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EFFECTS OF SHOT PEENING AND ROLLER-BURNISHING ON FATIGUE PERFORMANCE OF VARIOUS TITANIUM ALLOYS

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ABSTRACT

Shot peening and roller-burnishing were performed on various titanium alloys belonging to the α-, $(\alpha+\beta)$- and β-alloy classes. For both treatments, the main process parameters, i.e., Almen intensity and rolling force were varied to a wide extent and the process-induced changes in surface layer properties, e.g., surface topography and hardness profiles were evaluated. The fatigue performance of the α-, $(\alpha+\beta)$- and β-titanium alloys can be significantly improved by both shot peening and roller-burnishing. However, most marked improvements were found on α-alloys followed by $(\alpha+\beta)$- and β-alloys. The different response of the various alloy classes to mechanical surface treatments is interpreted in terms of the cyclic deformation behavior affecting the cyclic stability of the process-induced residual compressive stresses.

KEY WORDS

fatigue, titanium alloys, shot peening, roller-burnishing

INTRODUCTION

Mechanical surface treatments are often performed on steels, aluminum and titanium alloys to improve their fatigue performance (1-5). All mechanical surface treatments lead to a characteristic surface topography, an increase in dislocation density owing to plastic deformation and development of residual compressive stresses in the near-surface regions. Generally, shot peening leads to much higher roughness values than roller-burnishing and to smaller affected depths. The fatigue performance of a component after mechanical surface treatments depends in a complex manner on the changes in the surface layer properties and their cyclic stability. For example, the degree of work-hardening of the material will affect the amount of process-induced residual compressive stresses while their cyclic stability will depend mainly on the cyclic hardening/softening characteristics. While α-titanium alloys are known to cyclically harden, metastable β-titanium alloys are often found to cyclically soften. The present investigation was performed to correlate the fatigue response of mechanically surface treated titanium alloys with their cyclic hardening/softening characteristics. The well known titanium alloys Ti-2.5Cu, Ti-6Al-7Nb (Ti-6-7) and Ti-10V-2Fe-3Al (Ti-10-2-3) were taken to represent the α-, (α+β)- and metastable β-alloy classes, respectively.

MATERIAL AND SURFACE TREATMENT

Details of the thermal and/or thermomechanical treatments for the various alloys are given in (6-8). Tensile tests were conducted on cylindrical specimens (gage length 20 mm, diameter 4 mm) with an initial strain rate of 8.3×10^{-4} s^{-1}.Tensile properties of the various titanium alloys are listed in Table 1.

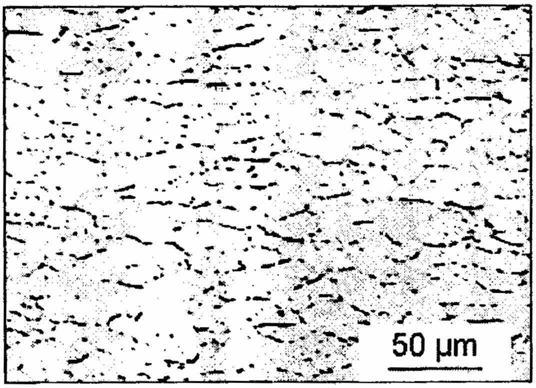
TABLE 1: Tensile properties of the various titanium alloys

alloy	condition	$\sigma_{0.2}$ (MPa)	UTS (MPa)	El (%)	RA (%)
Ti-2.5Cu	EQ	610	745	19	44
Ti-6-7	D20/AC	920	995	14	39
	D20/WQ	1030	1120	15	42
Ti-10-2-3	8h 480°C	1255	1320	6	20
	8h 580°C	1000	1020	13	48

