THERMAL RELAXATION OF SHOT PEENING INDUCED RESIDUAL STRESSES IN A QUENCHED AND TEMPERED STEEL 42 CR MO 4

Schulze,V., Vöhringer,O. and Macherauch,E.
Institut für Werkstoffkunde I, Universität Karlsruhe (TH),FRG

ABSTRACT

If machine parts bearing shot peening induced macro and micro residual stresses are exposed to elevated temperatures during application, thermal stress relaxation occurs. In order to obtain quantitative knowledge of the stress relaxation behaviour a quenched and tempered 42 CrMo 4 steel was investigated using X-rays. The thermal relaxation behaviour was described by the Avrami-approach whose parameters were determined applying a new, iterative method which allows to evaluate and compare the relaxation behaviour of macro and micro residual stresses. It was found out that the rate controlling process of thermal relaxation of shot peening induced macro and micro residual stresses is due to volume diffusion controlled dislocation creep. As at the beginning of annealing a very strong relaxation was observed, the transient relaxation of macro residual stresses during heating up to the temperature required is investigated. For the first time it is possible to model this material behaviour, extending the above-mentioned new iterative Avrami-approach to non-isothermal stress relaxation. A very good agreement with the data measured during the first stage of transient annealing is achieved by this method. It was found out that the further stress relaxation behaviour is not determined by the heating time already elapsed but rather by the relaxed residual stress value already achieved during heating up.

KEYWORDS

thermal stress relaxation, transient stress relaxation, Avrami-approach, macro residual stresses, micro residual stresses, half widths of interference lines, mean strains, dislocation creep, activation enthalpy, quenched and tempered steel

INTRODUCTION

Shot peening is a method frequently used in practice to increase the fatigue strength of metallic materials. As known from literature [1-9], this effect is due to shot peening induced changes of the residual stress state and the microstructure. However, sufficient supply of thermal energy leads to relaxation of macro and micro residual stresses as a function of temperature and time. This means that the positive effect of shot peening, e.g. on the fatigue life, is reduced. Therefore the thermal relaxation behaviour of macro and micro residual stresses is of great interest. The presented investigations were carried out with the quenched and tempered and subsequently shot peened 42 CrMo 4 steel and include the modelling of the experimental results. In this context, the transient relaxation of residual stresses during heating up to the temperature required is a special topic.

EXPERIMENTAL DETAILS

The experiments were carried out using the 42 CrMo 4 steel (AISI4140) with the chemical composition 0.44C, 1.05Cr, 0.21Mo, 0.22Si, 0.59Mn, 0.06Ni, 0.02P, 0.01S and rest Fe (all data in wt.-%). The specimens with the dimensions 12x12x2 mm were austenitized 20min at 850°C, quenched in oil and tempered for 2h at 450°C with subsequent slow cooling in a nitrogen-fluidized bed furnace. The following shot peening was carried out simultaneously from both sides using an air blast machine with a cast steel shot S170 (44-48HRC), a pressure of 1.6bar and a coverage of 98%. The annealing experiments were performed in a salt bath (AS140, Fa. Degussa) at temperatures between 250°C and 450°C up to 6000min. For registrating T(t)-curves during heating up, thermoelements were employed.
The characterization of near surface layers was realized by X-ray macro residual stress measurements, the evaluation of half widths of the interference lines and the X-ray line profile analysis. The macro residual stresses were determined before and after the annealing process using the $\sin^2\psi$-method [10]. For this purpose the shifting of {211}-interference lines was measured with CrKα-radiation. The stress measurements of subsurface layers were carried out after removing the surface layers of both sides of the specimens by the aid of an electrolytical polishing technique. The measured residual stress distributions were corrected for the surface removement applying the method according to [11]. The half widths of the {211}-interference lines are indicated by the average values of ψ = -9°, 0° and +9°.
In order to determine the mean strains $<\epsilon^2>^{1/2}$ and the domain sizes D the Warren-Averbach-analysis [12,13] modified by Delhez [14,15] was used analyzing the {110}- and {220}-interference lines which were measured with CoKα-radiation [16-18]. The mean micro residual stresses were calculated according to [19] with the equation

$$\sigma^{rs}_{micro} = E_{<110>} <\epsilon^2>^{1/2} \qquad (1)$$

using Youngs-modulus $E_{<110>}$ = 220 000N/mm² [20].

