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Property Improvement in Light Metals Using Shot Peening

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1 Abstract

The goal of this overview is to outline potential improvements in fatigue performance of light metals by shot peening. The overview is aimed at correlating the process-induced changes in surface layer properties (e.g., roughness, near-surface depth profiles of dislocation densities and residual stresses) of titanium, aluminum and magnesium based alloys with the changes in resistances to fatigue crack nucleation and microcrack propagation. Characteristic examples are presented for each alloy system including α, (α+β), metastable β titanium alloys and titanium aluminides, aluminum alloys with various age-hardening conditions as well as magnesium alloys. Depending on the alloy system, shot peening-affected surface layer properties such as process-induced damage, work-hardening and residual stresses and their cyclic stability were found to be the main parameters in affecting fatigue performance of light-weight alloys.

2 Introduction

The reduction of vehicle weight by using light-weight structural alloys such as those based on magnesium, aluminum and titanium for body as well as suspension parts is one of the most promising ways to reduce fuel consumption. Good fatigue performance is an important requirement for these applications. Therefore, the effect of shot peening on the fatigue performance of light-weight alloys is of particular importance. Among the various surface layer properties which are changed through shot peening, e.g., roughness, hardness, residual stresses and crystallographic textures [1], residual compressive stresses play a dominant role regarding fatigue performance since they can substantially hinder and even stop growth of surface cracks [2].

To what degree residual stresses can be effective mainly depends on their depth profile in the surface layer and its cyclic stability. The cyclic stability of the shot peening-induced residual stress-depth profile of the well known (α+β) titanium alloy Ti-6Al-4V is illustrated in Figure 1 [3]. The higher the stress amplitude (for a given number of cycles) in fatigue loading, the higher is the reduction in magnitude of the residual stress-depth profile. In addition to residual stresses, surface damage and work-hardening can be important parameters depending on the alloy system [4, 5]. This overview will present and discuss results which are characteristic for each alloy system. Results on titanium alloys will be contrasted to aluminum and magnesium alloys.

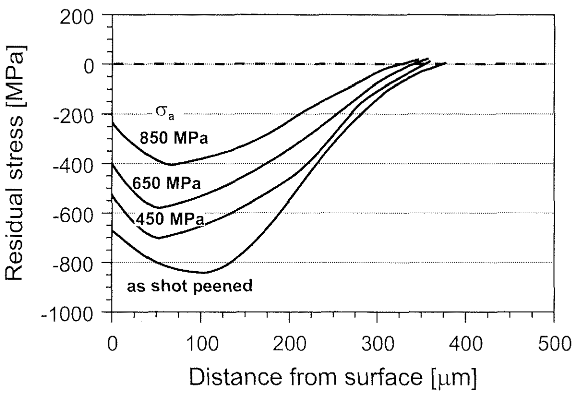


Figure 1: Effect of cyclic loading on shot peening-induced residual stress profile in Ti-6Al-4V [1]

3 Experimental

Shot peening was performed on a variety of light-weight alloys based on titanium, aluminum and magnesium and the effects on surface layer properties as well as on fatigue response were studied. In the case of titanium, alloys studied were Ti-2.5Cu, Ti-6Al-7Nb and Ti-3Al-8V-6Cr-4Mo-4Zr (Beta C) belonging to the α, (α+β) and metastable β alloy systems, respectively. In addition, a titanium aluminide Ti-47Al-3.7 (Nb, Cr, Mn, Si)-0.5B (γ-TiAl) was investigated. The well known AlCuMg based aircraft alloy 2024Al was taken in the tempers T3 and T6 to represent an age-hardenable aluminum alloy. Furthermore, the response of the high strength magnesium alloy AZ80 (Mg-8Al-0.5Si) to shot peening was investigated.

Tensile tests on the various alloys were performed on threaded cylindrical specimens having gage lengths and diameters of 20 and 4 mm, respectively. The initial strain rate was 8.3×10^{-4} s^{-1}. Tensile test results are listed in Table 1.

