Considering Environmental and Mean Stress Effects in Understanding HCF Performance of Mechanically Surface Treated Metallic Materials

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Abstract

It is often reported that high-cycle fatigue (HCF) cracks in metallic components that are mechanically surface treated by shot peening (SP) or ball-burnished (BB) nucleate subsurface rather than at the surface. This may be caused by residual tensile stresses balancing the outer process-induced residual compressive stress field. Therefore, for understanding fatigue results after SP and BB, the tensile mean stress sensitivity of the particular material should be known. Since subsurface fatigue cracks have to nucleate under quasi-vacuum conditions, the knowledge of the fatigue strength in vacuum is desirable, too. HCF tests in axial loading in vacuum and air were performed on bainitic and austenitic steels

as well as on a metastable β -titanium alloy. In addition to fatigue tests in fully reversed loading (R = -1), testing was also done at R = 0.1 in order to evaluate the effects of tensile mean stresses on HCF strength. The changes in HCF strength caused by SP and BB will be correlated with the mean stress and environmental sensitivities of the HCF strengths in the various alloys.

Keywords: Mechanical surface treatments, HCF strength, subsurface fatigue crack nucleation, environmental sensitivity, mean stress sensitivity

Introduction

It is common knowledge, that the HCF strength of metallic components can strongly be improved by mechanical surface treatments such as SP and BB [1-3]. However, the HCF response to SP and BB of some metallic materials such as titanium alloys strongly depends on alloy class [4-6]. For example, α -alloys were shown to exhibit considerable enhancements in fatigue strength after SP and BB whereas metastable β -alloys exhibited even a drop in fatigue strength [7]. HCF cracks were observed to nucleate subsurface in regions where residual tensile stresses balance the outer residual compressive stress field being induced by SP or BB. Since subsurface cracks have to nucleate under quasi-vacuum conditions, it was argued that the fatigue performance of specimens being treated by SP or BB and tested in air should depend on both the tensile mean stress sensitivity and the environmental sensitivity of the fatigue performance [8].

The present investigation was carried out to correlate the changes in HCF strength due to SP and BB to the environmental and mean stress sensitivities of Fe-based and Ti-based materials.

Experimental

The investigation was performed on the structural steel 42CrMo4, an austenitic stainless steel X5CrNi1810 and the metastable β -titanium alloy Beta C. Tensile tests were performed on the various alloys using threaded cylindrical specimens having gage lengths and diameters of 25 and 5 mm, respectively. Young's moduli were measured with strain gages attached to the gage length of the specimens. Initial strain rates were 6.7 x 10⁻⁴ s⁻¹.

HCF tests were performed on hour-glass shaped specimens having a minimum diameter of 3mm and 4mm in axial loading (R = -1 and R = 0.1) and rotating beam loading (R = -1),

respectively. Axial tests were done in air and high vacuum (p < 10^{-5} mbar). Before fatigue testing, the specimens were electrolytically polished (100 µm removal from the as-machined surface) to exclude any machining effects that could mask the results. This condition is denoted as EP. SP 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 either 0.20mmA or 0.33mmA. BB was performed using a conventional lathe and a hydrostatically driven tool with a hard metal ball (\emptyset 6mm). The burnishing pressure was kept constant at 300 bars.

The process-induced changes in the surface layer properties were characterized by microhardness-depth profiles. The nucleation sites of the fatigue cracks were determined by scanning electron microscopy (SEM).

Results and Discussion

The microstructures of the various alloys are illustrated in Figure 1.



Figure 1. Microstructures of the various alloys

The microstructure of the 42CrMo4 steel consists of fine bainite (Fig. 1a). X5CrNi1810 exhibits equiaxed austenite grains with an average size of $45\mu m$ (Fig. 1b). Beta C shows fully recrystallized grains with an average size of $155\mu m$ (Fig. 1c).

The heat treatments and tensile properties of the various alloys are listed in Table 1.

Alloy	Heat treatment	YS (MPa)	UTS (MPa)	UTS – YS (MPa)	El (%)	$\epsilon_F =$ In (A ₀ /A _F)
42CrMo4	0.5h at 850 °C/OQ 2h 450 °C/AC	1265	1330	65	12	0.70
X5CrNi1810	0,5h at 1050 °C/AC	270	660	390	73	0.97
Beta C	0.5h at 927 °C/AC	850	860	10	21	1.15

Table 1. Tensile properties of the tested steels	s
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The fatigue performance of the various alloys is illustrated in Figure 2 where S-N curves from axial loading of EP at R = -1 and R = 0.1 are plotted in terms of maximum stress. In addition, results from R = -1 tests in vacuum are also shown.

Both 42CrMo4 (Fig. 2a) and X5CrNi1810 (Fig. 2b) exhibit HCF strengths in vacuum significantly higher than in air, this effect presumably being related to detrimental effects of hydrogen in the air on both Fe-based alloys [8]. On the contrary, no loss in HCF strength by changing the environment from vacuum to air was observed on the titanium alloy Beta C (Fig. 2c).



