INFLUENCE OF SHOT PEENING AND BURNISHING ON SMOOTH AND NOTCHED FATIGUE STRENGTHS OF TITANIUM ALLOYS

T. Ludian, J. Atoura and L. Wagner

Institute of Materials Science and Engineering
Clausthal University of Technology
Agricolastraße 6, D-38678 Clausthal, Germany

ABSTRACT
The high cycle fatigue (**HCF**) response to shot peening (**SP**) and ball-burnishing (**BB**) of two titanium alloys - one belonging to the α-alloy class (Ti-2.5Cu) and the other belonging to the metastable β-alloy class (Beta C) - is compared and contrasted. Increases in surface layer hardness by process-induced high dislocation densities are quite different between these two alloys owing to marked differences in work-hardening capabilities. The pronounced improvement in HCF performance of Ti-2.5Cu can be correlated with the observed pronounced surface strengthening. On the other hand, surface strengthening is only marginal in Beta C which can explain the ineffectiveness of shot peening and ball-burnishing in improving the HCF strength of this alloy. In contrast to smooth specimens, fatigue performance of notched specimens of Beta C is improved by roller-burnishing (**RB**).

KEY WORDS

Shot peening, ball-burnishing, roller-burnishing, residual stresses, HCF strength

INTRODUCTION
Mechanical surface treatments are often applied to titanium alloys such as the near-α alloys TIMETAL 834 and Ti-6Al-2Sn-4Zr-2Mo or the (α+β) alloys Ti-6Al-4V and Ti-6Al-6V-2Sn [G. Lütjering and J. C. Williams 2003, G. A. Carek 1987] to improve their HCF strengths. This improvement was derived mainly from two contributing factors, namely surface strengthening by the induced high dislocation densities and residual compressive stresses [G. R. Leverant et al. 1979, L. Wagner and G. Lütjering 1982]. While surface strengthening is able to enhance the resistance to fatigue crack nucleation, micro-crack propagation resistances are detrimentally affected owing to low residual ductility in the cold worked and strengthened surface layer [B. S. Baxa et al. 1978]. On the other hand, there is experimental evidence that residual compressive stresses can drastically reduce the growth rate of tiny surface cracks [L. Wagner et al. 1989, L. Wagner and C. Müller 1992, L. Wagner 1996, J. Kiese et al. 2003] while crack nucleation resistances are less affected. Previous work has shown that metastable β alloys in contrast to (α+β) alloys can respond quite critically to mechanical surface treatments [T. Ludian et al. 2004, M. Kocan et al. 2005 a, M. Kocan 2005 b]. For example, age-hardened conditions of the alloy TIMETAL LCB were shown to respond to shot peening or ball-burnishing with a more or less pronounced loss in HCF strength if compared to an electropolished reference (**EP**).
The present investigation is intended to highlight differences in the fatigue response to mechanical surface treatments between α titanium alloys and metastable β titanium alloys including results on notched specimens. An age-hardened α alloy Ti-

2.5Cu and a solution heat treated metastable β alloy Beta C were chosen. This enabled a comparison of the effects of mechanical surface treatments on the basis of the same HCF strengths in the electropolished references.

EXPERIMENTAL

The investigation was performed on the α-titanium alloy Ti-2.5Cu and the metastable β-titanium alloy Ti-3Al-8V-6Cr-4Mo-4Zr (Beta C). The alloy Ti-2.5Cu was received as hot rolled plate of thickness 10 mm. Blanks (10x10x50 mm) were cut from this plate perpendicular to the rolling direction and were heat treated 1h at 805°C slightly above the eutectoid temperature followed by water-quenching. Material was subsequently age-hardened at 400°C for 8 hours followed by aging at 475°C for 8 hours to precipitate out fine Ti_2Cu particles. The alloy Beta C was hot rolled at 700°C (φ = 1) followed by water-quenching. Blanks (10x10x50 mm) were taken perpendicular to the rolling direction and heat treated above the β-transus temperature at 927°C for 1 hour followed by water-quenching. No aging treatment was performed on Beta C.
Tensile tests were performed on threaded cylindrical specimens having gage lengths and gage diameters of 20 and 4 mm, respectively. The initial strain rate was 10^{-3} s-1. Tensile properties of both alloys are listed in Table 1.