To determine the cyclic deformation of the various alloys which is known to affect the cyclic stability of residual stresses, stress controlled low cycle fatigue (LCF) tests were performed on threaded cylindrical specimens having gage lengths and diameters of 20 and 4 mm, respectively. These tests were done in stress control under axial loading at a stress ratio of R = -1 by means of a servohydraulic testing machine. The test frequency was 0.1 Hz. During testing, the axial strain was recorded by strain gages. From the hysteresis loops, the plastic strain was measured at zero load and plotted versus number of cycles.

For high cycle fatigue (HCF) testing, hour glass shaped specimens with a gage diameter of 3.6 mm were machined. Part of the specimens was electropolished (EP) to serve as reference. 100 μm were removed from the as-machined surface to ensure that any machining effect that could mask the results was absent. The other part was shot peened (SP) by means of an injector type machine using various shot materials including spherically conditioned cut wire SCCW14 (0.36 mm average shot size), cast steel S 230 and S 330 with 0.6 and 0.8 mm average shot sizes, respectively as well as spherical zirconia based ceramic shot with an average diameter of 0.5 mm. During the peening treatment, the specimens rotated at 1 s^{-1}. The distance between nozzle tip and specimen surface was 45 mm. Peening was done at full coverage to various Almen intensities ranging from 0.05 mmN to 0.28 mmA. The change in surface layer properties caused by shot peening was characterized by measurements of surface roughness through profilometry, microhardness-depth profiles, half width breadth- and residual stress-depth-profiles measured by X-ray diffraction techniques. In addition, residual stresses were measured by means of the incremental hole drilling method as described elsewhere [6].

High cycle fatigue (HCF) tests were performed mainly in rotating beam loading (R = –1) at frequencies of about 60 Hz. Some tests were done in axial loading using a servohydraulic testing maching at R = 0.1 and frequencies of about 60 Hz. Fatigue fracture surfaces were studied by SEM.

Table 1: Tensile properties of the various light alloys

Alloy	Microstructure	E [GPa]	$\sigma_{0.2}$ [MPa]	UTS [MPa]	El [%]	$\varepsilon_F = \ln A_0/A_F$
Ti-2.5Cu	equiaxed	107	610	745	20.0	0.55
Beta C	as-solutionized	80	840	850	25.0	1.12
Ti-6Al-7Nb	duplex / AC	122	920	995	13.5	0.50
	duplex / WQ	114	1030	1120	14.8	0.54
γ-TiAl	fully lamellar	170	440	440	1.0	0.01
			600*			
Al 2024	T3	72	360	550	13.2	0.21
	T6	72	420	510	10.9	0.33
AZ80	as-extruded (L)	44	245	340	12.0	0.20

* in compression

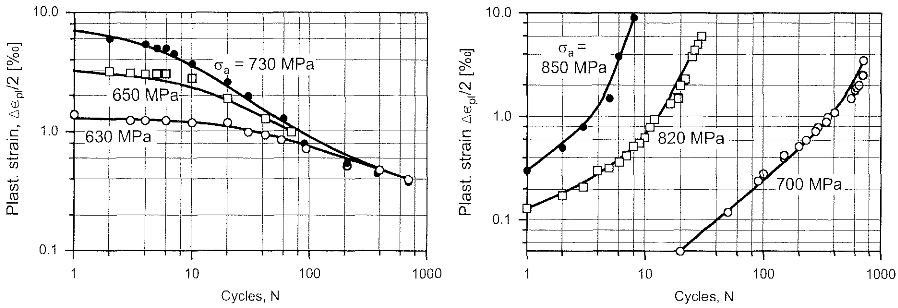
4 Results and Discussion

In addition to the stress amplitude in fatigue loading (Fig. 1), the cyclic stability of shot peening-induced residual stresses will depend on cyclic yield stress of the material. Presumably, materials which cyclically soften will exhibit less stable residual stresses compared to materials which cyclically harden.

