Fatigue Performance of Al7075-T73 and Ti-6Al-4V: Comparing Results after Shot Peening, Laser Shock Peening and Ball-Burnishing

M. Mhaede[1], Y. Sano[2], I. Altenberger[3], L. Wagner[1]

1 Institute of Materials Science and Engineering, Clausthal University of Technology, 38678 Clausthal-Zellerfeld, Germany
2 Power and Industrial Systems Research and Development Center, Toshiba Corporation, Yokohama 235-8523, Japan
3 Wieland-Werke AG, 89079 Ulm, Germany

Abstract
Rotating beam fatigue specimens of the well known high-strength aluminum alloy Al7075 and the titanium alloy Ti-6Al-4V were mechanically surface treated by various methods. Conventional shot peening (SP), ultrasound shot peening (USP), laser shock peening without coating (LPwC) and ball-burnishing (BB) were used and the resulting changes in surface topography, and residual stress-depth profiles were studied. Utilizing the same Almen intensity, USP led to roughness and micro-hardness values in near-surface regions slightly lower than SP, this result being explained by the larger shot size. However, the residual stress-depth profiles after SP and BB were very similar. LPwC and BB led to penetration depths of induced plastic deformation much greater than those observed after USP or SP. On average, micro-hardness values in near-surface regions were somewhat higher in BB compared to LwCP. Among the various mechanical surface treatments, ball-burnishing led to most marked fatigue strength enhancements.

Keywords Shot Peening, Ultrasound Shot Peening, Laser shock Peening, Ball-Burnishing, surface layer properties, fatigue performance

Introduction

Comparative studies on the effects of various mechanical surface treatments on fatigue performance are scarce. Some results can be found in [1], covering the laser-shock peened and deep rolled titanium alloy Ti-6Al-4V, or in [2], reporting on laser-shock peening and shot peening of Al2024-T351, or in [3], describing the effects of shot peening and ball-burnishing on Ti-6Al-4V. These investigations conclude that especially burnishing methods, but also laser peening treatments lead to fatigue performance more enhanced than that after conventional shot peening treatments. The basic physical mechanisms of mechanical surface treatments can be contradictory on the various stages in fatigue life. While near-surface cold work can retard crack nucleation, it may accelerate micro-crack propagation. Residual compressive stresses, on the other hand, have a minor or no effect on crack nucleation but can markedly retard micro-crack growth [4, 5]. Whether fatigue damage in mechanical surface treated materials is rather micro-crack propagation or crack nucleation controlled depends on the magnitude of the fatigue loading and on the surface roughness and thus, on the nature of the surface treatment itself. Shot peened surfaces can be considered as being pre-damaged since they usually contain tiny overlaps and even micro-cracks. In contrast, roller-burnishing (deep rolling) or ball-burnishing produce extremely smooth surfaces where crack nucleation can be much retarded, especially in the high-cycle-fatigue (HCF) regime [6]. Furthermore, an interpretation of the effects of mechanical surface treatments on fatigue performance is rather complex because the cyclic stability of the process-induced microstructural changes and residual stresses depend on the test parameters such as load level, stress ratio and test temperature. Material parameters such as age-hardening condition in precipitation hardenable alloys [7] and work-hardening capability [8] may also be of importance. In case of subsurface fatigue crack nucleation in

mechanically surface treated specimens, environmental effects should also be taken into account.
In the present investigation, the mechanical surface treatments BB, SP, USP and LPwC are compared regarding their effects on surface layer properties and resulting fatigue performance on two aircraft alloys Al7075 and Ti-6Al-4V.