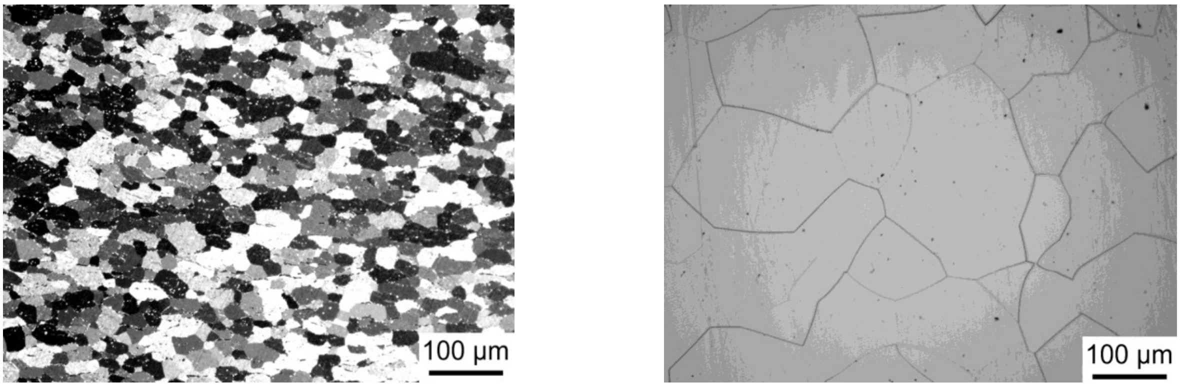
Table 1: Tensile properties of the titanium alloys Ti-2.5Cu and Beta C

	$\sigma_{0.2}$ (MPa)	UTS (MPa)	EL (%)	ε_F = ln (A_0/A_F)
Ti-2.5Cu	685	770	16.4	0.57
Beta C	840	850	25.0	1.05

Shot peening was performed using spherically conditioned cut wire (SCCW14) having an average shot size of 0.36 mm. Peening was done to full coverage at an Almen intensity of 0.20 mmA. Ball-burnishing was done using a conventional lathe and a hydrostatically driven tool with a hard metal ball of 3 mm in diameter. The burnishing pressure was kept at 300 bar. The process-induced changes in the surface layer properties were determined by microhardness-depth profiles and by residual stress-depth profiles as measured applying the incremental hole drilling method.
Fatigue tests in rotating beam loading were performed on smooth (k_t = 1) hour-glass shaped specimens having a minimum gage diameter of 4 mm. In addition to shot peened and ball-burnished conditions, electrolytically polished specimens were prepared to serve as reference. In addition, circumferentially V60°-notched cylindrical specimens were prepared for fatigue testing. Part of these specimens was roller-burnished using a 55° shaped roller element with a tip radius of 0.43 mm. The burnishing pressure was varied between 12.5 and 75 bar. Another part was electrolytically polished for reference purposes. Due to the change in notch tip radius caused by roller-burnishing, the geometrical notch factor increased from 2.2 in EP to 2.7 in RB.