Figure 2. S-N curves of the various alloys: Effects of R-ratio and environment

This result indicates that the β -phase in titanium alloys is hardly sensitive to hydrogen embrittlement [8]. Figure 2 also illustrates that for the tested alloys, the fatigue strengths at R = 0.1 in terms of maximum stress are much higher than the corresponding values at R = -1, this indicating a normal mean stress sensitivity of the HCF strength. This normal mean stress sensitivity of Beta C (Fig. 2c) was also found on other metastable β -alloys such as Ti-10-2-3 or TIMETAL LCB. However, it should be noted that the better known near- α and (α + β) titanium alloys such as Ti-6242 and Ti-6AI-4V most often exhibit anomalous mean stress sensitivities of their HCF strengths.

Figure 3 illustrates the micro-hardness-depth profiles in the various alloys after SP and BB. While not much of a difference in the maximum hardness values close to the surface is found between BB and SP, BB results in much greater depths of plastic deformation. Obviously, the most pronounced difference in the hardness-depth profiles between these three alloys is the degree of hardness increase relative to the bulk hardness (Fig. 3). X5CrNi1810 exhibits the most marked hardness increases after SP and BB (Fig. 3a) followed by 42CrMo4 (Fig. 3b) while on Beta C only very slight hardness increases were observed (Fig. 3c). These results can be correlated with the work hardening capabilities (UTS-YS) of the three alloys amounting to 390MPa in X5CrNi1810, 65MPa in 42CrMo4 and only 10 MPa in Beta C (Table 1). The very marked strain-hardening of X5CrNi1810 is explained by its very low stacking fault energy and in addition, by martensite formation during severe plastic deformation [9, 10]. The very low work-hardening capability observed in Beta C was also reported on other metastable β -alloys and indicates that the deformation-induced dislocation substructure in this alloy class is hardly able to increase the materials resistance to further dislocation motion.



Figure 3. Micro-hardness-depth profiles after SP and BB

The effect of SP and BB on the HCF performance in rotating beam loading of the various alloys is illustrated in Figure 5.



c) Beta C (SHT)

Figure 4. S-N curves in rotating beam loading (R = -1): Effects of SP and BB

As seen, the response of both 42CrMo4 (Fig. 4a) and X5CrNi1810 (Fig. 4b) to SP and BB is beneficial. However, the observed 10⁷ cycles fatigue strength enhancements relative to EP in X5CrNi1810 (Fig. 4b) are much more marked than in 42CrMo4 (Fig. 4a). For example, the 10⁷ cycles fatigue strength of X5CrNi1810 relative to EP increases after SP and BB by as much as 35% and 64% (Fig. 4b), respectively. The HCF enhancements in 42CrMo4 amount to 8% and 25% after SP and BB, respectively (Fig. 4a).

In contrast to the results on both steels, the HCF strength of Beta C is lowered by SP and BB as well (Fig. 4c). The 10⁷ cycles fatigue strength of EP decreases after SP and BB from 400 MPa to 325 MPa (23%) and 250 MPa (60%), respectively (Fig. 4c).

While fatigue cracks in EP always nucleated at the specimen surface independent of stress amplitude and environment, subsurface crack nucleation sites were observed on the fracture surfaces of HCF specimens after SP and BB (Fig. 5).





b) Beta C (BB)

⊢ 200 µm ⊣



Subsurface fatigue crack nucleation due to residual tensile stresses as-induced by SP and BB is more likely in materials with anomalous mean stress sensitivities of the fatigue strength as observed in Ti-6AI-4V [7]. However, the materials investigated in the present study all exhibit normal mean stress sensitivities as seen in Fig. 2. Therefore, the residual tensile stresses in SP and BB are thought to only slightly reduce the fatigue crack nucleation resistance in these subsurface regions. On the other hand, the difference in environmental sensitivity among the various materials can at least partially explain the change in HCF strength after SP and BB. The beneficial effect of vacuum as opposed to an air environment on HCF strength of both 42CrMo4 and X5CrNi1810 (Figs. 2a and 2b) can explain the enhancements in HCF strengths due to SP and BB (Figs. 4a and 4b). In contrast, the environmental insensitivity of the fatigue strength in Beta C (Fig. 2c) in addition to the aforementioned instability of the deformation induced dislocation substructure might contribute to the observed losses in HCF strength after SP and BB (Figs. 4c).

Conclusions

HCF cracks in metallic components after being treated by SP and BB often nucleate subsurface. The presented results indicate that the degree of improvement of the fatigue strength in air by changing the environment from air to vacuum can explain the resistance to subsurface fatigue crack nucleation. If this resistance is high because of a pronounced environmental sensitivity of the materials HCF strength as observed on 42CrMo4 and X5CrNi1810, marked HCF strength enhancements after SP and BB are likely while in case of a low environmental sensitivity of the HCF strength as observed on Beta C even a

deterioration of the HCF strength caused by the process-induced residual tensile stresses can occur.

Acknowledgements

One of the authors (K.Z.) would like to thank the DAAD for supporting his stay at IWW of TU Clausthal with a Long-Term Scholarship for Young Graduates for obtaining a PhD degree.

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