Influence of Mechanical Surface Treatments on Notched Fatigue Strength of Magnesium Alloys

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1 Introduction

High-strength wrought magnesium alloys are considered as potential candidates for application as suspension parts in future automobiles due to their high strength to weight ratio [1-3]. For this application, good HCF performance of notched components is one of the most demanding requirements. While previous work on magnesium alloys has demonstrated to what extent mechanical surface treatments such as shot peening and roller-burnishing can increase the HCF strength of smooth specimens compared to an electropolished reference [4-7], corresponding results on notched specimens are not available yet. From earlier work on titanium and aluminum alloys [8-10], it is known that particularly notched components beneficially react to mechanical surface treatments such as shot peening or deep rolling. This result was explained by the interaction of the notch root stress field with the process-induced residual compressive stresses affecting mainly microcrack growth. In addition, the triaxial stress state at the notch root was thought to result in residual stresses being more stable during cyclic loading compared to those in the surface layer of smooth specimens.

2 Experimental

The wrought magnesium alloy AZ80 (nominal composition in weight percent: 8Al, 0.5Zn, 0.2Mn, balance: Mg) was received as an extrusion from Otto Fuchs Metallwerke, Meinerzhagen, Germany. The rectangular bar had a cross section of 110 × 70 mm (extrusion ratio: 9). The alloy was tested in the as-fabricated condition. Specimens were machined with the load axis parallel to the extrusion direction (L). Tensile tests were performed on threaded cylindrical specimens having gage lengths of 20 mm. The initial strain rate was $8.3 \times 10^{-4} s^{-1}$. Tensile test results are listed in Table 1.

Table 1: Tensile test results on AZ80 (L-direction)

E (GPa)	$\sigma_{0.2}$ (MPa)	UTS (MPa)	El (%)	RA (%)
44	245	340	12	14

For fatigue testing, circumferentially notched cylindical specimens having a 60° V-notch were machined. After machining, about 50 μm were removed from the notch root surface by electropolishing (EP) to ensure that any machining effect that could mask the results was absent. This electropolished condition was taken to serve as reference. Specimens were tested in rotating beam loading (R = –1) at frequencies of about 60 Hz.

Shot peening (SP) was performed with an injector type machine using spherically conditioned cut wire SCCW 14 (0.36 mm average shot size). During the peening treatment, the specimens rotated at $1s^{-1}$. The distance between nozzle tip and specimen surface was 70 mm. To determine optimum process parameters with regard to HCF life, the Almen intensity was varied in a wide range.

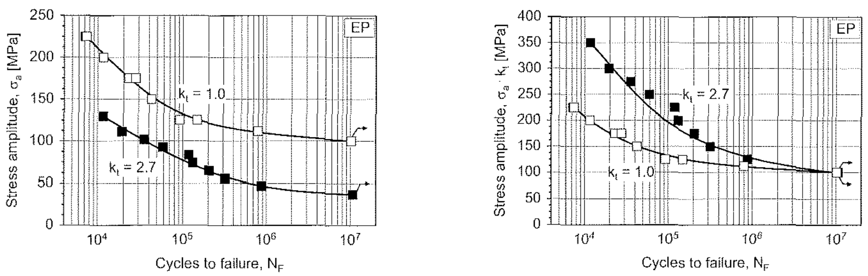
Deep rolling (DR) was performed by a hydraulically driven three-roll device by means of a conventional lathe. The diameter of the hardmetal rolls was 30 mm. The rolls had a 55° cross section and a tip radius of 0.3 mm. During deep rolling, the number of revolutions was kept constant at 45. To determine optimum process parameters in deep rolling, the rolling force was varied in a wide range. In order to keep the geometrical notch factor (i.e., the notch root radius) constant for the various surface treated conditions, the specimens to serve as reference as well as those to be shot peened were machined with a notch root radius of 0.3 mm while specimens to be deep rolled had a starting notch root radius of 0.43 mm. During deep rolling, this radius was also reduced to 0.3 mm. As a result, all specimens had a notch factor of about 2.7. The exact value for each individual specimen was calculated by measuring the net diameter (d_n), notch depth (t) and notch root radius (ρ) using the formula (1) for bending [11]:

$$k_t = 1 + \frac{1}{\sqrt{\dfrac{0,12}{\left(\dfrac{t}{\rho}\right)^{0,45}} + 4\left[\dfrac{1+\dfrac{d_n}{2\rho}}{\dfrac{d_n}{2\rho}\sqrt{\dfrac{d_n}{2\rho}}}\right]^{2,66} + 0,1\dfrac{\dfrac{d_n}{2\rho}}{\left(\dfrac{d_n}{2\rho}+\dfrac{t}{\rho}\right)\left(\dfrac{t}{\rho}\right)^{1,2}}}} \quad (1)$$