RESULTS AND DISCUSSION

Fig.1 shows the states of macro residual stresses σ^{rs}_{macro}, half widths HW, mean strains $<\epsilon^2>^{1/2}$ and domain sizes D after shot peening as a function of distance x from surface. The macro residual stresses are characterized by maximum compressive values at 0.11mm below the surface and a rapid decrease with increasing distance from surface. The half widths show maximum values at the surface and minimum values for 0.02<x<0.12mm. This points to shot peening induced structural softening in this region and is confirmed by the distribution of mean strains which is similar to that of the half width values. In comparison to this the domain sizes show an inverted dependence on distance from surface.
The isothermal relaxation of macro residual stresses is illustrated in Fig.2. The amounts of the macro residual stresses are plotted as a function of the logarithm of the annealing time for various annealing temperatures. The amounts of the

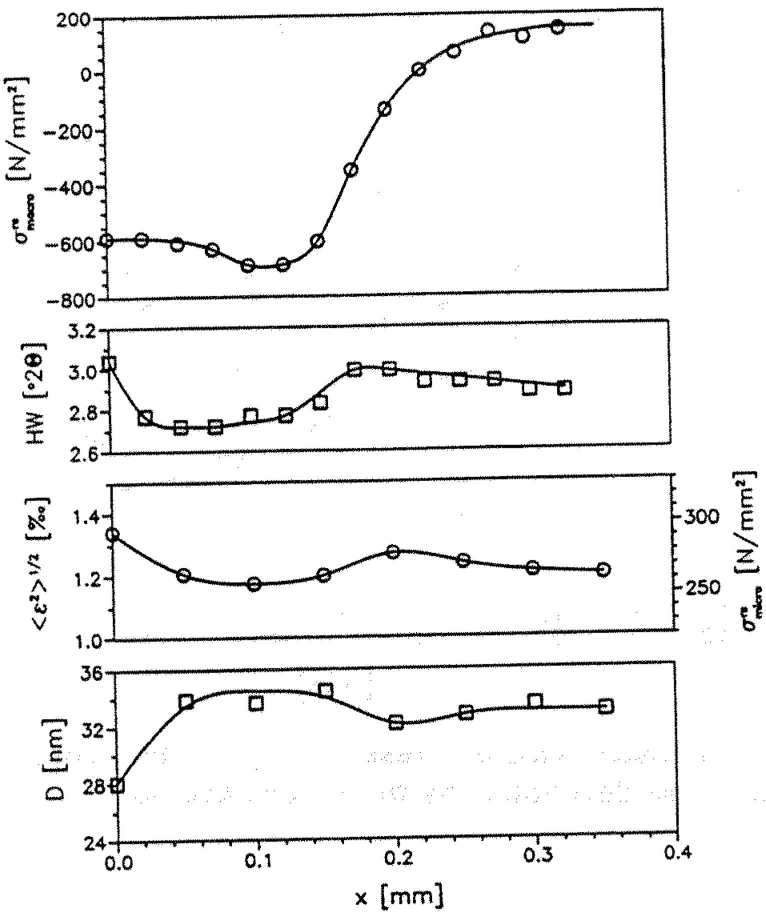

Fig. 1: Macro residual stresses, half widths, mean strains and micro residual stresses, resp., and domain sizes after shot peening vs. distance from surface

macro residual stresses decrease with increasing time and temperature and can be described by the Avrami-approach [21]

$$\frac{\sigma^{rs}(T,t)}{\sigma^{rs}_o} = \exp\{-[C \exp(-\Delta H_A/kT)t]^m\} \tag{2}$$