4.1 α and Metastable β Titanium Alloys

The cyclic deformation behavior of the various alloys used in this study is illustrated in Figure 2 comparing results on the α titanium alloy Ti-2.5Cu (Fig. 2a) with results on the metastable β alloy Beta C (Fig. 2b). Cyclic hardening was observed in Ti-2.5Cu (Fig. 2a) while marked cyclic softening was found in Beta C (Fig. 2b).

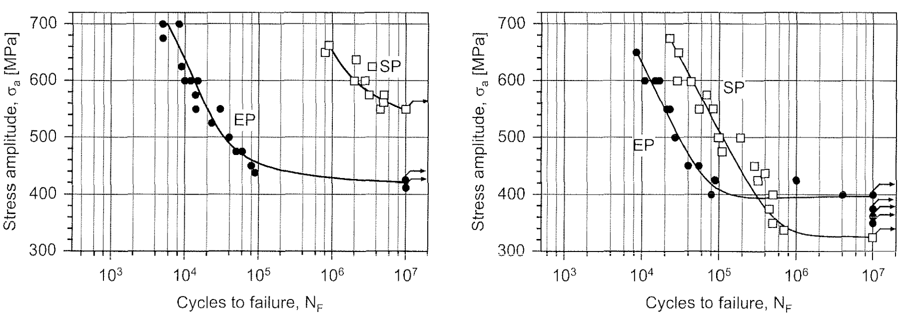
This difference in cyclic deformation behavior corresponds to the different work-hardening capacity (UTS – $\sigma_{0.2}$) of the two alloys observed in tensile loading (Table 1) amounting to 135 MPa and only 10 MPa for Ti-2.5Cu and Beta C, respectively. As expected, shot peening



a) Ti-2.5Cu b) Beta C

Figure 2: Cyclic deformation behavior (R = –1)

leads to marked increases in the fatigue life and HCF strength of Ti-2.5Cu (Fig. 3a) whereas only slight increases in fatigue life and no HCF improvement were observed on Beta C



a) Ti-2.5Cu b) Beta C

Figure 3: S-N curves in rotating beam loading (R = –1)

(Fig. 3b).

Similarly, this comparatively poor response of metastable β titanium alloys to shot peening was observed in work on Ti-10V-2Fe-3Al [7] and LCB [8] which exhibit similar cyclic softening indicating again that residual compressive stresses in this alloy group are not very effective presumably, due to cyclic decay.

However, mechanical surface treatments such as shot peening or roller-burnishing of the metastable β titanium alloy Beta C can be used to preferentially age the affected surface layer as demonstrated in Figure 4. The marked hardening in the surface layer which is the result of the effect of cold work prior to aging can stabilize the residual compressive stress field thus increasing the HCF strength as illustrated in Figure 5 [9,10].

Stabilizing of shot peening-induced residual stresses was also observed in selectively surface hardened TIMETAL 21s [11] and in bake-hardening steels [12].

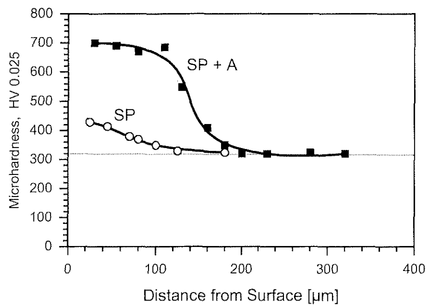


Figure 4: Microhardness-depth profile in Beta C, after shot peening (SP) and preferential aging (SP+A)

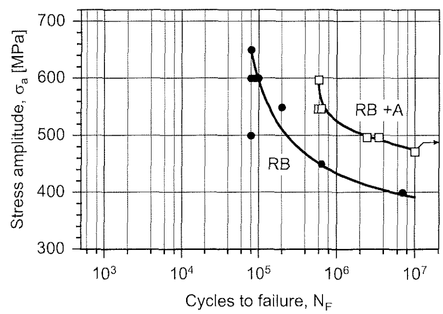
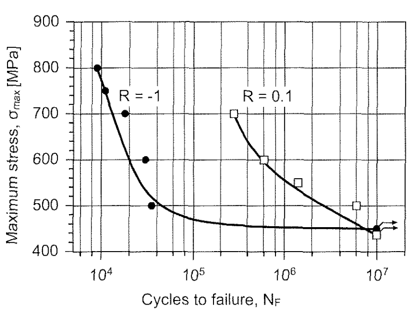