After shot peening and deep rolling, the change in surface layer properties was evaluated by roughness measurements taken circumferentially at the notch root and by measurements of the depth profiles of microhardness.

3 Results and Discussion

The S-N curves of the electropolished reference conditions of AZ80 are plotted in Fig.1 comparing the performance of smooth (k_t = 1.0) specimens [12] and notched (k_t = 2.7) specimens. As expected, introducing a notch clearly deteriorates the fatigue performance in terms of nominal stresses (Fig.1a). To what extent this notch factor of 2.7 reduces the HCF strength can be seen in Fig. 1b where the data of Fig. 1a are replotted in terms of maximum (axial) notch root stresses ($\sigma_a \cdot k_t$). Since notched and smooth specimens have the same run-out stress amplitude of 100 MPa, it can be derived that AZ80 is 100 % notch sensitive in fatigue, a result also found on titanium alloys [13]. Obviously, fatigue crack nucleation determines the HCF strength. Within the finite life regime, notched specimens have an apparent higher life since microcrack growth now determines life. The marked stress gradient below the notch root reduces the driving force for crack growth compared to the smooth specimens thus, increasing fatigue life (Fig 1b).



a) nominal stress

b) maximum notch root stress

Figure 1: S-N curves of AZ80 (EP) in rotating beam loading (R = -1), comparison of smooth (k_t = 1.0) and notched (k_t = 2.7) specimens

Typical changes in surface layer properties due to shot peening are shown in Figs. 2 and 3. Compared to the electropolished reference, the shot peening-induced roughness linearly increases with Almen intensity (Fig. 2). An example of a microhardness-depth profile is plotted for a given Almen intensity of 0.48 mmN in Fig. 3. The marked increase of near-surface microhardness from about 82 to 130 HV 0.04 is caused by pronounced work-hardening of the material also seen in tensile testing (Table 1).

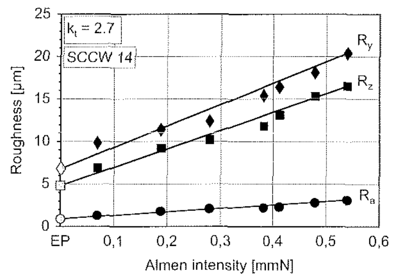


Figure 2: Roughness values vs. Almen intensity

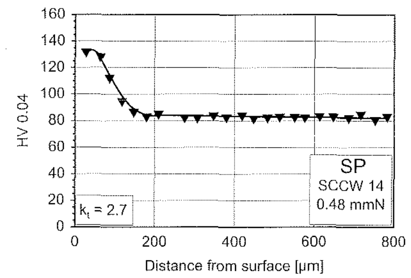
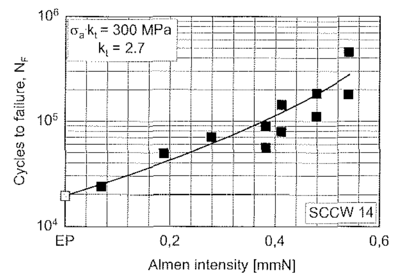


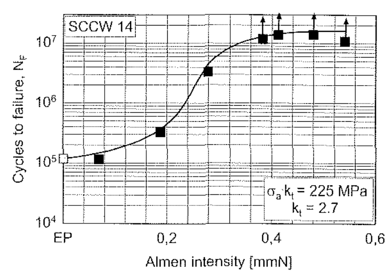
Figure 3: Microhardness-depth profile after shot peening (0.48 mmN)

The effect of Almen intensity on fatigue life at constant stress amplitudes in rotating beam loading is plotted in Fig. 4. At the high stress amplitude of $\sigma_a \cdot k_t$ = 300 MPa, the fatigue life starting with the electropolished condition continuously increases with Almen intensity within the range of intensities utilized (Fig. 4a). At the low stress amplitude of $\sigma_a \cdot k_t$ = 225 MPa, the fatigue life similarly increases. However, run-outs (10^7 cycles) were found already at intermediate Almen intensities of 0.38 mmN.