with $\sigma^{rs}(T,t)$ the residual stress value after annealing time t at the absolute temperature T, σ^{rs}_o the residual stress value before annealing, ΔH_A the activation enthalpy of the rate controlling process, m the exponent, C the velocity constant and k the Boltzmann-constant. Due to the fact that the conventional way to determine the material properties ΔH_A, m and C [21,22] requires strong extrapolations to very high or low annealing times, in this investigation a new iterative method is used [23-25] which allows to determine these properties by a nonlinear minimization of the residual sum of squares. The algorithm yields ΔH_A = 3.29eV, m = 0.122 and C = $1.22 \cdot 10^{21}$ 1/min for the surface values of the macro residual stresses. The curves in Fig.2 were calculated using these constants in eq.(2) and describe the time- and temperature-dependence of the relaxation process in a very good manner. The mean deviation between measured and calculated values is 5.3N/mm².

Because the conventional determination led to a mean deviation of 9N/mm² this new iterative method improves the approximation nearly by a factor of two.

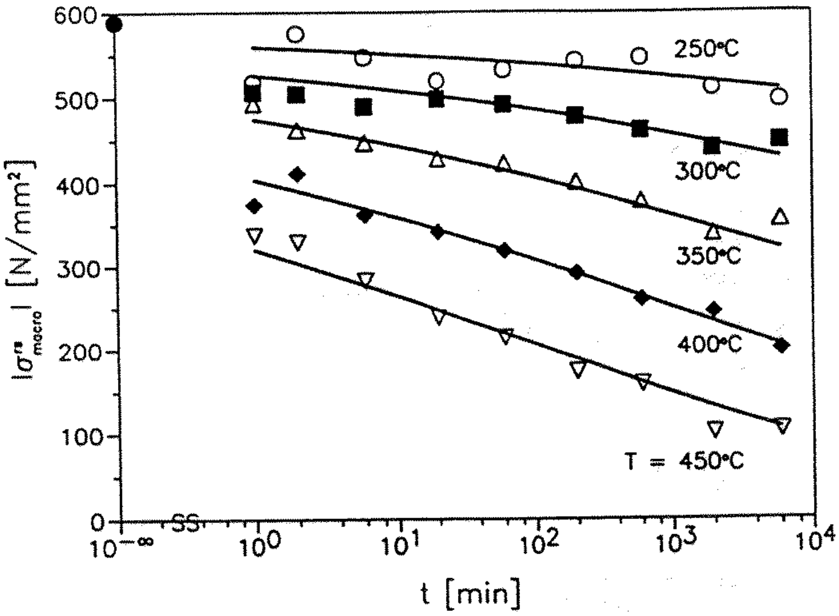

Fig. 2: Amounts of macro residual stresses vs. lg t at different annealing temperatures and their description by the Avrami-approach

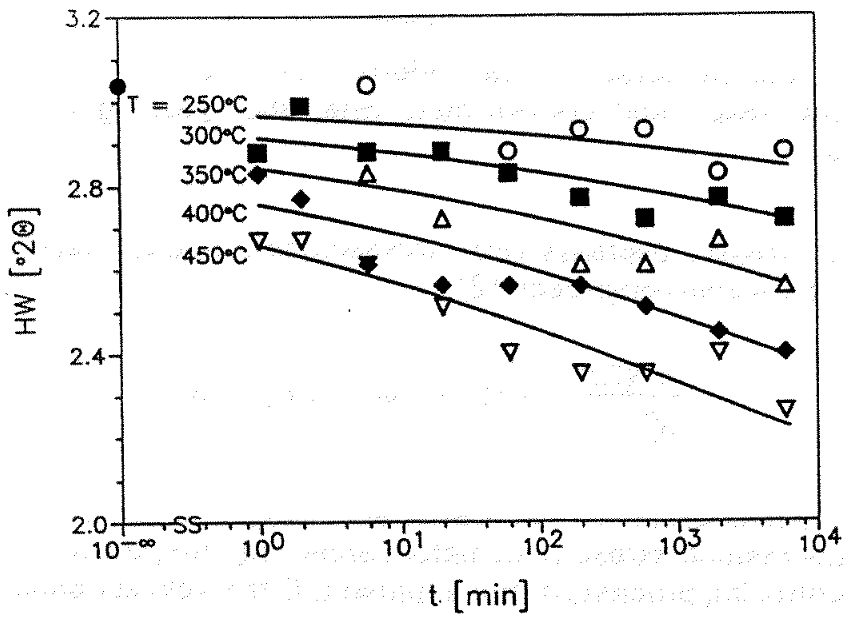

Fig. 3: Half widths vs. lg t at different annealing temperatures and their description by the Avrami-approach

