EFFECT OF DEEP ROLLING ON THE CYCLIC PERFORMANCE OF MAGNESIUM AND ALUMINUM ALLOYS IN THE TEMPERATURE RANGE 20-250°C

I. Altenberger 1, L. Wagner 2, M. Mhaede 2, P. Juijerm 3, U. Noster 4

1 German University in Cairo (GUC), New Cairo, Egypt
2 Clausthal University of Technology, Germany
3 Kasetsart University, Bangkok, Thailand
4 ARC Leichtmetallkompetenzzentrum Ranshofen, Austria

ABSTRACT

Mechanical surface treatments such as deep rolling or laser-shock peening can markedly affect the cyclic performance of light-weight alloys, especially if significantly thick work hardened surface regions are induced. At room temperature, the cyclic deformation behaviour is strongly influenced by the nature of the induced near-surface microstructures provided that they remain stable during fatigue loading. At elevated temperatures, the stability of near-surface work hardening and local microstructures plays an even more important role since the process-induced residual compressive stresses are likely to anneal out partially or completely. This overview illustrates to what extent deep rolling can affect the cyclic performance of various light alloys being fatigue loaded in stress control at ambient and elevated temperatures.

KEY WORDS

Deep Rolling, Aluminum Alloys, Magnesium Alloys, High Temperature Fatigue

INTRODUCTION

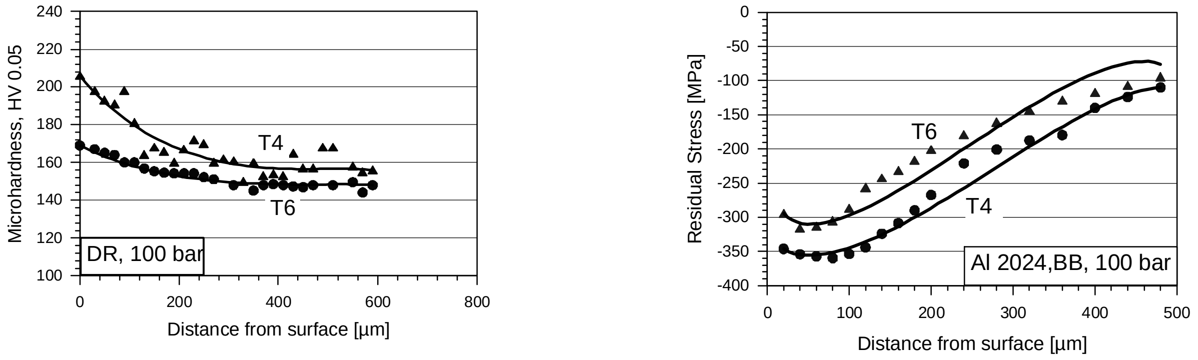
The highly beneficial impact of mechanical surface treatments with deep penetration depths such as deep rolling or laser-shock peening on the fatigue strength is irrefutable and one of the basic concepts of achieving high specific fatigue strengths. In recent years, mechanical surface treatments and their effects on fatigue behavior not only at ambient but at elevated temperatures as well has gained much interest. Of particular importance in traffic engineering is the performance of titanium, magnesium and aluminum alloys [1-4]. Interestingly, there is a lack of information to what extent mechanical surface treatments are effective if fatigue loading is done at more severe combinations of stress level and temperature.

RESULTS AND DISCUSSION

In the following chapter we will divide our results into a section on aluminum alloys AA2024, AA5083 and AA6110 and a section on magnesium alloys AZ31 and AZ91.

1. ALUMINUM ALLOYS

Deep rolling-induced depth profiles of microhardness and residual stresses in AA2024 are illustrated in Figure 1 comparing results of T4 and T6 tempers.

