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High Temperature Fatigue of Mechanically Surface Treated Materials

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1 Introduction

The most well known effect of mechanical surface treatments on metallic materials is the improvement in fatigue properties. It is therefore not surprising that most of the archival literature on mechanical surface treatments, such as shot peening, deep rolling and laser shock peening, deals with the effect of near-surface properties on fatigue behavior. Most of these studies, however, are confined to room temperature fatigue behavior; in comparison, the effect of mechanical surface treatment on fatigue behavior at high temperatures has been rarely investigated [1-5]. The reason for this disparity can be found in the popular belief that fatigue strength improvement by mechanical surface treatments is mainly due to the presence of compressive residual stresses, and since such stresses should anneal out at elevated temperatures, mechanical surface treatments for high temperature applications would appear questionable. However, this view may be over simplistic as there is always a possibility that the residual stresses may be at least partially stable at elevated temperatures [6]; in addition, other factors may be involved, such as the nature of the near-surface microstructure. Accordingly, it is the objective of this study to examine the role of mechanical surface treatments on the high temperature fatigue behavior of several metallic engineering materials. Moreover, it is the aim of this work to clarify what are the critical temperature “thresholds” at which near-surface microstructures and residual stresses become unstable and whether this can explain the observed fatigue behavior.

2 Fatigue Behavior

We begin by reviewing the high temperature stress-controlled fatigue of mechanically surface treated metallic materials. For all materials studied, the range of homologous temperatures was between 0.35 and 0.6 T_m where T_m is the melting temperature.

Fig. 1 presents the cyclic deformation behavior of a titanium alloy Ti-6Al-4V (bimodal microstructure) at a temperature of 450 °C (0.4 T_m) in the untreated and mechanically surface treated condition. In this case, laser shock peening (intensity 7 GW/cm^2, coverage 200 %) and deep rolling (rolling pressure 150 bar, spherical rolling element ∅ 6.6 mm) were selected as surface treatments.

Both untreated and treated materials exhibit an initial increase in the plastic strain amplitude (cyclic softening) with number of cycles, followed by a decrease (cyclic hardening) until fracture. The untreated microstructure shows a quasi-elastic incubation period before cyclic softening, in contrast to the mechanically surface treated conditions, where softening starts immediately with cycling. The early onset of softening is most likely caused by the high degree

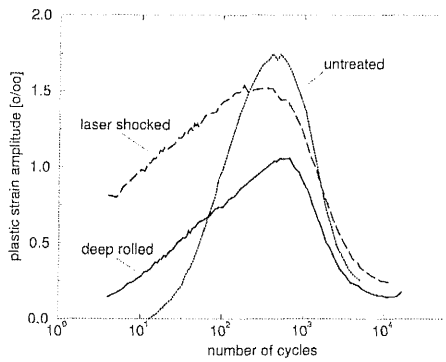

Figure 1: Cyclic deformation behavior of Ti-6Al-4V at behavior of AISI 304 450 °C (σ_a= 460 MPa, R = −1, f = 5 Hz)

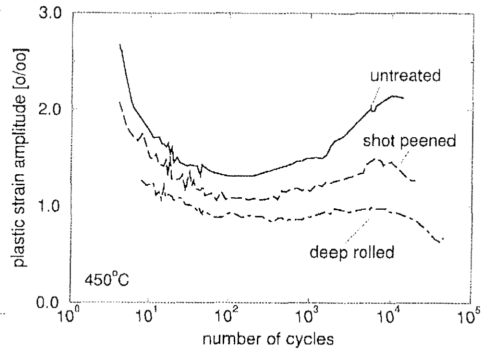

Figure 2: Cyclic deformation at 450 °C (σ_a = 200 MPa, R = −1, f = 5 Hz)

of work hardening (increased dislocation density) in the mechanically treated surface layers. With this alloy, both deep rolling and laser shock peening lead to an improvement of fatigue life compared to the untreated state. The deep rolling gave better life enhancement, consistent with a more pronounced reduction in plastic strain amplitude. The high temperature cyclic deformation behavior of an austenitic stainless steel AISI 304 in different surface conditions is shown in Fig. 2 for a test temperature of 450 °C (0.4 T_m) [7]. Both shot peened and deep rolled conditions show pronounced secondary cyclic hardening, with plastic strain amplitudes decreasing with increasing lifetime, particularly for the deep rolled material. The untreated material, conversely, exhibited the highest plastic strain amplitudes combined with the shortest lifetime. It can be seen that, even at 450 °C, the fatigue lifetime can be considerably enhanced by mechanical surface treatments compared to the untreated material (Fig. 3). For the selected process parameters, at all temperatures, deep rolling enhanced the fatigue life more effectively than shot peening. It