The alterations of surface half widths by annealing at temperatures between 250°C and 450°C for different annealing times are shown in Fig.3. The reductions of half widths are similar to the relaxation of macro residual stresses, which was shown in Fig.2. For this reason the Avrami-approach is used to describe the relaxation of half widths, applying the new iterative method to the differences between the half widths after annealing and the value HW_N = 1.65° of a normalized specimen related to their starting values instead of the ratio $\sigma^{rs}(T,t)/\sigma_o^{rs}$ in eq.(2). The curves in Fig.3 were calculated by means of the material properties $\Delta H_{A,HW}$ = 2.48eV, m_{HW} = 0.116 and C_{HW} = $1.09 \cdot 10^{13}$1/min and agree well with the measured values. The dependence of the relaxation of mean strains and micro

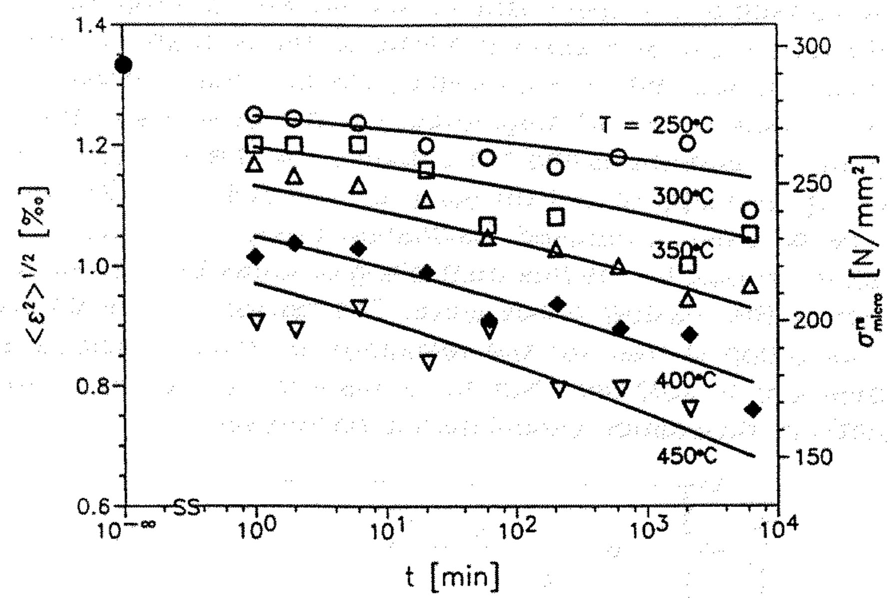

Fig. 4: Mean strains and micro residual stresses, resp., vs. lg t at different annealing temperatures and their description by the Avrami-approach

