EFFECT OF PRIOR COLD WORK ON FATIGUE PERFORMANCE OF SHOT PEENED TI-2.5CU

2005/06

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INTRODUCTION

Ti-2.5Cu is an age-hardenable α-titanium alloy commonly used at ambient and slightly elevated temperatures up to 350°C. High strengths are achieved by solution heat treating at 805°C followed by a two-step aging treatment of 400°C for 8h + 475°C for 8h. These aging cycle leads to the formation of finely dispersed Ti_2Cu precipitates in the α-matrix [1]. As often observed in age-hardenable alloys, cold working prior to aging results in improved strength values. Since Ti-2.5Cu in the solution heat treated condition is capable of undergoing considerable cold deformation without cracking, any forming operation is normally carried out prior to aging [2]. Forming operations (e.g., bending) which result in gradients of plastic deformation will after the aging treatment lead to a graded material with highest strengths at locations where the prior deformation was at maximum. Because fatigue performance of Ti-2.5Cu is a major issue in aircraft application [3], the effect of shot peening on potential fatigue strength improvements was studied on materials with various degrees of prior plastic deformation.

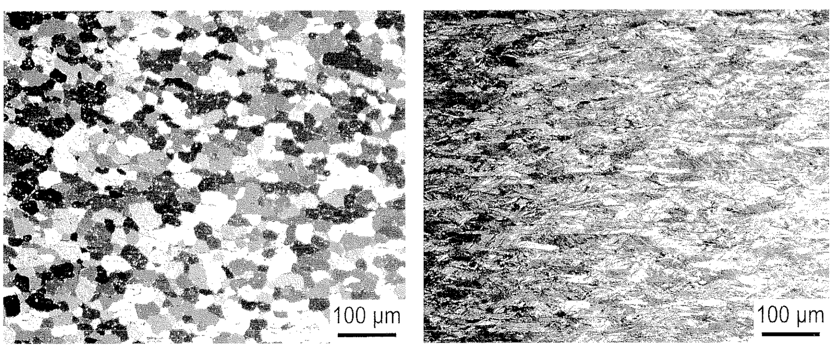
EXPERIMENTAL

The Ti-2.5Cu alloy was received as 10.5 mm thick hot rolled plate. From this plate, 40 x 100 mm blanks were cut with the long axis perpendicular to the rolling direction (RD). The conventional equiaxed microstructure was achieved by solution heat treating the material at 805°C followed by water-quenching (condition SHT). Part of this material was given a two-step aging treatment at 400°C for 8h + 475°C for 8h (condition A). Another part was unidirectionally cold rolled perpendicular to the rolling direction to deformation degrees of 2.5, 10, 20, 30 and 40% before aging (conditions CW + A). All specimen blanks were taken with the load axis parallel to the original rolling direction.
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 $\dot{\varepsilon}$ = $8{,}3 \times 10^{-4}$ s^{-1}.
Shot peening was performed by means of a direct pressure blast system using spherically conditioned cut wire with an average shot size of 0,36 mm (SCCW14). During peening, the specimens rotated at 0.5 s^{-1}. The peening distance between nozzle and specimen surface was kept at 90 mm. Specimens were peened to full coverage at Almen intensities ranging from 0.05 to 0.60 mmA.
The shot peening-induced changes in surface layer properties were characterized by microhardness-depth profiles and residual stress-depth profiles. Residual stresses were measured by the incremental hole drilling technique using an oscillating drill with a 1.7 mm diameter 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 residual stresses at each depth were calculated from the measured strain gage response using the macroscopic Young's moduli for the various conditions.
High cycle fatigue (HCF) tests were performed on hour-glass shaped specimens with a gage diameter of 3.1 mm in rotating beam loading (R = -1) in air at a frequency of about 50 Hz. Electrolytically polished specimens were taken as reference. Roughly 100 µm were removed from the as-machined and mechanically pre-polished surface to ensure that any machining effect that could mask the results was absent.
Fatigue fracture surfaces of failed specimens were studied by SEM.