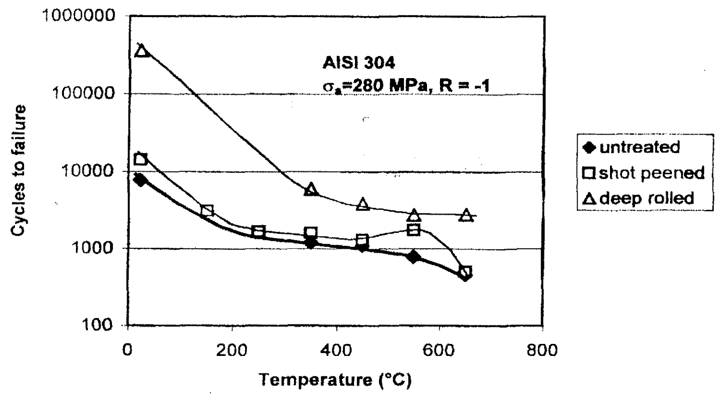

Figure 3: Stress controlled fatigue lifetimes of AISI 304 in different surface treatment states for temperatures from room temperature to 650 °C (σ_a = 280 MPa, R = −1, f = 5 Hz)

should be noted that a reduction of plastic strain amplitude due to mechanical surface treatment does not always lead to enhanced fatigue lifetimes. In fact, for a wrought magnesium alloy AZ31 [8], it was found that despite a reduction of plastic strain amplitude at test temperatures above 100 °C by surface treatment no lifetime increase was observed. This was attributed to a strong influence of creep to the damage mechanism [5].

2.1 Stability of Near Surface Residual Stress

To examine why mechanical surface treatments influence the high temperature fatigue behavior of various materials so differently, the stability of the near surface properties involving both residual stresses and near surface microstructures is considered during fatigue loading. The depth profiles of near-surface residual stresses and half-width values (FWHM = full width at half maximum) of x-ray diffraction peaks are shown in Fig. 4 for the deep rolled magnesium AZ31, after cycling at different temperatures up to half the number of cycles to failure. It is apparent, that the residual stresses, as well as half-width (FWHM) values, are markedly unstable during isothermal fatigue at temperatures above ~100 °C; indeed they are eventually reduced to the initial values of the virgin material. Here, the relaxation in both macro- and micro-stresses occurs primarily by thermal annealing, although aided by the cyclic deformation [8,9]. The corresponding stability of near-surface macro- and micro-stresses in the titanium alloy Ti-6Al-4V after isothermal fatigue at 450 °C i.e., at a similar homologous temperature is shown in Fig. 5 for the deep rolled and laser shock peened conditions. Here for both surface-treated conditions, the compressive residual stresses at the surface relax significantly after half the number of cycles to failure, from initial values of –700 and –400 MPa down to –100 to –200 MPa. Interestingly, the stress relaxation at this temperature affects mainly the macro-stresses, whereas inhomogeneous micro-stresses, which are responsible for line-broadening (FWHM-values),

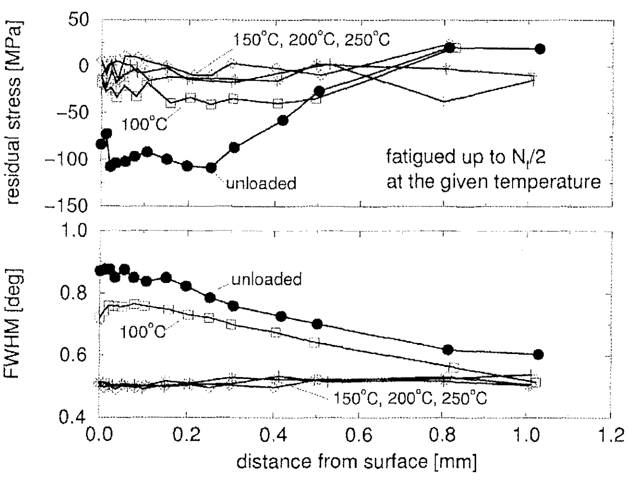

Figure 4: Relaxation of near surface residual stresses and FWHMs in deep rolled magnesium alloy AZ31 (rolling pressure 100 bar) after stress-controlled fatigue at temperatures from 100 to 300 °C (σ_a = 75 MPa, $R = -1$, f = 5 Hz, $N_f/2$ cycles (N_f = cycles to failure)).