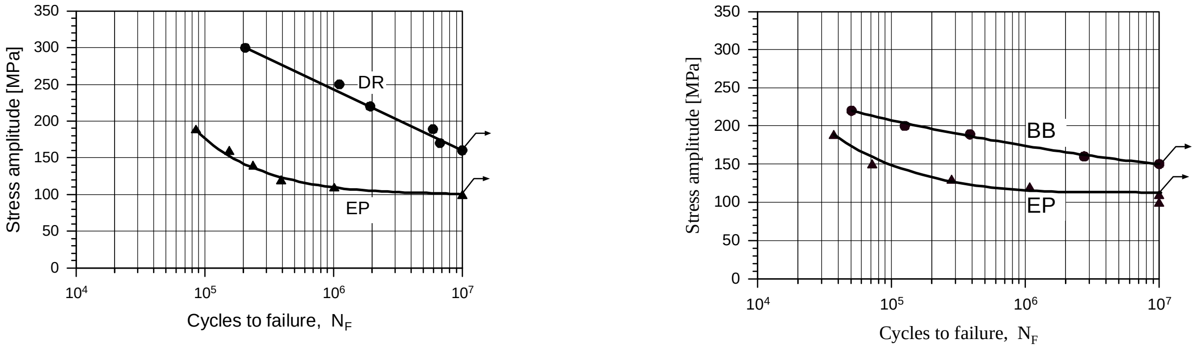


a) Microhardness-depth profiles b) Residual stress-depth profiles

Fig. 1: Surface layer properties after deep rolling of AA2024 (100 bar rolling pressure)

As seen, near-surface microhardness values (Fig. 1a) and residual compressive stresses (Fig. 1b) are generally higher in the naturally aged T4 as opposed to the artificially aged T6 temper. These results can be explained by the more pronounced work-hardening capability in the underaged compared to the peak-aged microstructure.

The S-N curves of the deep rolled and electropolished conditions are compared in Figure 2 illustrating a more beneficial response of the T4 (Fig. 2a) as opposed to the T6 tempers (Fig. 2b).



a) T4 temper b) T6 temper

Fig. 2: S-N curves in rotating beam loading (R = -1, f = 50 Hz) of AA2024, electropolished vs. deep rolled conditions (100 bar rolling pressure)

The stress-life fatigue properties of non-precipitation hardenable aluminum alloys such as AA5083 can be significantly improved by deep rolling if critical values of stress amplitude and service temperature are not exceeded. At too high stress amplitudes or temperatures the beneficial effect of deep rolling as compared to the polished surface condition vanishes due to a rearrangement of surface treatment-induced dislocation structures, a decrease of dislocation density and relaxation of residual compressive stresses by dislocation climb or cross-slip. Figure 3 illustrates the fatigue life of deep rolled and of polished AA5083 as a function of isothermal fatigue temperature for a constant stress amplitude of 190 MPa. At room temperature the fatigue life in the high cycle fatigue (HCF) regime is increased by one order of magnitude by deep rolling (rolling pressure 100 bar). This benefit continuously decreases with increasing test temperature but principally still prevails although less pronounced at 200°C, where the fatigue lives have shifted into the low cycle fatigue regime due to decreased yield strength at elevated temperature. Finally, at 250°C, deep rolling has lost its beneficial effect on fatigue life and electrolytically polished and deep rolled samples show practically identical fatigue lives.

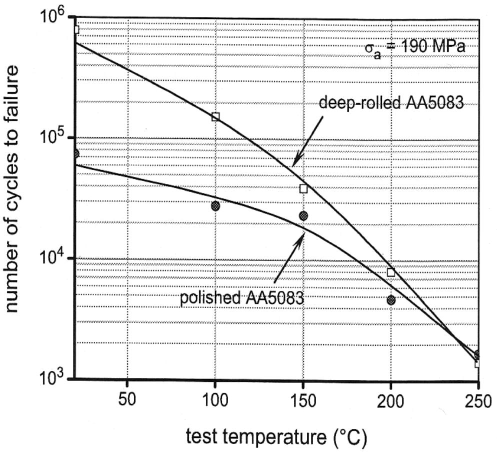


Fig. 3: Fatigue life (σ_a = 190 MPa) of polished and deep rolled (100 bar rolling pressure) AA5083 as a function of test temperature (R = -1, f = 5 Hz)

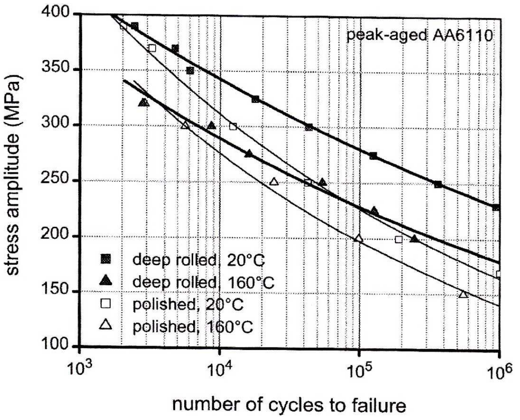


Fig. 4: S-N curves of deep rolled and of polished AA6110 (T6) tested at room temperature and at T= 160 °C

A similar picture is observed for precipitation hardenable alloys as can be seen in an exemplary manner for the precipitation-hardenable aluminum alloy AA6110. Figure 4 shows the effect of deep rolling on the S/N-behaviour of peak-aged AA6110 as compared to the polished condition for room temperature fatigue as well for a test temperature of 160°C. The fatigue strength declines with increasing temperature and the intersection point, where the two S/N-curves (polished and deep rolled) intersect each other is shifted to higher number of cycles to failure for the elevated temperature.

