EFFECTS OF AGING TREATMENT AND SHOT PEENING VARIABLES ON HCF PERFORMANCE OF TIMETAL LCB

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INTRODUCTION

Metastable beta-titanium alloys are considered as potential candidates for suspension spring materials because of their high specific strength, low elastic modulus and outstanding corrosion resistance. The substitution of conventional spring steels by these alloys can result in a weight reduction of approx. 40% [1, 2, 3]. Because high costs of titanium alloys have hindered so far their wide use in automotive application, the alloy LCB (Low-Cost Beta) was specifically developed to lower the formulation costs through substituting the more costly beta stabilizing elements such as V and Nb through Fe and Mo. To take full advantage of this new alloy, systematic investigations aimed at optimizing the mechanical behavior particularly, fatigue performance are needed.

In the present investigation, we will focus on the effects of aging treatments and shot peening variables, i.e., shot hardness and Almen intensity on the high cycle fatigue (HCF) performance of TIMETAL LCB.

EXPERIMENTAL

The alloy examined in this investigation was received from TIMET, Henderson, NV (USA) as 14.3mm diameter rod that had been solution heat treated at 760°C for 20 minutes followed by fan air cooling. Its chemical composition as determined by TIMET was (wt. %): 4.5 Fe, 6.6 Mo, 1.5 Al, 0.142 O, balance Ti. In order to achieve an equiaxed microstructure, the material was swaged at 760°C to 10 mm diameter and recrystallization annealed at 760°C for 0.5h (condition RX). Part of this material was tensile pre-strained at room temperature to about 10 % (condition RX+PS) to simulate the plastic strain that will occur during cold winding of a coil spring in production. Both conditions RX as well as RX+PS were exposed to aging at 500°C for either 0.5h or 4h [4, 5].

Tensile tests were performed on threaded cylindrical specimens having a gage length and gage diameter of 25 and 5 mm, respectively. The initial strain rate was 10^{-3} s^{-1}. Tensile properties of the various conditions are listed in Table 1.

Table 1: Tensile properties of TIMETAL LCB

Condition	E [GPa]	$\sigma_{0.2}$ [MPa]	UTS [MPa]	σ_F [MPa]	e_u [%]	El [%]	RA [%]	$\varepsilon_F = \ln A_0/A_F$
RX	81	1105	1115	1680	10.1	19.4	53.2	0.76
RX+0.5h 500°C	106	1475	1565	1815	3.6	7.6	20.7	0.24
RX+4h 500°C	113	1430	1500	1850	5.3	10.0	30.6	0.35
RX+PS	84	1270	1275	1720	0.2	9.5	50.0	0.69
RX+PS+0.5h 500°C	110	1665	1725	1860	3.0	3.3	7.8	0.08
RX+PS+ 4h 500°C	121	1275	1390	1530	5.0	8.5	16.0	0.18

HCF tests were performed on hour-glass shaped specimens (minimum diameter 3.0 mm) in rotating beam loading (R = -1) at frequencies of 50 Hz in air.

Shot peening was done using either spherically conditioned cut wire of a quenched and tempered steel having a hardness of 800 HV and an average shot size of 0.6 mm (C92D) or cast steel having a much lower hardness of 460 HV and an average shot size of 0.8 mm (S330). Shot peening was performed using Almen intensities of 0.15, 0.27 and 0.55 mmA. All specimens were peened to full coverage. In addition, some specimens were roller-burnished using a hydraulically driven hard metal ball having a 6 mm diameter (HG6) and a rolling force of 550 N, being based on a previous study [6, 7]. Finally, specimens were electrolytically polished to serve as reference. After machining and mechanically pre-polishing, about 100 μm were removed from the surface to ensure that any machining effect that could mask the results was absent. The various surface conditions are summarized in Table 2.

Table 2: *Surface conditions tested*

EP	electrolytically polished
SP1	shot peened (C92D, 0.55 mmA)
SP2	shot peened (S330, 0.55 mmA)
SP3	shot peened (S330, 0.27 mmA)
SP4	shot peened (S330, 0.15 mmA)
RB	roller-burnished (HG6, 550 N)

After applying the various mechanical surface treatments, the changes in surface layer properties were evaluated by microhardness-depth and residual stress-depth profiles, the latter determined by the incremental hole drilling technique as described elsewhere [8]. Following fatigue failure, fracture surfaces were examined by SEM.

RESULTS AND DISCUSSION

The microstructure of TIMETAL LCB after swaging and recrystallization is illustrated in Fig. 1. It consists of fine equiaxed primary alpha phase in a beta matrix.