Experimental Methods

The aluminum alloy Al7075-T73, was delivered as ∅ 70mm extrusion from Otto Fuchs Metallwerke AG, Meinerzhagen, Germany. The titanium alloy Ti-6Al-4V was received as round bar (∅ 100mm) from Baker Hughes, Celle, Germany. From both alloys, tensile and fatigue specimens were taken with the load axis in longitudinal direction. Tensile testing was done on specimens with cylindrical gage lengths and gage diameters of 25 mm and 5 mm, respectively. The initial strain rate was 8.3 x 10^{-4} s^{-1}. The results of the two alloys are listed in table 1. While both alloys are very ductile, the yield stress (YS) and ultimate tensile strength (UTS) in Ti-6Al-4V are roughly twice as high as in Al7075-T73.

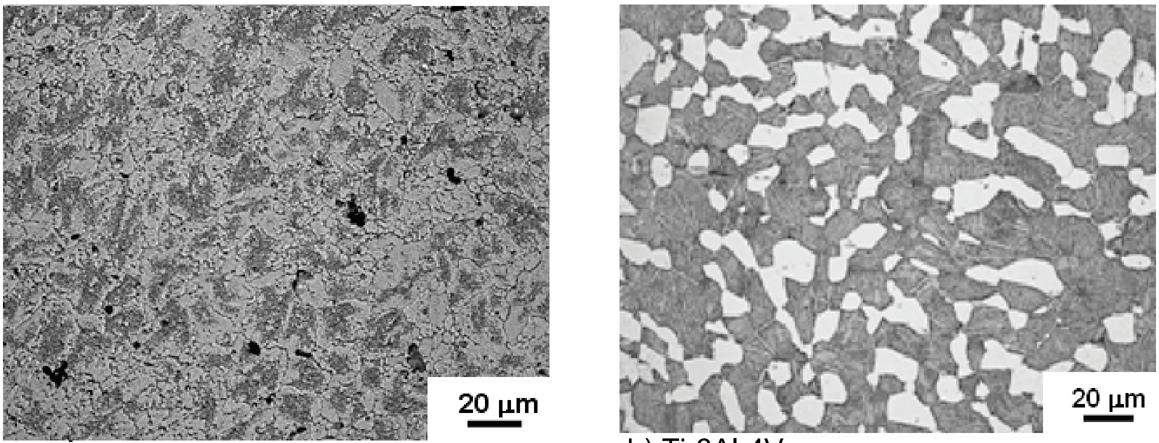
Table 1. Tensile properties of the tested alloys

Alloy	E (GPa)	YS (MPa)	UTS (MPa)	$\varepsilon_F = \ln (A_0/A_F)$
Al 7075-T73	72	480	550	0.56
Ti-6Al-4V	115	965	1065	0.60

Fatigue tests were performed on hour-glass shaped specimens with 6mm minimum gage diameter in rotating beam loading (R = -1) in air at a frequency of 50 s^{-1}. An electrolytically polished (EP) condition was used as a reference to which the various mechanically surface treated conditions were compared.
LPwC was performed at Toshiba, Yokohama, Japan. On the as-machined specimens of Al 7075-T73, 100mJ pulse energy, 0.7mm focal spot diameter and 27 pulses/mm^2 irradiation density were applied. Process parameters of the LPwC on Ti-6Al-4V were as follows: 200mJ pulse energy, 0.8mm focal spot diameter and 36 pulses/mm^2 irradiation density to take into account the higher strength of the titanium alloy.
SP was done using a direct pressure blast system of OSK at IWW of TU Clausthal. Spherically conditioned cut wire (SCCW14) having an average diameter of 0.35mm was used. All peening was performed to full (100%) coverage at an Almen intensity of 0.20mmA.
USP was performed at MTU Aero Engines in Munich using a generator/amplifier/sonotrode system and bearing steel balls 100Cr6 with an average diameter of 1.5 mm. USP was also done to full coverage at the same Almen intensity of 0.20 mmA. BB was performed at IWW of TU Clausthal by using a conventional lathe and a hydrostatically driven device from Ecoroll AG, Celle, Germany. A hard metal ball of ∅ 6mm (HG 6) was utilized at a working pressure of 200 bar.
After applying the various surface treatments, the surface roughness was determined by a profilometer from Perthen Company. Residual stresses were determined by means of the incremental hole drilling method using a drill with 1.9 mm diameter and strain gage rosettes. The oscillating drill was driven by an air turbine at a rotational speed of 2×10^5 rpm. From the measured back strains, the residual stresses were calculated by linear elasticity concepts, using the Young´s moduli for Al7075–T73 and Ti-6Al-4V as listed in Table 1.

