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Thermal Fatigue of Shot Peened or Hard Turned Hot-Work Steel AISI H11

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1 Introduction

The lifetime of hot-work tools is often limited by the development of thermal fatigue cracks, which occur as a consequence of alternating temperatures connected with thermal stresses [1, 2]. It is well known, that in the case of mechanically loaded components, strength or lifetime can be enhanced by appropriate mechanical surface treatments. This is mostly attributed to near surface residual stress distributions and strain hardening effects [3 - 5]. Although in the case of combined thermo-mechanical loading, near surface microstructures are expected to be less stable compared to isothermal conditions at moderate temperatures, the question arises, whether such beneficial effects can also be realized in the case of thermal fatigue. In what follows, characteristic results of such investigations are presented.

2 Material Investigated and Experimental Details

The specimens used in the present investigation have been machined from a forged ingot, with the chemical composition (wt-%) 0.37 C, 1.2 Si, 0.23 Mn, 4.96 Cr, 1.25 Mo, 0.45 V, 0.003 P, 0.002 S, Fe bal. (AISI H11, german grade X38CrMoV5-1). The steel was heat treated (austenitisated for 20 min at 1015 °C, quenched in oil, two times tempered for 2 h at 625 °C) to achieve a hardness of 43 HRC. In Figure 1 the quasi-homogeneous microstructure of the tempered martensite, with some fine carbides, is shown. Tensile properties at room temperature were: $R_{p0.2}$ = 1153 MPa, UTS = 1384 MPa. From heat treated blanks cylindrical specimens with a diameter of 7 mm and a gauge length of 10 mm were machined. To achieve identical starting

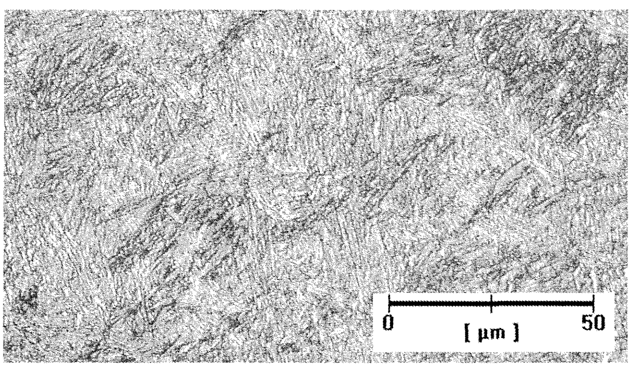

Figure 1: Optical micrograph of the annealed hot-work tool steel AISI H11

conditions, at first all samples were hard turned with the same machining parameters like the reference state (v_c = 150 m/min, f = 0.06 mm, a = 0.25 mm, diluted soluble oil: Plasocut 2000 (7 %), carbide tip: Sandvik DCMT II T3 08-PM P15).

This pre-treatment was followed, according to the variation of the surface states, by two different shot peening treatements or by deep rolling. The combined shot peening treatments were carried out on a pneumatically operated industrial blast jet system. In the first processing step for the coarse peened variation blast grain of larger diameter and a several times higher intensity was used, than for the weak peened variation. The second processing step was identical for both variations. For deep rolling a spherical rolling element (∅6.6 mm) was used with a feed of 0.1125 mm per revolution and a rolling pressure of 150 bar.

Thermal fatigue experiments simulating complete suppression of the thermal expansion were carried out under axial loading conditions [6]. For this, a servohydraulic fatigue testing device with a maximum load capacity of 160 kN was used. Heating of the specimens was performed by a 5 kW induction heating system, cooling was realized by forced air, blown by three nozzles around the heating coil. For temperature measurement, a Ni-CrNi thermocouple was spot welded in the middle of the gauge length. The axial strain was controlled and measured with a high temperature capacitative extensometer. All tests were carried out with a triangular temperature-time-course, a heating or cooling rate of 10 °C/s and a minimum temperature T_{min} of 200 °C. Maximum temperatures T_{max} of 550, 600, 625 or 650 °C were chosen. At the beginning of each test, specimens were heated up under free expansion to the mean temperature $T_m = (T_{min} + T_{max})/2$. After reaching T_m, the total strain was kept constant by the mechanical loading system. Consequently during the following thermal cycling, out of phase loading conditions with maximum compressive thermal stresses at the maximum temperature result. From the registred stress-temperature hysteresis loops stress amplitudes, mean stresses and plastic strain amplitudes were calculated.