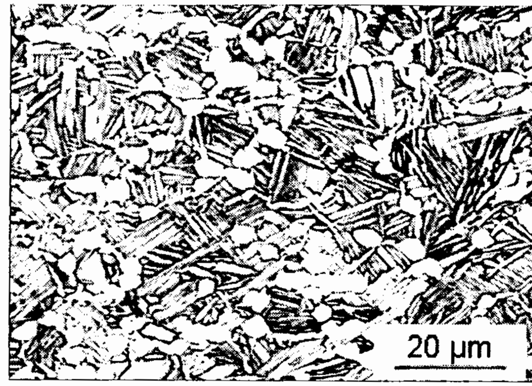
Fatigue tests were performed on hour-glass shaped specimens (gage diameter 3.8mm) in rotating beam loading (R=-1) at frequencies of about 100 Hz. After machining, about 100 μm were removed from the surface by electropolishing to ensure that any machining effect that could mask the results was absent. This electropolished (EP) condition is taken as the reference. Shot peening (SP) was performed with spherically conditioned cut wire SCCW14 (Ø 0.36mm) using an injector type system. Roller-burnishing (RB) was done by means of a conventional lathe using a one-roll hydraulic system with a hardmetal ball (Ø 6 mm). In order to determine process parameters for optimum lifetime improvements, Almen intensities and rolling forces were varied to a wide extent for shot peening and roller-burnishing, respectively.
The process-induced surface roughness profiles were evaluated by a profilometer. Fracture surfaces were studied by SEM.

RESULTS AND DISCUSSION

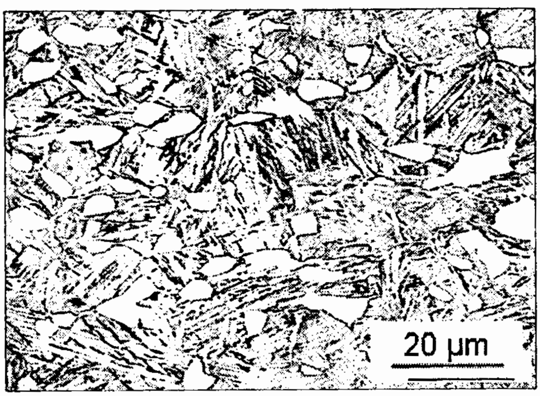
Optical micrographs of the various alloys are shown in Fig. 1.The microstructure of Ti-2.5Cu (Fig. 1a) consists of slightly elongated α–grains separated by the eutectoid component (α+Ti_2Cu). The (α+β)-alloy Ti-6-7 was tested with a duplex microstructure having about 20% primary α-phase in a lamellar (α+β) matrix. Owing to the lower cooling rate from the solution anneal, the width of the α-lamellae for Ti-6-7/AC (Fig. 1b) is markedly coarser than for Ti-6-7/WQ (Fig. 1c). This in turn results in yield stress and UTS values being roughly 100 MPa lower for the lower cooling rates (Table 1). The metastable β-alloy Ti-10-2-3 was tested with 15% primary α-phase embedded in a β-matrix age-hardened by small secondary α-precipitates (Fig. 1d). Increasing the temperature of the final anneal from 480 to 580 °C results in overaging indicated by a significant drop in yield stress and UTS value with a concomitant marked increase in El and RA values (Table 1).