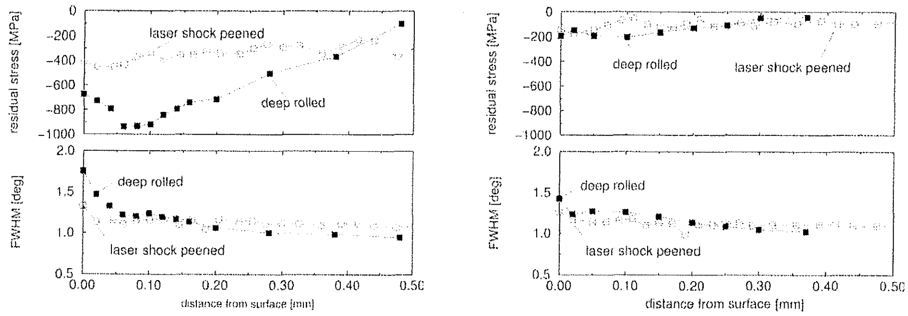

Figure 5: Near surface residual stress and FWHM-depth profiles of deep rolled (rolling pressure 150 bar) and of laser shock peened (peening intensity 7 GW/cm^2, coverage 200 %) Ti-6Al-4V before (left) and after (right) high temperature fatigue (σ_a = 460 MPa, R = –1, f = 5 Hz, N = N_f/2)

are more stable at this loading condition (σ_a = 460 MPa) and temperature (450 °C). Additionally, pronounced pure thermal stress relaxation was found for this material.

A similar trend in the stability of the macro- and micro-stresses can be seen for a mechanically surface-treated austenitic stainless steel AISI 304 (c.f., Fig. 6 and 7). In this alloy, the near surface work hardening seems to be more stable than the macro residual stresses after high temperature fatigue, especially in the temperature range ≤ 450 °C. Fig. 6 shows residual stress values at the surface of deep rolled and fatigued AISI 304 (after half the number of cycles to failure at different temperatures). After cycling at 450 °C, the surface residual stresses relax by more than 50 %, whereas at 650 °C, they relax by more than 70%. In general, shot peened specimens exhibited more stable FWHM values after high temperature fatigue (Fig. 7), owing to a higher initial dislocation density at the surface; however, the corresponding residual stresses relaxed more severely than in deep rolled samples [10].

An important finding of this work on Ti-6Al-4V, AZ31 and AISI 304 is that work hardening (elevated FWHM-values) is still prevalent at temperatures higher than where the (macro) resi-

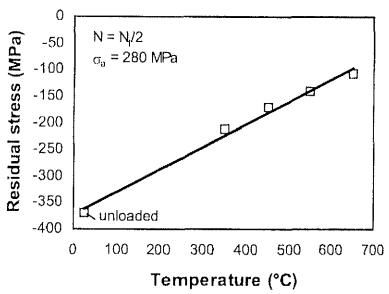

Figure 6: Surface residual stresses of deep rolled AISI 304 (rolling pressure 150 bar) before and after stress-controlled high temperature fatigue at different temperatures (σ_a = 280 MPa, R = –1, f = 5 Hz, N = N_f/2)

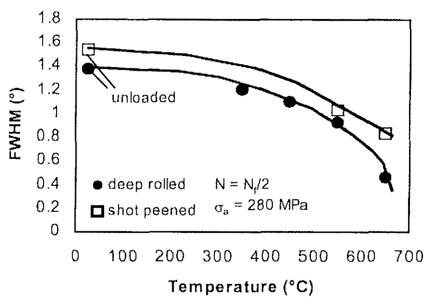

Figure 7: Surface FWHM-values of deep rolled and of shot peened (peening intensity 0.120 mmA) AISI 304 before and after stress-controlled fatigue at different temperatures (σ_a = 280 MPa, R = –1, f = 5 Hz, N = N_f/2)

dual stresses have already relaxed, which is also known for the case of pure thermal stress relaxation [3].

2.2 Stability of Near Surface Microstructures

Cyclic and thermal stability of near-surface microstructures in mechanically surface-treated metallic materials is crucial for fatigue life improvement, especially if residual stresses are known to be unstable. For room temperature fatigue, the microstructural and loading factors that determine the stability of the near-surface microstructures are well known [11,12,13,14]. For example, in AISI 304 austenitic stainless steel, the formation of a near-surface nanocrystalline layer and a strain-induced martensitic transformation lead to very stable near-surface microstructures for room-temperature fatigue, even at high stress and strain-amplitudes [12]. By examining the variation in microstructure with depth below the surface, using cross-sectional transmission electron microscopy (XTEM), the nanocrystalline surface layers and transformed martensitic regions, together with the near-surface FWHM-values, all appeared to be cyclically stable before and after cycling at room temperature [12].

Preliminary results also exist for high temperature fatigue in AISI 304. Fig. 10 shows XTEM images of the near-surface microstructure for deep rolled AISI 304 before and after fatigue at 450 °C (σ_a = 280 MPa, cycling frequency f = 5 Hz) for half the number of cycles to failure. Interestingly, the microstructures initially observed after deep rolling again appear to be quite stable after fatigue at high temperature, although a slight decrease in the dislocation density could be detected microscopically and by FWHM-measurements. *In situ* heating of TEM foils of the deep rolled condition yielded recrystallization temperatures for the "nanolayer' of 600–650 °C.