Residual stresses were determined by X-ray diffraction technique [7], using the interference of CrKα–radiation at the {211}-planes of the annealed martensite. For stress evaluation, the $\sin^2\psi$-method was applied and the elastic constant $½s_2 = 6{,}09 * 10^{-6}$ Mpa^{-1} was used. Residual stress depth profiles were determined without correction of stress relieve by successive electrochemical materials removal. To estimate micro residual stresses, caused by work hardening, full width at half maximum (FWHM) values of X-ray interference lines were determined.

3 Results

3.1 Near Surface Materials States

Compared with the hard turned reference state (R_{max} = 4.7 µm), surface roughness was diminished by deep rolling (R_{max} = 1.9µm) and increased by shot peening (R_{max} = 9.9 and 11.6 µm resp.). Near surface depth distributions of residual stresses and half-width-values of the different materials states investigated are shown in Figure 2. In all cases, compressive residual stresses were observed immediately at the surface, which were lowest for the hard turned state and highest for the deep rolled one. Considerable differences exist with respect to the thicknesses of the affected surface layers. Whereas in the case of hard turned specimens, only a thin layer with compressive residual stresses was produced, coarse shot peening and deep rolling produced much thicker layers with compressive residual stresses. Similar observations can be made regarding depth distributions of interference line FWHM-values. Deep rolled and shot peened specimens exhibit maximum values immediately at the surface, which decrease drastically within a small distance from the surface. Lowest values are observed for the hard turned reference state.

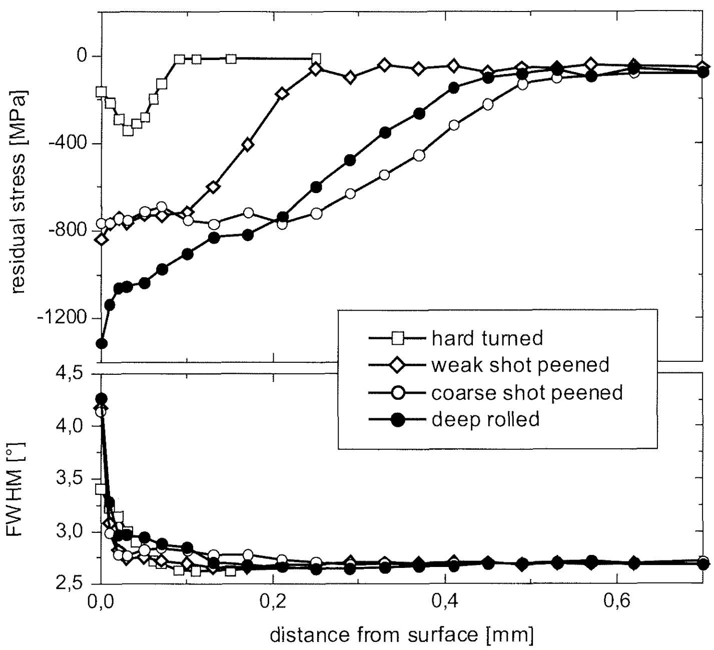

Figure 2: Residual stress and full with at half maximum values after different mechanical surface treatments

3.2 Results of Thermal Fatigue Tests

For all materials states investigated, in the main, the same behavior was observed during thermal fatigue loading. Characteristic results are summarized in Figure 3, using specimens of the coarse peening condition. Here the development of stress amplitude and mean stress for the cyclic temperature ranges indicated are given. In the case of an upper temperature of 550 °C, up to 10^4 cycles a constant stress amplitude, but an increasing tensile mean stress is observed. For lower numbers of cycles, increasing cyclic temperature ranges lead to increasing stress amplitudes as well as mean stresses. The formation of mean stresses is due to the fact, that maximum compressive thermal loading stresses occur at highest temperatures, whereas lowest thermal stresses occur at lower temperatures (out of phase loading conditions) [8]. Due to the temperature dependence of yield strength, compressive plastic deformation at higher temperatures is prevailing, leading to a contraction of the specimen. However, it can be observed, that for higher numbers of cycles, stress amplitudes as well as mean stresses tend to relax, which can be attributed to strain softening processes as well as crack formation and propagation [9, 10]. In the same way, a characteristic influence of the cyclic temperature range on the plastic strain amplitude can be detected (see Figure 3, bottom). It increases with the cyclic temperature range and, except for the lowest temperature range of 350 °C investigated, with increasing numbers of temperature cycles. Again, the temperature dependence of the yield strength is decisive, but also damage and strain softening processes at higher numbers of cycles. As expected, fatigue lifetime also decreases with increasing temperature amplitude.

