STABILITY OF SURFACE CHANGES INDUCED BY MECHANICAL SURFACE TREATMENTS

V. Schulze
Universität Karlsruhe (TH), Institut für Werkstoffkunde I,
Kaiserstrasse 12, D-76128 Karlsruhe, Germany

ABSTRACT

The stability of the surface state induced by mechanical surface treatments during thermal, quasi-static and cyclic loading is of high interest in order to understand the effects of these processes on the mechanical properties. In this paper mechanisms leading to and models describing the relaxation of residual stresses as representative of the surface state as well as typical experimental findings are presented at the steel AISI4140 which is taken as an example material. Effects of different modified peening processes are included in the evaluation.

SUBJECT INDEX

Residual Stresses, Relaxation of Residual Stresses, Thermal loading, Quasi-static loading, Cyclic loading

INTRODUCTION

Mechanical surface treatments yield to changes in the surface state which is characterized by properties as residual stresses, work-hardening state, topography, and others. Their distributions depend on process parameters, material and material state in a typical manner. Details can be seen from [1], e.g. As the changes in fatigue properties intended by mechanical surface treatments severely depend on the stability of the surface states during loading, investigations and descriptions of the stability of surface characteristics are absolutely essential for evaluating mechanical surface treatment processes. Therefore a large number of papers dealing with the stability of surface states at different loading conditions can be seen from literature, as summarized in reviewing articles or handbooks like [2], e.g.

In this paper an overview about the actual state of experimental work and of models as well as apparent mechanisms in the field of stability of surface states induced by mechanical surface treatments will be given. The paper is separated into thermal, quasi-static and cyclic loadings. In order to keep with the limits of the length of the paper the author was forced to reduce the presented investigations to typical results concerning the residual stress states and to the well investigated steel AISI4140, only.

THERMAL LOADING

At thermal loading relaxation of residual stresses is caused by creep processes which are due to dislocation climbing controlled by dislocation core or volume diffusion. Only at highest temperatures - usually avoided in technical application - additional effects of recrystallization may be apparent. The creep processes transform the elastic strains combined with the residual stress state into micro plastic strains and therefore reduce the residual stresses. The residual stress relaxation processes can be modeled using two different approaches. The first was introduced by [3] and is based on the Zener-Wert-Avrami-equation according to

$$\frac{\sigma^{rs}(T,t)}{\sigma^{rs}_{o}} = \exp\left\{-\left[C\cdot\exp\left(-\frac{\Delta H_A}{kT}\right)t\right]^{m}\right\} \qquad \text{eq. 1}$$

where $\sigma^{rs}(T,t)$ is the residual stress value after annealing for a time t at a temperature T and σ^{rs}_{o} is the initial residual stress value and k equals the Boltzmann constant. ΔH_A as the activation enthalpy of the rate controlling process, m as an exponent and C as a velocity constant are material dependent properties. According to [4] the residual stress relaxation can also be described applying the Norton-equation well known from high temperature deformation processes

$$\dot{\varepsilon}_p = A(\sigma^{rs}_{m})^{n}\exp\left(-\frac{\Delta H_N}{kT}\right) \qquad \text{eq. 2}$$

where the plastic strain rate $\dot{\varepsilon}_p$ at a certain time may be determined assuming a vanishing total strain rate from the inverse elastic strain rate. This can be calculated from the change in the residual stresses within a time interval related to the Young's modulus. σ^{rs}_{m} equals the average value of residual stresses within the time interval regarded. Again ΔH_N as the activation enthalpy of the rate controlling process, n as the Norton-exponent and A as a velocity constant are material dependent properties.

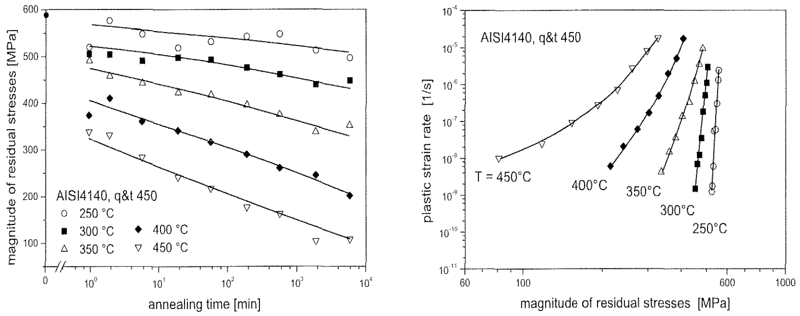

Figure 1: Thermal residual stress relaxation and its description by Avrami-equation (left) and Norton-creep-relation (right) at shot peened AISI4140 in a state quenched and tempered at 450°C [5].