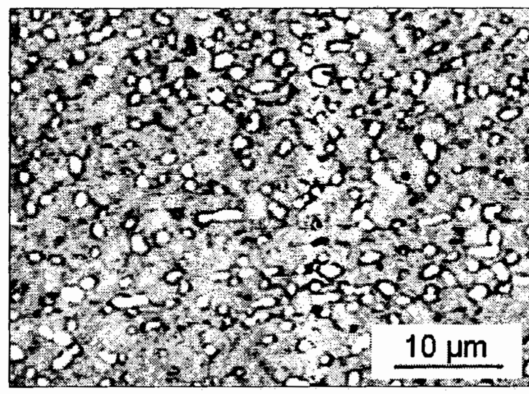
a) Ti-2.5Cu



b) Ti-6-7/AC



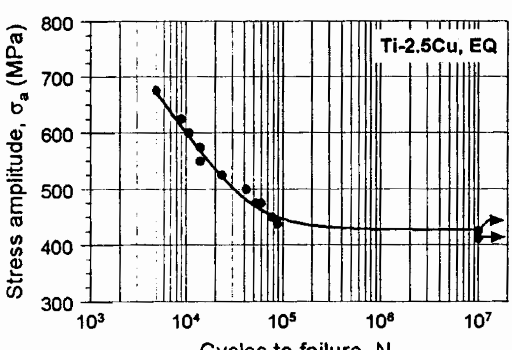
c) Ti-6-7/WQ



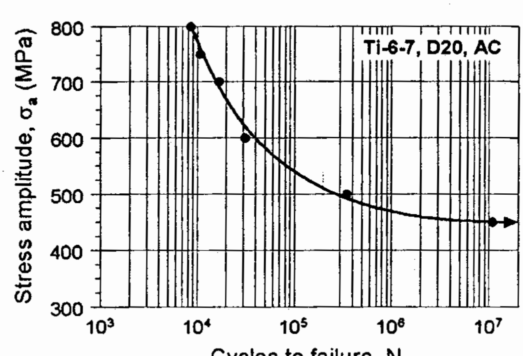
d) Ti-10-2-3 (8h 480°C)

Fig. 1: Microstructures of the various titanium alloys

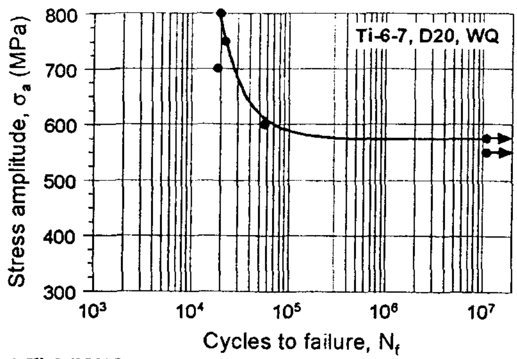
The S-N curves of the reference conditions EP for the various alloys are shown in Fig. 2. The 10^7 cycles fatigue strength values are about 425 MPa for Ti-2.5Cu (Fig. 2a), 450 MPa and 575 MPa for Ti-6-7/AC (Fig. 2b) and Ti-6-7/WQ (Fig. 2c), respectively and 625 MPa and 750 MPa for Ti-10-2-3 which was final heat treated 8h at 580 °C and 480 °C, respectively (Fig. 2d).



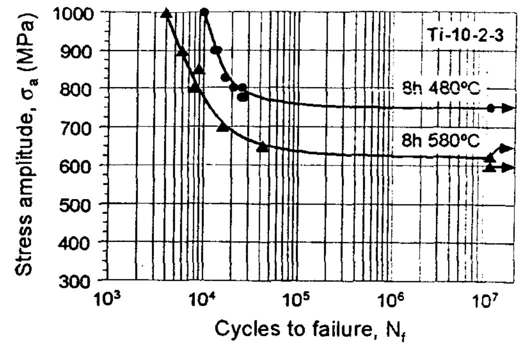
a) Ti-2.5Cu



b) Ti-6-7/AC



c) Ti-6-7/WQ



d) Ti-10-2-3

Fig. 2: S-N curves of titanium alloys, electropolished condition, rotating beam loading (R = –1)

Examples of typical roughness profiles for the various surface treatments are given on Ti-10-2-3 in Fig. 3 to characterize the conditions EP (Fig. 3a), SP (Fig. 3b) and RB (Fig. 3c). As expected, shot peening leads to highest roughness. The surface topography after roller-burnishing is characteristically different and almost as low as in the electropolished reference (Fig. 3). For both mechanical surface treatments, there is an increase in roughness with increasing Almen intensity and rolling force for shot peening and roller-burnishing, respectively (Fig. 4). However, this increase is much more pronounced for shot peening (Fig. 4). For the same surface treatment, no marked difference in surface roughness was observed among the various alloys.