RESULTS AND DISCUSSION

Examples of the optical microstructures of the Ti-2.5Cu alloy in the various conditions are illustrated in Fig. 1.



a) Condition A (RD →)   b) Condition 40% CW + A (RD →)

Fig. 1: Microstructures of Ti-2.5Cu

The conventional equiaxed microstructure (Fig. 1a) consists of α-grains slightly elongated in rolling direction (RD). After 40 % cold work, the α-grains are much more elongated and appear as pancakes (Fig. 1b).
The tensile properties of the various aging conditions are listed in Table 1.

Table 1: Tensile properties of Ti-2.5Cu

Condition	**E (GPa)**	$\sigma_{0.2}$ **(MPa)**	**UTS (MPa)**	**UTS - $\sigma_{0.2}$ (MPa)**	e_u **(%)**	**El (%)**	**RA (%)**	ε_F $=\ln(A_0/A_F)$
SHT	105	510	615	105	15.8	27.6	50.6	0.71
A	110	670	740	70	6.8	14.2	44.0	0.59
2,5%CW+A	115	730	780	50	7.1	16.4	42.5	0.56
10%CW+A	111	760	790	30	2.7	7.2	45.5	0.61
20%CW+A	114	765	805	40	4.1	9.9	50.0	0.69
30%CW+A	109	770	805	35	3.8	9.7	47.0	0.64
40%CW+A	109	750	780	30	3.7	9.6	47.0	0.64

As seen in table 1, the conventional two-step aging increases the yield stress ($\sigma_{0.2}$) and tensile strength (UTS) of the SHT condition by as much as 160 and 135 MPa, respectively. Further increases were observed on material being cold worked prior to aging as already reported in [4]. The dependencies of $\sigma_{0.2}$, UTS, uniform strain (e_u) and tensile elongation (El) on the amount of prior cold work is illustrated in Fig. 2. Both $\sigma_{0.2}$ and UTS first increase with the amount of prior cold work and then saturate at about 10% cold work. Accordingly, e_u and El decrease as the amount of prior cold work increases and then saturate at similar percentages of cold work.

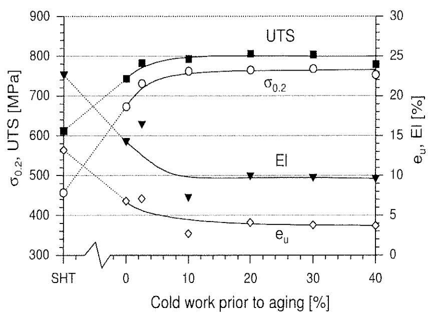
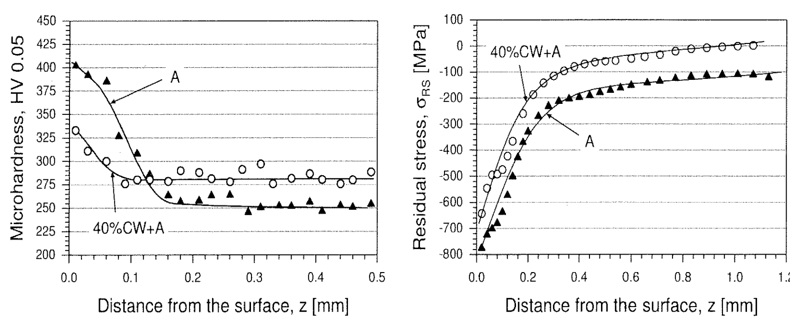


Fig. 2: Tensile properties vs. amount of cold work prior to aging

Examples of the changes in shot peening-induced surface layer properties of characteristic aging conditions are illustrated in Fig. 3.



a) Microhardness-depth profiles b) Residual stress-depth profiles

Fig. 3: Surface layer properties after shot peening (0.20 mmA)