Typical experimental results are given in Fig. 1 [5]. Its left part shows the increasing relaxation of residual stresses with increasing annealing time and annealing temperature in the range of 250 °C to 450 °C for a quenched and tempered state of the steel AISI4140 after conventional shot peening. The lines included show the good agreement of experimental values with the description using the Avrami-equation. Similar results were observed after stress peening, warm peening and laser shock treatments [1,2,6]. With increasing hardness of the material state increasing driving forces for recovery processes accelerate residual stress relaxation [3]. The Avrami-equation could also be used for the description of subsurface residual stress changes and lead to good agreements. Only directly at the surface the relaxation is accelerated compared to the inner part of the material where no significant differences of the relaxation behavior were found [5]. Last but not least the Avrami-equation was successfully used for the description of the transient residual stress relaxation during heating processes [5]. The right part of Fig. 1 shows the application of the Norton-relation to the same data as already given in the left part of Fig. 1. While at low temperatures a very high Norton exponent of up to 120 is apparent it reduces severely at higher temperatures down to 3 at 450 °C and low stresses. This means that at low temperatures power-law breakdown indicates thermally activated dislocation movements via short range obstacles and that at high temperatures volume diffusion controlled dislocation creep is rate controlling [5].

QUASI-STATIC LOADING

At quasi-static loading residual stress relaxation occurs due to locally different plastic deformations which are due to the stress states and due to the deformation behavior dependent on the distance from surface. The Bauschinger-effect plays a major role depending on the direction of quasi-static deformation compared to that of the plastic deformations during mechanical surface treatment [7]. The deformation behavior and quasi-static residual stress relaxation can be understood and in a simplified manner be described using the surface-core-model [8]. It is assumed that firstly the deformation can be described uniaxially, secondly the surface treated specimen can be viewed as a compound of surface and core region with the same total strains, thirdly the initial residual stresses are included as initial conditions and fourthly the deformation behavior may be different in both regions. This leads to the deformation behavior and the residual stress relaxation given in Fig. 2 for an ideal elastic-plastic material (left) and for a linearly work-hardening material with increased yield strength in the surface area (right) at tensile and compressive loading both showing the compressive residual stresses typical for mechanical surface treatments [8].

Both behaviors yield to a trilinear stress-strain-curve for both loading directions. While the ideal elastic-plastic material leads independent of the loading direction to equal and constant stresses after initiation of plastic deformation in both regions and therefore to vanishing residual stresses, the increased yield strength of the surface

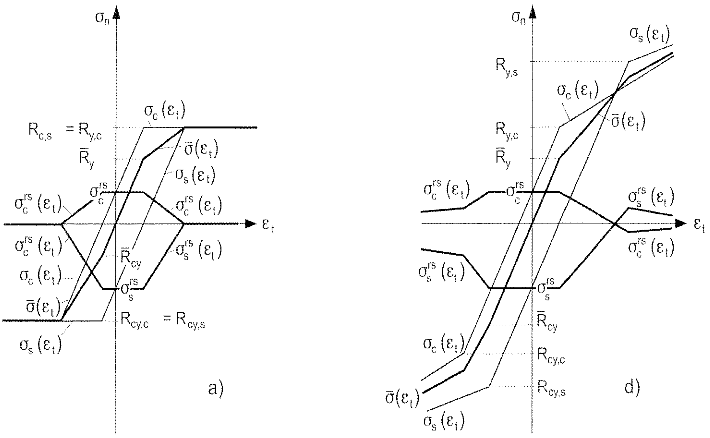

Figure 2: Schematic description of the deformation behavior and the changes in the residual stress state according to the surface-core-model for ideal elastic-plastic behavior (left) and for increased surface yield strength and linear work-hardning behavior (right) [8].

area leads to a change of the sign of the residual stresses at tensile loading and incomplete relaxation at compressive loading. The different work-hardening rates lead to changes of the residual stresses even at high strains. In both cases the initiation of residual stress relaxation at the yield strength of the compound can be estimated. As the uniaxial surface core model is relatively simple its major advantage is its clearness. This causes reductions in precision which can be overcome using a multiaxial multilayer model described in [9] or a Finite-Element-Model given in [10], both including more features.