Experimental Results and Discussion

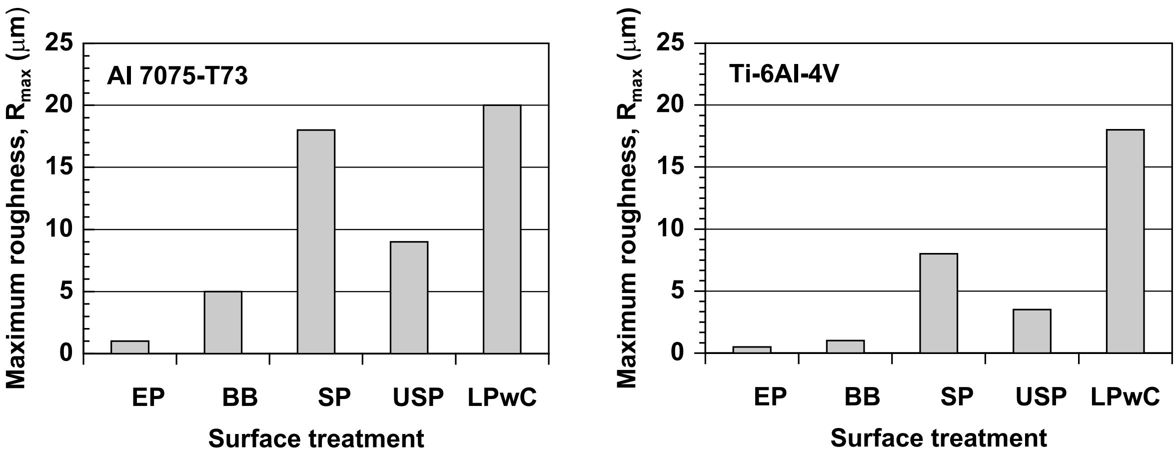
The optical microstructures of the two alloys are illustrated in Figure 1. While the grains in extruded Al 7075-T73 are typically highly elongated in extrusion direction, the grain sizes in a section perpendicular to the extrusion direction appear quite equiaxed (Fig. 1a) indicating cigar-like grain shapes. As seen in Figure 1b, the duplex microstructure of the $(\alpha+\beta)$ titanium alloy Ti-6Al-4V consists of about 30% primary-alpha phase embedded in a lamellar transformed $(\alpha+\beta)$ matrix.