Interestingly, condition A not only shows much higher near-surface hardness values after shot peening than condition 40% CW + A (Fig. 3a) but also significantly higher residual compressive stresses (Fig. 3b) [5]. It is argued that both can be related to the work-hardening capability (UTS - $\sigma_{0.2}$) being much higher in condition A as compared to condition 40% CW + A (see table 1) as also pointed out in [6].
The fatigue life of the shot peened condition A at a stress amplitude of σ_a = 575 MPa is shown vs. Almen intensity in Fig. 4. In addition, the fatigue life of the electropolished baseline (EP) is also plotted. Starting with EP, the fatigue life after shot peening (SP) first strongly increases with an increase in Almen intensity

up to 2 orders of magnitude and then reaches a saturation value already at low intensities. No over-peening effect was observed even at very high intensities (Fig. 4). From these results, a fixed Almen intensity of 0.20 mmA was taken for further fatigue testing.

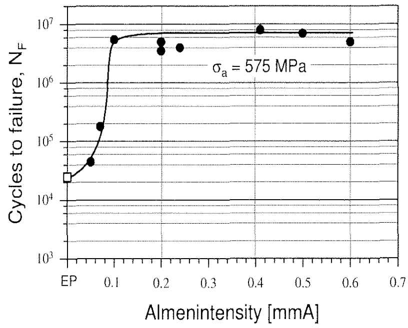
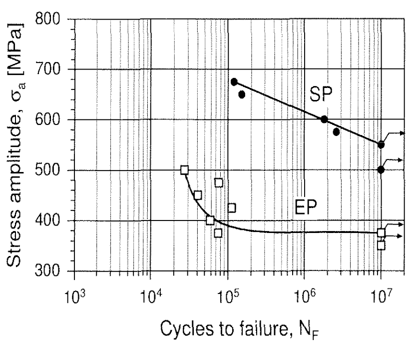
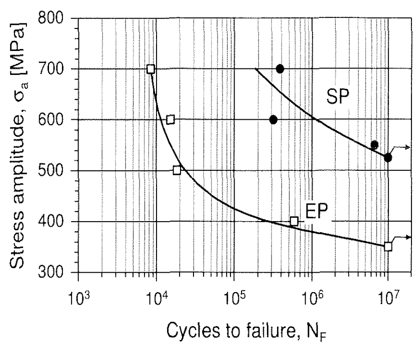


Fig. 4: Fatigue life (σ_a = 575 MPa) vs. Almen intensity in Ti-2.5Cu (condition A)

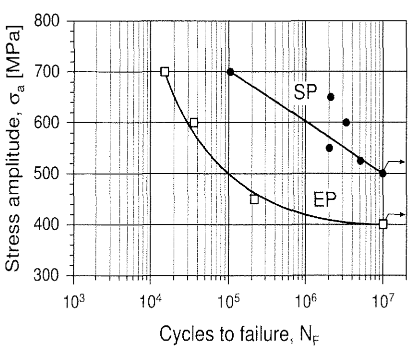
The S-N curves of the various aging conditions of Ti-2.5Cu are illustrated in Fig. 5 comparing in each case conditions EP and SP.