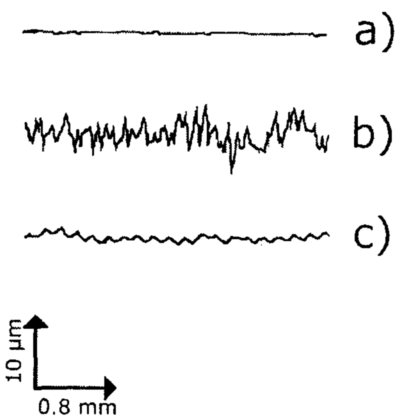


Fig. 3: Surface profiles after various surface treatments in Ti-10-2-3, 8h 480°C a) EP, b) SP (0.15 mmA), c) RB (670 N)

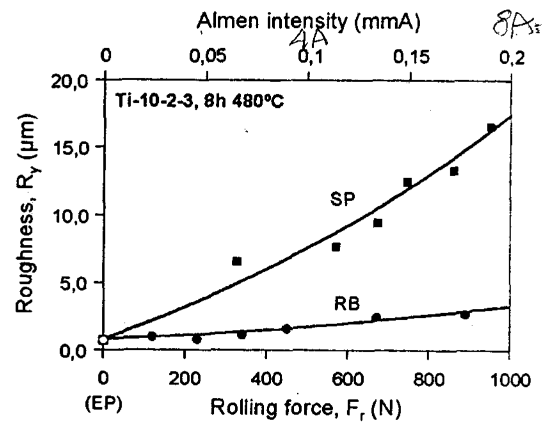


Fig. 4: Surface roughness after mechanical surface treatment in Ti-10-2-3

As shown in Fig. 5, the shot peening- or roller-burnishing-induced plastic deformation increases the surface layer hardness in the α-alloy Ti-2.5Cu much more than in the β-alloy Ti-10-2-3. This clearly reflects the difference in work-hardening capacity of the two alloy classes being much higher in Ti-2.5 Cu than in Ti-10-2-3 (Table 1).

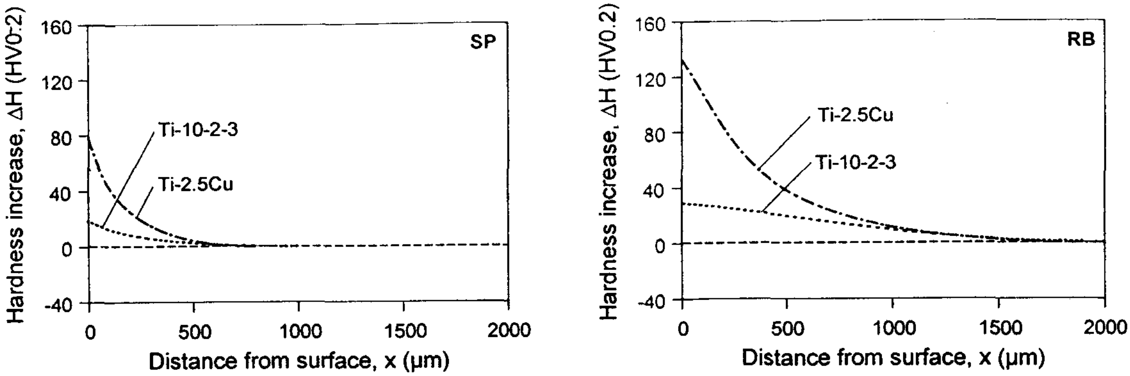
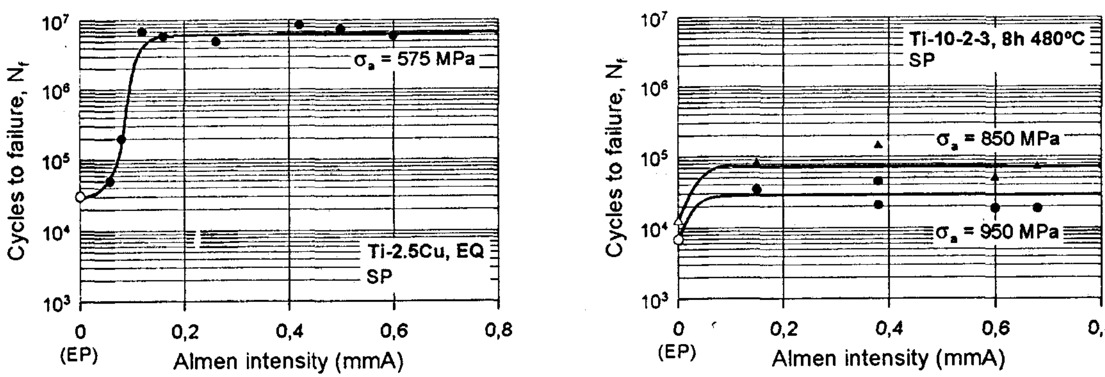