a) Al 7075-T73 b) Ti-6Al-4V

Figure 1. Microstructures of the tested alloys

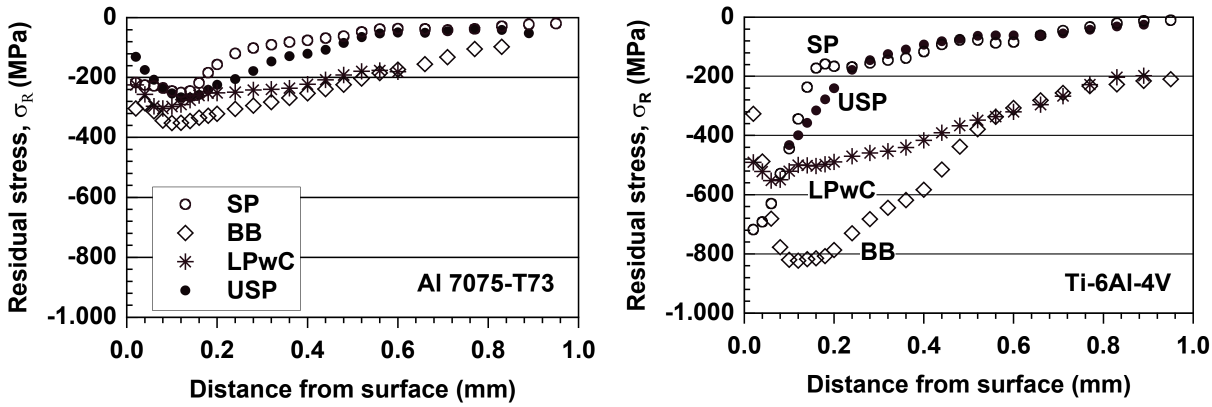
As opposed to BB, all peened conditions SP, USP and LPwC showed marked roughening of the surface. The maximum roughness values of the tested surface conditions are plotted in Figure 2 comparing results on Al7075-T73 (Fig. 2a) and Ti-6Al-4V (Fig. 2b). While roughness values of SP and LPwC in Al7075-T73 (Fig. 2a) are comparable, USP and in particular BB resulted in much lower roughening. This can be explained by the difference in ball size. In BB, a ball size of 6mm was used as opposed to 0.35mm and 1.5mm in SP and USP, respectively. Comparing now roughness values of BB, SP and USP between the two alloys, those of Al7075-T73 (Fig. 2a) are approximately twice as high as those of Ti-6Al-4V (Fig. 2b). probably owing to the difference in the strength of both alloys (Table 1). Interestingly, LPwC of Al7075-T73 and Ti-6Al-4V leads to similar roughness values.



a) Al-7075-T73 b) Ti-6Al-4V

Figure 2. Maximum surface roughness of the various conditions

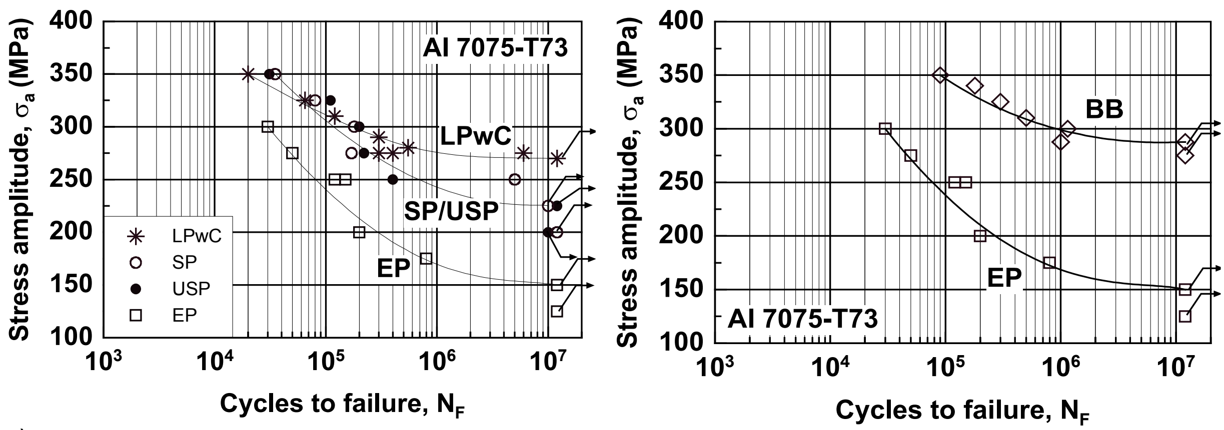
Residual stress-depth profiles are illustrated in Figure 3 comparing results on the various mechanically surface treated Al7075-T73 (Fig. 3a) with those of Ti-6Al-4V (Fig. 3b). Generally, residual compressive stresses were observed on both alloys. As expected from the difference in strength values (Table 1), the magnitude of the residual stresses in Ti-6Al-4V (Fig. 3b) is much higher than that in Al-7075-T73 (Fig. 3a). On both alloys, the penetration depths of residual compressive stresses in BB and LPwC are comparable and much higher than those of conditions SP and USP.