As shown in Table 1, pre-straining without subsequent aging led to a slight increase in strength, the low level of increase being associated with the typical low work-hardening capability of metastable beta titanium alloys. However, pre-straining followed by aging at 500°C for 0.5h resulted in yield stress and ultimate tensile strengths markedly higher than those of material aged without pre-strain. While an increase in aging time from 0.5 to 4 hours at 500°C only slightly decreased strength values of material with no pre-strain, the same increase in aging time led to a drastic loss of the strength values and a concomitant pronounced increase in ductility of pre-strained material (Table 1) This effect of pre-strain on the kinetics of alpha precipitation is consistent with prior efforts on other metastable beta alloys [9, 10].

Selected examples of shot peening-induced changes in surface layer properties of the various conditions of TIMETAL LCB are illustrated in Fig. 2 and Fig. 3.

Fig. 2 illustrates a typical microhardness-depth profile after shot peening. There is only a slight hardness increase in the shot-peening affected surface layer, this response corresponding to the low work-hardening capability of the condition RX+PS+0.5h 500°C (see Table 1).

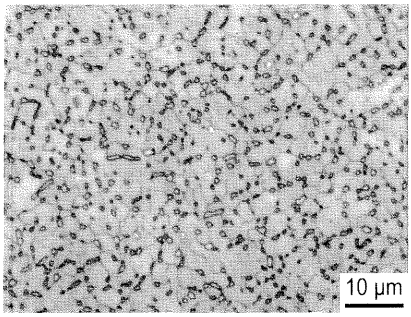


Fig. 1: Microstructure of swaged and recrystallized TIMETAL LCB

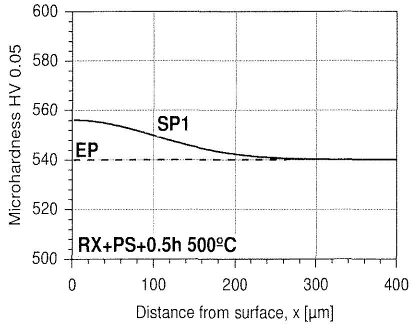
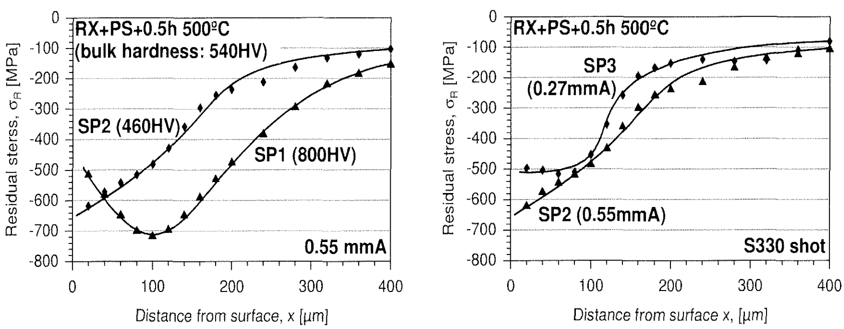


Fig. 2: Microhardness-depth profile in condition RX+PS+0.5h 500°C after SP1

The shot peening-induced residual stress-depth profiles are shown in Fig. 3 illustrating the effects of shot hardness (Fig. 3a) and Almen intensity (Fig. 3b).



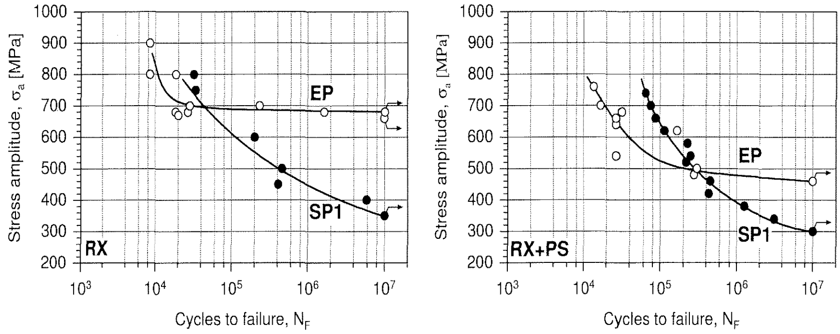
a) Influence of shot hardness

b) Influence of Almen intensity

Fig. 3: Residual stress-depth profiles in shot peened condition RX+PS+0.5h 500°C

Despite the fact that the Almen intensity in shot peening with C92D and S330 was kept constant, the depth-profiles of the induced residual stresses look quite different. Shot peening with C92D leads to a pronounced residual stress maximum below the surface and a greater depth of penetration presumably, owing to its hardness level being much higher than that of S330 (Fig. 3a). Note that the hardness of S330 (460HV) is significantly lower than the bulk hardness of the condition RX+PS+0.5h 500°C (540HV). For a given shot material, the change in Almen intensity from 0.27 to 0.55 mmA results in expected variations in the residual stress-depth profiles (Fig. 3b).

