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FATIGUE PERFORMANCE OF LIGHT-WEIGHT ALLOYS: INFLUENCES OF SHOT PEENING AND PRE-CORROSION

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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 and improve driving performance. Superior fatigue properties of the materials are an important requirement for these applications [1, 2]. Since shot peening is known as a low cost finishing treatment that is able to markedly improve the fatigue life of many structural materials such as steels and cast irons, the effect of shot peening on the fatigue performance of the more expensive light-weight alloys is of particular importance for automotive applications. In addition to fatigue loading, exterior body as well as suspension components of a vehicle are subjected to aggressive environments, e.g., aqueous NaCl solutions. Thus, the fatigue performance of these materials in such corrosive environments needs to be studied [3, 4].
In the present investigation, potential improvements in high cycle fatigue (HCF) performance of light-weight alloys based on Al, Mg and Ti by shot peening are outlined with particular emphasis put on the effect of corrosive environments.

EXPERIMENTAL

The light alloys examined in this investigation were the high-strength age-hardening aluminum alloy Al 7050, the wrought magnesium alloy AZ80, commercially pure titanium cp-Ti (grade 2) as well as the well known (α+β) titanium alloy Ti-6Al-4V. Tensile tests were performed on threaded cylindrical specimens having a gage length and gage diameter of 25 and 5 mm, respectively. The initial strain rate was 10^{-3} s^{-1}.
The heat treatments utilized for the various alloys and their tensile properties (initial strain rate 10^{-3} s^{-1}) are listed in Table 1.

Table 1: Tensile properties of the various light alloys and conditions

Alloy	Heat treatment	Condition	$\sigma_{0.2}$ [MPa]	UTS [MPa]	El [%]
Al 7050	1h 490°C/WQ 10h 100°C/AC	Under-aged (UA)	475	570	12
	as-received	Peak-aged (PA)	505	580	9
	70h 190°C/AC	Over-aged (OA)	265	360	10
AZ 80	-	as-extruded	220	320	6
cp-Ti	-	as-received	410	530	22
Ti-6Al-4V	0.25h 1050°C/WQ 1h 800°C/WQ 24h 500°C/AC	fine lamellar	1040	1100	8

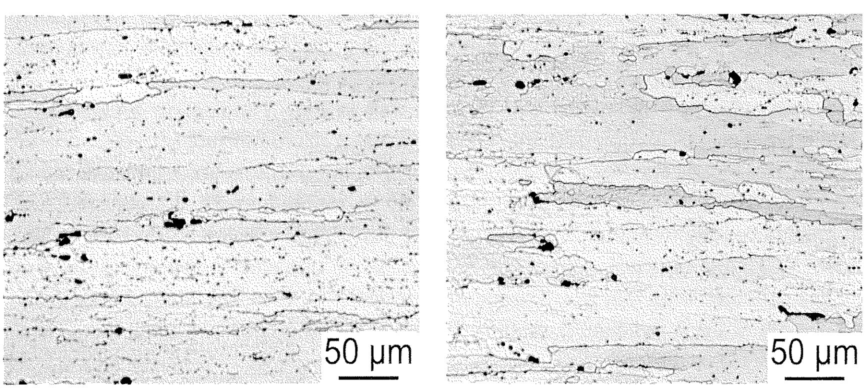
Shot peening was done using spherically conditioned cut wire with an average shot size of 0.36 mm (SCCW14). A gravitation induction system was used in case of Al 7050 and AZ80 while a direct pressure blast system was used in case of cp-Ti and Ti-6Al-4V. With the exception of AZ80 being shot peened to an Almen intensity of only 0.10 mmN, all other materials were peened to a higher intensity of 0.20 mmA (conditions SP). All peening was done to full coverage. In addition, some specimens of AZ80 were roller-burnished (condition RB) using a hydraulically driven hard metal ball having a 6 mm diameter (HG6) and a rolling force of 285 N. Process parameters in shot peening and roller-burnishing of the various alloys are based on previous studies [5, 6]. Finally, specimens were electrolytically polished (condition EP) to serve as reference. After applying the various mechanical surface treatments, the change in surface layer properties was evaluated by micro-hardness-depth profiles. Before fatigue testing, part of the surface treated specimens of the various alloys and conditions was pre-corroded in an aqueous 5 % NaCl solution. While AZ80 was exposed for only 3 hours all other materials were pre-corroded for 168 hours (7 days) [7]. The various surface conditions studied are summarized in Table 2.

