INFLUENCE OF SURFACE CONDITION ON THE FATIGUE STRENGTH OF ISOTHERMALLY FORGED Ti-6Al-4V

Gernot H. Gessinger and Christopher W. Corti*

Brown Boveri Research Center, Baden, Switzerland
*now: Johnson Matthey Research Center, Reading,
England

Introduction

It is well known that the fatigue strength of titanium alloys is influenced not only by the microstructure |1-3| but also by the surface condition of a part made from it |1,4,5|. This latter factor has important consequences for all net-shape forging operations. In net-shape isothermal and hot-die forging much of the surface of the forging will remain in the as-forged, i.e. unmachined, condition. Thus, factors such as surface roughness, contaminated surface layers and residual surface stresses are important.

The present work was undertaken, therefore, to determine the fatigue properties of isothermally forged specimens containing as-forged surface and to determine the effects of various surface treatments on the fatigue strength of such specimens. This latter was considered to be important in view of recent work |6| on the so called 'Forging Skin' effect which indicated that shot-peening leads to a degradation in fatigue strength.

Experimental Procedure

Fatigue testing in the bending mode was considered to be the most suitable, since the highest stresses occur in the surface layers. Thus, surface conditions that lead to a degradation in fatigue strength would play a dominant role, in contrast to tension-compression testing since titanium alloys are susceptible to fatigue crack initiation at internal sources |1,7,8|. Specimens of Ti-6Al-4V bar stock material were isothermally upset forged by 50 % reduction in height at a temperature of 950°C. Specimens were forged using TZM-tooling in an argon atmosphere and using both boron nitride and boric oxide, B_2O_3, as lubricants. From the forged pieces with dimensions 60x20x5 mm fatigue specimens were made with the as-forged surfaces remaining unmachined (Fig. 1). From a second size of forgings with 7 mm thickness 1 mm was machined by milling from each side producing fatigue specimens with machined surfaces of similar surface roughness (R_t= 2-10 µm) to that of the as-forged specimens. Fatigue testing at room temperature was carried out in a fully-instrumented Schenck 25 Hz bending machine at zero mean load to produce fatigue lives in the range 10^4-$2 \cdot 10^6$ cycles.

The test programm was carried out in three stages.

Stage I: Determination of S-N curves for specimens in the as-forged condition and in the as-machined condition.

Stage II: Fatigue life at ± 500 MPa for specimens in (a) the as-forged plus chemically milled condition, (b) the as-forged and shot-peened condition and (c) the as-forged, chemically milled and shot-peened condition.

Stage III: Determination of S-N curves in (a) the as-forged and shot-peened condition, but in this instance, the fatigue specimens were modified to produce a 1 mm radius on the edges of the radiussed gauge length section prior to shot-peening; (b) the as-forged condition, but using B_2O_3 as lubricant.

Additional machined specimens were reheated to 950°C for 10 min with BN lying on the surface prior to machining and were tested at selected stress levels.

Results

Stage I Results: The fatigue results are shown in Fig. 2, in which it is clear that the fatigue curve for the machined specimens lies much higher than that for the specimens with as-forged surfaces. The mean fatigue strength at $2 \cdot 10^6$ cycles by the stair-case method is ± 337 MPa for as-forged surfaces (using boron nitride lubricant) and ± 568 MPa for machined surfaces. Metallographic examination (both optical and scanning electron mircroscopy) showed that fatigue failure in the specimens with as-forged surfaces were initiated at local indentations caused by the forging process. In addition, an 'alpha case' of about 15-18 μm depth was observed, which indicated that oxygen contamination occurred during forging despite a flowing argon atmosphere around the dies. In all specimens examined, a fine equiaxed (alpha plus beta) microstructure was found.