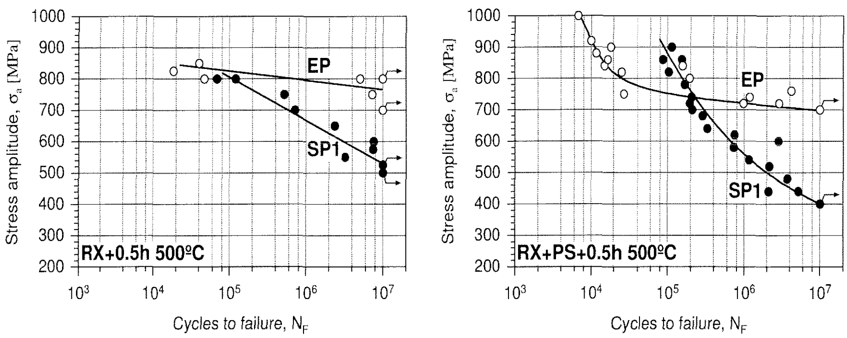
The S-N curves of the un-aged conditions RX and RX+PS are illustrated in Fig. 4. The use of the high strength shot material C92D and the high Almen intensity of 0.55 mmA results in a dramatic loss of the 10^7 cycles fatigue strength as compared to the electropolished reference conditions that amounts to as much as 330 MPa for material without pre-strain (Fig. 4a) and 175 MPa for pre-strained material (Fig. 4b).



a) no pre-strain b) pre-strained

Fig. 4: S-N curves in rotating beam loading (R = -1), effect of SP1 (un-aged conditions)

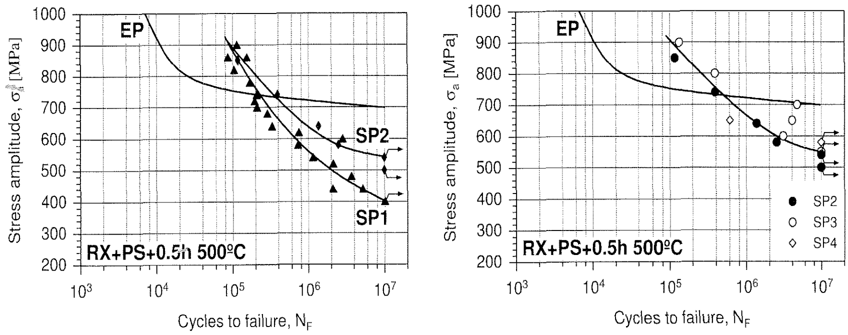
The S-N curves of the aged conditions RX+0.5h 500°C and RX+PS+0.5h 500°C are illustrated in Fig. 5. Very similar to the results on un-aged material, the 10^7 cycles fatigue strengths are markedly lowered by shot peening. This drop in HCF strength amounts to 210 MPa in case of material without pre-strain (Fig. 5a) and 300 MPa in case of pre-strained material (Fig. 5b) if compared to the electropolished references.



a) no pre-strain b) pre-strained

Fig. 5: S-N curves in rotating beam loading (R = -1), effect of SP1 (aged conditions)

The influences of a variation in shot material and Almen intensity on the S-N curves of the condition RX+PS+0.5h 500°C are shown in Fig. 6. Peening with the comparatively soft shot S330 leads to an improvement of the 10^7 cycles fatigue strength of about 150 MPa relative to peening with the much harder shot C92D (Fig. 6a). However, there is still a loss of about 150 MPa in HCF strength relative to the electropolished reference. As illustrated in Fig. 6b, no significant further changes in HCF performance could be observed in case of peening with S330 even if the Almen intensity was reduced from 0.55 to 0.27 and 0.15 mmA.



a) Effect of shot hardness b) Effect of Almen intensity

Fig. 6: S-N curves in rotating beam loading (R = -1), effects of various shot peening treatments (pre-strained and aged condition)

The fatigue performance after roller-burnishing (RB) is shown in Fig. 7.

