Relaxation of residual stresses—some new results

残留応力緩和 — 幾つかの新しい結果

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If residual stress states induced by shot peening are sufficiently stable, they lead to enhancements of fatigue life. On the other hand, relaxation of shot peening induced residual stresses occurs as a consequence of high temperatures, high tensile or compressive loading or high cyclic loading. Therefore, stability and relaxation of residual stresses are a topic of considerable interest in theory and practice. New results are presented and discussed concerning all three causes of residual stress relaxation mentioned above. Especially, the conventional models describing the relaxation behaviour are compared with improved models which have been developed in the last few years.

Keywords: residual stresses, shot peening, thermal, quasistatic and cyclic loading

I. INTRODUCTION

Shot peening causes changes in topography, residual stress state and microstructure in superficial regions of metallic materials.¹ Whereas increased roughness is detrimental to fatigue life, the shot peening induced compressive residual stress state and the work-hardening state found in most metallic materials can cause enhanced fatigue life and fatigue strength. This holds under the prerequisite that the shot peening induced residual stresses are sufficiently stable and not reduced during operation. The same is valid for the shot peening induced superficial changes in the microstructure. A reduction of residual stresses and work-hardening state is possible if shot peened parts are exposed to high temperatures, high tensile or compressive loading or high cyclic loading during operation. Therefore stability and relaxation behaviour of residual stresses were investigated by several authors.²⁻¹⁰ and have been reviewed from a general viewpoint.^{11, 12}

A survey is given on new results of surface residual stress relaxation due to thermal or mechanical treatments. Characteristic findings are presented concerning macro residual stresses induced by shot peening. One of the main points of this review deals with the improvements of models used to describe the relaxation of residual stresses.

II. MATERIALS AND EXPERIMENTAL DETAILS

The results presented were obtained from investigations on the steel 42 CrMo 4 (AISI 4140; 0.42 wt.-% C, 1 wt.-% Cr, small amounts of Mo, Si, Mn, Ni, P, S and rest Fe). Samples produced according to the requirements of the individual experiments were investigated in normalized, differently quenched and tempered and as quenched states. The precise heat treating conditions will be given together with the description of the individual experiments. After the heat treatments all specimens were shot peened in an air blast machine using cast steel shot S 170 (44-48HRC), a pressure of 1.6 bar and a coverage of 98%. Whereas flat specimens were shot peened simultaneously on both sides, cylindrical specimens were rotated during the shot peening treatment.

X-ray macro residual stress determinations were performed with automated ψ -diffractometers of the Karlsruhe type measuring {211}-interference lines using CrK_α -radiation. The residual stresses were evaluated from the measured lattice strains applying the $\sin^2\psi$ -method¹³ and using the elastic constants $E = 220\,000\text{ N/mm}^2$ and $\nu = 0.28$. Subsurface residual stress distributions were determined by electrolytical removal of material layers and subsequent X-ray residual stress measurements. The measured values were corrected for residual stress changes due to material removal applying

the Moore-Evans-method¹⁴

III. THERMAL TREATMENTS

A. Models

Relaxation of residual stresses due to thermal treatment is caused by thermally activated processes which can be described by the Avrami-approach^{11, 12}

$$\frac{\sigma_o^{RS}(t,T)}{\sigma_o^{RS}} = \exp \left\{ - \left[C \exp \left(\frac{-\Delta H_A}{k T} \right) t \right]^m \right\} \quad (1)$$

with $\sigma_o^{RS}(t,T)$ the residual stress value after annealing at the absolute temperature T for the time t , σ_o^{RS} the residual stress value before annealing, ΔH_A the activation enthalpy of the rate controlling process of residual stress relaxation, C a velocity constant, m an exponent and k the Boltzmann-constant. The material constants ΔH_A , C and m characterizing the residual stress relaxation can be determined from measured residual stress values using a conventional or a new iterative method. The conventional method uses linear regression lines in the plots $\log [\ln (\sigma_o^{RS} / \sigma_o^{RS})]$, $\log t$ and $\log t$, $1/kT$ to determine ΔH_A , C and m from their slopes and intercepts², as shown in Fig. 1. It requires strong extrapolations to very low or very high annealing times and therefore does not allow an equal consideration of all measured values in the determination of ΔH_A , C and m . To avoid these disadvantages, a new iterative method was developed^{15, 16} which uses a non-linear least-squares algorithm and leads to lower mean deviations between measured and calculated values of residual stresses.