Stage II Results: As-forged specimens were chemically etched to remove the α-case layer in a bath of HNO_3 + HF in the recommended ratio |9| to prevent hydrogen pick-up. Relatively short fatigue lives resulted (Fig. 3), which lay on the curve for the as-forged specimens and suggested that the alpha case was probably not very detrimental. Several fatigue specimens in the as-forged condition were subjected to shot-peening before testing at ± 500 MPa: Four specimens were shot-peened with steel balls (conditions are given in Table 1). A further two specimens were chemically etched before shot-peening with steel balls and yet another two were chemically etched and shot-peened with glass balls. The fatigue results, Fig. 3, show an improvement in fatigue lives compared to the as-forged specimens and the chemically milled specimens, but there is considerable scatter. The longest life was achieved with a specimen that had been etched and peened with glass balls (unbroken at $2 \cdot 10^6$ cycles), which suggests that perhaps glass-bead peening is better than steel-ball peening. Fractographic examination showed that in all cases, shot-peening led to material flow at the edge of the specimen, resulting in a 'peened-over' edge which was the origin of the fracture. This suggested that elimination of this peened-over edge should result in improved lives and less scatter.

Table 1 Shot-peening conditions

		Almen intensity	Gas pressure (atm)	Ball size (mm)	Coverage (%)	
Steel balls:	Dry	A 0,2	5,2	0,4	200	Automatic
Glass beads:	Wet	N 0,25	4	0,18-0,3	200	By hand for 30 sec

Stage III Results: The modified edge radius on as-forged and shot-peened specimens leads to considerable improvement of fatigue strength (Fig. 4), especially at longer lives (increase of 50 MPa) over machined specimens. The mean fatigue strength at $2 \cdot 10^6$ cycles by the stair-case method is ± 608 MPa for the as-forged and shot-peened (with glass beads) surface and ± 316 MPa for the as-forged surface (using boric oxide lubricant). Fig. 4 also shows that B_2O_3 lubricant, which fluxes away any oxide, and heating at 950°C of machined surfaces in the presence of BN, give the same results as from BN lubricant specimens.

Discussion

The lower fatigue strength of isothermally forged Ti-6Al-4V specimens compared to machined ones could be explained by the so-called 'Forging Skin' effect. We would, however, like to suggest that there is no (or, at best, little) forging skin effect as such but rather there is an effect of working the surface mechanically which causes an improvement in fatigue strength.

The low fatigue strength in the as-forged condition occurs irrespective of whether boron nitride (solid) or boric oxide (molten glas) is used as a forging lubricant. The specimens that were machined (thereby removing any mechanical defects arising from forging) and reannealed in the presence of boron nitride also show similar (possibly slightly better) properties (the surface working effect of machining is annealed out); additionally the chemically etched specimens tested at ± 500 MPa show fatigue lives which fall on the curves for the as-forged condition. Thus, degradation of fatigue properties due to chemical, physical or mechanical surface effects arising from the forging process can be ruled out. The fatigue properties can be considered to be the inherent (or slightly lower than the) properties of annealed Ti-6Al-4V at this surface roughness level. Removal of the alpha case layer by chemical milling did not improve fatigue life and also it was not apparently detrimental when the surface was shot-peened. According to a review on surface effects |4| there is no conclusive data in the literature to support or disagree with this conclusion although recent work |10| suggests a degradation by an oxygen-enriched layer, but not when the surface is shot-peened. It is tentatively suggested in |4| that the lower strength of the chemically milled specimens could be due to hydrogen pick-up, but in the light of the present knowledge of surface-working effects, this explanation does not seem probable.