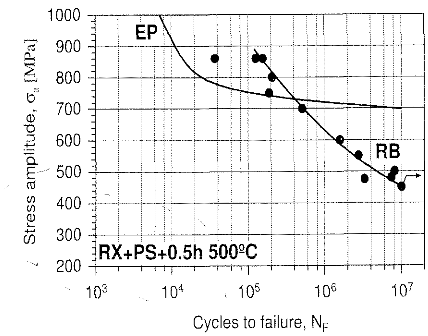
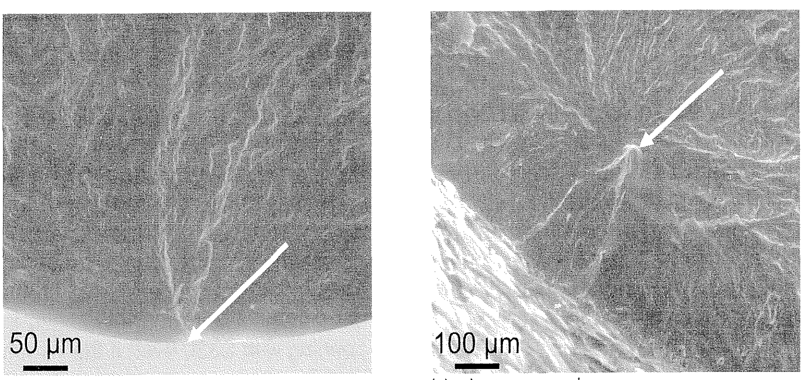


Fig. 7: S-N curves in rotating beam loading (R = -1), effect of roller-burnishing (pre-strained and aged condition)



a) electrollyticaly polished b) shot peened

Fig. 8: Fatigue fracture surfaces of failed specimens (crack nucleation sites are indicated by an arrow)

Interestingly, roller-burnishing led to a drop in HCF strength very similar to that after shot peening (compare Fig. 7 with Fig. 6). The loss in HCF strength relative to the electropolished baseline amounts to 250 MPa (Fig. 7). As opposed to the electropolished reference which exhibited fatigue crack nucleation at the surface (Fig. 8a), all shot peened and roller-burnished specimens failed by subsurface fatigue crack nucleation irrespective of shot hardness and Almen intensity. An example of subsurface crack nucleation in a shot peened specimen is illustrated in Fig. 8b.

Presumably, residual tensile stresses which balance the outer compressive stresses are the reason for the observed losses in HCF strength. On the other hand, subsurface (quasi-vacuum) fatigue crack nucleation is quite a common feature in shot peened or roller-burnished specimens failed in the HCF regime [11]. However, such a pronounced loss in HCF strength as observed in this investigation has not been reported to date to the authors' knowledge. It is thought that this pronounced loss in fatigue strength of shot peened or roller-burnished TIMETAL LCB is caused by the low environmental sensitivity of its fatigue strength [5].

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REFERENCES

[1] A. Sherman and S. Seagle, "Torsional Properties and Performance of Beta Titanium Alloy Automotive Suspension Springs" in: Beta Titanium Alloys in the 1980's (eds.: R. R. Boyer and H. Rosenberg), p. 281, TMS, Warrendale (1984).
[2] P. J. Bania, in: Beta Titanium Alloys in the 1990's (eds.: D. Eylon, R. R. Boyer, D. A. Koss), p. 3, TMS, Warrandale (1993).
[3] C. Sommer and D. Peacock, in Titanium '95; Science and Technology (eds.: P. A. Blenkinsop, W. J. Evans, H. M. Flower), p. 1836, The University Press, Cambridge (1996).
[4] M. Kocan, T. Ludian, M. Ishii, H. J. Rack and L. Wagner, "Optimization of Microstructure of TIMETAL LCB for Application as Suspension Springs", in: Light Materials for Transportation Systems (eds.: W. E. Frazier, Y. D. Han, N. J. Kim, E. W. Lee) CAAM (2004), 417.
[5] M. Kocan, H. J. Rack, L. Wagner, "Fatigue Performance of Metastable Beta Titanium Alloys: Effects of Microstructure and Surface Finish" in: Beta Titanium Alloys in the 2000's (eds.: R. R. Boyer, R. F. Denkenberger, J. Fanning, H. J. Rack), TMS (2005), in press.
[6] J. Kiese, J. Zhang, O. Schauerte and L. Wagner, „Shot Peening to Enhance Fatigue Strength of TIMETAL LCB for Application as Suspension Springs" in: Shot Peening (ed.: L. Wagner) Wiley-VCH, Weinheim (2003) 374.
[7] A. Boettcher, Diploma-thesis, Clausthal University of Technology (2005)
[8] T. Schwarz, H. Kockelmann, VDI Report 940 (1992), 99.
[9] H. J. Rack, T. Headley, Met. Trans., Vol. 10A, 909 (1979).
[10] S. Azimzadeh, H. J. Rack, Met. Trans., Vol. 29A, 2455 (1998).
[11] T. Doerr, L. Wagner, "Fatigue Behavior of Shot Peened TIMETAL 1100: Effects of Microstructure and Stress Gradient" in: Surface Performance of Titanium (eds.: J. K. Gregory, H. J. Rack, D. Eylon), TMS (1997), 231.