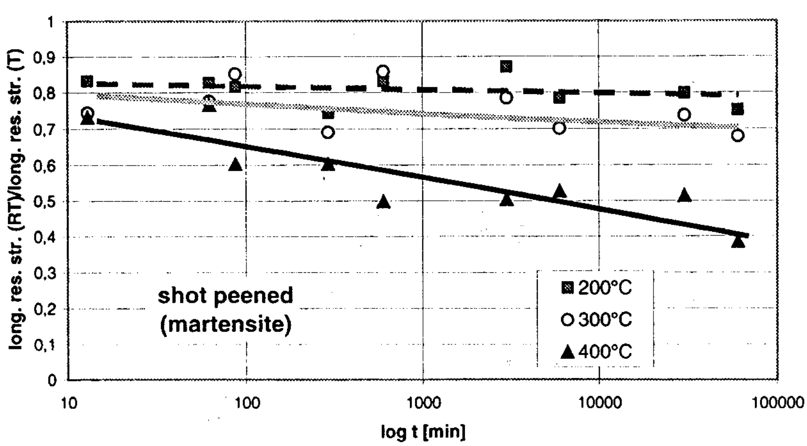


Fig. 4 Specific residual stresses in austenite and martensite of shot peened specimens corresponding to figures 2 and 3

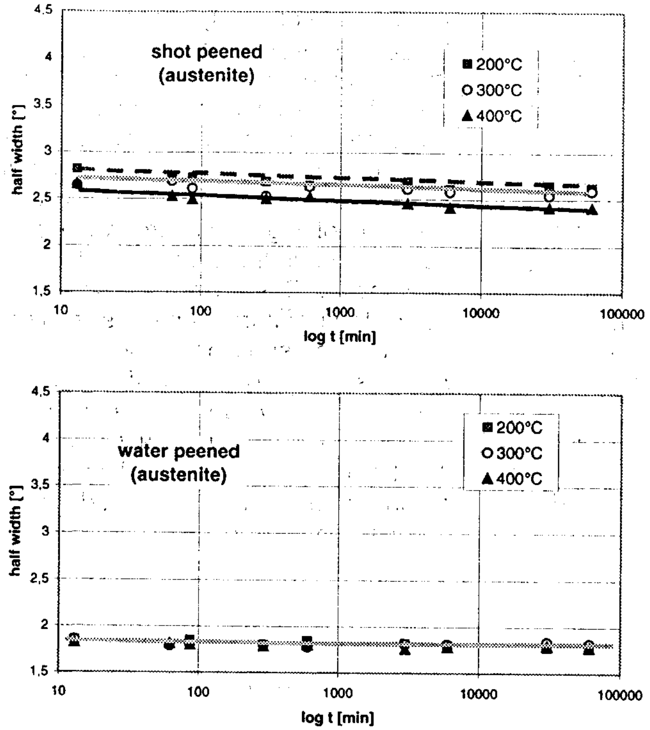


Fig. 5 Half widths in the austenite of shot peened and high pressure water peened specimens versus time of exposure to different temperatures

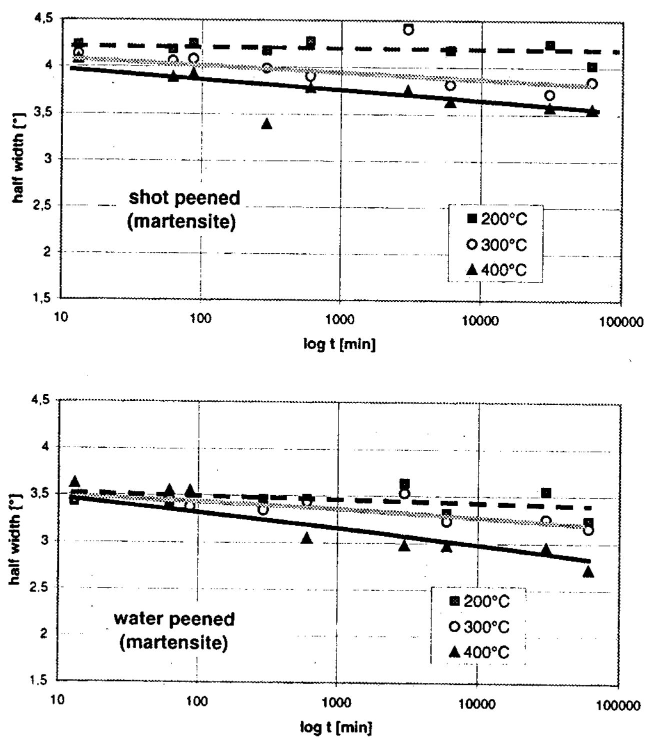


Fig. 6 Half widths in the martensite of shot peened and high pressure water peened specimens versus time of exposure to different temperatures