Typical experimental results are given in Fig. 3 at shot peened specimens of the steel AISI4140 in different heat treatment states. Its left part shows the longitudinal residual stresses at tensile and compressive loading [7,9,11]. With increasing material hardness the residual stresses as well as the loading stresses necessary to initiate residual stress relaxation increase. While at the normalized state and the state quenched and tempered at 650 °C the residual stresses change their sign twice during tensile and once at compressive loading, they remain in the compressive region at tensile loading of the state quenched and tempered at 450 °C. The residual stress relaxation rate generally is smaller at compressive than at tensile loading. Using the surface-core-model this can be interpreted as an effect of severe work-hardening during shot peening in the softer states, which is lower in the hardest state, and of lower plastic deformations during the quasi-static loading before failure occurs in the hardest state [2]. Additional investigations of the changes of the transverse residual stresses yield lower and at tensile loading incomplete relaxation at all material states. This may be due to the vanishing loading stress in that direction. The right part of Fig. 3 shows the residual stress relaxation behavior at bending loading after the first loading and after a load reversal as a function of the fictitious (elastically extrapolated) surface stress during the first loading [7,12]. The effects of the material states are similar to those reported for the homogeneous loading before. It can be seen that the residual stress relaxation is primarily induced at the compressively loaded top side of the specimens and that at the tensilely loaded side only slight reactions to this relaxation appear. After load reversal the results are viceversa. Now the bottom side shows severe residual stress relaxation and the top side which is now tensilely loaded shows almost vanishing residual stress relaxation. Finally, both sides show almost similar residual stress states at all material states.

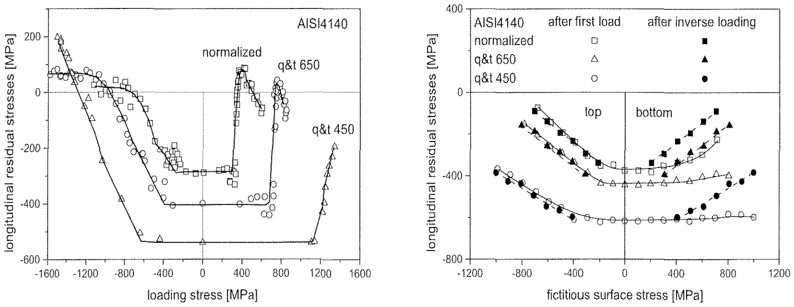

Figure 3: Quasi-static residual stress relaxation at tensile (left) and bending (right) loading at shot peened AISI4140 in differently heat treated states [7,9,11,12].

CYCLIC LOADING

At cyclic loading residual stress relaxation has to be separated into 3 phases [8,10,13]. The quasi-static loading in the first loading cycle leads to effects which can be described as before. The further cyclic loading up to the phase of crack growth will be the major point of this section. Finally, within the phase of crack growth the residual stress relaxation is increased due to crack growth effects. Within the second phase micro-plastic strains accumulating from cycle to cycle due to cyclic creep effects caused by local differences in the stress state and the cyclic deformation behavior of the different regions yield to the relaxation effects. The residual stress relaxation can be described using

$$\sigma^{rs} = \sigma^{rs}(N = 1) - \mu \cdot \log N \qquad \text{eq. 3}$$

where $\sigma^{rs}(N = 1)$ is the residual stress value after the first cycle and μ is a slope linearly depending on the stress amplitude [14]. Therefore the increase of residual stress relaxation with increasing number of cycles and loading stress amplitude can be described. Critical loading stresses separating loading situations with cyclically stabile and cyclically relaxing residual stresses can be determined by evaluation of the highest loading stress amplitude leading to μ = 0 [13] or by measuring the dependence of the residual stresses remaining after the first and, e.g., the 10^{4th} cycle on the loading stress amplitude and evaluation the lowest stress amplitude leading to changes of the residual stresses within this numbers of cycles [15,16].