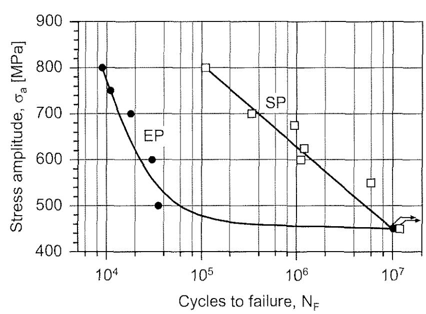
Figure 5: S-N curves (R = -1) in Beta C, after roller-burnishing (RB) and preferential aging (RB+A)

4.2 (α + β) Titanium Alloys

(α+β) titanium alloys such as Ti-6Al-4V or Ti-6Al-7Nb tend to exhibit slight cyclic softening. Thus, their response to shot peening is not as good as that of the α alloys but also not as poor as that of the metastable β alloys. However, this alloy group tends to exhibit a so called anomalous mean stress sensitivity [13], i.e., tensile mean stresses can dramatically decrease the HCF strength. This can be important also in fully reversed (R = –1) loading of shot peened conditions since residual compressive stresses are balanced by residual tensile stresses in deeper regions which can lead to subsurface fatigue crack nucleation. S-N curves of the (α+β) titanium alloy Ti-6Al-7Nb with a duplex (primary α in transformed β matrix) microstructure exhibiting the anomalous mean stress sensitivity are shown in Figure 6.



a) Effect of mean stress



b) Effect of shot peening (R = -1)

Figure 6: S-N curves in Ti-6Al-7Nb (Duplex/AC)

As seen in Figure 6a, the 10^7 cycles fatigue strength in terms of maximum stresses at R = 0.1 is not higher than at R = –1. Evidently, the material has a low resistance to fatigue crack nucleation at tensile mean stresses. This behavior directly shows up in the HCF performance of shot peened specimens (Fig. 6b) since fatigue cracks were found to nucleate in subsurface regions (Fig. 7).

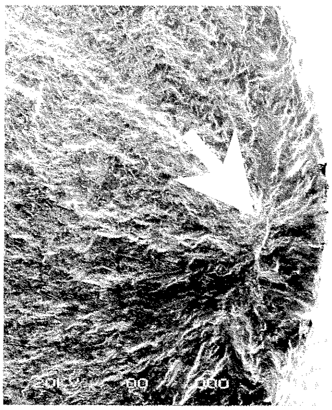
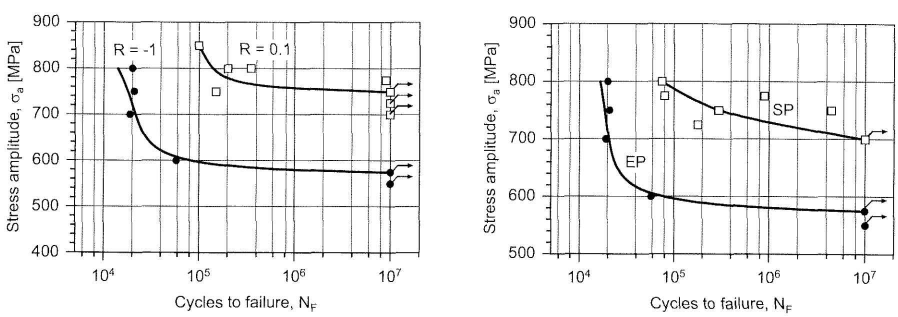


Figure 7: Subsurface fatigue crack nucleation in shot peened specimens of Ti-6Al-7Nb

This anomalous mean stress sensitivity in duplex microstructures of (α+β) titanium alloys can be eliminated by increasing the strength of the lamellar (transformed β) component through an increased rate of cooling from the duplex anneal, e.g., by using water-quenching instead of air cooling [14]. As seen in Figure 8, the faster cooling rate not only increases the fatigue strength particularly at tensile mean stresses (Fig. 8a), but also drastically increases the fatigue performance of shot peened specimens tested at R = −1 (Fig. 8b).



a) Effect of mean stress

b) Effect of shot peening

Figure 8: S-N curves in Ti-6Al-7Nb

In both cases, the increased strength of the lamellar portion of the duplex microstructure leads to higher resistances to dislocation motion and crack nucleation at tensile mean stresses thus, to improved fatigue performance.