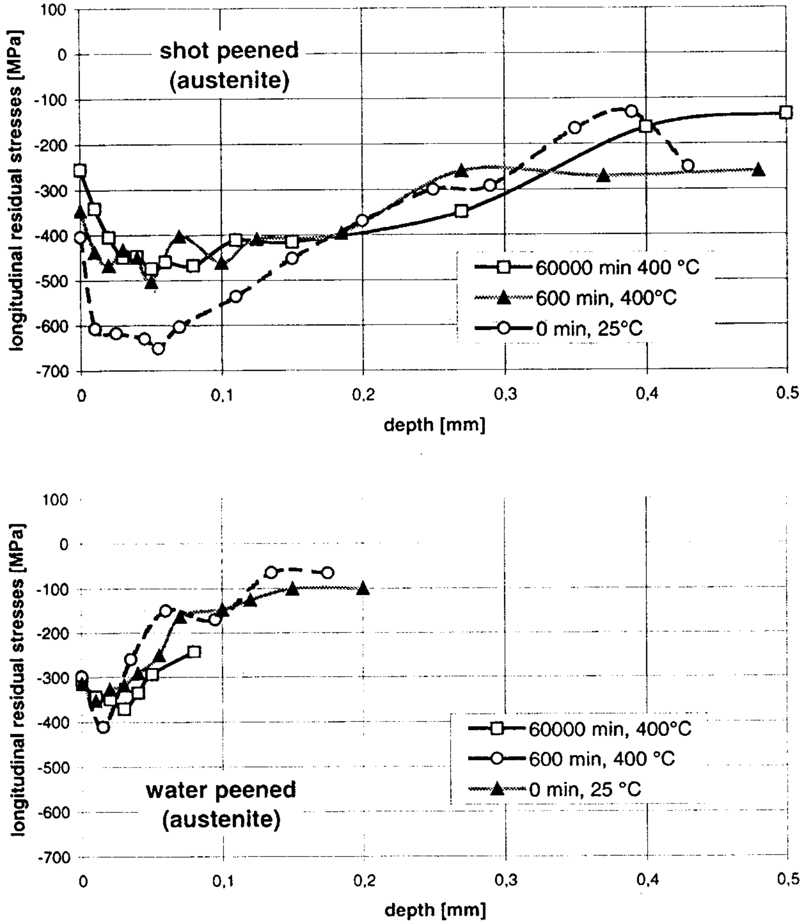
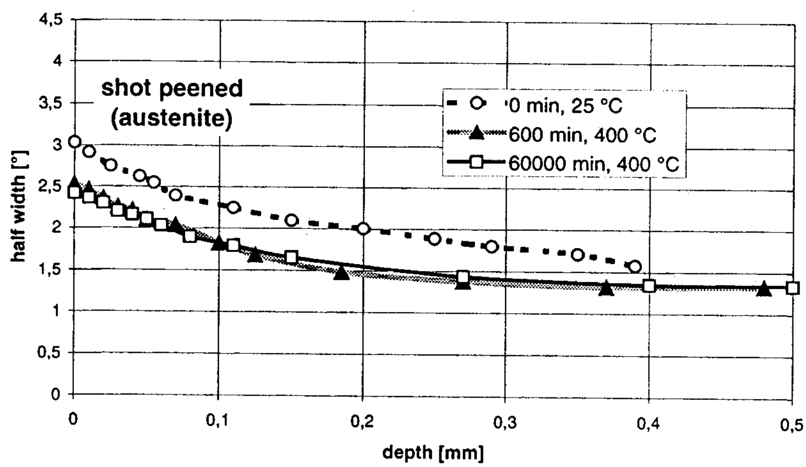


Fig. 7 Residual stress depth profiles in the austenite of shot peened and high pressure water peened specimens at different exposure times (400 °C)

Figure 6 reveals the half widths of the martensite corresponding with the residual stress measurements in figure 3. Without exception the half widths of both peened conditions are higher in the martensite as in the austenite (approximately 1.2°-1.4°/shot peened and 1.7°-1.3°/high pressure water peened). The lowering of half widths with increase of time was observed to be the stronger the higher the annealing temperature was. The same result was found for ferritic steels by [5, 6]. In contrast with the results of the austenitic phase the decrease of the half widths after high pressure water peening is at all annealing temperatures at least as strong as after shot peening.