Fig. 5: Hardness profiles after shot peening or roller-burnishing

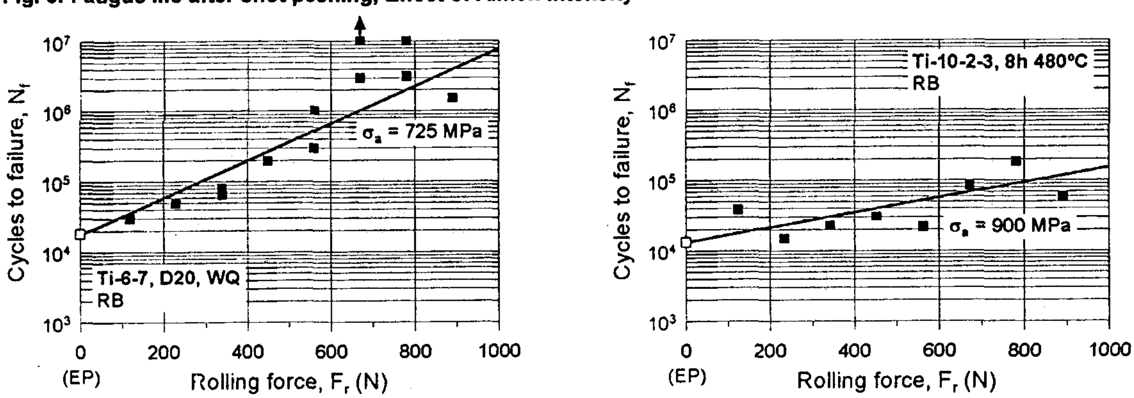
The effect of the process parameters Almen intensity and rolling force on the fatigue response of the various alloys after shot peening and roller-burnishing are shown in Figure 6 and Figure 7, respectively. While shot peening leads to very marked lifetime improvements in Ti-2.5Cu (Fig. 6a), improvements for Ti-10-2-3 are rather small (Fig. 6b). For both alloys, the fatigue life approaches a saturation value already at low Almen intensities (Fig. 6). Roller-burnishing (Fig. 7) results in lifetime improvements for Ti-6-7 (Fig. 7a) which are much more pronounced than for Ti-10-2-3 (Fig. 7b). In contrast to the effect of Almen intensity on fatigue life, a steady increase in fatigue life with increasing rolling forces was observed for roller-burnishing (Fig. 7, compare Fig. 7 with Fig. 6).



a) Ti-2.5Cu

b) Ti-10-2-3

Fig. 6: Fatigue life after shot peening, Effect of Almen intensity



a) Ti-6-7

b) Ti-10-2-3

Fig. 7: Fatigue life after roller-burnishing, Effect of rolling force

Further fatigue testing was performed using Almen intensities and rolling forces as listed in Table 2.