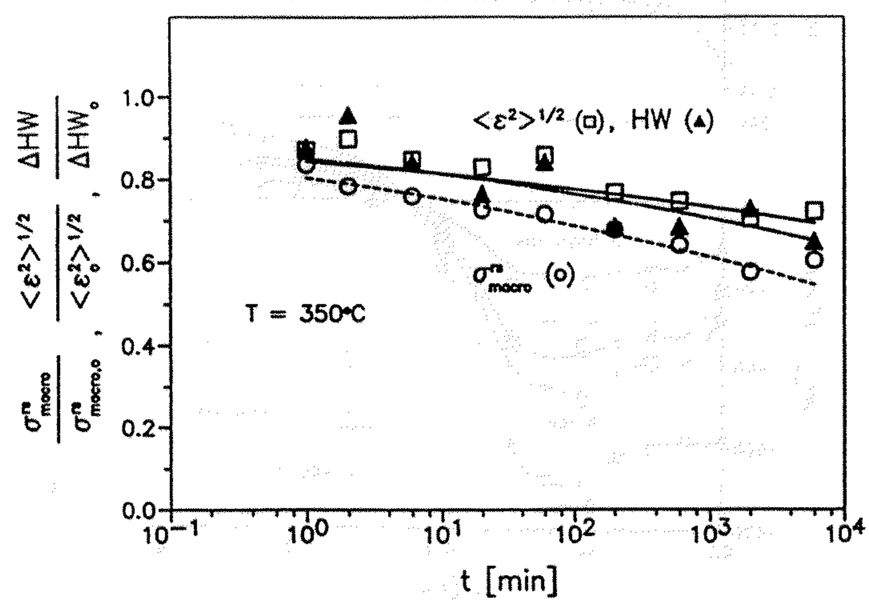

Fig. 5: Relative values of macro residual stresses, mean strains and half widths at 350 °C vs. lg t

residual stresses, respectively, on the annealing time was measured in the temperature range between 250°C and 450°C. The data are shown in Fig.4 and can also be modelled by the Avrami-approach using $<\epsilon^2(T,t)>^{1/2}/<\epsilon_0^2>^{1/2}$ instead of $\sigma^{rs}(T,t)/\sigma_0^{rs}$ in eq.(2). The new algorithm was used to determine the material properties $\Delta H_{A,\epsilon}$ = 2.64eV, m_ϵ = 0.096 and C_ϵ = $5.31 \cdot 10^{12}$1/min which allow to describe the measured values as shown in Fig.4. Fig.5 shows in a related plot a comparison of the relaxation of macro residual stresses, half widths and mean strains at the surface of the specimens for the annealing temperature 350°C. The relaxation of macro residual stresses is a little bit faster than the relaxation of half widths and mean strains, which is caused by the fact that the velocity constant C differs by nearly nine orders of magnitude. On the other hand the exponents m show no significant alterations and the activation enthalpies approach the values of the activation enthalpy of self diffusion of iron ΔH_S = 2.78 eV [26]. Accordingly, volume diffusion controlled dislocation creep dominated by climbing of edge dislocations should be the rate controlling process for the relaxation of these characteristics of the residual stress state. The reason for the differences in the velocity of relaxation is that for the relaxation of macro residual stresses dislocation movement is sufficient but for a distinct relaxation of micro residual stresses additional dislocation annihilation is neccessary.