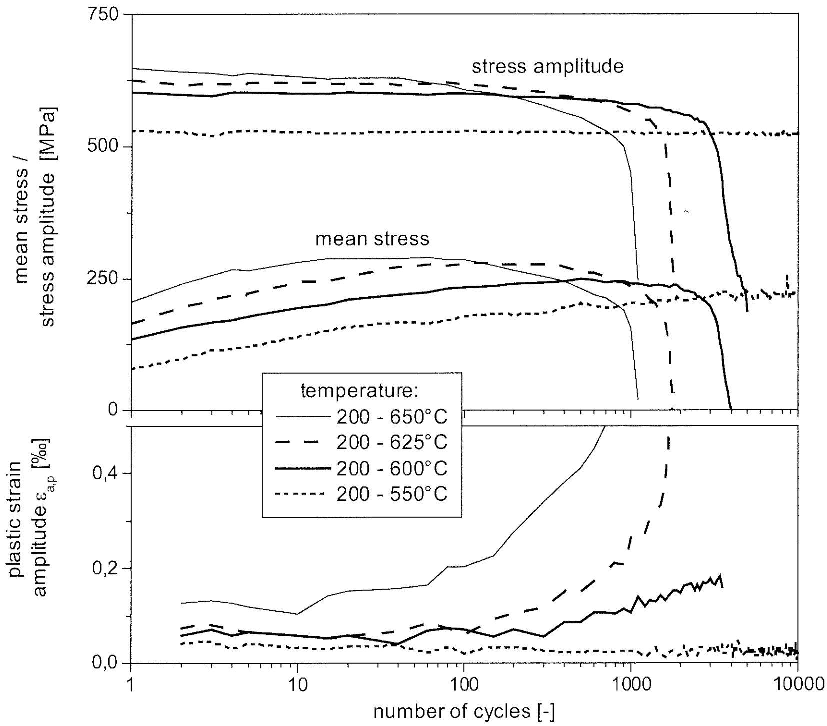

Figure 3: Stress amplitude, mean stress (top) and plastic strain amplitude (bottom) as a function of cyclic temperature ranges during thermal fatigue

Only insignificant consequences of the different near surface materials states on characteristic properties during thermal fatigue experiments have been observed. One example is presented in Figure 4. Here, mean stresses are plotted as a function of the number of thermal cycles for a cyclic temperature range of 425 °C. Clearly different plots can be seen with lowest values for the hard turned reference state and highest values for deep rolled specimens. Results of shot peened specimens can be found between these distributions. This observation can be explained by the amount and distribution of near surface compressive residual stresses, which control the amount of plastic compression during the first loading cycles. Onset of plastic compression is determined by the superposition of residual and thermal loading stresses [11]. This effect is the more pronounced, the thicker the surface layer with compressive residual stresses is.

An important consequence of such pronounced plastic deformations already during the first loading cycles is, that near surface materials states are drastically altered. Especially residual stresses relax considerably, as can be seen in Figure 5 for a coarse peening condition and a cyclic temperature range of 400 °C. It is clearly to be seen, that residual stresses relax preferably