TABLE 2: Used process parameters for SP and RB

alloy	condition	Almen intensity (mmA)	rolling force (N)
Ti-2.5Cu	EQ	0,20	670
Ti-6-7	D20/AC	0,15	780
	D20/WQ	0,15	780
Ti-10-2-3	8h 480°C	0,15	780
	8h 580°C	0,15	780

The corresponding S-N curves of the various alloys are shown in Fig. 8, comparing results after optimum shot peening and roller-burnishing with the electropolished references. Very marked improvements in fatigue performance were observed in Ti-2.5Cu (Fig. 8a), while the effect of mechanical surface treatments on S-N curves was significantly less pronounced for Ti-10-2-3 (Fig. 8d). Intermediate improvements in fatigue performance were observed on Ti-6-7/AC (Fig. 8b). Mechanical surface treatments resulted in a marked change in the slope of the S-N curves in Ti-6-7/WQ (Fig. 8c) owing to pronounced lifetime improvements in the HCF regime while finite life was only slightly improved.

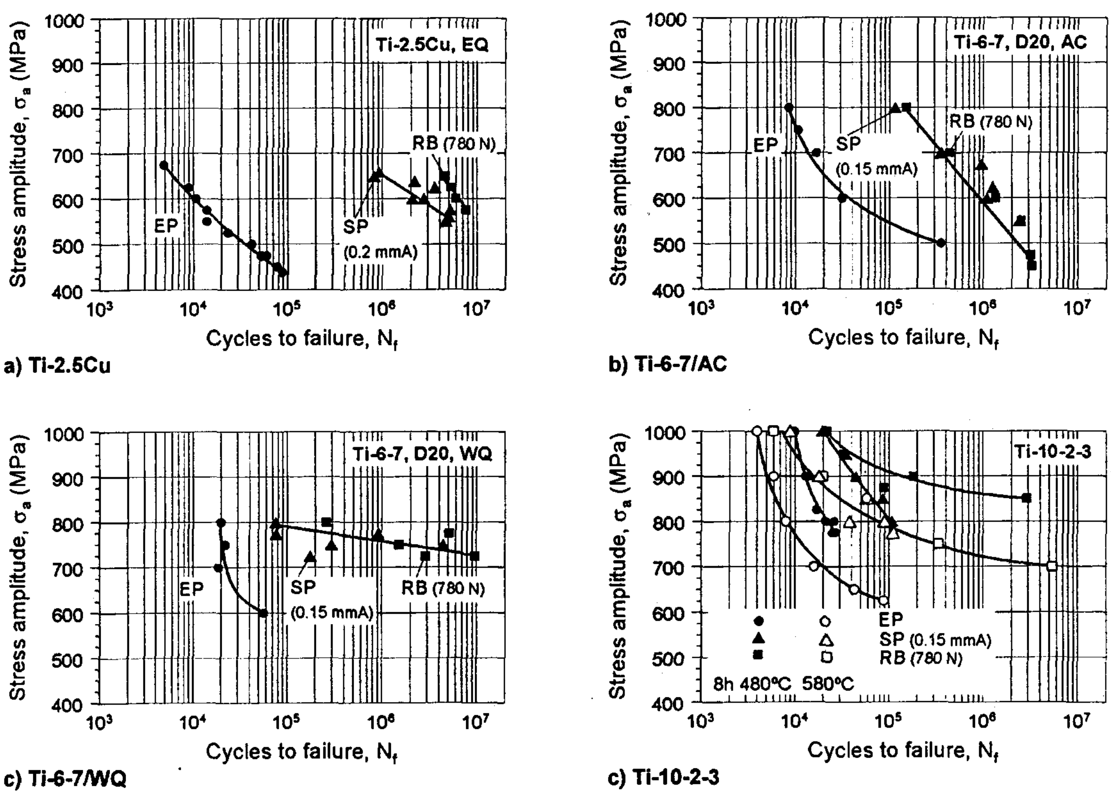
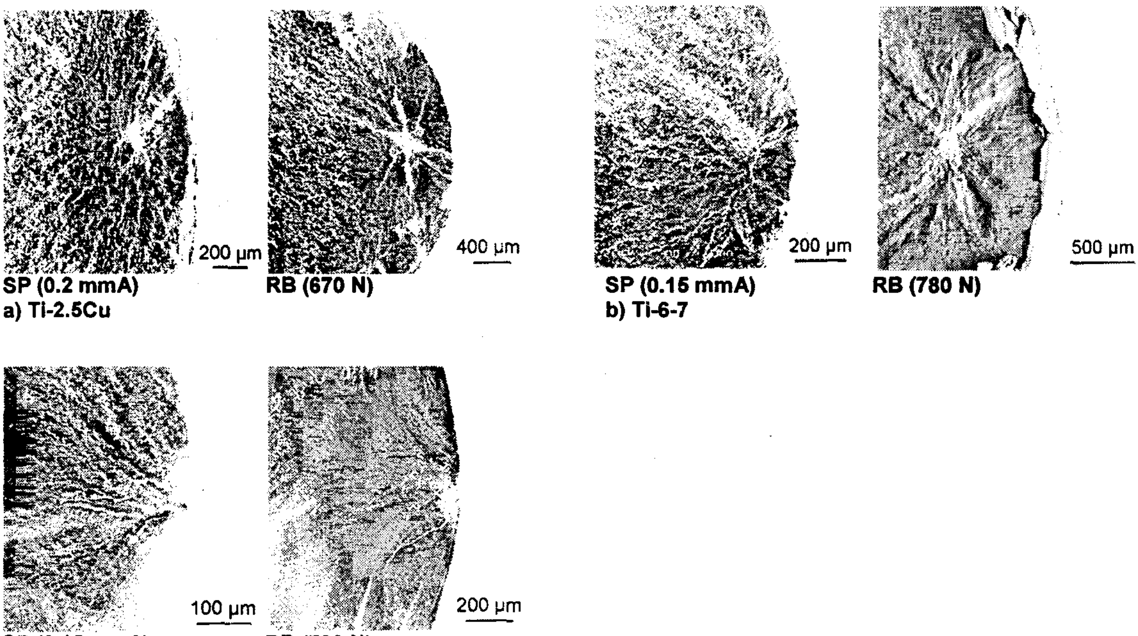


