Shot Peening to Enhance Fatigue Strength of TIMETAL LCB for Application as Suspension Springs

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1 Abstract

The titanium alloy Low Cost Beta (TIMETAL LCB) was specifically developed for automotive applications. The combination of high yield stress, low Young's modulus, low density and reasonable material costs makes this alloy most suitable for substituting spring steels for suspension springs. Goal of the present investigation was twofold. Firstly, the material's microstructure was optimized by suitable heat treatments for good yield stress-ductility combinations and best high cycle fatigue (HCF) performance. Secondly, shot peening was applied using various Almen intensities to further improve the fatigue behavior. Fatigue performance of optimum shot peened conditions will be compared with an electropolished reference.

2 Introduction

Besides improvements in engine efficiency, the reduction of vehicle weight by using lightweight 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. While both aluminum and magnesium alloys have been introduced already decades ago into industrial scale manufacture of automobiles, there was for a long time no use of titanium alloys in large volume automobile production due to cost arguments. Recently, a low cost beta titanium alloy (LCB) having the composition Ti-6.8Mo-4.5Fe-1.5Al was developed by TIMET specifically for automobile applications [1, 2]. As opposed to other metastable beta titanium alloys, costly alloying elements such as Cr, Nb and V are omitted. In addition, the formulation cost of this alloy is lowered by adding the Mo in the form of a ferro-molybdenum master alloy. For application as suspension coil spring material and by substitution for spring steels, weight savings in excess of 50 % were anticipated [3].

This investigation was performed to optimize for a given volume fraction of primary á phase the final age-hardening treatment for LCB with regard to tensile properties and HCF performance. As is the case with conventional steel springs, shot peening was then applied to further improve fatigue behavior. The shot peening process was widely varied to establish optimum treatments with regard to HCF performance.

3 Experimental

The LCB material was received from TIMET, Henderson, NV (USA) as 10 mm bar stock. After working above the beta transus temperature followed by working through the transus, the material had been given a solution anneal shortly below the transus at 760°C. Blanks 50 mm in length were cut from the bar stock and were given various aging treatments for 4h at temperatures ranging from 460 to 540°C.

Tensile tests were performed on threaded cylindrical specimens having gage lengths and gage diameters of 20 mm and 4 mm, respectively. The initial strain rate was $8.3 \times 10^{-4} s^{-1}$.

To evaluate cyclic deformation behavior, LCF tests were conducted on threaded cylindrical specimens having gage lengths and gage diameters of 20 and 4 mm, respectively. Axial fatigue tests were performed in fully reversed loading (R = –1) using a servohydraulic tester in stress control at a frequency of $0.1 s^{-1}$. The axial strain was measured by strain gages. From the hysteresis loops, the plastic strain was measured and plotted vs. number of cycles.

HCF tests were done on hour-glass shaped specimens in rotating beam loading (R = –1) at about 60 Hz. An electrolytically polished surface condition was taken as reference. After machining, around 100 μm was removed from the surface by electropolishing to ensure that any machining effect that could mask the results was absent.

Shot peening was performed by means of a direct pressure blast system using cast steel shot S 330 (0.8 mm average shot size) and a wide range of Almen intensities. The distance between the tip of the nozzle and the work piece surface was 50 mm. During the shot peening process, the specimens rotated at $1 s^{-1}$.

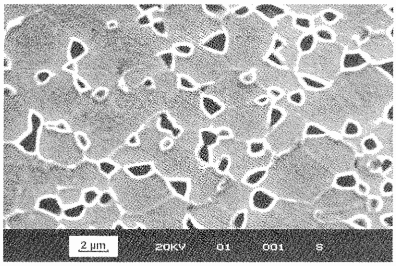
After shot peening, the change in surface layer properties was determined by roughness measurements through profilometry, microhardness profiles and measurements of macroscopic residual stresses through the incremental hole drilling method. The diameter of the drill was 1.7 mm. The oscillating drill was driven by an air turbine with a rotational speed of about 200.000 rpm. The shot peening-induced strains in the surface layer were measured with strain gage rosettes at drilled depths of about every 20 μm. The measured strains were converted into stresses by using an average Young's modulus of 115 GPa.

The fracture surfaces of the fatigue specimens were studied by SEM.

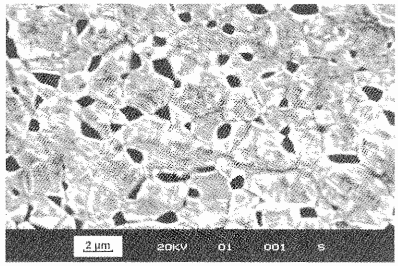
4 Results and Discussion

The microstructure of the as-received bar stock consists of β grains with about 15 % primary α phase. After aging, the resulting SEM microstructures are illustrated in Figure 1 comparing the conditions aged at 460°C (Fig. 1a) and 540°C (Fig. 1b). As seen from Figure 1, the primary α grains are located at the triple points of the β grains. Aging at 540°C (Fig. 1b) leads to a change in the appearance of the β phase owing to coarser secondary α precipitates (compare Fig. 1b with Fig. 1a).