Shot-peening is a widely-used technique, not only for titanium alloys, for improving the fatigue lives of components. The peening process induces compressive stresses in the surface layers. It is argued |4| that these compressive stresses act mainly to reduce crack propagation rather than initiation (on smooth surfaces), but where surface defects cause premature initiation, as is often the case for titanium alloys, then peening must also inhibit crack initiation. Some surface roughening occurs during peening which may, in extreme cases, have a damaging effect on fatigue |4|. In the case of titanium alloys, glass bead peening is preferred to steel shot (balls) since iron contamination of the surface can lead to corrosion problems. In a recent paper, Leverant |5| showed that the sharpness of machining grooves, more than their depth, controls the fatigue resistance. Surface residual stresses are subject to decay resulting from cyclic shake down at both room and elevated temperatures. A compressive stress of 820 MPa at a depth of 40 µm was measured. Other data |4| show that the peening intensity (Almen N 0.01-0.02) has little influence on this stress which is in agreement with the prediction that the maximum value will approach the 0.1 % proof stress, and the depth ca. 1/4 - 1/2 the ball diameter. Other studies |10-14| have also shown that shot-peening improves fatigue life of Ti-6Al-4V alloy. In the work at IMI, they showed that in push-pull fatigue testing, fracture originated subsurface, due to the tensile residual stress in the regions below the compressively-stressed surface layer. Beck, quoted in |4|, showed that compared to polished, lathe turned or ground surfaces, shot-peening slightly reduced the 13^7 cycle fatigue strength although the 13^6 cycle fatigue strength was better. This was attributed to the increased surface roughness resulting from the shot-peening. Chemically milled specimens showed the lowest fatigue strength. The lowering of the fatigue strength by electrochemical milling (compared to machined surfaces) is also reported by Meleka and Flew |13| for several alloy classes; they claim this can be improved by shot-peening. Weisgerber |14| in bending fatigue testing at a stress of ± 590 MPa observed peened-over edges on specimens shot-peened with steel balls (but not on those peened with glass beads). By putting a radius on the specimen edge, as done in the present work, he observed a fatigue life increase over machined (milled) specimens of 10 x for steel ball peening (intensity A 0.2) and only by 40 % or by 60 % for glass bead peening (intensity N 0.16 and N 0.25 respectively). With this background, it is worthwhile to examine the 'Forging Skin' work of Broichhausen and Van Kann |6|. They forged Ti-6Al-4V specimens and either (a) just chemically etched them to remove the surface layer or (b) machined them all over by 1.5 mm depth or (c) chemically milled them all over dy 1.5 mm depth. All three conditions were also tested after shot-peening. The results are consistent with the present work and the literature except for the detrimental influence of shot-peening. This implies that shot-peening was not correctly carried out. The poorer fatigue strength in the flash-line only machined condition is due to the much poorer surface roughness.

Conclusions

The fatigue strength of isothermally forged Ti-6Al-4V specimens at $2 \cdot 10^6$ cycles is much lower when the surface is in the as-forged condition than the fatigue strength of machined specimens. Further, the fatigue strength of as-forged specimens can be improved to the level of the machined specimens by a shot-peening treatment.

The improved fatigue properties of the shot-peened or machined specimens over those of the as-forged specimens is due to compressive surface stresses which inhibit premature crack initiation at the surface.

References

1. C.A. Stubbington: AGARD Conf. *Alloy Design for Fatigue and Fracture Resistance*, (1975), Brussels.
2. N.E. Paten, J.C. Williams, J.C. Chesnutt and A.W. Thompson, ibid.
3. R.J.H. Wanhill: *AGARDS Approach to Fatigue and Fracture Resistance*, NTIS Report N76-24399/7GA (May 1975).
4. D.N. Williams and R.A. Wood: *Effects of Surface Condition on the Mechanical Properties of Titanium and its Alloys*, MCIC-71-01 (August 1971).
5. G.R. Leverant, B.S. Langer, A. Yuen and S.W. Hopkins, Met. Trans. 10A (1979), 251.
6. J. Broichhausen and H. Van Kann: *Forging and Properties of Aerospace Materials* (1978), Chameleon Press, London.
7. C.A. Stubbington and A.W. Bowen, J. Materials Science, 9 (1974), 941.
8. R.K. Steele and A.J. McEvily: *Proceed. 3rd International Conference on Titanium*, Moscow (1976). In press.
9. *Metals Handbook*, 5 (1970), 147. ASM.
10. H. Agne, Ph.D. Dissertation, (1969) University of Stuttgart.
11. E.C. Reed and J.A. Viens, Trans. ASME, 82 (1960), 76.
12. IMI, priv. communication (1977).
13. A.H. Meleka and D.A. Glew, Int. Met. Reviews, No. 221 (1977), 221.
14. D. Weisgerber: Laboratorium für Betriebsfestigkeit, Report S-133, *Review of Investigations in Aeroautical Fatigue in the Federal Republic of Germany*, ICAF Conference (1977).