Table 2: Surface conditions tested

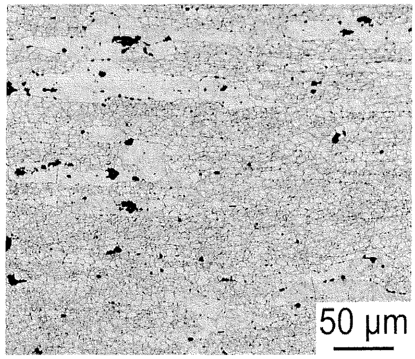
EP	electrolytically polished
EP+PC	electrolytically polished + pre-corroded
SP	shot peened
SP+PC	shot peened + pre-corroded
RB	roller-burnished
RB+PC	roller-burnished + pre-corroded

HCF tests were performed on hour-glass shaped specimens (7 mm minimum diameters for Al 7050 and Ti-6Al-4V, 5 mm minimum diameter for cp-Ti and AZ80) in rotating beam loading (R = -1) at a frequency of 50 Hz in air.
Following fatigue failure, fracture surfaces were examined using SEM.

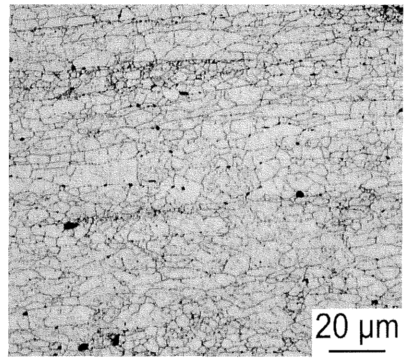
RESULTS AND DISCUSSION
The microstructures of the various alloys and conditions are illustrated in Figs. 1-4.



a) under-aged (UA) b) peak-aged (PA)



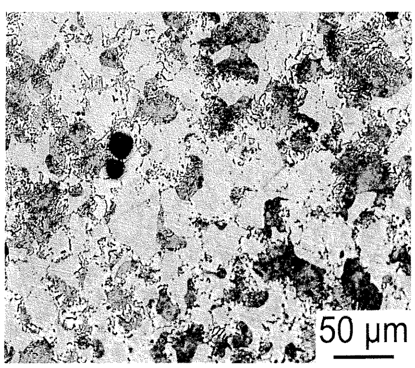
c) over-aged (OA)



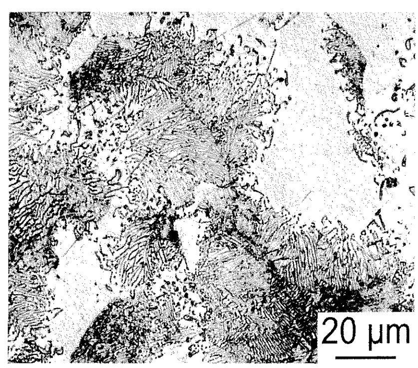
d) over-aged (OA), detail

Fig. 1: Microstructures of Al 7050

Fig. 1 shows the various aging conditions of Al 7050. For both UA (Fig. 1a) as well as PA (Fig. 1b), second phase stringers resulting from the rolling procedure are clearly visible. The fcc β grain size of the alloy can best be seen in OA (Fig. 1c). As resolved at higher magnification (Fig. 1d), the β grain size amounts to only 10 μm.



a) overview



b) detail

Fig. 2: Microstructure of AZ80

Fig. 2 illustrates the microstructure of AZ80. As seen in Fig. 2a, the hcp β grain size is roughly 30 μm. At higher magnification (Fig. 2b), the eutectoid component (β + $Mg_{17}Al_{12}$) adjacent to the β grains can clearly be seen.