RESULTS AND DISCUSSION

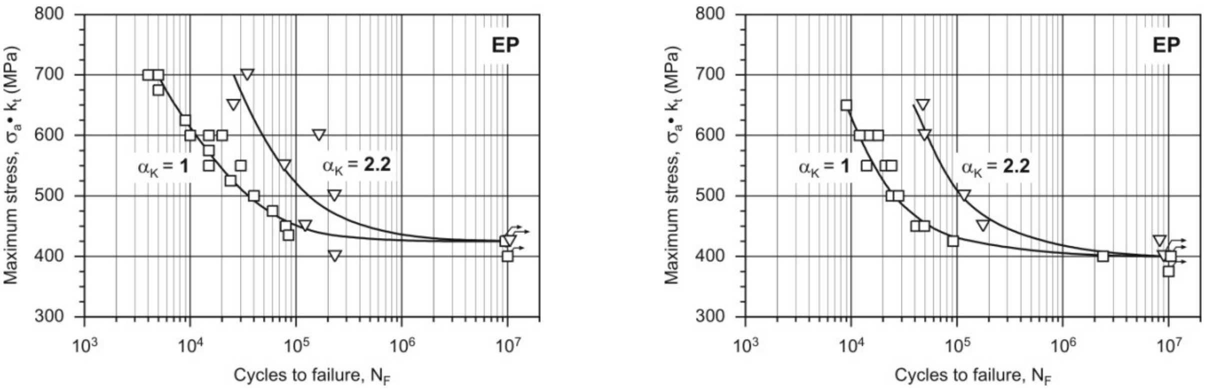
The optical microstructures of the two alloys are illustrated in Figure 1. The hcp α-grains in Ti-2.5Cu are slightly elongated in rolling direction. The average grain size is about 15 μm (Fig. 1a). The bcc β-grains in Beta C are quite equiaxed and have an average size of about 150 μm (Fig. 1b).



a) Ti-2.5Cu b) Beta C

Fig. 1: Microstructures of the titanium alloys

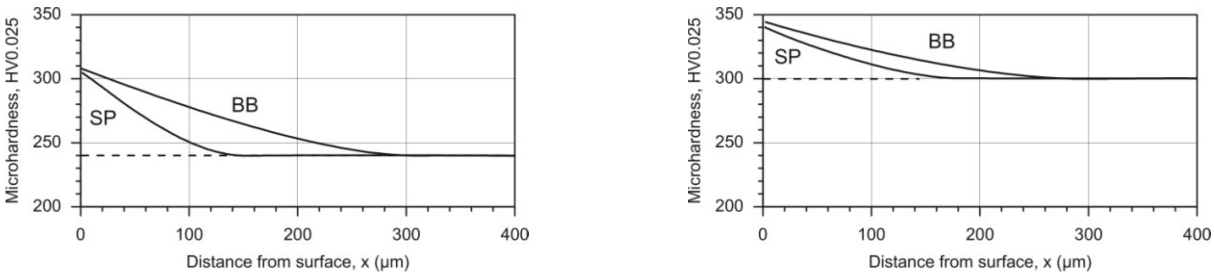
The S-N curves of the electropolished references are illustrated in Figure 2 where results on smooth (k_t = 1) and notched (k_t = 2.2) specimens of Ti-2.5Cu (Fig. 2a) and Beta C (Fig. 2b) are shown. In order to compare the fatigue performance of smooth and notched specimens, results are shown in terms of maximum stress amplitude σ_a x k_t as being present at the notch root. Despite the differences in yield stresses amounting to YS = 670 MPa and 840 MPa for Ti-2.5Cu and Beta C, respectively, the smooth HCF strengths of both alloys are about 400 MPa (Fig. 2). Furthermore, the smooth and notched fatigue performances approach each other in the HCF regime indicating that in both alloys the maximum stress at the notch root determines the resistance to fatigue crack nucleation. Since the geometrical notch factor fully affects the notched HCF strength, both Ti-2.5Cu (Fig. 2a) and Beta C (Fig. 2b) can be considered as 100% notch sensitive in fatigue.