In figure 7 the depth profiles of the residual stresses in the austenite of shot peened and high pressure water peened specimens are compared at exposure times of 0 min, 600 min and 60 000 min and a temperature of 400 °C. All distributions of the residual stresses in the austenite of the shot peened specimens show a shape typical for peening processes with the maximum magnitude of compressive residual stresses below the surface due to the Hertz'ian pressure [3]. The affected depths differ. In the shot peened condition the maximum magnitude was found in a depth of 0.05 mm and after high pressure water peening in a depth of approximately 0.02 mm, which was also reported by [2, 4]. The relaxation of the compressive residual stresses at the surface was observed clearly in the shot peened condition, scarcely in the high pressure water peened specimens. The maximum of compressive residual stresses below the surface in the shot peened specimens relaxes with an increase of temperature but not with a further increase of time over 600 min. These effects could not be observed unambiguously at the high pressure water peened specimens.

The depth profiles of the half widths of the austenite corresponding with the residual stress depth profiles of figure 7 are revealed by figure 8. The maximum of the half widths was measured at the surface and a continuous decrease was observed with increasing depth. As a consequence of elevated temperatures the half widths of shot peened specimens were lowered by 0.5 °. The reduction was obviously nearly complete after 600 min of annealing at 400 °C. The maximum of the high pressure water peened specimens was also reduced due to elevated temperatures and the very shallow distributions of the half widths versus depth after annealing at 400 °C for 600 min and 60 000 min equal each other.



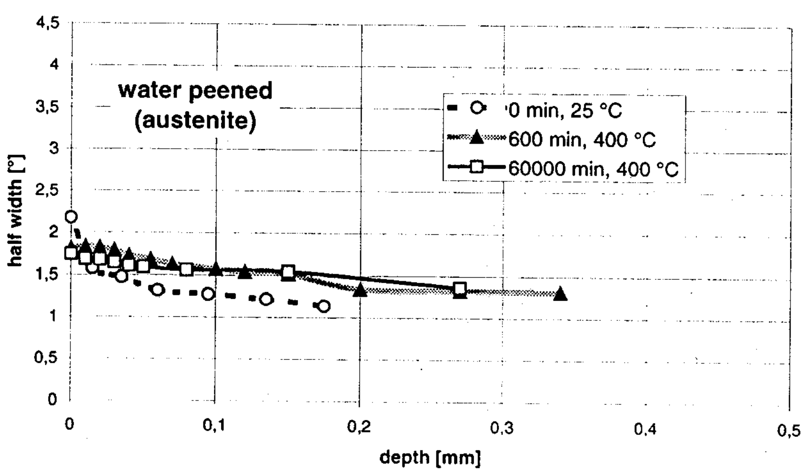


Fig. 8 Half width depth profiles in the austenite of shot peened and high pressure water peened specimens at different exposure times (400 °C)

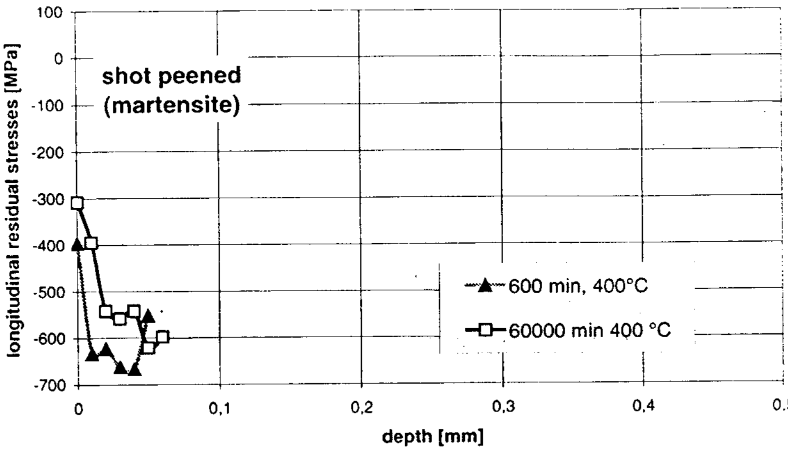


Fig. 9 Residual stress depth profiles in the martensite of shot peened specimens at different exposure times (400 °C)

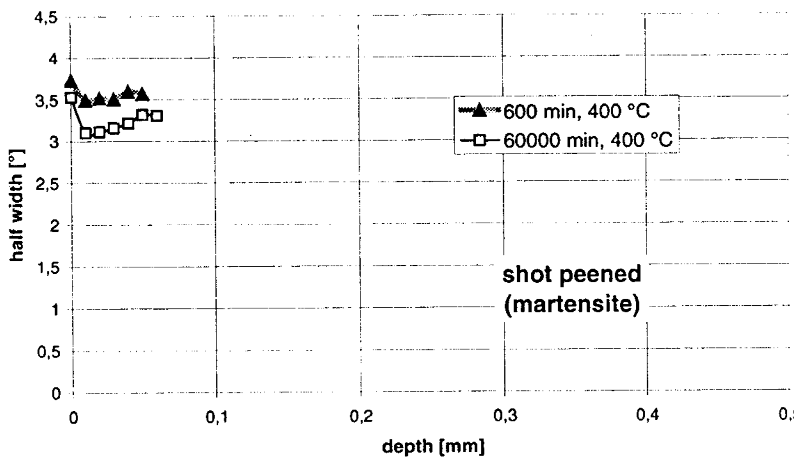


Fig. 10 Half width depth profiles in the martensite of shot peened specimens at different exposure times (400 °C)