The microstructure of cp-titanium is illustrated in Fig. 3 indicating an equiaxed hcp β grain size of roughly 100 μm. The fine lamellar microstructure (FL) of Ti-6Al-4V is shown in Fig. 4. The hcp β lamellae (light) surrounded by thin bcc β lamellae (dark) can be resolved. Since FL was generated by annealing an β' martensite at temperatures high enough to precipitate out the β phase at the martensite plates, there is a random distribution of the β lamellae as opposed to the colony type of phase arrangements that would result from a slower cooling from the β phase field. The width of the β lamellae is roughly 2 μm while their length can reach the size of the prior β grains (Fig. 4).

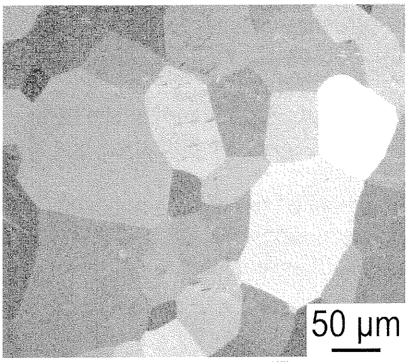


Fig. 3: Microstructure of cp-Ti

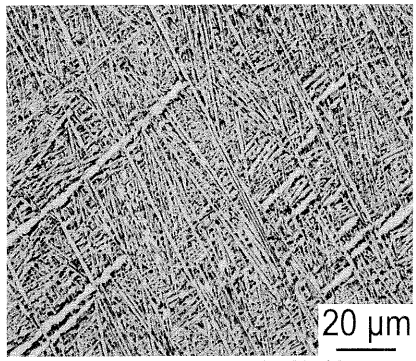
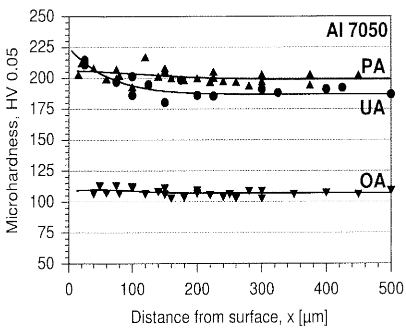
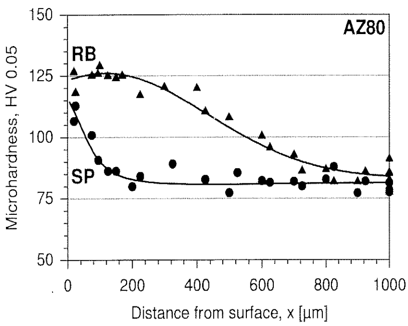


Fig. 4: Microstructure of Ti-6Al-4V

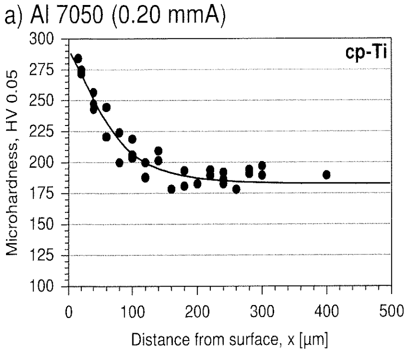
The shot peening-induced micro-hardness-depth profiles of the various alloys and conditions are illustrated in Fig. 5.