Typical experimental results are given in Fig. 4 (left) at shot peened specimens of the steel AISI4140 in a heat treatment state quenched and tempered at 450 °C which was alternating bended at different fictitious stress amplitudes at the surface [13]. The 3 phases of residual stress relaxation can easily be separated. Firstly, changes of the residual stresses occur within the first loading cycle. These are increasing with increasing loading stress amplitude and due to quasi-static relaxation effects. Secondly, linear relationships between the residual stresses and the logarithm of the number of cycles come up which show increasing slopes with increasing loading stress amplitude. In the third phase, when cracks already play a major role, the residual stresses decrease more pronounced than expected from the extrapolation of the previous behavior. According to Fig. 4 (right) the residual stress stability at the relatively high stress amplitude at the surface of $\sigma^*_{a,s}$ = 1000 MPa is severely affected by the shot peening parameters [15]. While stress peening allows to induce increased residual stresses which tend to relax within the first loading cycle to stress values similar to the conventionally peened state, warm peening and stress peening at elevated temperatures lead to slightly increased stresses compared to the same treatments performed at room temperature. But the residual stresses induced at elevated temperatures are much more stabile than those induced at room temperature so that significantly increased residual stresses are apparent during the whole fatigue process. According to [17] this can be led back to dynamic and static strain ageing effects occurring during warm peening and when cooling down from peening temperature. Annealing processes after conventional peening treatments reduce the residual stresses available during cyclic loading [18]. As shown in Fig. 4 (right), due to the lower sum of loading and residual stresses they relax to similar values as the residual stresses after conventional peening.

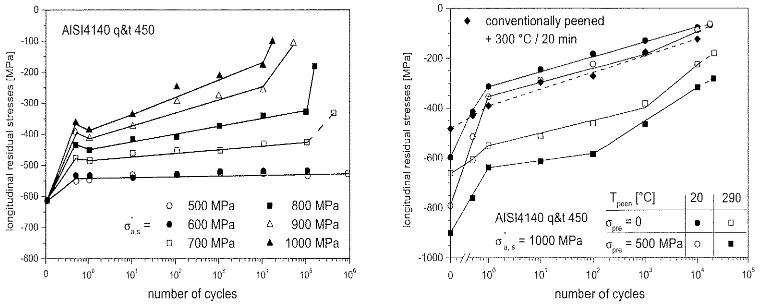

Figure 4: Cyclic residual stress relaxation at alternating bending loading with different fictitious stress amplitudes of conventionally shot peened AISI4140 (left) and with a fictitious stress amplitude of 1000 MPa of differently shot peened AISI4140 (right) in a state quenched and tempered at 450 °C [13,15].

Fig. 5. summarizes the stability of the residual stresses after conventional shot peening, warm peening and conventional peening plus annealing according to the two descriptions previously mentioned in this paragraph [15,16]. As can be seen from the comparison of the critical loading stress amplitudes both descriptions yield to the same results. It is apparent that warm peening leads to higher residual stresses which are stabile up to the highest critical loading stress amplitude of 714 MPa. Therefore this state can be assumed to bear the most stabile residual stresses. The conventionally peened and finally annealed state shows lower residual stresses but a critical loading stress amplitude of 690 MPa which is also significantly higher than that of the conventionally peened state where only 514 MPa were measured. This means that though the residual stresses initially are relaxed and are severely relaxing during cyclic loading with a very high stress amplitude (see Fig. 4 right), they show an enhanced stability at intermediate loading stresses. In [19] this was traced back to static strain ageing effects.