a) Ti-2.5Cu b) Beta C

Fig. 2: S-N curves in rotating beam loading (R = -1), condition EP

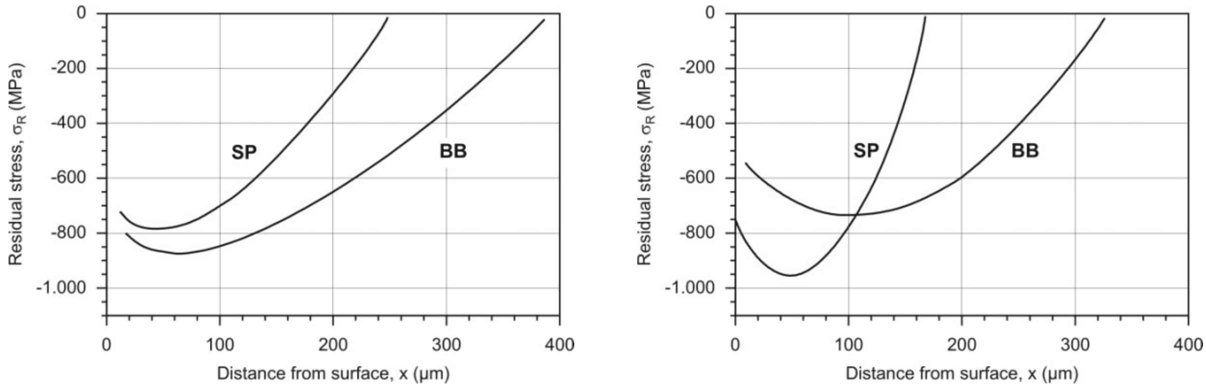
Examples of the microhardness-depth profiles in both alloys after shot peening and ball burnishing are given in Figure 3, respectively.



a) Ti-2.5Cu b) Beta C

Fig. 3: Microhardness-depth profiles after mechanical surface treatments

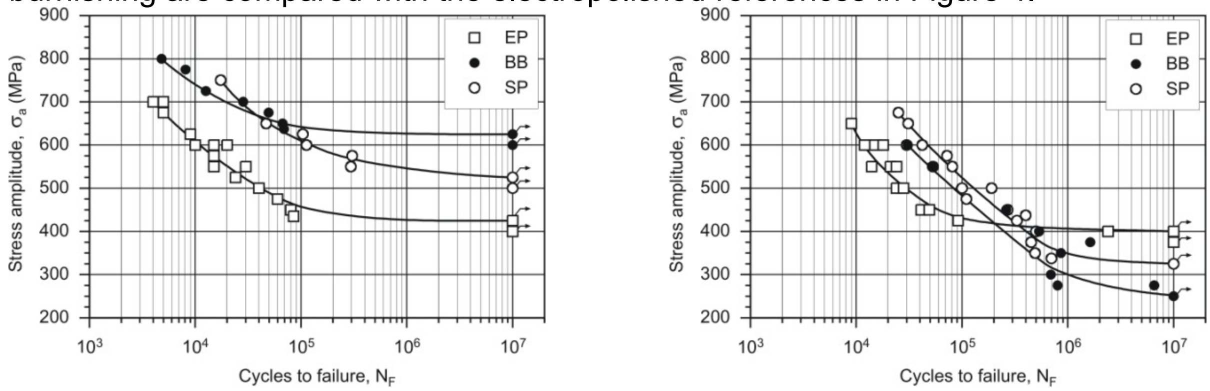
In contrast to Ti-2.5Cu (Fig. 3a), near-surface microhardness values in Beta C (Fig. 3b) are hardly affected by shot peening or ball-burnishing. This result can be derived from the very low work hardening capability in Beta C being also evident from its low UTS-YS value (Table 1). Roller-burnishing of the notched specimens as compared to ball-burnishing of the smooth specimens resulted in slightly higher microhardness values in the near-surface regions and much greater penetration depths. For example, penetration depths of 1000 µm were measured after roller burnishing of Ti-2.5Cu using 62.5 bar. No residual stresses were determined on notched specimens.
The residual stress-depth profiles after shot peening and ball-burnishing are shown in Figure 4 illustrating results on Ti-2.5Cu (Fig. 4a) and Beta C (Fig. 4b).



a) Ti-2.5Cu b) Beta C

Fig. 4: Residual stress-depth profiles after mechanical surface treatments

Near-surface compressive residual stresses were observed after shot peening and ball-burnishing in both alloys Ti-2.5Cu (Fig. 4a) and Beta C (Fig. 4b). As expected, ball-burnishing leads to residual stress fields much deeper than measured after shot peening.
The S-N curves of the smooth specimens of both alloys after shot peening and ball-burnishing are compared with the electropolished references in Figure 4.