FIG. 1. Conventional determination of material constants of the Avrami-approach (schematically).

B. Experimental results

The thermal residual stress relaxation was investigated on samples of 42 CrMo 4 with the dimensions 12x12x2 mm³ which were normalized at 930°C/3h, oil-quenched from 850°C or oil-quenched and finally

tempered at 450°C or 650°C for 2 h. After shot peening the residual stress relaxation experiments were carried out by annealing in salt baths with temperatures between 250°C and 450°C and annealing times up to 6000 min.

FIG. 2. Amounts of residual stresses vs. annealing time at different annealing temperatures and their description by the Avrami-approach (quenched and tempered, 450°C).

As an example, the experimental results obtained at the quenched and tempered state with the tempering treatment at 450°C are shown in Fig. 2. The amounts of residual stresses are plotted as a function of the logarithm of the annealing time for various annealing temperatures. They decrease with increasing time and temperature. The curves in Fig. 2 were calculated using the Avrami-approach. The material constants determined by the new iterative method are $\Delta H_A = 3.29$ eV, $C = 1.22 \cdot 10^{21}$ 1/min and $m = 0.122$. It is evident that the time and temperature dependence of relaxation behaviour can be described in a very good manner. The mean deviation between measured and calculated values is 5.3 N/mm², whereas the conventional method led to a mean deviation of 9 N/mm². Hence, the new iterative method improves the approximation nearly by a factor of two.

The relaxation behaviour of shot peening induced residual stresses due to thermal treatments was investigated in corresponding experiments for different heat treatment conditions of the steel 42CrMo4. The new iterative method was used in all cases to determine the materials constants ΔH_A , C and m listed in Table 1. Whereas the changes of C and m cannot be discussed now, it is possible to discuss them for the ΔH_A -values. These are close to 3.3 eV for the normalized and the quenched and tempered states and hence approach the value of the activation enthalpy of self diffusion of iron $\Delta H_S = 2.78$ eV¹⁷. Accordingly, volume diffusion controlled dislocation creep dominated by climbing of edge

dislocations is assumed to be the rate controlling process for the relaxation of the residual stresses in these heat treatment conditions. On the other hand, the as quenched condition shows a significantly lower value $\Delta H_A = 2.33$ eV. Due to the higher dislocation density, pipe-diffusion controlled climbing of edge dislocations seems to be one of the rate controlling processes. Additionally, the formation of carbides due to the tempering treatment of the primarily as quenched material state restricts the relaxation of residual stresses and leads to the low ΔH_A -value.

heat treatment	ΔH_A [eV]	C [1/min]	m
normalized	3.30	$1.40 \cdot 10^{18}$	0.080
quenched and tempered 450°C	3.38	$1.90 \cdot 10^{21}$	0.080
quenched and tempered 650°C	3.29	$1.22 \cdot 10^{21}$	0.122
as quenched 850°C	2.33	$1.20 \cdot 10^{16}$	0.110

TABLE 1. Material constants ΔH_A , C and m of the Avrami-approach determined for different heat treatment conditions applying the new iterative method.

During heating up to sufficiently high temperatures a distinct relaxation of residual stresses occurs. Therefore this behaviour was modelled by extending the Avrami-approach to non-isothermal stress relaxation. Two methods were drawn up for this purpose¹², a so-called time-transient-method and a stress-transient-method. In both cases the real $T(t)$ -relationship is splitted into equidistant steps of time Δt . When passing these steps a relaxation of residual stress $\Delta \sigma^{RS}$ occurs at the mean temperature T_m , which is considered to be constant within Δt . While the time-transient-method assumes that this relaxation is determined by the totally elapsed heating time, the stress-transient-method assumes that the relaxed residual stress values determine the further relaxation. Both methods were used to calculate the relaxation of residual stresses for specimens quenched and tempered at 450°C which were immersed up to 90 s in salt baths. As the measured values could be described in an excellent manner by the stress-transient-method the further relaxation of residual stresses during heating-up seems to be determined by the relaxed residual stress values.¹⁵ Figure 3 shows the amounts of macro residual stresses in specimens which were immersed in salt baths of 300, 350 and 450°C for different times. The curves calculated using the stress-transient-method

describe the measured values indicated by the symbols relatively well. Only at 300°C the measured values are systematically lower than the calculated values. This is assumed to be caused by the Avrami-approach which supposes that the material constants ΔH_A , C and m do not depend on the temperature. In reality, however, this assumption does not hold.