The intersection points between S/N-curves of the polished and deep rolled conditions, where deep rolling became ineffective, are depicted in Figure 5 for various test temperatures as so-called effective boundary lines for deep rolling [5]. It can be concluded that too high stress amplitudes and temperatures are certainly the main detrimental effects on the fatigue life of deep rolled age-hardenable aluminum alloys. The shape of the effective boundary line for deep rolling as depicted in Figure 6 depends on the aging conditions. Whereas the curvature of the boundary line for the underaged, peak-aged and overaged conditions has a convex shape, it is concave for the as-quenched state owing to age-hardening during the high temperature fatigue thus compensating the detrimental effects of relaxed deep rolling induced compressive residual stresses and decrease of near-surface cold work [6].

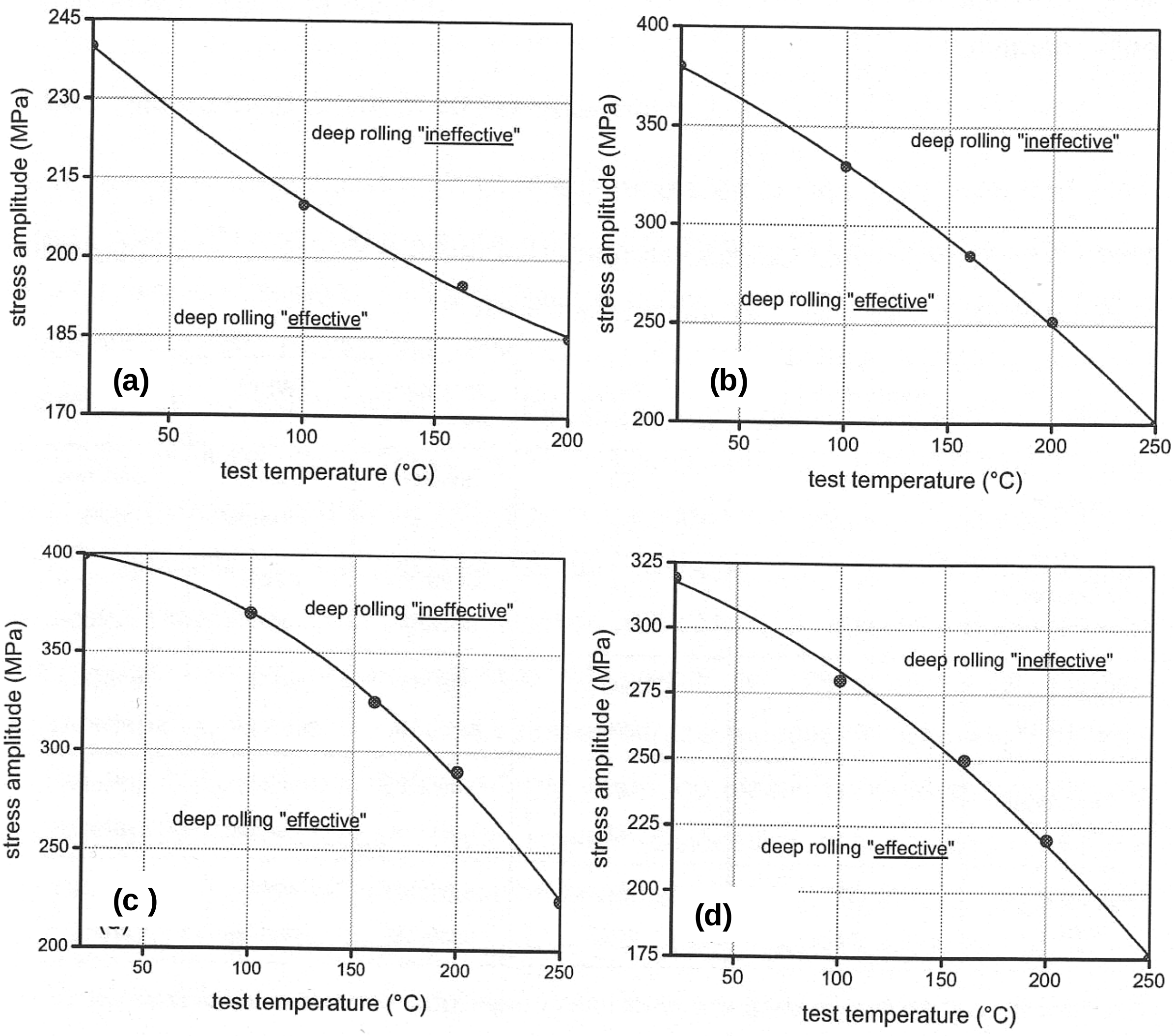


Fig. 5: Effective boundary line plots for the applied deep rolling treatment (100 bar rolling pressure) for as-quenched (a), under-aged (b), peak-aged (c) and over-aged AA6110 (d) as a function of stress amplitude and test temperature

2. MAGNESIUM ALLOYS AZ31 AND AZ91

The high temperature fatigue response of magnesium alloys AZ31 and AZ91 to mechanical surface treatments depends on the temperature regime. Although deep rolling leads to pronounced fatigue life enhancement at room temperature, especially at high rolling pressures (Fig. 6) [7], at temperatures around or above 150°C, the beneficial effect of the mechanical surface treatment decreases significantly due to instability of