a) Al-7075-T73
b) Ti-6Al-4V

Figure 3: Residual stress-depth profiles

S-N curves in Al7075-T73 are shown in Figure 4 illustrating the effects of the various mechanical surface treatments on HCF performance relative to the reference EP. Among the various peening treatments, LPwC leads to the best HCF performance while no marked differences are observed between SP and USP (Fig. 4a). The superior HCF performance of LPwC is explained by the residual compressive stress field reaching to depths much greater than in condition SP or USP (Fig. 4a). Thus, the growth of microcracks in LPwC can be hindered much more effectively than in SP resulting in higher fatigue life and endurance improvements. On the other hand, the HCF performance of condition BB in Al 7075-T73 (Fig. 4b) is even superior to that of LPwC (compare Fig. 4b with Fig. 4a). This may be caused by the very low surface roughness of condition BB that in addition, leads to a retardation of fatigue crack nucleation resulting in most marked overall HCF strength improvement.



a)
b)

Figure 4: S-N curves in Al 7075-T73

The HCF performance of the various peened conditions of Ti-6Al-4V is illustrated in comparison to the electropolished reference in Figure 5. Similar to the results obtained on Al7075-T73, no marked differences in the HCF performance between SP and USP are observed (compare Figures 5a and 4a). Again, this result can be explained by the same Almen intensity used which introduces comparable residual stress-depth profiles. On the other hand, LPwC of Ti-6Al-4V yields a HCF performance clearly inferior to that observed in SP and USP. As shown below, this result is probably related to the comparatively high surface roughness (Fig. 2b) leading to early fatigue crack nucleation at the surface. The HCF performance of BB (Fig. 5b) is quite similar to condition SP.

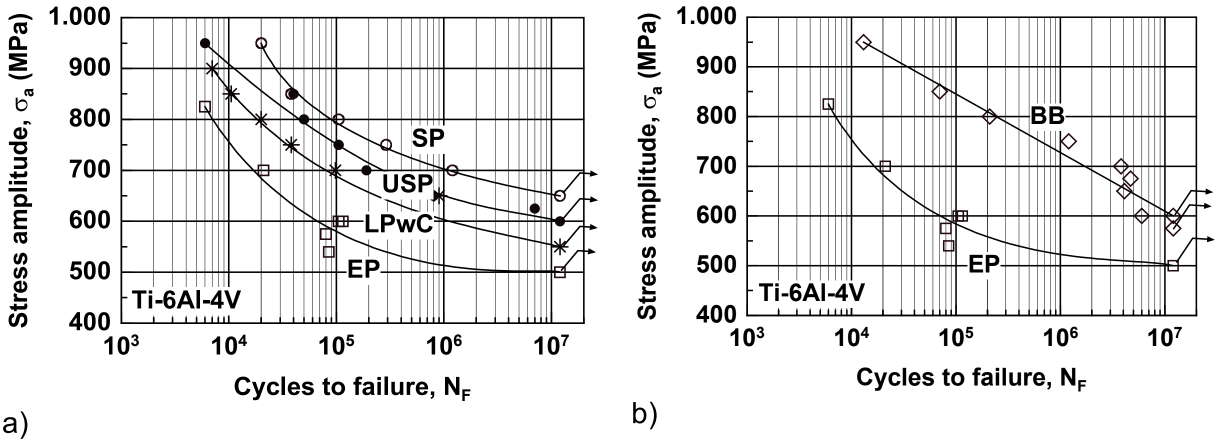


Figure 5: S-N curves in Ti-6Al-4V

In order to evaluate if the rather disappointing HCF performance of condition LPwC in Ti-6Al-4V can be explained by the comparatively high surface roughness (Fig. 2b), specimens were mechanically polished after applying LPwC. By this polishing treatment, a surface layer of about 50 μm were removed from the as-LPwC treated surface resulting in the same very smooth surface condition as observed in Condition EP. The resulting change in fatigue performance is illustrated in Figure 6. There is a clear improved HCF performance of this condition LPwC + P. This improvement is explained by an increase in the resistance to fatigue crack nucleation.