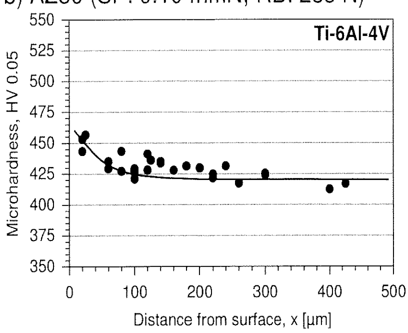
a) Al 7050 (0.20 mmA)



b) AZ80 (SP: 0.10 mmN, RB: 285 N)



c) cp-Ti (0.20 mmA)

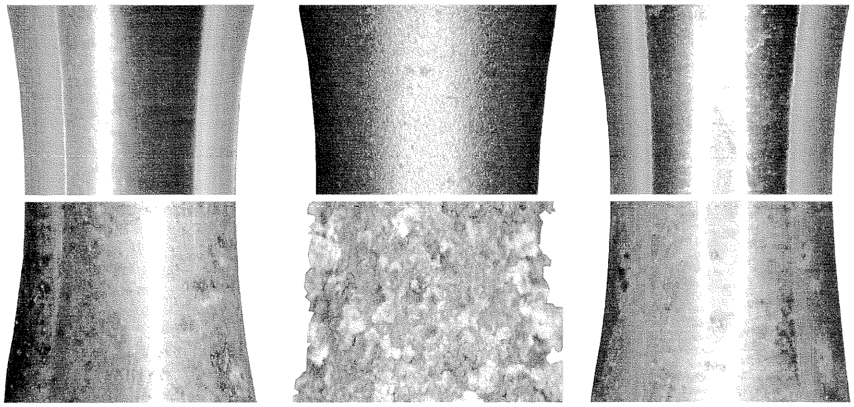


d) Ti-6Al-4V (0.20 mmA)

Fig. 5: Micro-hardness-depth profiles after shot peening (SP) and roller-burnishing (RB)

For Al 7050 (Fig. 5a), the degree of the increase in near-surface hardness depends on the aging condition. While pronounced increases in near-surface micro-hardness were measured on UA, almost no such increases were observed on PA and OA. The pronounced shot peening-induced increase in micro-hardness in an under-aged condition was also reported on naturally aged Al 2024 and explained by marked work-hardening of this particular microstructure containing ordered finely dispersed

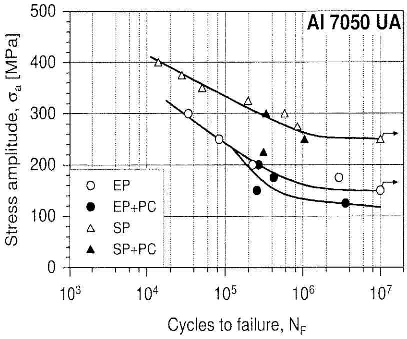
coherent precipitates [8]. Very marked micro-hardness increases were observed on conditions SP as well as RB in AZ80 (Fig. 5b). As expected from the utilized process parameters, the measured penetration depth of plastic deformation in RB is much higher than in SP (Fig. 5b). Shot peening-induced increases in near-surface hardness in cp-Ti (Fig. 5c) were more pronounced than in Ti-6Al-4V (Fig. 5d), again due to the lower work-hardening capability of the latter.
Examples of the effect of the pre-corrosion treatment on the surface appearance are shown in Fig. 6 comparing the various surface conditions EP, SP and RB of AZ80 before and after the exposure to the aggressive NaCl environment.



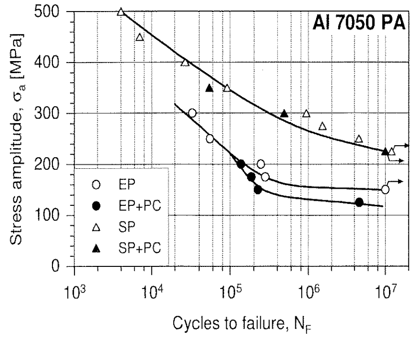
a) EP / EP+PC b) SP / SP+PC c) RB / RB+PC

Fig. 6: Surface appearance of AZ80 before (upper part) and after (lower part) the exposure to pre-corrosion