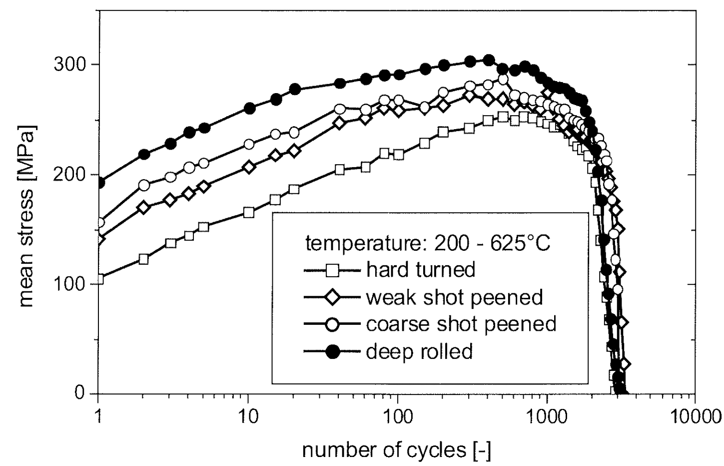

Figure 4: Mean stress evolution during thermal fatigue for specimens with different surface conditions

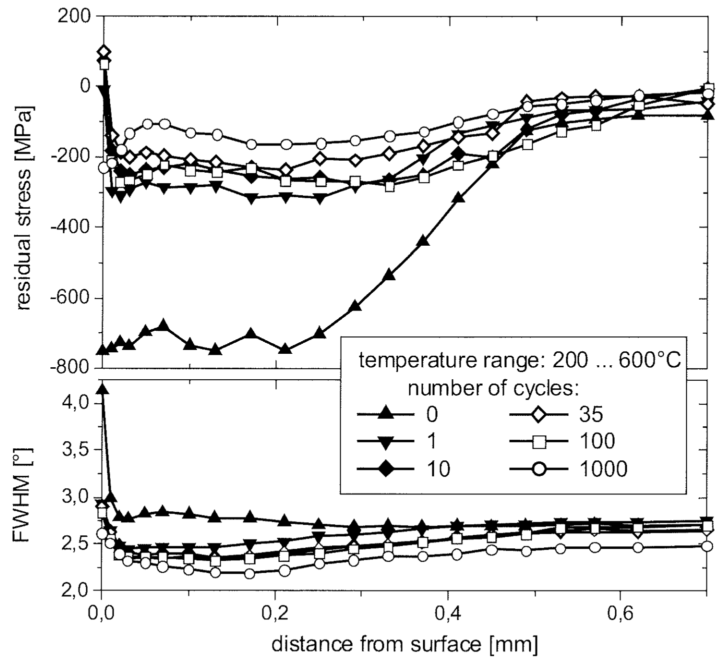

Figure 5: Residual stress and FWHM values of coarse shot peened surfaces after thermal fatigue

already during the first loading cycle and decrease further with increasing numbers of thermal cycles. This stress relaxation is much more pronounced compared with the case of pure thermal stress relaxation [12]. FWHM-values decrease also considerably as well as hardness values (not shown here), indicating microstructural alterations in near surface layers during the thermal fatigue process.

As a consequence of residual stress relaxation and microstructural alteration during the first stage of thermal fatigue, for the conditions investigated here, no significant influence of the near surface materials state on lifetime was detected. Obviously, such effects can only be expected in the case of moderate temperatures and cyclic temperature ranges connected with small plastic strain amplitudes.

4 Conclusion

To analyze the influence of near-surface materials states on the damage process during thermal fatigue loading, isothermal annealing experiments and thermal fatigue tests with hot-work tool steel AISI H11 (German grade X38CrMoV 5-1) in either shot-peened or hard turned surface condition were performed.

Tension-compression thermal fatigue tests were carried out using a servohydraulic testing system, keeping the macroscopic strain of the gauge length constant, while triangular time-temperature cycles were applied. The temperature range was chosen in such a way that numbers of cycles to fracture between 1,000 and 10,000 were achieved. The development of plastic strain amplitudes as well as of mean stresses were analyzed during the tests.

All surface types examined revealed similar lifetimes for identical thermal loadings. While the residual stress state during simple annealing was still relatively stable, almost all residual stresses relaxed during a few thermal fatigue cycles. In addition, also the work hardening effects produced by shot-peening in near-surface areas were not stable under thermal fatigue loading conditions. Universal hardness measurements revealed a decrease of work hardening in near-surface areas, even below the level of the bulk material. Similar results were obtained by performing X-ray diffraction experiments and analyzing FWHM-values.

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