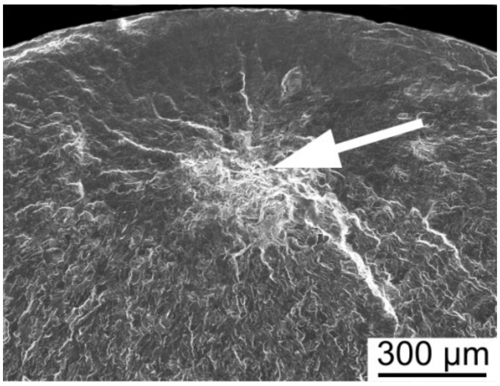


a) Ti-2.5Cu b) Beta C

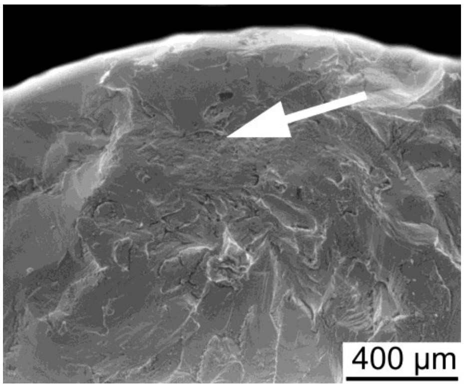
Fig. 5: S-N curves in rotating beam loading (R = -1)

The HCF performance of electropolished Ti-2.5Cu is highly improved by shot peening and even more by ball burnishing (Fig. 5a). The 10^7 cycles fatigue strength increases from 400 MPa to 525 MPa and 625 MPa after shot peening and ball-burnishing, respectively. On the contrary, the HCF performance of electropolished Beta C even decreases from the same starting value of 400 MPa in the electropolished reference to 325 MPa and 250 MPa after shot peening and ball burnishing, respectively (Fig. 5b). Similar results are reported on another metastable β-titanium alloy TIMETAL LCB [M. Kocan et al. 2005 b]

HCF cracks in shot peened and ball-burnished specimens of Ti-2.5Cu and Beta nucleate from subsurface regions (Fig. 6). Examples of fracture surfaces of ball burnished specimens of Ti-2.5Cu and Beta C are shown in Figures 6a and b, respectively. Obviosly, surface roughness effects are not involved in the crack nucleation process.