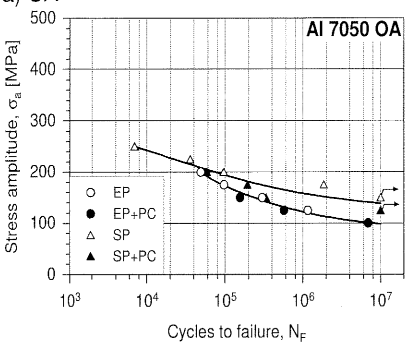
While the surface appearance of AZ80 only slightly changed for both conditions EP (Fig. 6a) and RB (Fig. 6c), the surface of condition SP (Fig. 6b) was drastically attacked during the exposure to pre-corrosion (compare lower and upper parts of Fig. 6b). This result can be derived from the Fe-contamination caused by peening with SCCW14 since Fe-particles act as local elements for corrosion in magnesium [9, 10]. The change in surface appearance due to pre-corrosion of both conditions EP and SP of Al 7050 was not as pronounced as observed on AZ80 although the exposure time to pre-corrosion was increased from 3 hours to a whole week. As expected, no significant change in surface appearance due to pre-corrosion was observed on cp-Ti and Ti-6Al-4V.
The S-N curves of Al 7050 are illustrated in Fig. 7 indicating the effects of pre-corrosion on both EP and SP for the various aging conditions. Independent of the aging condition, shot peening led to pronounced improvements in HCF performance (Fig. 7). A one-week pre-corrosion was not found to deteriorate this improved fatigue performance of conditions SP, while the HCF strengths of conditions EP of aging conditions UA (Fig. 7a) and PA (Fig. 7b) somewhat dropped. Aging condition OA exhibited the lowest HCF strengths for both EP and SP (Fig. 7c). No loss of these strength values was observed after exposure to pre-corrosion indicating superior corrosion resistance of this aging condition.



a) UA



b) PA



c) OA

Fig. 7: S-N curves (R =-1) in Al 7050, effects of shot peening and pre-corrosion

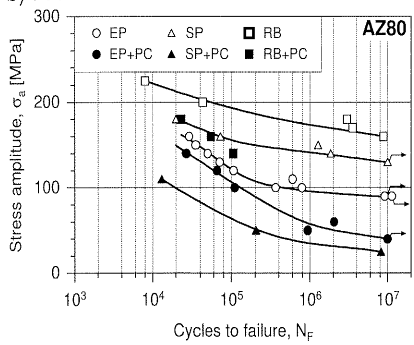
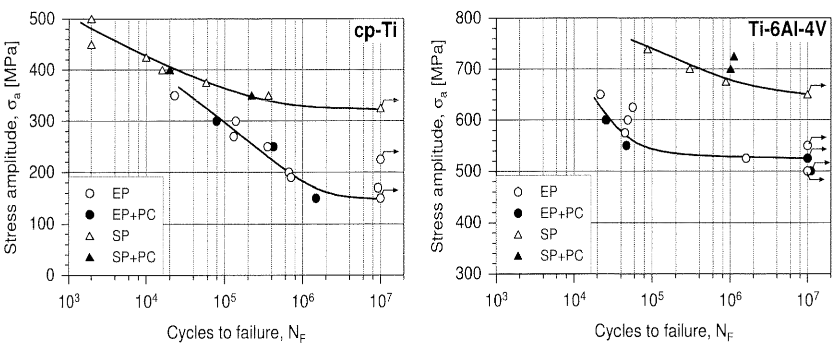