FIG. 3. Amounts of residual stresses after short-time immersion in a salt bath of 300°C, 350°C and 450°C and comparison with courses calculated applying the stress-transient-method (quenched and tempered, 450°C).

IV. TENSILE OR COMPRESSIVE LOADING

A. Models

The relaxation behaviour of residual stresses and the deformation behaviour of prismatical rods bearing residual stresses can be described using two methods, the so-called surface-core-model and the surfacelayers-core-model. The simpler surface-core-model which is shown schematically in Fig. 4 separates the cross-section of the rod into two parts, a surface and a core layer.^{6,11} Within these layers the residual stresses are assumed to be constant. In order to take into account the shot peening induced superficial microstructure, the deformation behaviour of surface and core put into the model may vary from each other. Surface and core are coupled axially by cross beams. Therefore, axially loa-

FIG. 4. Surface-core-model (schematically).

ding of the compound results in total strains ϵ_t which are equal in both layers. The strain-depending stress in the two layers and the external loading stress of the compound are evaluated from the stress-strain-curves of surface and core. For this reason the curves are shifted in the direction of strain so that the initial residual stresses appear at $\epsilon_t = 0$. Residual stresses in tangential direction are not taken into account in this model.

FIG. 5. Surfacelayers-core-model (schematically).

An improved version of the model described is the so-called surfacelayers-core-model which has been developed in the last few years.¹⁸ It can be seen from the scheme in Fig. 5 that this model allows a better approach of the measured dependence of the residual stresses on the distance to surface. This is due to the assumption of multiple surfacelayers s and a corelayer c are separated. All layers can be understood as hollow cylinders bearing axial and tangential residual stresses. They are coupled in axial direction so that they show equal total strain values if the compound is loaded. In radial and tangential direction no coupling is realized. The second major advantage of this model is that tangential residual stresses are taken into account. For this reason, the von-Mises-hypothesis¹⁹ is used to determine whether or not plastic deformation occurs. The degree of plastic deformation in axial and in tangential direction is evaluated using the flow-rule by Prandtl-Reuss.²⁰ From the stresses in the layers and the loading stress of the compound the residual stresses in each layer can be calculated assuming linear elastic unloading behaviour. A disadvantage of this model is that the calculation durations are extremely long.

B. Experimental results

The investigations on residual stress relaxation due to tensile or compressive loading were carried out with specimens of 42 CrMo 4 with a diameter of 5 mm. The specimens were oil-quenched and tempered at 650°C for

2 h. Subsequently, they were shot peened to induce a characteristic residual stress state. After loading with different tensile or compressive stresses and subsequent unloading the remaining residual stresses were measured.

Figure 6 shows the dependence of axial and tangential residual stresses on the distance to surface after shot peening using lines interpolating the measured values. Compressive axial residual stresses with amounts of 400 N/mm² were found in superficial regions. Maximum amounts are registered 0.05 mm below the surface. At higher distances to surface the axial residual stresses rapidly decrease and vanish at $x \approx 0.30$ mm. Then tensile residual stresses were observed. Tangential residual stresses show somewhat lower amounts and no sub-surface-maximum. The bars in Fig. 6 represent the values of residual stresses used in the model. This gives an idea of the thickness of the separated surfacelayers s_1 to s_6 and the corelayer c , too. In addition to the residual stress values, distinct stress-strain-curves have to be associated to all layers. After multiple modelling with different deformation behaviours for each layer the stress-strain-curves shown in Fig. 7 seemed to be most suitable for the description of residual stress relaxation and deformation behaviour of the multilayer compound. Only the first two layers s_1 and s_2 show a deformation behaviour which differs from the core and the other

FIG. 6. Axial and tangential residual stresses vs. distance to surface and their approach by the surfacelayers-core-model (quenched and tempered, 650°C).

FIG. 7. Stress-strain-curves of the layers used in the surfacelayers-core-model (quenched and tempered, 650°C).

surfacelayers and can be modelled using the stress-strain-curve of an unpeened specimen. At tensile loading the surfacelayer s_1 is workhardened in comparison with the layer s_2 which shows a little higher yield strength than the core. At total strains higher than 1.5% an inverse behaviour is observed. At compressive loading the yield strength of the surfacelayer s_1 is much lower than that of the layer s_2 . Both layers show lower yield strengths than the unpeened material. Because of the high workhardening rate in the surfacelayers s_1 and s_2 after 0.5% total strain these layers bear higher amounts of stress than the core. The lower yield strength and higher workhardening rate of the surfacelayers at compressive loading can be explained by the occurrence of a Bauschinger-effect, which results from internal backstresses.²¹ This Bauschinger-effect leads to small yield strengths if a predeformed material is loaded in reverse direction. It occurs in the superficial region of the shot peened specimens at compressive loading after the shot peening treatment. The latter leads to a stretching of this region and therefore can be understood as a tensile preloading.²²