The change in surface layer properties due to deep rolling is illustrated in Figs. 5 and 6. Compared to shot peening, the increase in surface roughness caused by deep rolling is much less pronounced (compare Fig. 5 with Fig. 2). One should keep in mind, that deep rolling might even decrease surface roughness if comparison is done with an as-turned as opposed to an elec-



a) $\sigma_a \cdot k_t = 300$ MPa



b) $\sigma_a \cdot k_t = 225$ MPa

Figure 4: Fatigue life vs. Almen intensity

tropolished surface. The penetration depth of plastic deformation caused by deep rolling is typically much greater as compared to that after shot peening (Fig. 6, compare Fig. 6 with Fig. 3).

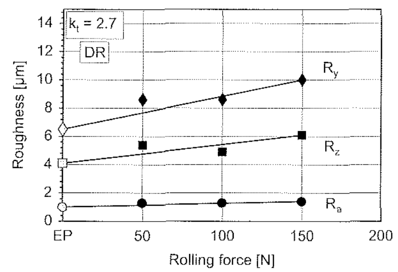


Figure 5: Roughness values vs. rolling force

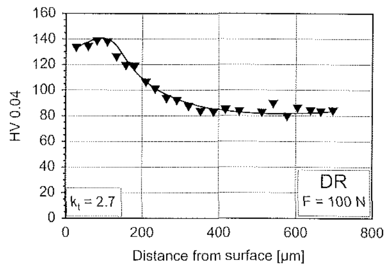


Figure 6: Microhardness-depth profile after deep rolling (F = 100 N)

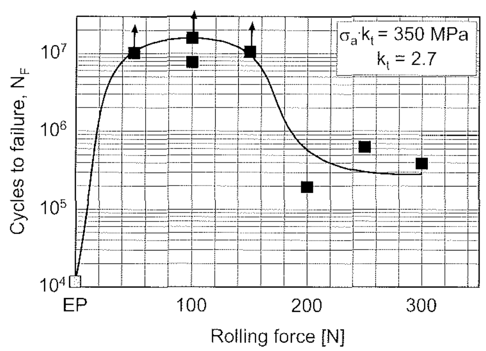
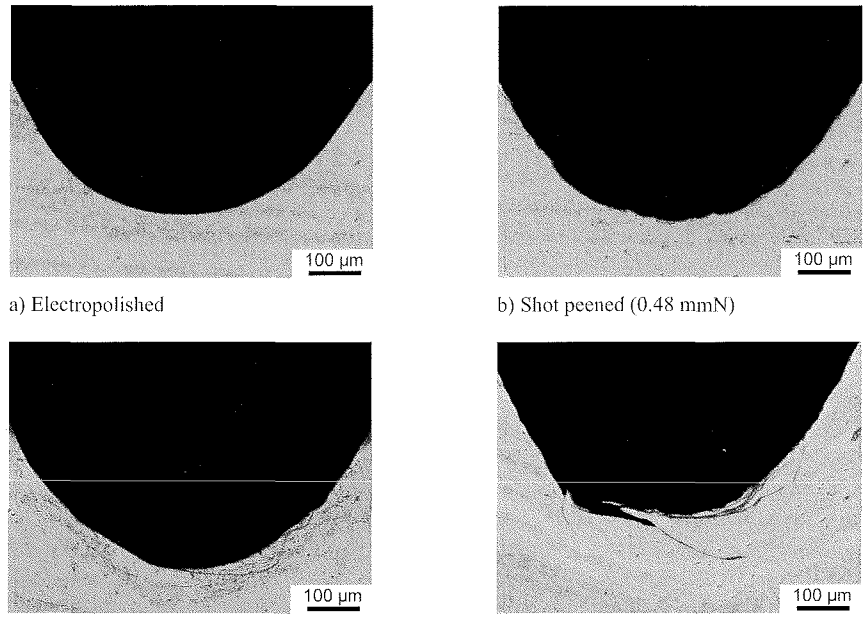


Figure 7: Fatigue life ($\sigma_a \cdot k_t$ = 350 MPa) vs. rolling force

Interestingly, best fatigue performance was found after deep rolling with low or intermediate rolling forces whereas higher forces led to marked losses in fatigue life (Fig. 7). This deterioration of the fatigue performance after rolling with higher forces is presumably caused by rolling-induced defects such as overlaps and microcracks.