Fig. 6 summarizes the residual stress changes within the first and up to the 10^7th cycle at alternating bending loading with a fictitious stress amplitude in the range of

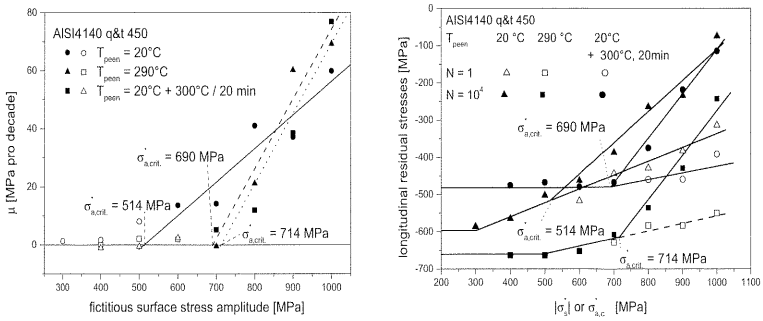

Figure 5: Influence of fictitious stress amplitude on the slope μ (left) and on the residual stresses after 1 and 10^4 cycles (right) at alternating bending loading of differently shot peened and annealed AISI4140 in a state quenched and tempered at 450 °C [15,16].

the alternating bending strength at AISI4140 in differently heat treated states [16]. It can be seen that after all heat treatments the residual stresses are relaxing more pronounced after stress peening and are severely more stabile after warm peening. Additionally it is obvious that the residual stresses are the more stabile the higher the materials hardness is, even if the initial residual stresses increase simultaneously.

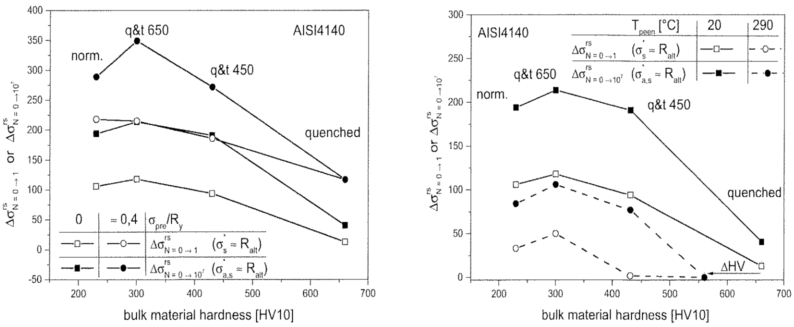

Figure 6: Influence of stress peening (left) and warm peening (right) on the residual stress changes in the first and up to the 10^7th cycle at alternating bending loading with a fictitious stress amplitude in the range of the alternating bending strength at AISI4140 in different heat treatment states [16].

CONCLUSIONS AND CONSEQUENCES

The stability of residual stresses induced by shot peening due to thermal, quasi-static and cyclic loading was presented in this paper. In all cases mechanisms, models describing the residual stress relaxation and their most important dependencies as well as experimental results were given. In all cases the residual stress relaxation could be traced back to inhomogeneous micro-plastic strains caused by the transformation of the elastic residual strains combined with the residual stresses. At thermal loading creep effects lead to residual stresses relaxing with increasing time and temperature, where time and temperature for similar residual stress relaxation depend on each other according to an Arrhenius-term. At quasi-static loading the residual stresses can be described by a surface-core model and therefore are correlated to the differences in the residual stress states at different distances from surface and to the different deformation behavior at these areas. At cyclic loading two empiric models were introduced both good acquainted to describe the residual stress relaxation. A special focus of this part of the paper was on modifications of the shot peening treatments leading to increased stabilities of the residual stresses like warm peening and conventional peening plus annealing. Additionally it could be shown that residual stresses are relaxing the more pronounced the lower the material hardness is. As a consequence of this, mechanical surface treatments at low material hardness lead to effects on the fatigue strength mainly caused by work hardening effects, whereas at high material hardness the effects on the fatigue strength is much more pronounced and can be led back to severe effects of the compressive residual stresses induced. The modifications of the shot peening treatments mentioned lead to more stabile residual stresses due to dynamic and static strain ageing effects and therefore allow for severely increased fatigue strengths compared to conventional peening [19,20].

ACKNOWLEDGMENTS

Financial support by the Deutsche Forschungsgemeinschaft (DFG) is gratefully acknowledged.

REFERENCES

[1] V. Schulze: Characteristics of Surface Layers Produced by Shot Peening, In: L. Wagner (ed.), Shot Peening, Proc. Int. Conf. Shot Peening 8, Garmisch-Partenkirchen, Wiley-VCh, Weinheim, 2003, 145-160.

[2] V. Schulze: Modern Mechanical Surface Treatment - Surface Layer States, Stabilities and Effects, Wiley-VCH, Weinheim, 2005, in print.