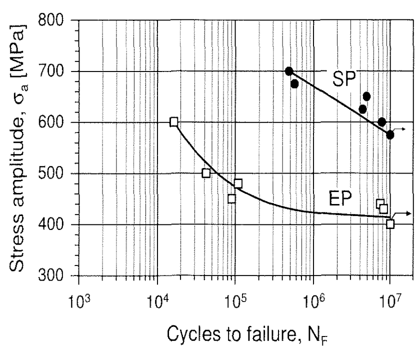
a) Condition SHT



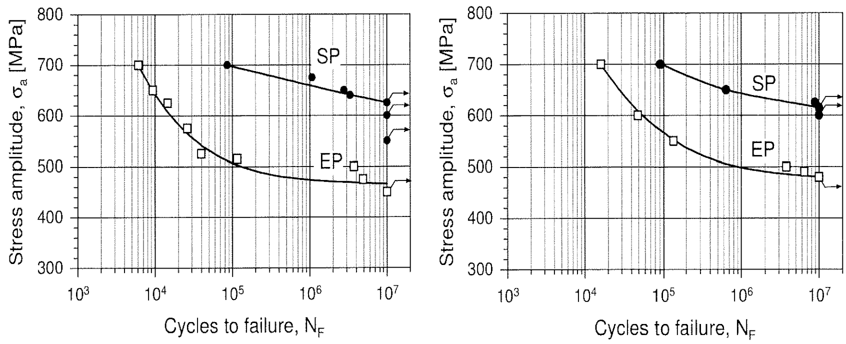
b) Condition 2.5% CW + A



c) Condition 10% CW + A



d) Condition 20% CW + A



e) Condition 30% CW + A f) Condition 40% CW + A

Fig. 5: S-N curves of Ti-2.5Cu comparing conditions EP and SP (0.20 mmA)

As seen in Fig. 5, shot peening generally improves the fatigue performance of Ti-2.5Cu. The dependencies of the HCF strengths of the conditions EP and SP after aging on the amount of prior cold work is illustrated in Fig. 6.

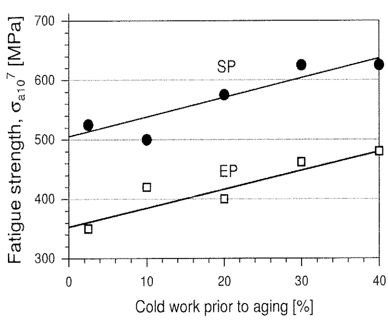


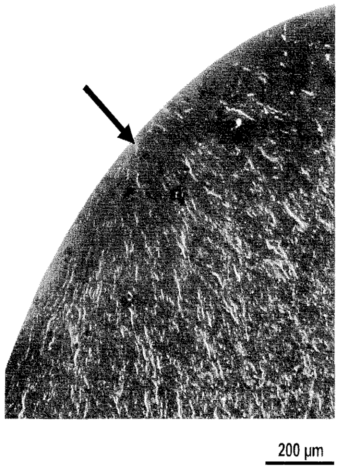
Fig. 6: HCF strengths vs. amount of cold work prior to aging

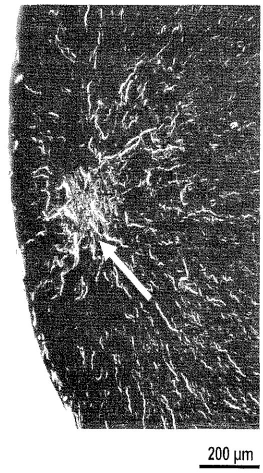
On average, shot peening improves the HCF strengths of Ti-2.5Cu by as much as 150 MPa.

Interestingly, amounts of cold work prior to aging above 10% clearly increase the fatigue strengths of both conditions EP and SP although the quasi-static properties such as $\sigma_{0.2}$ and UTS already saturate at this pre-strain level (compare Fig. 6 with Fig. 2). While specimens of condition EP showed fatigue crack nucleation at the surface independent of stress amplitude, subsurface fatigue crack nucleation was always observed in the HCF regime for conditions SP (Fig. 7).

Comparing surface and subsurface crack nucleation (Fig. 7), an important issue is the difference in environment present at the crack nucleation site [7], being air in case of crack nucleation at the surface (Fig. 7a) and a quasi-vacuum environment in case of subsurface crack nucleation (Fig. 7b).

Since the hexagonal α-phase as opposed to the bcc β-phase tends to locally embrittle by hydrogen from the air environment, the marked shot peening-induced HCF strength improvements observed on shot peened Ti-2.5Cu can be understood.





a) EP: at surface b) SP: subsurface

Fig. 7: Fatigue crack nucleation sites in Ti-2.5Cu

ACKNOWLEDGEMENTS

The authors would like to acknowledge the experimental assistance of their co-workers at the Institute of Materials Science and Engineering at Clausthal University of Technology. Particularly, thanks are due to Tomasz Ludian for shot peening, Peter Koenig for SEM analysis, Dieter Brinkmann for metallography and Oliver Fischer for residual stress measurements.

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