Tensile properties comparing the solution heat treated (as-received condition) with various age-hardened conditions are listed in Table 1.



a) 4h 460°C



b) 4h 540°C

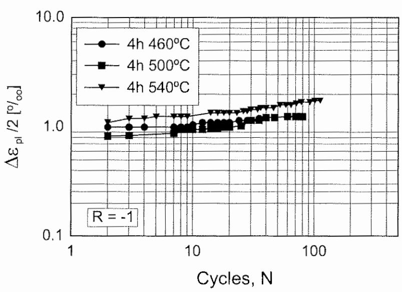
Figure 1: Microstructures of TIMETAL LCB

Table 1: Tensile properties of LCB

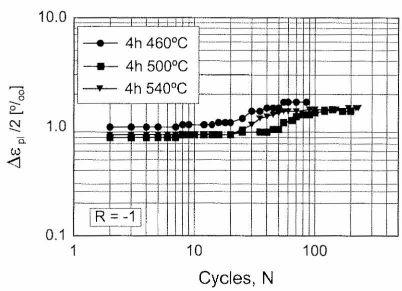
Heat treatment	E [GPa]	$\sigma_{0.2}$ [MPa]	UTS [MPa]	El [%]
as-received	91	1105	1125	18.7
4h 460°C	112	1605	1685	3.5
4h 500°C	114	1445	1540	7.6
4h 540°C	117	1285	1355	11.9

As expected, the Young's modulus is lowest in the solutionized condition and increases with age-hardening. This is due to the contribution of fine secondary α being precipitated within the β matrix which also leads to increases in yield stress und tensile strength. With an increase in aging temperature from 460 to 540°C, these stress values drop while a concomitant increase in elongation to fracture is found (Table 1).

The cyclic deformation behavior of the various age-hardening conditions is illustrated in Figure 2. For both stress amplitudes of 0.9 $\sigma_{0.2}$ (Fig. 2a) and 0.8 $\sigma_{0.2}$ (Fig. 2b), the plastic strain increases with number of cycles, i.e. cyclic softening occurs. This indicates that the microstructure of LCB is cyclically not stable. Such cyclic softening behavior was also observed in other



a) $\sigma_a = 0.9\ \sigma_{0.2}$



b) $\sigma_a = 0.8\ \sigma_{0.2}$

Figure 2: Cyclic deformation (R = –1) behavior of TIMETAL LCB

metastable β titanium alloys, namely Ti-3Al-8V-6Cr-4Mo-4Zr (Beta C) and Ti-10V-2Fe-3Al [4].

The S-N curves of the as-received and various age-hardened conditions are plotted in Figure 3. The lowest HCF strength of about 600 MPa was found for the as-received condition. Although the yield stress or tensile strength values of the age-hardened conditions differ by as much as 330 MPa (Table 1), no significant differences were found in HCF performance. Similar results were reported in work on Beta C, where an upper limit of fatigue strengths (R = -1) was found that apparently could not be exceeded by further increases in yield stress. Presumably, microstructural instabilities during cyclic deformation lead to this limit in fatigue strength of metastable β titanium alloys [5].

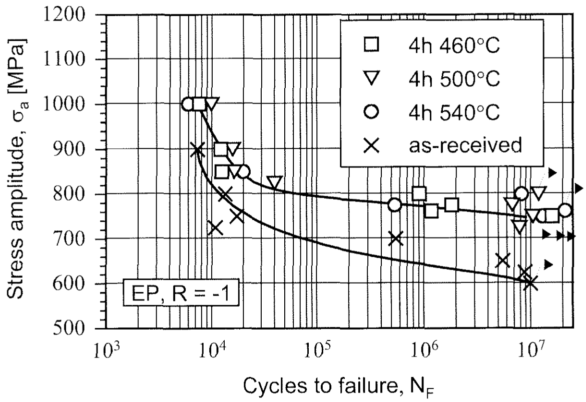
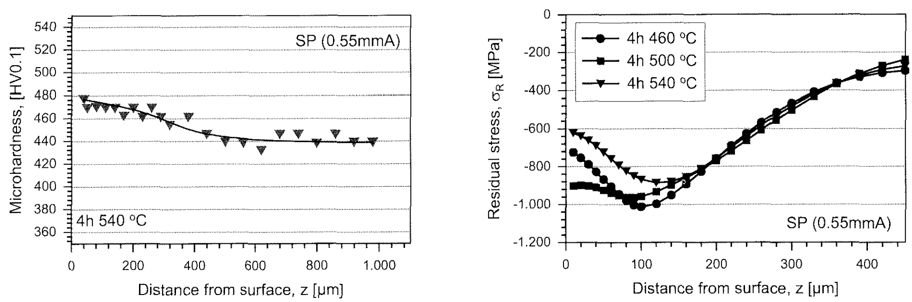