[3] O. Vöhringer: Abbau von Eigenspannungen, In: V. Hauk, E. Macherauch (eds.), Eigenspannungen, DGM-Informationsgesellschaft, Oberursel, 1983, pp. 49-83.

[4] D. Viereck, D. Löhe, O. Vöhringer, E. Macherauch: Relaxation of residual stresses in a nickel-base superalloy due to dislocation creep, In: D. G. Brandon, R. Chaim, A. Rosen (eds.), Proc. Int. Conf. Strength of Metals and Alloys 9, Freund Publishing, London, 1991, pp. 14-19.

[5] V. Schulze, F. Burgahn, O. Vöhringer, E. Macherauch: Zum thermischen Abbau von Kugelstrahl-Eigenspannungen bei vergütetem 42 CrMo 4, Materialwissenschaft und Werkstofftechnik 24(1993), pp. 258-267.

[6] R. Menig, V. Schulze: unveröffentlicht, Universität Karlsruhe (TH), 2002.

[7] H. Holzapfel, V. Schulze, O. Vöhringer, E. Macherauch: Residual stress relaxation an an AISI 4140 steel due to quasistatic and cyclic loading at higher temperatures, Materials Science and Engineering A248(1998), pp. 9-18.

[8] B. Scholtes: Eigenspannungen in mechanisch randschichtverformten Werkstoffzuständen, Ursachen-Ermittlung-Bewertung, DGM-Informationsgesellschaft, Oberursel, 1990.

[9] V. Schulze, O. Vöhringer, E. Macherauch: Modellierung des Verformungsverhaltens und der Makroeigenspannungsänderungen bei quasistatischer Beanspruchung von vergütetem und kugelgestrahltem 42 CrMo 4, Zeitschrift für Metallkunde 89(1998), pp. 719-728.

[10] H. Holzapfel: Das Abbauverhalten kugelgestrahlter Eigenspannungen bei 42CrMo4 in verschiedenen Wärmebehandlungszuständen, Dissertation, Universität Karlsruhe (TH), 1994.

[11] F. Theobald, V. Schulze: unveröffentlicht, Universität Karlsruhe (TH), 1992.

[12] H. Holzapfel: unveröffentlicht, Universität Karlsruhe (TH), 1994.

[13] E. Macherauch H. Wohlfahrt: Eigenspannungen und Ermüdung, In: D. Munz (ed.), Ermüdungsverhalten metallischer Werkstoffe, DGM-Informationsgesellschaft Verlag, Oberursel, 1985, pp. 237-283.

[14] J. Morrow, A. S. Ross, G. M. Sinclair : Relaxation of residual stresses due to fatigue loading, SAE Transactions 68(1960), pp. 40-48.

[15] A. Wick: Randschichtzustand und Schwingfestigkeit von 42CrMo4 nach Kugelstrahlen unter Vorspannung und bei erhöhter Temperatur, Dissertation, Universität Karlsruhe (TH), 1999.

[16] R. Menig: Randschichtzustand, Eigenspannungsstabilität und Schwingfestigkeit von unterschiedlich wärmebehandeltem 42 CrMo 4 nach modifizierten Kugelstrahlbehandlungen, Dissertation, Universität Karlsruhe (TH), 2002.

[17] A. Wick, V. Schulze, O. Vöhringer: Effects of stress- and/or warm peening of AISI 4140 on fatigue life, Steel Research 71(2000) 8, pp. 316-321

[18] R. Menig, V. Schulze, O. Vöhringer: Kugelstrahlen und anschließendes Auslagern - Steigerung der Eigenspannungsstabilität und der Wechselfestigkeit

am Beispiel von 42CrMo4, Härterei Technische Mitteilungen 58(2003), pp. 127-132.

[19] R. Menig, V. Schulze, O. Vöhringer: Effects of Static Strain Aging on Residual Stress Stability and Alternating Bending Strength of Shot Peened AISI 4140, Zeitschrift für Metallkunde 93(2002) 7, pp. 635-640.

[20] R. Menig, V. Schulze, O. Vöhringer: Optimized warm peening of the quenched and tempered steel AISI 4140, Materials Science and Engineering A335(2002), pp. 198-206.