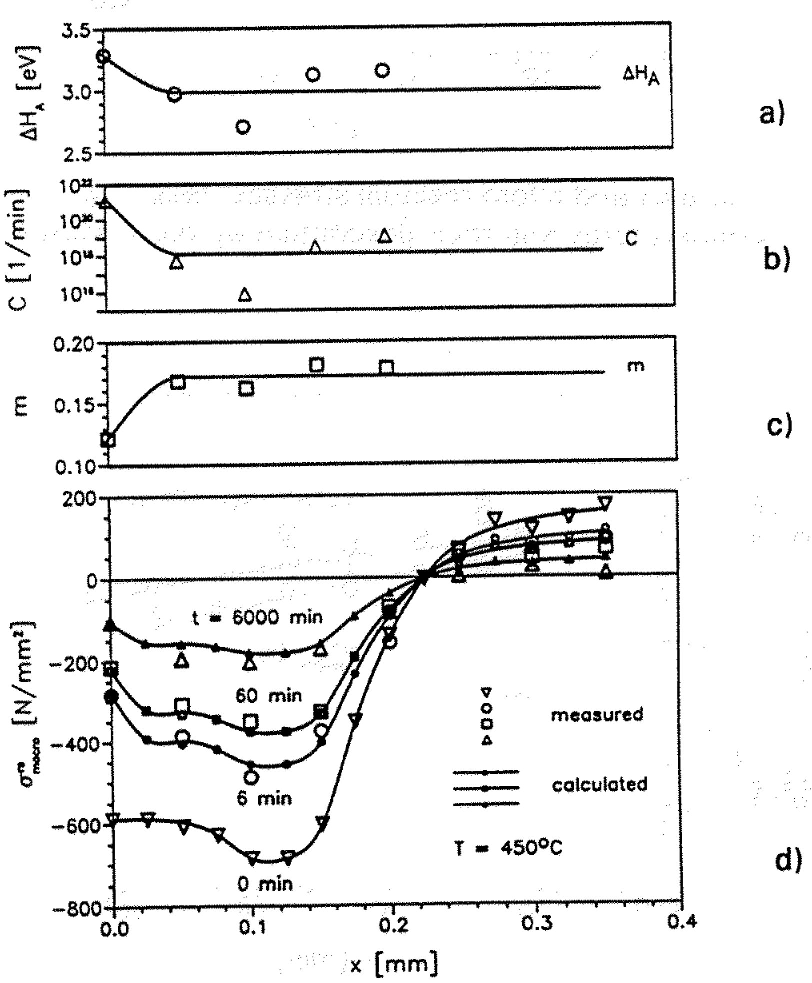

Fig. 6: Material properties ΔH_A, C and m of Avrami-aproach vs. distance from surface (a-c) and measured macro residual stresses at 450°C vs. distance from surface in comparison to calculated values (d)

In order to obtain some information about the relaxation behaviour of macro residual stresses in subsurface layers, the values of macro residual stresses after the annealing processes mentioned above were measured for different distances from surface. According to 45 measured values at each distance from surface, the material properties of the Avrami-approach were evaluated. Fig.6a-c show that these properties vary only at the surface itself from those values measured below the surface. The material properties below the surface show no significant tendency and amount to the mean values $\overline{\Delta H_A} = 2.99eV$, $\overline{m} = 0.172$ and $\overline{C} = 6.09 \cdot 10^{17} 1/min$. As shown in Fig.6d the dependence of macro residual stresses after different annealing times at 450°C on distance from surface can be described quantitatively using the surface material properties for the surface and the mean properties for all layers below the surface. The agreement between measured values and modelled curves is also very good. Fig.7 shows the dependence of mean strains and micro residual stresses, respectively, on the distance from surface for different annealing times at 400°C. This indicates that in the subsurface region influenced by shot peening relaxation leads to smaller values of mean strains than in the bulk material which is not influenced by shot peening. The bulk material shows only little relaxation due to the annealing process. Accordingly, the microstructural worksoftening in the subsurface region influenced by shot peening leads to an instability of the micro residual stress state .

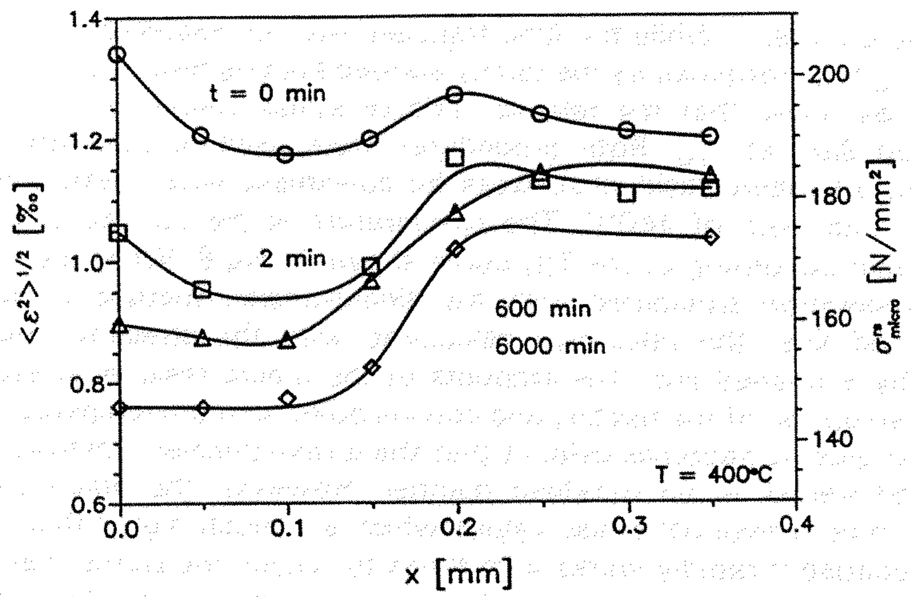

Fig. 7: Mean strains and micro residual stresses, resp., after different annealing times at 400°C vs. distance from surface