4.3 γ-TiAl

Gamma titanium aluminides are highly sensitive to tensile loading with typical elongations to fracture (El) of only 1 to 3%. However, in compressive loading, marked plastic strains can be achieved without premature failure [6]. This is demonstrated in Figure 9.

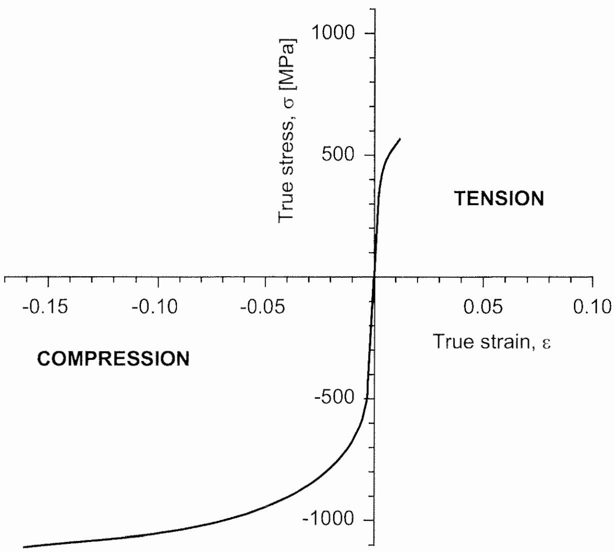


Figure 9: Stress-strain curves in tension and compression of γ-TiAl

Obviously, these plastic strains lead to pronounced work-hardening that can not be observed in a tensile test. By using Considère's construction where the true stress is plotted vs. conventional strain (in compression), the ultimate tensile strength of the material was estimated to UTS = 965 MPa which indicates marked work-hardening if compared to the yield stress of 600 MPa measured in compression (Table 1). The much lower apparent yield stress in tension (440 MPa) might result from early pore nucleation in tension leading to premature failure without macroscopic plasticity.

After shot peening, the microhardness at the surface increases from about 320 to values above 700 HV 0.1 (Figure 10) which is much higher than measured on titanium alloys.

Residual stresses as determined by the hole drilling method are shown in Figure 11. Although cyclic deformation of this γ-TiAl was not studied, from the marked hardening in monotonic loading (UTS – $\sigma_{0.2}$ = 360 MPa), it is argued that the material will also cyclically harden which prevents cyclic decay of the residual stresses. Accordingly, the fatigue response of this γ-TiAl to shot peening is excellent (Figure 12). The HCF strength increases from 550 MPa of the electropolished reference to 675 MPa after shot peening.