Figure 3: S-N curves (R = -1) of TIMETAL LCB (rotating beam loading in air), electropolished condition (EP)

Shot peening-induced changes of the surface layer properties in LCB are shown in Figure 4. A typical depth profile of microhardness after shot peening is given in Figure 4a. There is only a slight increase in near-surface microhardness, presumably owing to the low work-hardening capacity in LCB (Table 1). The residual macrostresses for the various aging conditions after peening to 0.55 mmA are illustrated in Figure 4b. For the various conditions, there are marked



a) Microhardness-depth profile

b) Residual stress profile

Figure 4: Surface layer properties in TIMETAL LCB after shot peening

maxima in residual compressive stresses at depths of roughly 100 to 150 μm below the surface (Fig. 4b).

The effect of Almen intensity on fatigue life at a stress amplitude of σ_a = 900 MPa is illustrated in Figure 5 indicating a saturation in life improvement at intermediate Almen intensities. From these data, an Almen intensity of 0.55 mmA was utilized for further testing.

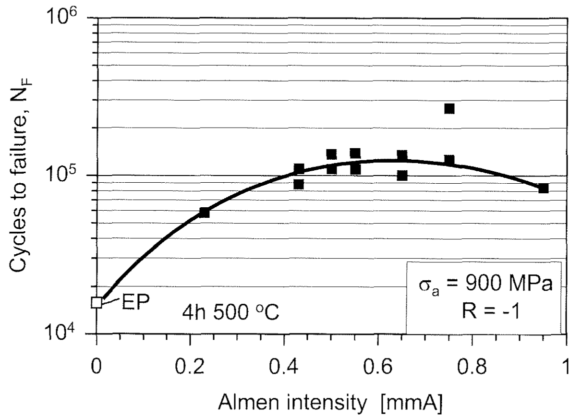


Figure 5: Fatigue life (σ_a = 900 MPa) vs. Almen intensity

S-N curves are shown in Figure 6 comparing optimum shot peened with electrolytically polished conditions for the various aging treatments. As opposed to the electropolished condition (Fig. 3), there is a ranking in fatigue performance after shot peening (Fig. 6) indicating superior HCF life for aging treatments at 500 and 540°C whereas in the finite life regime, aging at 460°C

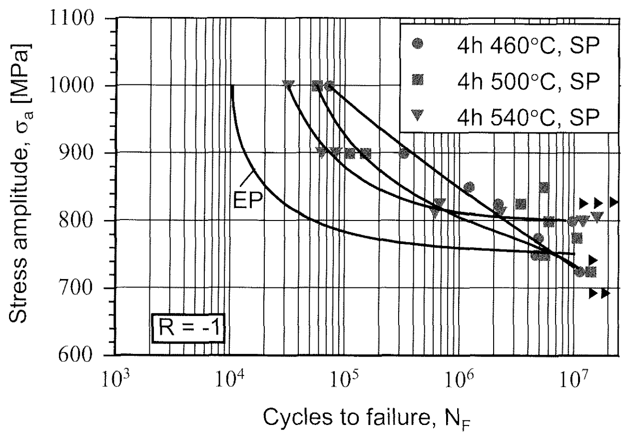


Figure 6: S-N curves (R = –1) of TIMETAL LCB (rotating beam loading in air) comparison of optimum shot peened (SP) with electropolished (EP) conditions

seems to be superior. Since suspension springs in automobiles will see fatigue loading in excess of 10^6 cycles, the overall best performance is given by the condition aged at 540°C.

A typical fatigue fracture surface of shot peened HCF specimens of LCB is shown in Figure 7. Fatigue crack nucleation was found below the surface as often observed in titanium alloys. In case of fatigue crack nucleation below the surface, the fatigue strength in rotating beam loading (bending) is affected by the applied stress gradient, the residual stress profile, the mean stress sensitivity of the material and the material's fatigue strength in vacuum. Further work is needed to understand the comparatively poor fatigue response of LCB to shot peening.

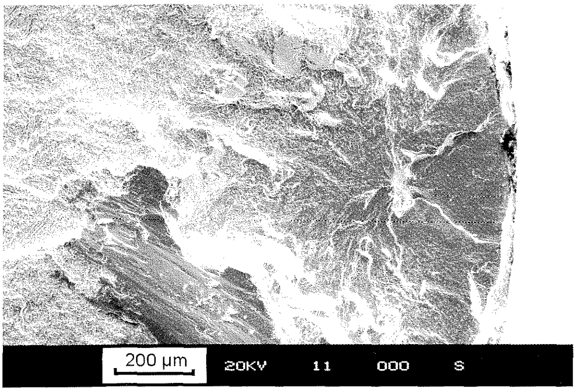


Figure 7: Fatigue fracture surface of a shot peened HCF specimen of TIMETAL LCB

5 Acknowledgements

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6 References

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