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Subsurface deformation during precision turning of a near-alpha titanium alloy

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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. Subsurface microstructural damage, such as mechanical twins and intense slip bands, provides nucleation sites for silicide precipitation during thermal exposure at 750 °C, indicating that creep and fatigue strength could be locally reduced at the machined surface.

Keywords: Twinning; Silicides; EBSD; Plastic deformation; Machining

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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 [1], in most part due to approximately 95% of the starting material being removed as swarf [2]. To minimize 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 [3,4]. However, a fundamental knowledge gap in 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. This paper investigates the effects of turning on the subsurface microstructure and subsequent thermal exposure.

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.

Outer-diameter precision turning trials were performed using a range of cutting surface speeds; 50, 70, 80, 95, 105 and 120 $\mathrm{m\,min^{-1}}$, at a constant feed rate of 0.1 $\mathrm{mm\,rev^{-1}}$ and a depth of cut of 1 mm. Figure 1a shows the stepped Ti-834 as-forged billet after multiple roughing passes, carried out at a surface speed of 20 $\mathrm{m\,min^{-1}}$, a feed of 0.15 $\mathrm{mm\,rev^{-1}}$ and a depth of cut of 1.5 mm. The starting diameters of the stepped cutting faces ranged from 200 to 250 mm in 10 mm increments. To allow for the variance in diameter, the width of each cutting face was adjusted to allow for a comparable spiral cut length for each speed, which ranged from 76 to 83 m. Turning was undertaken using a Mori Seiki NT5400 lathe with Sandvik CNMG 120408-23 H13A cutting inserts mounted in a Sandvik C5-DCLNL-35060-12 tool holder, providing a clearance angle of 6° and a rake angle of 7°. Water-based coolant Houghcut 795B at 4–7% concentration was “flood” delivered at 13 $\mathrm{l\,min^{-1}}$. For each pass, a fresh cutting edge on the insert was used.

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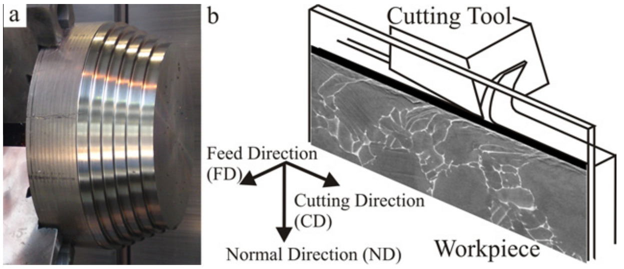

Figure 1. (a) Photograph of stepped Ti-834 billet workpiece prior to the outer diameter precision turning trials; (b) schematic illustrating the cutting process and typical subsurface microstructure deformation, sectioned parallel to the cutting direction.

Following the turning operation, the workpiece was sectioned parallel to the normal direction–cutting direction plane (Fig. 1b) and prepared for metallography using standard methods. Microstructure analysis was carried out using an FEI Sirion field emission gun scanning electron microscope and quantitative crystallographic orientation data was acquired using electron backscatter diffraction (EBSD) with a 20 kV accelerating voltage, a 10 nA probe current and a step size of 0.06 μm. Automated indexing and post-processing of the electron diffraction data were performed using Oxford Instruments HKL Channel 5 software.

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 [5,6] and finite element models [7].

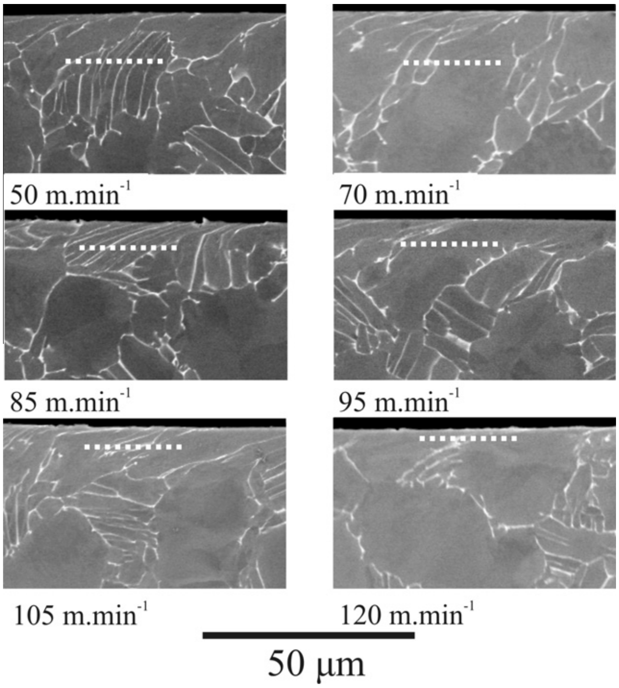

Figure 2. Electron backscatter images of the machined surface with increasing surface speed. The delineated line signifies the interface between the undeformed bulk material and the average depth of deformation assessed using beta distortion at 10 μm intervals across approximately 2000 μm of surface material.

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. However, twin formation has been reported in shot-peened Ti-834 [8]. Features such as mechanical twins and slip bands have been shown to provide sites of crack initiation during cyclic loading [9–12]. Therefore, for critical service applications, features such as mechanical twinning and intense slip bands can be referred to as damage.

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. Furthermore, as the surface speed (and strain rate) is increased, the twins appear to form more frequently and the twin morphology progressively evolves from lenticular to needle-like, in agreement with Chichili et al. [13] and Sun and Wang [14]. 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 $\{10\bar{1}0\}$ and first-order pyramidal $\{10\bar{1}1\}$ planes.

The comparative levels of plastic deformation from electron microscopy and EBSD are summarized 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 depths of microstructural damage from EBSD follow 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}, 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 a similarly orientated structural unit (i.e. a colony of secondary alpha). The role crystallographic texture plays in determining the mode of deformation sustained is the subject of current further work.

An increase in tool wear and galling at slow surface speeds has been previously observed [15]. The degree of surface damage at the slowest surface speed of 50 m min^{-1} is attributed to the formation of a blunt, unstable built-up edge (BUE) ahead of the tool during turning. The unstable BUE induces excessive localized surface damage each time it breaks and is pulled under the leading edge [16]. Therefore, for such tooling/workpiece combinations, turning surface speeds of the order of 70 m min^{-1} are recommended for optimum tool life [17], which correlates with the observed minimum depth of induced microstructure damage. It is important to note that the increase in observed microstructure damage with increasing surface speed cannot exclusively be attributed to the expected increase in sustained strain