The attempt to measure the residual stress depth profiles of the martensite was successful in the shot peened specimens, but due to the decrease of X-ray intensities with increasing depth only up to a depth of ~ 0.6 mm. The intensities of the martensitic phase of the high pressure water peened specimens were only measurable at the surface (fig. 3). The curves of the shot peened specimens in figure 9 reveal a decrease of the magnitudes of compressive residual stresses with an increase of the exposure time from 600 min to 60 000 min (100 MPa at the surface, 50 MPa at the maximum), which could not be observed so distinctly in the austenite. The maximum of compressive residual stresses remained under the surface. The half widths also decreased with increasing annealing time (0.2° at the surface, ~0.4° under the surface) and the maxima appeared at the surface (fig. 10). The small increase of the half widths in a depth between 0.01 mm and 0.06 mm may be affected by the extreme lowering of X-ray intensities with increasing depth as the content of the martensitic phase was about 5 %.

Conclusions

The foregoing investigations of the peened steel 316 Ti lead to the following conclusions:

1. The induced quite different magnitudes of compressive residual stresses in the austenite and the martensite after shot peening and high pressure water peening can be explained as a consequence of the differences in the yield strength of the two phases in the steel.

2. In comparison with the austenite the reduction of residual stresses was stronger in the shot peened martensite at an annealing temperature of 400 °C. The lower magnitudes of the residual stresses after high pressure water peening are less reduced by temperature and time in both phases than the higher magnitudes after shot peening. The reduction of the half widths of the diffraction lines was clearly more pronounced in the shot peened and high pressure water peened martensite than in the austenite. These results have to be discussed in terms of the different initial residual stresses and of the different dislocation densities after both peening processes in the austenite and the martensite.

3. In the depth profiles of the residual stresses as well as of the half widths of the shot peened austenite a reduction of their magnitudes could also be clearly found due to annealing at 400 °C. A prolongation of the annealing time from 600 min to 60 000 min, however, had only a minor influence on the residual stresses close to the surface and nearly no influence on the half widths. In the high pressure water peened condition of the austenite no significant changes could be detected in the depth profiles of residual stresses or half widths.

4. In contrast with these results for the austenite a remarkable reduction of the magnitudes was observed in the depth profiles of the residual stresses and of the half widths of the shot peened martensite, if the annealing time was prolonged from 600 min to 60 000 min at 400 °C.

Acknowledgement

The authors wish to gratefully thank the Metal Improvement Inc., Unna/Germany, for shot peening of the specimens.

References

1. Hauk, V., Macherauch, E.: Die Zweckmäßige Durchführung röntgenographischer Spannungsermittlungen. in: HTM-Beiheft „Eigenspannungen und Lastspannungen" ed. V. Hauk and E. Macherauch, Hanser 1982 1 – 19
2. Krull, P., Nitschke-Pagel, Th., Wohlfahrt, H.: Influence of mechanical and thermal loading on the stability of residual stresses in shot peened and high pressure water peened stainless steels. EUROMAT'98 Lisbon Conf. Proc. Vol. I 519 – 528
3. Wohlfahrt, H.: A model for predicting residual stresses produced by shot peening. in: Residual stresses, ed. E. Macherauch, V. Hauk DGM 1986 347 – 364
4. Krull, P., Nitschke-Pagel, Th., Wohlfahrt, H.: Influence of shot peening and high pressure water peening on near surface microstructure of 316 Ti stainless steel. 4th Int. Conf. Surface Treatment, 20. – 22.09.1999 Assisi/Italy, in press
5. Vöhringer, O.: Relaxation of residual stresses by annealing or mechanical treatment. In „Advances in surface treatments Volume 4" ed. A. Niku-Lari, Perg. Press Oxford 1987 367 - 396
6. Schulze, V., Burgahn, F., Vöhringer, O., Macherauch, E.: Zum thermischen Abbau von Eigenspannungen bei vergütetem 42 CrMo 4. Mat.-wiss. u. Werkstofftech. 24 (1993) 258 – 267
7. Altenberger, I., Scholtes, B., Martin, U., Oettel, H.: Cyclic deformation and near surface microstructures of shot peened or deep rolled austenitic stainless steel AISI 304. Materials, Science & Engineering A 1999 264 1 –16