Typical metallographic cross sections of the notch root regions are shown in Fig. 8 comparing the various surface treated conditions electrolytically polished (Fig. 8a), shot peened, 0.48 mmN (Fig. 8b), deep rolled, F = 100 N (Fig. 8c) and deep rolled, F = 300 N (Fig. 8 d). Clearly, the high rolling force of F = 300 N leads to material separation in the notch root (Fig. 8d) thus, explaining the observed marked overrolling effect (Fig. 7). In contrast, no process-induced overlaps were found after shot peening (Fig. 8b) or deep rolling using low rolling forces (Fig. 8c) although some roughening is clearly present if compared with the electropolished reference (compare Figs. 8b and 8d with Fig. 8a).



a) Electropolished

b) Shot peened (0.48 mmN)

c) Deep rolled (F = 100 N)

d) Deep rolled (F = 300 N)

Figure 8: Notch root after various surface treatments

From Figs. 4 and 7, the process parameters resulting in the most marked fatigue life improvement after shot peening (0.48 mmN) and deep rolling (F = 100 N) were used to determine the S-N curves in Fig. 9. The 10^7 cycles notch fatigue strength of the electropolished reference increases in terms of $\sigma_a \cdot k_t$ from 100 MPa (EP) to 270 MPa (SP) and 350 MPa (DR). Thus, optimum shot peening fully counterbalances the geometrical notch factor of $k_t = 2.7$, while deep rolling even significantly overcompensates this stress concentration (Fig. 9). After sectioning the deep rolled run-out specimen ($\sigma_a \cdot k_t = 350$ MPa) and metallographic investigating the notch root region, so called non-propagating microcracks, i.e., cracks which had nucleated at the notch root and had slowly propagated into the interior, were clearly visible (Fig. 10).

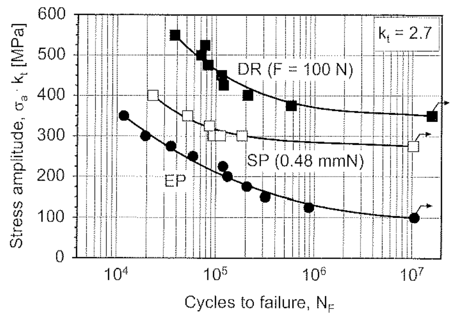


Figure 9: S-N curves of AZ80 in rotating beam loading (R = –1), comparison of optimum deep rolled (DR) with optimum shot peened (SP) and reference (EP) conditions

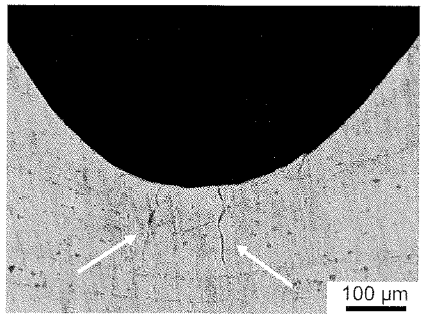


Figure 10: Notch root of run-out ($\sigma_a \cdot k_t$ = 350 MPa) deep rolled specimen

These cracks may have become arrested when the amplitude of the local stress intensity factor at the crack tip ΔK, which is a function of the applied stresses, process-induced residual stresses and crack length reaches the threshold value ΔK_{th} for microcrack growth [10].

4 Summary

From fatigue tests of the electropolished reference, it is concluded that the HCF strength of notched (k_t = 2.7) specimens of the high-strength wrought magnesium alloy AZ80 is fully affected by the geometrical notch factor, i.e., the material is 100 % notch sensitive. However, this notch sensitivity in fatigue can be easily overcome by suitable mechanical surface treatments applied before the component is put into service. For example, shot peening is able to fully counterbalance this geometrical notch factor if optimum process parameters are utilized. While deep rolling AZ80 results in the most marked improvement of the notch fatigue strength, it should be taken into account that the component to be treated by deep rolling needs some rotational symmetry. On the other hand, shot peening is much more versatile since it can be applied to almost any component's geometry.

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6 References

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