compressive residual stresses as well as of near-surface work hardening. A similar picture can be observed for laser-shock peened AZ31, where the surface treatment does not exhibit any benefial effects on the fatigue strength at test temperatures above 100-150°C.

These results suggest that methods to stabilize near-surface microstructures and residual stresses, e.g. by strain ageing, as already known for several steels [9] have yet to be explored for these alloys.

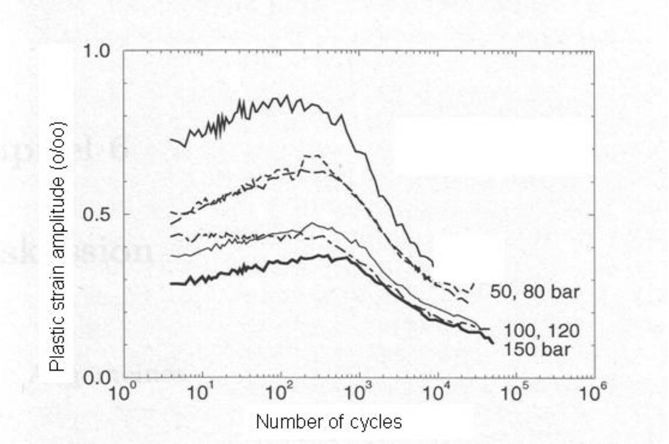


Fig. 6: Influence of deep rolling pressure on the cyclic deformation curve of AZ91 for a constant stress amplitude of σ_a = 125 MPa [7]

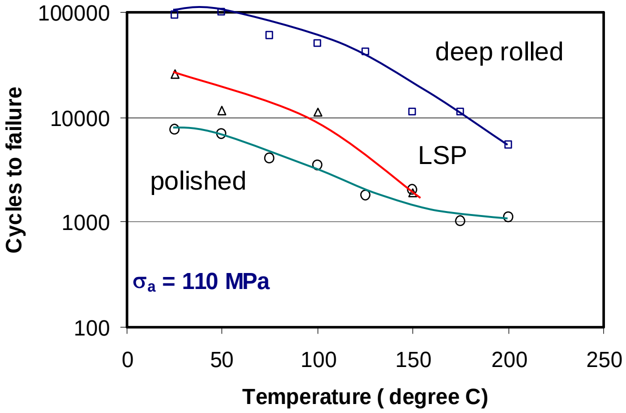


Fig. 7: Fatigue life of AZ 31 comparing polished, deep rolled and laser-shock peened conditions (push-pull fatigue, σ_a = 110 MPa, f = 5 Hz)

CONCLUSIONS

Deep rolling is a nowadays routinely used mechanical surface treatment for fatigue strength enhancement, also for aluminium and magnesium alloys. The outstanding benefit of this surface treatment depends significantly on the applied stress amplitude/temperature combination. Due to the low melting temperatures of aluminium and magnesium alloys, already at 150-200°C homologous temperatures greater than 0.5 T_m are reached, leading to instability of the deep rolling induced work hardened layer and to little effect on fatigue life at high stress amplitudes. An important factor for the assessment of deep rolling is in addition to residual stresses the work-hardening capability and thus the heat treatment condition of the light alloy.

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