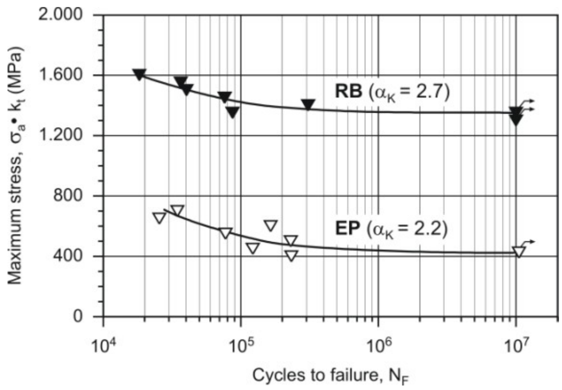
a) Ti-2.5Cu



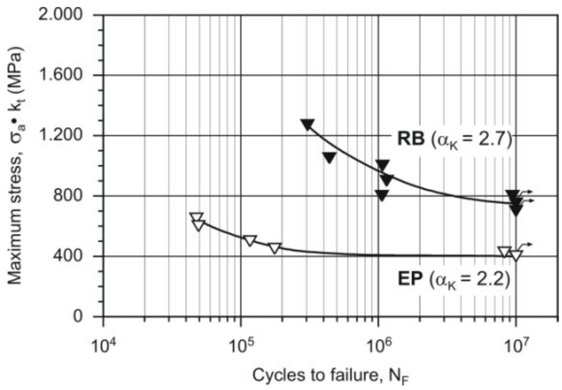
b) Beta C

Fig. 6: Subsurface fatigue crack nucleation in ball burnished specimens

Note that these crack nucleation sites which are located well below the residual compressive stress field must have nucleated under quasi-vacuum conditions. Thus, both the tensile mean stress sensitivity and the environmental sensitivity of a material are important in determining the change in HCF strength.
The S-N curves after roller-burnishing of the notched specimens using 62.5 bar on both alloys are compared with the electropolished references in Figure 7.



a) Ti-2.5Cu



b) Beta C

Figure 7: S-N curves in rotating beam loading (R = -1)

Comparing the fatigue response of notched specimens to roller-burnishing between Ti-2.5Cu (Fig. 7a) and Beta C (Fig. 7b), it is obvious that the HCF strength in Ti-2.5Cu after roller-burnishing is much more superior than that of Beta C. In terms of σ_a x k_t, the fatigue strength of Ti-2.5Cu of the electropolished reference is improved from 400 MPa to as much as 1300 MPa after roller-burnishing. Thus, the geometrical notch factor of 2.7 is clearly overcompensated by roller-burnishing. As opposed to Ti-2.5Cu, the fatigue strength of notched specimens in Beta C is much less enhanced from 400 MPa to only 700 MPa after roller-burnishing. Thus, in Beta C, roller-burnishing can not compensate the geometrical notch factor.

CONCLUSIONS

The HCF response to mechanical surface treatments of titanium alloys is characterized by the occurrence of subsurface crack nucleation. The resistance to subsurface crack nucleation is shown to strongly depend on the titanium alloy class. Materials with high tensile mean stress and low environmental sensitivities can show drastic losses in HCF strength compared to an electropolished reference. On the other hand, marked improvements in HCF performance are observed on alloys which exhibit normal mean stress and high environmental sensitivities. In contrast to smooth specimens, the HCF strengths of notched titanium specimens are generally more or less improved irrespective of the titanium alloy class.

ACKNOWLEDGEMENTS

The authors would like to thank the Deutsche Forschungsgemeinschaft DFG for financial support through contract WA 692/30-1.

REFERENCES

B. S. Baxa, Y. A. Chang, C. H. Burck, Met. Trans. 9 (1978) 1141.

G. A. Carek: NASA Technical Paper 2711 (1987) 1.

G. Lütjering and J. C. Williams, Titanium, Springer, Berlin (2003)

G. R. Leverant, S. Langer, A. Yuen and S. W. Hopkins, Met. Trans. 10A (1979) 250.

J. Kiese, J. Zhang, O. Schauerte and L. Wagner, Shot Peening (L. Wagner, ed.), Wiley-VCH, Weinheim (2003), 380.

L. Wagner, G. Lütjering, Shot Peening (A. Niku-Lari, ed.), Pergamon Press (1982) 453.

L. Wagner, G. Lütjering and V. Sedlácek, ICRS 2, Elsevier Applied Science (1989) 803.

L. Wagner and C. Müller, J. Materials Manufacturing & Processing (1992) 423.

L. Wagner, Surface Performance of Titanium Alloys (J. K. Gregory, H. J. Rack and D. Eylon, eds.) TMS-AIME (1996) 199.

M. Kocan, H. J. Rack and L. Wagner, JMEPEG 14 (6), (2005 a), 677.

M. Kocan, H. J. Rack and L. Wagner, Shot Peening and other Mechanical Surface Treatments (V. Schulze and A. Niku-Lari, eds.), IITT-International (2005 b) 320.

T. Ludian, M. Kocan and L. Wagner, LIMAT (W. E. Frazier, Y. D. Han, N. J. Kim, and E. W. Lee, eds.), CAAM (2004) 387.