The University Of Sheffield.
Advanced Manufacturing Research Centre
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Subsurface deformation during precision turning of a near-alpha titanium alloy

Precision turning is an energy intensive, yet important machining operation for critical aero-structural titanium alloy parts. High-resolution electron backscatter diffraction reveals an increase in induced subsurface deformation with increasing surface speed, contradicting observations when applying standard surface integrity techniques.

Aims

For this study, near-alpha titanium alloy Timetal®834 (Ti-834) was supplied in the as-forged billet condition from Timet UK. Ti-834 is an advanced aerospace material employed in the compressor sections of gas turbine engines in discs and blades. In order to measure the plastic deformation characteristics during turning, an as-forged condition with coarse alpha grains provides a model microstructure for ease of analysis compared to in-service Ti-834 which has a finer bimodal morphology.

Background

The increasing use of large monolithic titanium alloy components in the next generation of civil aircraft, in conjunction with large order books, has led to a drive for higher production rates. Machining is a costly process and accounts for 60% of the total cost of critical titanium aerospace components, in most part due to approximately 95% of the starting material being removed as swarf. To minimise costs, the advanced manufacturing community is developing techniques to machine titanium products at higher rates. For turning, this equates to higher surface speeds, and thus, higher strain rates at tool/workpiece interfaces. Through the use of finite element modelling, researchers have provided a greater understanding of chip formation mechanics during the machining of titanium alloys. However, a fundamental knowledge gap on the role of machining on the resultant subsurface plastic deformation and microstructure damage still exists. In addition, the influence of machined induced subsurface features on the components in-service performance is of increasing concern to original equipment manufacturers.

Trials

Outer-diameter precision turning trials were performed using a range of cutting surface speeds; 50, 70, 80, 95, 105 and 120 m.min-1, at a constant feed rate of 0.1 mm.rev-1 and depth of cut of 1 mm. Figure 1 shows the stepped Ti-834 as-forged billet after multiple roughing passes, carried out at a surface speed of 20 m.min-1, feed of 0.15 mm.rev-1, and a depth of cut of 1.5 mm. The starting diameters of the stepped cutting faces ranged from 200 mm to 250 mm in 10 mm increments.

Turning was undertaken using a Mori Seiki NT6600 lathe with Sandvik CNMG 120408-23 H13A cutting inserts mounted in a Sandvik C5-DCLNL-35060-12 tool holder providing a clearance angle of 6º and a rake angle of 7º. For each pass, a fresh cutting edge on the insert was used.

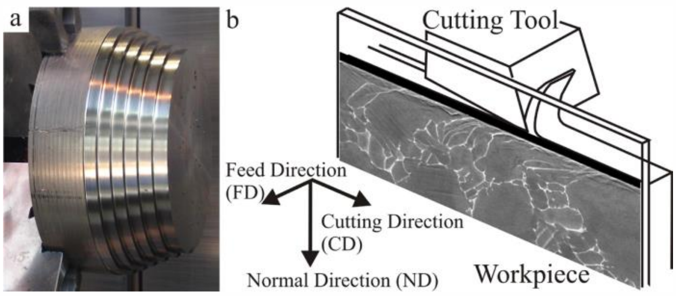

Figure 1 a) Photograph of stepped Ti-834 billet workpiece prior to the outer diameter precision turning trials; b) Schematic illustrating the cutting process and typical subsurface microstructure deformation, sectioned parallel to the cutting direction.

Results

Severe plastic deformation (SPD) was observed within both primary alpha grains and secondary alpha lamellae. Figure 2 shows that as the surface speed is increased, the average SPD depth reduces from 10 µm at 50 m.min-1 to 3 µm at 120 m.min-1, which is in line with observations typical for conventional surface integrity techniques and finite element models.

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The regions shown in figure 2 were further analysed using EBSD. The first observation from figure 3a is that evidence of deformation, both slip and twinning, is observed to much greater depths than defined using electron microscopy. The formation of twins caused by a machining process has never been reported in Ti-834. Features such as mechanical twins and slip bands have been shown to provide sites of crack initiation during cyclic loading. Therefore, for critical service applications, features such as mechanical twinning and intense slip bands can be referred to as damage.