Fig. 8: S-N curves of the various titanium allöys, Effect of shot peening or roller-burnishing

As seen in Fig. 9, subsurface fatigue crack nucleation was observed in shot peened or roller-burnished conditions of Ti-2.5Cu (Fig. 9a) and Ti-6-7 (Fig. 9b). Compared to shot peening, much deeper nucleation sites were found in roller-burnished specimens reflecting the significantly greater process-affected depth (Fig. 5, compare Figure 5b with Figure 5a). In contrast to the results on the α- and (α+β)-alloys, fatigue cracks nucleated at the surface for the solute-lean metastable β-alloy Ti-10-2-3 (Fig. 9c). Similar results were reported on the solute-rich metastable β-alloy Ti-3Al-8V-6Cr-4Mo-4Zr (9).



SP (0.2 mmA) RB (670 N)
a) Ti-2.5Cu

SP (0.15 mmA) RB (780 N)
b) Ti-6-7

SP (0.15 mmA) RB (780 N)
c) Ti-10-2-3

Fig. 9: HCF crack nucleation sites after mechanical surface treatments

Generally, subsurface fatigue cracks in mechanically surface treated components nucleate in regions of residual tensile stresses which balance the outer residual compressive stress field. In titanium alloys, which are generally free of inclusions or other defects, the tendency for internal fatigue crack nucleation will primarily depend on the amount and cyclic stability of the residual tensile peak stress, the tensile mean stress sensitivity of the material and its fatigue strength in vacuum (it is presumed that conditions comparable to that of a vacuum prevail in the interior of a material). Since both α- and β-alloys show a normal mean stress sensitivity of the fatigue strength (7) and no marked differences with regard to environmental effects on fatigue strength, it is argued that subsurface fatigue cracks in the α- and (α+β)-alloy classes are presumably the result of cyclically stable residual tensile stresses (8). The corresponding residual compressive stresses in turn effectively retard or even stop microcrack growth from the surface into the interior (9). On the other hand, early residual stress decay as expected in a material that cyclically softens will prevent internal fatigue crack nucleation. Thus, cracks will start at the surface (Fig. 9c) as they also do in the residual stress free electropolished reference.

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