During heating up to sufficiently high annealing temperatures a distinct relaxation of macro residual stresses occurs. Therefore this behaviour was tried to model by extending the Avrami-approach to non-isothermal stress relaxation. Two methods were drawn up for this purpose, a so-called time-transient-method and a stress-transient-method. In both cases the real T(t)-relationship is splitted into small equidistant steps of time $\Delta t = t_{i+1} - t_i$. When passing these steps, a relaxation of residual stress $\Delta\sigma_i^{rs}$ occurs at the temperature $T_{m,i} = ½ (T_{i+1} + T_i)$ which is conside-

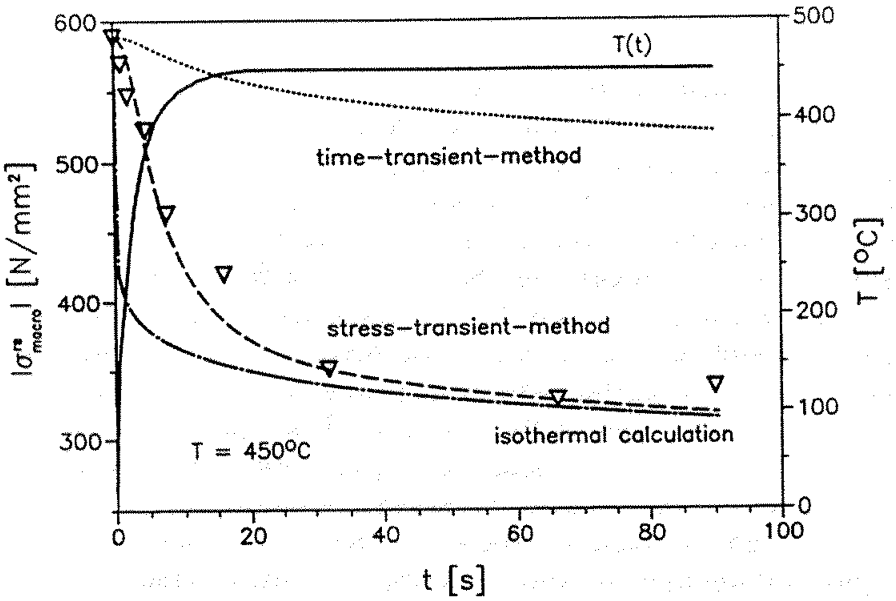

Fig. 8: Amounts of macro residual stresses after short-time immersion in a salt bath of 450°C; comparison with courses calculated applying the time-transient-method and the stress-transient-method using the occuring T(t) - dependence; comparison with modelling for isothermal annealing

red to be constant. While the time-transient-method assumes that this relaxation $\Delta\sigma_i^{rs}$ at $T_{m,i}$ is determined by the totally elapsed heating time t_i, the stress-transient-method assumes that the relaxed residual stress values determine the further relaxation $\Delta\sigma_i^{rs}$ at $T_{m,i}$. Both procedures were used to calculate the transient relaxation of macro residual stresses for specimens which were immersed up to 90s in a salt bath of 450°C. The temperature at the surface of the specimens developped according to the T(t)-curve shown in Fig.8. While the macro residual stress relaxation calculated with the time-transient-method is indicated by a punctuated line, the relaxation calculated with the stress-transient-method is shown by a dashed line. The amounts of the macro residual stresses measured after interruption of the heating and cooling down to room temperature are marked with triangles. It becomes evident that the stress-transient-method describes the measured values in an excellent manner. However, the time-transient-method leads to macro residual stress values which are much higher than the measured ones, because it rapidly works with times for which the isothermals of relaxation show only very small reductions of macro residual stresses. Thus it can be concluded that the further relaxation of residual stresses during heating up is determined by the relaxed residual stress values and not by the totally elapsed heating time. Fig.8 also shows the isothermally calculated relationship between heating time and amounts of residual stresses. While there are distinct differences during the first stage of heating time, the curves calculated isothermally and by the stress-transient-method closely approach for sufficiently high annealing times. Fig.9 shows the amounts of macro residual stresses existing in specimens which were immersed in salt baths of 300°C, 350°C and 450°C for different times. The curves were calculated using the stress-transient-method for the T(t)-relationships measured in these media. The correspondence between measured and calculated values is relatively good, but the measured values at 300°C are systematically a little bit lower than the calculated values. This is caused by the Avrami-approach which assumes that the material properties ΔH_A, m and C are no functions of temperature. In reality the rate controlling process of thermal stress relaxation has a decreasing activation enthalpy with decreasing temperature [21]. Due to this temperature-dependence the mean activation enthalpy used for this calculation is too high at 300°C and leads to residual stress values which are also higher than the measured values.