The knowledge of the residual stress distribution and of the deformation behaviour of all layers enables the calculation of the deformation behaviour of the compound and the comparison with the experimental stress-strain-curve of a shot peened specimen in Fig. 8. The deformation behaviour can be described in an excellent manner using the model. The largest differences between the curves occur in the Lüders-region and amount to 1.5%, only. The second very important result of the modelling consists in the description of the residual stress relaxation in axial and in tangential direction as a

FIG. 8. Deformation behaviour of a shot peened specimen and comparison with modelled behaviour of the compound (quenched and tempered, 650°C).

function of tensile or compressive loading stress in Fig.

9. The symbols representing the measured values show that the relaxation of axial residual stresses begins at $\sigma^{LS} = 700 \text{ N/mm}^2$ and shows a very high relaxation rate. For this reason the axial residual stresses rapidly vanish and then change their sign for a short interval of loading stress. Therefore, tensile residual stresses are measured. Afterwards, a second sign reversal occurs and small compressive residual stresses were built up again. The relaxation during compressive loading starts at $\sigma^{LS} = -400 \text{ N/mm}^2$ and is much smaller than during tensile loa-

FIG. 9. Axial and tangential residual stresses vs. loading stress and description by the surfacelayers-core-model (quenched and tempered, 650°C).

ding. For this reason the residual stresses vanish at approximately $\sigma^{LS} = -1000 \text{ N/mm}^2$. Subsequently small tensile residual stresses are observed. Tangential residual stress relaxation begins at the same amount of loading stresses but remains incomplete during tensile loading. The curves shown in Fig. 9 are calculated using the surfacelayers-core-model. They describe the relaxation behaviour very well. The relaxation rates and their changes of sign are modelled correctly. Only the tangential residual stresses at high amounts of loading stress cannot be described in a good manner.

As many technical parts are exposed to tensile or compressive loadings at higher temperatures, the residual stress relaxation behaviour was investigated for additional thermal treatments using a quenched and tempered state of the steel 42 Cr Mo 4 with 450°C annealing temperature and 2 h annealing time. Specimens with 7 mm diameter were shot peened after fabrication and loaded with tensile or compressive stresses at room temperature, 250°C and 400°C. The higher temperatures were realized by a mirror furnace adapted to the testing machine. After heating up to test temperature a 5 min holding time was followed to ensure temperature equalization before starting the test. The relaxation behaviour was modelled in this case, too. In order to achieve a better axial and tangential coupling than in the surfacelayers-core-model, finite-element-modelling was used in this case. Isoparametric rectangular elements with plane strain behaviour were applied for this purpose.²³ Figure 10 shows the measured values of axial residual stresses after loading with different loading stresses at the three temperatures and their description by the finite-element-modelling. The values at $\sigma^{LS} = 0$ decrease with increasing testing temperature due to increasing thermal relaxation of residual stresses before the tensile or compres-

FIG. 10. Axial residual stresses vs. loading stress at room temperature, 250°C and 400°C and description by the finite-element-model (quenched and tempered, 450°C).

sive loading. They were measured after the holding-time at test temperature and agree very well with the values determined by the Avrami-approach, applying the material constants mentioned in table 1. The following relaxation due to tensile or compressive loading is similar to room temperature if the lower yield strengths at higher temperatures are taken into account. Due to the short durations of the experiments, thermal relaxation could be neglected after heating up. The finite-element-modelling leads to a very good accordance with the measured values.

V. CYCLIC LOADING

A. Models

In the case of cyclic loading relaxation of residual stresses can be modelled using the empirical equation

$$\frac{\sigma_a^{RS}}{\sigma_o^{RS}} = A(\sigma_a) - m(\sigma_a) \log N \quad (2)$$

with σ_a^{RS} the residual stress value after cyclic loading for N cycles, σ_o^{RS} the initial value of residual stresses and $A(\sigma_a)$ and $m(\sigma_a)$ two material constants which depend on the stress amplitude σ_a .²⁴

B. Experimental results

Alternating bending experiments at normalized and shot peened flat specimens with a thickness of 2 mm were carried out at room temperature. The amounts of residual stresses measured after predefined values of N at the side primarily deformed in compressive direction are shown in Fig. 11. They decrease strongly within the first cycle due to the tensile and especially compressive loading discussed before. At higher numbers of cycles the residual stresses show a linear dependence on the logarithm of N with slopes increasing with increasing fictitious stress amplitude at the surface $\sigma_{a,S}^*$. Hence, eq

FIG. 11. Axial residual stresses vs. number of cycles during alternating bending tests at different fictitious stress amplitudes at the surface (normalized).