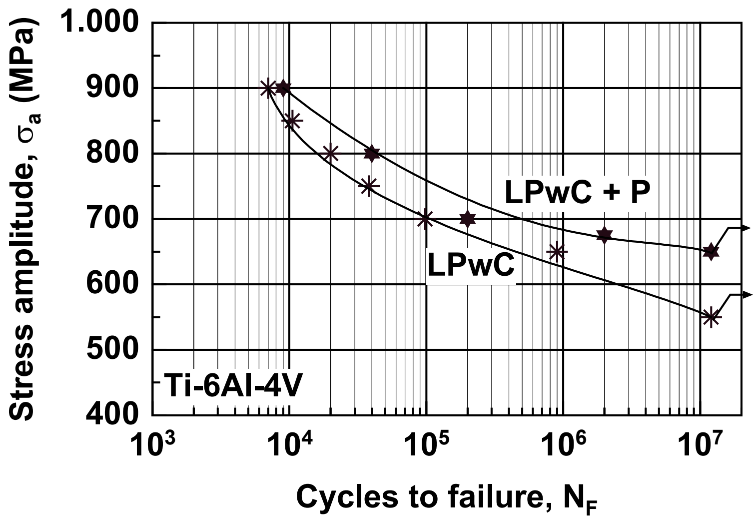


Figure 6. S-N curves in Ti-6Al-4V

Acknowledgements

The authors would like to thank Mr. Holger Polanetzki of MTU Aero Engines, Munich who provided USP treatments on Al7075-T73 and Ti-6Al-4V. Part of this work was supported by the Deutsche Forschungsgemeinschaft (DFG) under contract WA 692/31.

References

1) R.K. Nalla, I. Altenberger, U. Noster, G. Liu, B. Scholtes, R.O. Ritchie, *On the influence of mechanical surface treatments-deep rolling and laser shock peening-on the fatigue behavior of Ti-6Al-4V at ambient and elevated temperatures*, Mater. Sci. Eng. 355 A (2003) pp 216.
2) C.A. Rodopoulos, J.S. Romero, S.A. Curtis, E.R. de Los Rios, P. Peyre, *The Effect of Controlled Shot Peening and Laser Shock Peening on the Fatigue Performance of 2024-T351 Aluminium Alloy*, Journal of Materials Engineering and Performance, 12(4), pp 414.
3) T. Ludian, L.Wagner, *Mechanical Surface Treatments for Improving Fatigue Behaviour of Titanium Alloys,* Advances in Materials Science 8 (2008) p 44.
4) L.Wagner, T. Ludian, M. Wollmann, *Ball-Burnishing and Roller-Burnishing to Improve Fatigue Performance of Structural Alloys*, Engineering Against Fracture (S. Pantelakis and C. Rodopoulos, ed), Springer Netherlands (2009) pp. 1.
5) L.Wagner, *Mechanical Surface Treatments on Titanium, Aluminium and Magnesium Alloys,* Mater. Sci. Eng. A 263 (1999) pp 210.
6) H.Gray, L.Wagner, G. Lütjering, *Influence of Shot peening on the Fatigue Strength of Ti-Alloys at Elevated Temperatures,* in: J.T. Barnby (Ed.), Fatigue Prevention and Design, Chamelion Press, London, UK (1986) pp 363.
7) P. Juijerm, I. Altenberger, *Effect of temperature on cyclic deformation behavior and residual stress relaxation of deep rolled under-aged aluminium alloy AA6110,* Mater. Sci. Eng A 452-456 (2007) pp 475.
8) I. Altenberger, E. A. Stach, G Liu, R. K. Nalla, R. O. Ritchie, *An in situ transmission electron microscope study of the thermal stability of near-surface microstructures induced by deep rolling and laser-shock peening,* Scripta Materialia 48 (2003) pp 1593.

- -