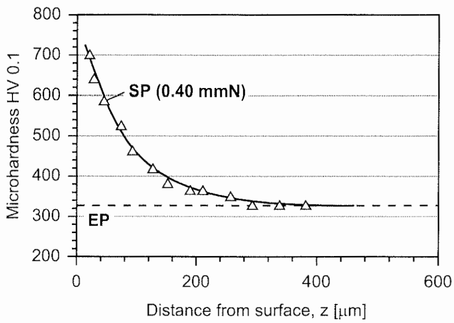


Figure 10: Microhardness-depth profile after shot peening of γ-TiAl

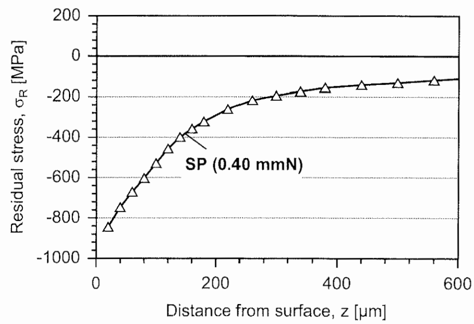


Figure 11: Residual stress-depth profile after shot peening of γ-TiAl

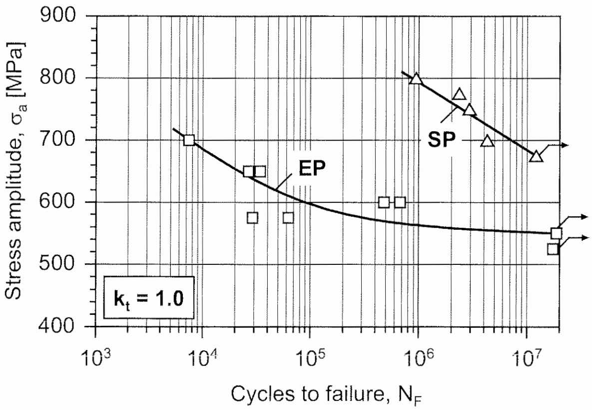
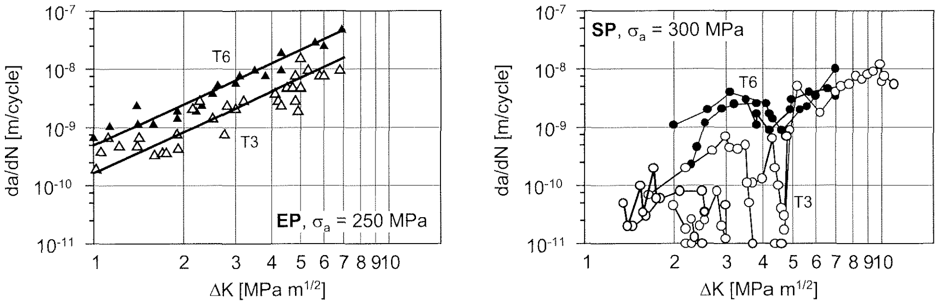


Figure 12: S-N curves in rotating beam loading (R = -1) of γ-TiAl, effect of shot peening

4.4 Aluminum Alloys

The fatigue response of age-hardenable aluminum alloys to shot peening significantly depends on the induced residual stress profile and its cyclic stability. Both properties highly depend on the aging condition utilized, e.g. higher residual stresses and greater cyclic stability are usually measured in underaged (T3, T4) tempers which cyclically harden compared to peak-aged (T6) or overaged conditions which tend to cyclically soften [14-16].

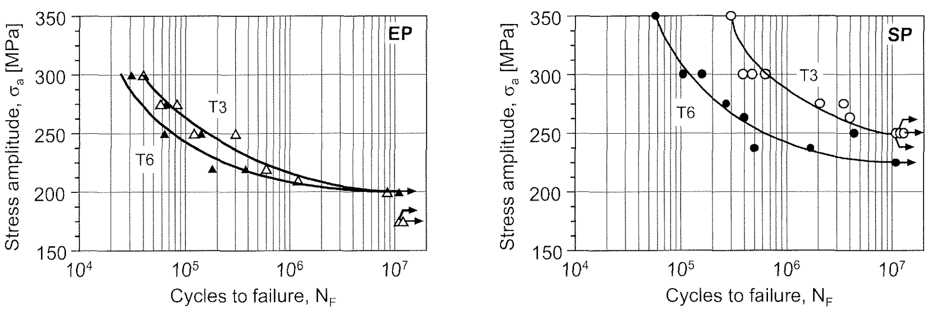
While the resistance to fatigue crack propagation of the electropolished reference in Al 2024 is already somewhat greater in T3 than in T6 (Figure 13a), after shot peening, crack growth in T3 is much more hindered than in T6 owing to higher and more stable residual stresses in T3 as compared to T6 (Figure 13b). Accordingly, the HCF strength in Al 2024 (Figure 14) is much more beneficially affected in the T3 temper (Figure 14a) than in the T6 temper (Figure 14b).