FIG. 12: Slope m vs. fictitious stress amplitudes at the surface during alternating bending tests (normalized and quenched and tempered, 450°C).

2 is confirmed. Evaluation of the slopes leads to Fig. 12 which shows that m depends linearly on the fictitious stress amplitude at the surface. In this figure the results of corresponding experiments in a quenched and tempered state with 2 h annealing treatment at 450°C are also shown. The slopes m show similar values and a similar dependency on the stress amplitude but occur at higher stress amplitudes due to the higher strength of this state.

Additionally, push-pull-tests were carried out with shot peened specimens which were quenched and tempered at an annealing temperature of 600°C and an

annealing time of 2 h and had a diameter of 5 mm. Their results differ from the above-described finding. Figure 13 shows the plastic strain amplitudes and axial residual stress values during stress-controlled cyclic loading with different stress amplitudes versus the number of cycles. Initially, the specimens show macroscopic quasi-elastic cyclic deformation behaviour for 400, 500 and 600 N/mm². At loading with $\sigma_a = 700$ N/mm², plastic strain amplitudes occur from the beginning of the test. After a distinct number of cycles for incubation which decreases with increasing stress amplitude cyclic worksoftening occurs at all amplitudes. This augmentation of plastic strain amplitude continues until failure of the specimen. The maximum of plastic strain amplitudes observed just before failure increases with increasing stress amplitude. The residual stress values are strongly reduced in the first cycle. Afterwards, a linear dependence on the logarithm of N occurs which can be described using eq 2. For the two highest stress amplitudes at the end of fatigue life greater residual stress relaxation rates are observed than predicted by the log N -law. The beginning of this phase can be correlated with the onset of cyclic work-softening. Hence, increasing plastic strain amplitudes at constant stress amplitude may cause increasing relaxation rates of residual stresses. This is confirmed by strain-controlled tests with different strain amplitudes. The obtained cyclic deformation behaviour and

FIG. 13: Plastic strain amplitudes and axial residual stresses vs. number of cycles during stress-controlled push-pull-tests with different amplitudes (quenched and tempered, 600°C).

FIG. 14: Plastic strain amplitudes and axial residual stresses vs. number of cycles during strain-controlled push-pull-tests with different amplitudes (quenched and tempered, 600°C).

FIG. 15. Axial residual stresses vs. plastic strain amplitudes at half of the number of cycles to crack initiation at stress- and strain-controlled push-pull-tests with different amplitudes (quenched and tempered, 600°C).

the residual stress relaxation are shown in Fig. 14. In

these experiments increased relaxation rates are also observed at the end of fatigue life according to the onset of cyclic worksoftening. At the highest amplitude $\epsilon_{a,t} = 4.5\%$, no linear dependence of residual stresses on $\log N$ can be found because cyclic worksoftening begins at the first cycles. As can be seen from experiments at other heat treatment conditions, the nonlinear phases of residual stress relaxation can be observed under two prerequisites only: First, the loading amplitude has to be high enough to induce sufficiently high values of the plastic strain amplitude and second, the residual stresses remaining at the onset of cyclic worksoftening have to be sufficiently high. If the residual stresses and plastic strain amplitudes at half of the number of cycles to crack initiation $N_i/2$ are plotted as in Fig. 15, all experiments can be described by one straight line without any dependence on stress- or strain-control¹⁸. The higher the plastic strain amplitudes are, the lower the amounts of remaining residual stresses will be.

VI. CONCLUSION

Recent results concerning relaxation of residual stresses due to thermal treatments, tensile or compressive loading at room temperature and higher temperatures or cyclic loading were presented and discussed. This review focused on the modelling of the relaxation behaviour of residual stresses and showed that modelling could be improved in all cases. It not only describes the material behaviour but also informs about non-measurable quantities such as stress-strain-relation of shot peened

surface regions in tensile or compressive tests, e.g..

VII. REFERENCES

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