Fig. 8: S-N curves (R =-1) in AZ80, effects of shot peening and pre-corrosion

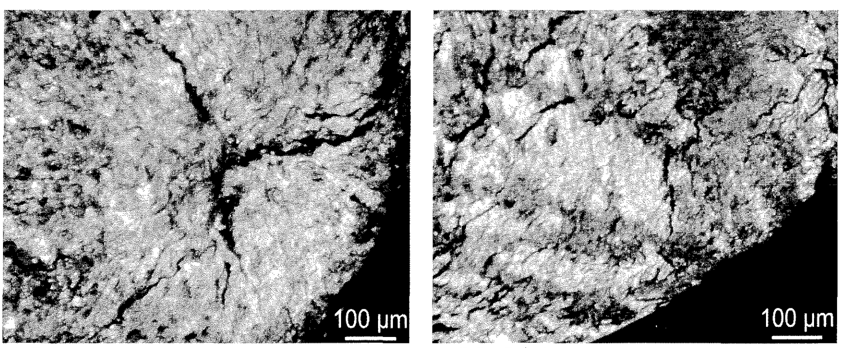
Compared to Al 7050, the fatigue performance of AZ80 of both conditions EP and SP was significantly affected by pre-corrosion despite the fact that the exposure time was reduced from one week (Al 7050) to only 3 hours (Fig. 8). The relative loss of the fatigue strength of SP was much more pronounced than that of EP. While pre-corrosion of condition RB also decreased the fatigue strength (Fig. 8), this loss was markedly lower, presumably, due to the absence of any Fe-contamination and local element corrosion.



a) cp-Ti b) Ti-6Al-4V

Fig. 9: S-N curves (R = -1), effect of shot peening and pre-corrosion

Both cp-Ti (Fig. 9a) and Ti-6Al-4V (Fig. 9b) exhibited pronounced improvements of the HCF strengths due to shot peening. Since titanium is well known for its superior corrosion resistance to chloride containing environments, the exposure to pre-corrosion did not change the S-N curves of conditions EP for both cp-Ti (Fig. 9a) and Ti-6Al-4V (Fig. 9b). Similarly to the fatigue results on Al 7050 (Fig. 7), Fe-contamination of the titanium surfaces by the steel shot did not drop the HCF strengths of the conditions SP for both cp-Ti (Fig. 9a) and Ti-6Al-4V (Fig. 9b) [11].
Examples of HCF fracture surfaces of AZ80 are shown in Fig. 10 comparing fatigue crack nucleation sites in condition RB with those in condition RB+PC. Whereas surface fatigue crack nucleation was always found in EP, subsurface (quasi-vacuum) fatigue crack nucleation was observed in RB (Fig. 10a) as well as in conditions SP of the various materials. While the exposure to pre-corrosion did not affect this crack nucleation site in conditions SP of Al 7050, cp-Ti and Ti-6Al-4V, a shift in crack nucleation site from subsurface regions to the surface was observed in AZ80 on pre-corroded conditions SP and RB. An example is shown in Fig. 10b. Obviously, the exposure to pre-corrosion led to early crack nucleation at the surface. Unlike the case of subsurface crack nucleation (Fig. 10a), initial crack propagation occurred in air instead of quasi-vacuum (Fig. 10b). This explains why the fatigue strength of mechanically surface treated AZ80 is markedly affected by the exposure to pre-corrosion.



a) RB (subsurface) b) RB+PC (at surface)

Fig. 10: Fatigue crack nucleation sites in AZ80

SUMMARY

The present investigation confirms previous results indicating that the HCF performance in rotating beam loading of light alloys based on Al, Mg and Ti can be markedly improved by shot peening and roller-burnishing provided that suitable process parameters regarding Almen intensity and rolling force being utilized. The HCF performance of shot peened Ti- and Al-based alloys in air is hardly affected by a one-week exposure to pre-corrosion in an aqueous 5 % NaCl solution, these results being very similar to those on the electropolished references. In contrast, pre-corrosion exposure for only 3 hours markedly decreased the HCF performance of the high-strength magnesium alloy AZ80. Compared to the electropolished reference, this loss in fatigue strength was even more pronounced for the shot peened condition. This result is explained by local element corrosion provided by the Fe-contamination of the magnesium surface during shot peening with steel shot SCCW14.

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