a) Condition EP

b) Condition SP

Figure 13: da/dN-ΔK curves of small surface cracks in 2024 Al, rotating beam loading (R = –1)



a) Condition EP

b) Condition SP

Figure 14: S-N curves in 2024 Al, rotating beam loading (R = –1)

4.5 Magnesium Alloys

Mechanical surface treatments on magnesium alloys are known to modify the cyclic deformation behavior [18, 19]. Results regarding HCF performance of the wrought magnesium alloys AZ80 and AZ31 have shown that this alloy group responds quite critically to shot peening [20-22]. For example, marked life improvements were found on the high strength alloy AZ80 after low intensity peening while increasing the Almen intensity led to a pronounced drop in life (Figure 15).

Specimens with this optimum in fatigue performance showed subsurface fatigue crack nucleation while at higher intensities multiple surface crack nucleation sites were observed [20]. This sensitivity of the magnesium alloys to shot peening can also be seen in Figure 16. Low intensity peening is clearly superior to high intensity peening regarding HCF strength. From parallel work [23], it is known that heavier peening not only drastically increases roughness and induces microcracks in magnesium alloys, but also leads to lower near surface residual compressive stresses. If this shot peening-induced damage is removed, e.g. by additional polishing, the HCF strength of heavily peened specimens can markedly be improved (Fig. 17).

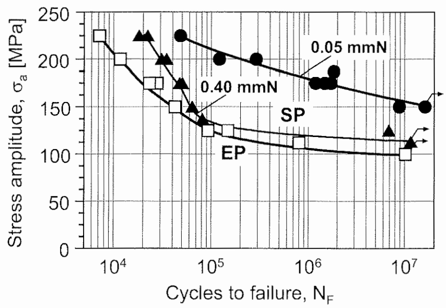


Figure 15: Effect of Almen intensity on fatigue life in AZ80, rotating beam loading

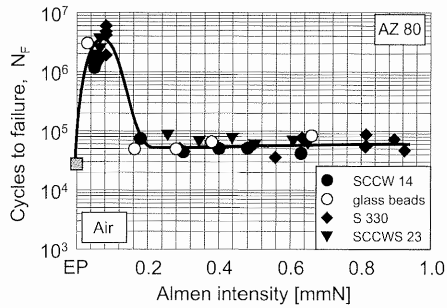


Figure 16: S-N curves in AZ80, rotating beam loading (R = –1)

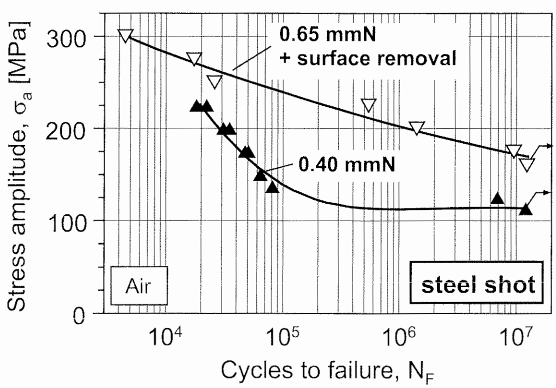


Figure 17: S-N curves in AZ80, rotating beam loading (R = –1)

Interestingly, a concomitant shift in fatigue crack nucleation site from the surface to the interior could be observed.

5 Summary

Depending on the alloy system of the various light-weight metals, the fatigue response to shot peening can be quite different. Excellent fatigue response was found in materials which exhibit cyclic hardening as observed in α titanium alloys, γ-TiAl and naturally aged aluminum alloys. Comparable poor fatigue response was observed in metastable β alloys and peak-aged aluminum alloys which both exhibit cyclic softening. In (α+β) titanium alloys, additional effects can result from the presence or absence of an anomalous mean stress sensitivity. Magnesium alloys were found to react very sensitively to shot peening presumably caused by the limited room temperature deformability of its hexagonal crystal structure.

6 Acknowledgements

The authors would like to thank the Deutsche Forschungsgemeinschaft for financial support.

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