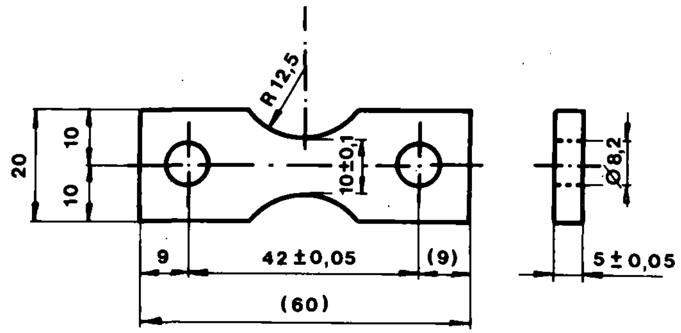

Fig. 1 Geometry of fatigue specimen.

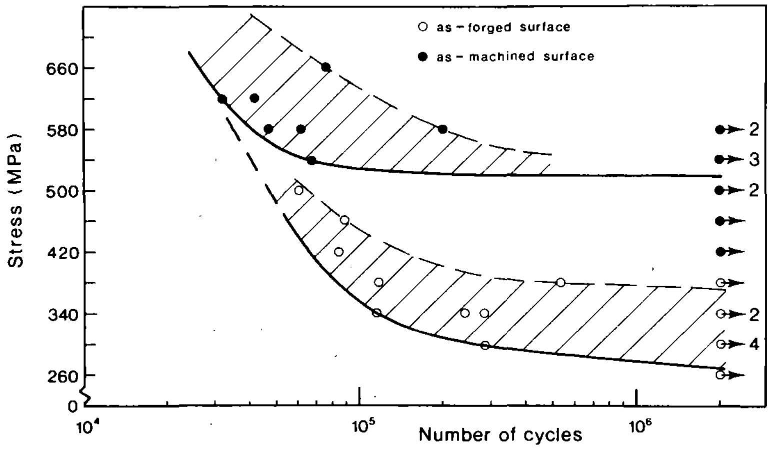

Fig. 2 S-N curves for Ti-6Al-4V specimens in the (I) as-forged condition and (II) the machined condition.

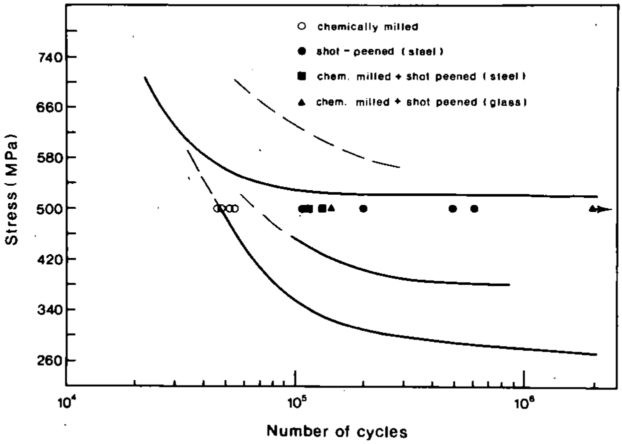

Fig. 3 Fatigue lives of specimens subjected to (I) chemical etching to remove α-case (II) shot peening or (III) chemical etching and shot peening before testing at ± 500 MPa.

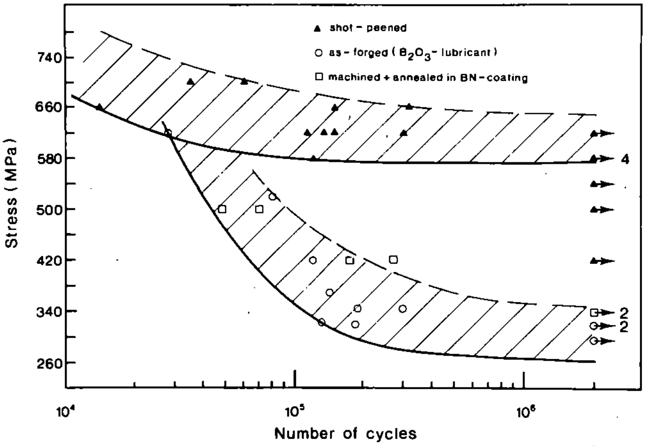

Fig. 4 S-N curves for Ti-6Al-4V specimens in the (I) shot peened condition (II) the as-forged (with boric oxid) condition and the (III) machined and reannealed in the precence of boron nitride condition.