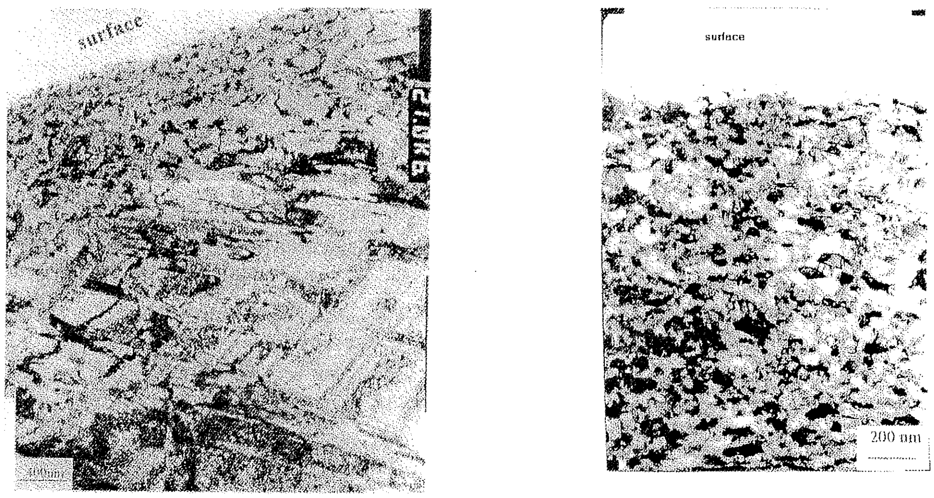

Figure 8: Cross-sectional TEM micrograph of deep rolled AISI 304 (rolling pressure 150 bar) of direct surface-regions before (left) and after (right) high temperature fatigue (s_a = 280 MPa, R = –1, f = 5 Hz, $N = N_f/2$) revealing nanocrystalline regions.

In contrast, the magnesium alloy AZ31 in the deep rolled condition showed no such stability in the near-surface microstructures and the residual stresses after fatigue loading at temperatures as low as 100 °C (Fig. 6). In fact, this alloy shows typical annealing and recrystallization behavior, e.g., induced deformation twins vanished after only 10 sec at 300 °C (Fig. 11). This behavior was also observed after longer exposures at lower temperatures [9].

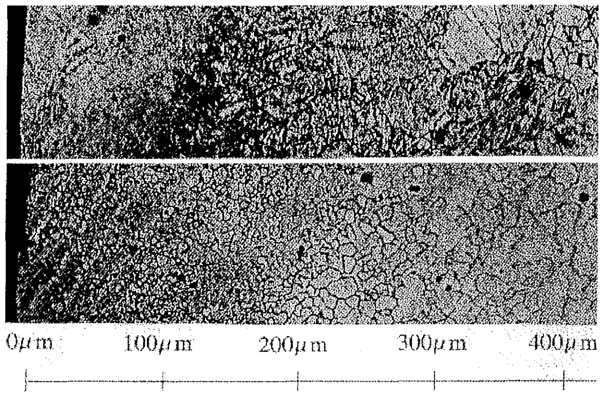

Figure 9: Near-surface microstructure of deep rolled AZ31 before (above) and after (below) high thermal exposure (300 °C, 10 seconds)

3 Conclusions

1. There are marked differences in the response of materials to mechanical surface treatments, performed in order to enhance high-temperature fatigue resistance. While some mechanically surface treated materials show poor high-temperature fatigue properties, such as the magnesium alloy AZ31 at temperatures of 0.4–0.6 T_m, other materials, such AISI 304 austenitic stainless steel, at 0.4–0.5 T_m, show an improvement in high-temperature fatigue behavior compared to the untreated condition.
2. Inhomogeneous micro residual stresses (as indicated by FWHM-values) generally relax at higher temperatures than macro residual stresses.
3. The critical temperature threshold for lifetime improvement of mechanically surface-treated states was found to occur at the temperature where the near-surface work hardening (inhomogeneous micro residual stresses) "anneals out", rather than at the relaxation of the macro residual stresses for all the materials investigated.
4. A useful parameter to assess the high-temperature fatigue behavior of mechanically surface treated materials is the plastic strain amplitude during cyclic loading. Improvement in life can be expected if mechanical surface treatments, such as laser shock peening and deep rolling can induce significantly deep work-hardened and cyclically stable surface layers, so as to lead to a finite reduction of the plastic strain amplitude during most of the lifetime.

4 Acknowledgements

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