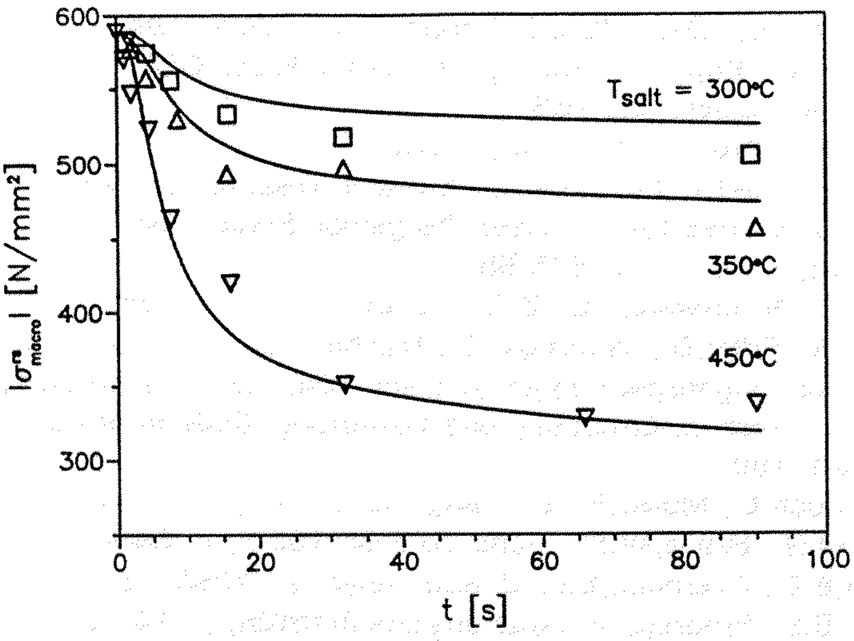

Fig. 9: Amounts of macro residual stresses after short-time immersion in a salt bath of 300°C, 350°C and 450°C; comparison with courses calculated applying the stress-transient-method using the occuring T(t)-dependence

CONCLUSION

The time- and temperature-dependence of the relaxation of shot peening induced macro and micro residual stresses was investigated using the quenched and tempered 42 CrMo 4 steel. It was found out that the relaxation of macro residual stresses advances faster than the relaxation of micro residual stresses. Moreover, the reduction of macro residual stresses is more pronounced directly at the surface than in the subsurface regions. On the other hand, in the whole shot peening influenced subsurface region the reduction of micro residual stresses leads to lower values than in the bulk material.
A better agreement between measured and calculated values of macro residual stresses, half widths and mean strains was achieved by applying a new iterative instead of the conventional method to determine the material properties of the Avrami-approach. The obtained activation enthalpies show that volume diffusion controlled creep is the rate contolling process for relaxation. The dependence of the macro residual stress relaxation on the distance from surface can be described by the Avrami-approach taking in account the change of the material properties directly at the surface. The transient relaxation of macro residual stresses can be

modelled by the stress-transient-method as described in this paper. As a result it can be stated that the relaxed residual stress values determine the further reduction of residual stresses.

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