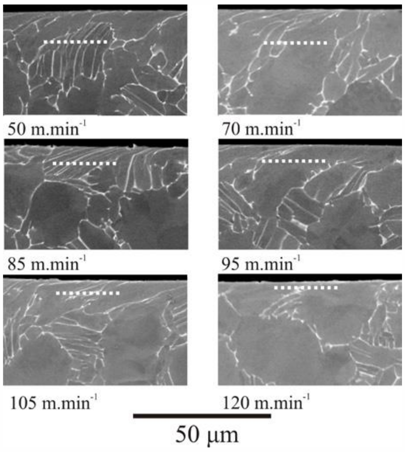

Figure 2 Electron backscatter images of the machined surface with increasing surface speed. The delineated line signifies the interface between the undeformed bulk material and the average depth of deformation assessed using beta

The EBSD data displayed in figure 3a shows an SPD layer of approximately 5 µm to be evident for all surface speeds, due to a region of unindexed data points. Beneath this SPD layer, slip and twinning is evident, even at depths where grains appear undistorted. Figure 3a shows that the average depth to which twinning occurs, increases with speed. At slower surface speeds, intense slip bands appear to be more prevalent, for example at 70 m.min-1 in figure 3a, where slip has been indexed to have occurred along the prism {1010} and first order pyramidal {1011} planes.

The comparative levels of plastic deformation from electron microscopy and EBSD are summarised in figure 3b. EBSD reveals evidence of damage within all grains beneath the SPD layer, and a consistently greater extent of damage to that observed under electron microscopy in figure 2. Both the maximum and average depth of microstructural damage from EBSD follows a similar trend. Figure 3b illustrates that the depth of subsurface damage initially decreases from 50 m.min-1 to a minimum at approximately 70 m.min-1, and then increases up to 120 m.min-1. At the higher surface speed range (>70 m.min-1), the increase in subsurface damage depth corresponds to increasing strain rate. The regions of maximum damage depth are normally contained within a single grain or similarly orientated structural unit (i.e. colony of secondary alpha). The role crystallographic texture plays in determining the mode of deformation sustained is a field of current further work.

The conflicting results shown in figure 3b from electron microscopy and EBSD have implications for; (i) the strategy of increasing surface speeds to improve productivity and; (ii) the effectiveness of current surface integrity analysis methods for determining the nature of deformation for machined titanium alloys.

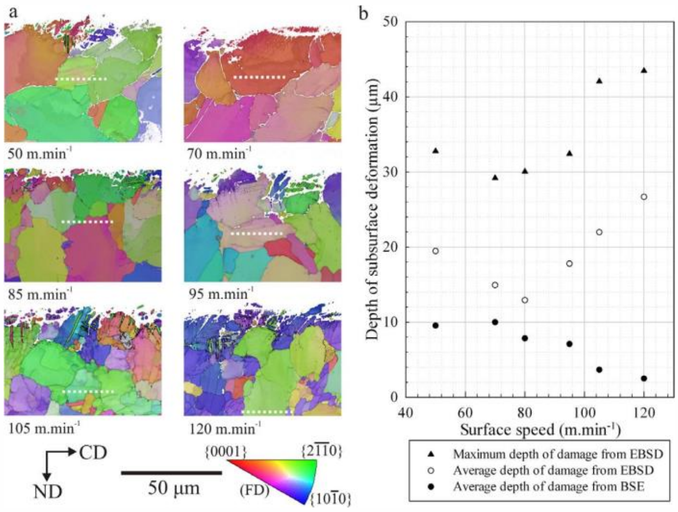

Figure 3 (a) EBSD inverse pole figure (IPF) maps of the machined surface with increasing surface speed. The white delineated line signifies the interface between the undeformed bulk material and the maximum depth of damage. (b) Graph illustrating the effect of surface speed on the depth of surface deformation assessed by measuring beta distortion using backscatter electron images and EBSD.