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Ultrasonic assisted creep feed grinding of gamma titanium aluminide using conventional and superabrasive wheels

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ABSTRACT

The paper details experimental work on ultrasonic assisted creep feed grinding (UACFG) of γ-TiAl intermetallic alloy: Ti–45Al–2Mn–2Nb + 0.8 vol.%TiB$_2$XD (wt%), using conventional SiC and electroplated diamond wheels. The majority of forces recorded were lower when using vibration assistance compared to conventional CFG by up to $\sim$35%, while grinding-ratios for the superabrasive wheel were substantially higher by a factor of 2–7. A reduction in workpiece surface roughness by up to $\sim$10% together with fewer defects and marginally increased subsurface microhardness by a maximum of $\sim$8%, was obtained when employing ultrasonic assistance. With uprated process parameters however, the effects of UACFG were less apparent.

1. Introduction

Despite the potential for gamma titanium aluminide (γ-TiAl) intermetallic alloys to replace heavier nickel based superalloy components such as turbine and compressor blades in gas turbine aeroengines, few civil or military applications currently exist. Several factors are responsible, not least the lack of a comprehensive material supply base and the requirement for stringent safety standards, but also alloy sensitivity to secondary production/manufacturing methods and associated post processing costs [1]. Key conventional machining operations for blades include high speed milling and grinding, the latter proving less of a problem in terms of machinability and the generation of acceptable workpiece surface integrity, due in part to the low room temperature ductility ($\sim$2%) of many γ-TiAl alloys [2]. While several researchers have shown the feasibility of creep feed grinding (CFG) γ-TiAl, published results highlight the need for reduced operating levels in order to achieve the necessary workpiece integrity, thus compromising productivity [3,4].

The use of ultrasonic (US) vibration (>20 kHz frequency) to aid machining appeared in the late 1920s with the development of US assisted grinding following in the 1950s. A comprehensive review of 'hybrid' machining processes including those associated with vibration/US assistance is detailed by Lauwers et al. [5]. The majority of published work on ultrasonic assisted grinding (UAG) has shown significant reductions in grinding forces and benefits in relation to cutting temperature, together with an improvement in workpiece surface integrity [6]. To date, UAG has largely been applied on some ceramics [7], glass and ferrous based materials [8], with only limited literature involving advanced aerospace alloys. In addition, commercial turn-key equipment is scarce. Work on UAG has mainly been associated with surface grinding configurations with depths of cut typically limited to $\leq$0.3 mm. Relatively few papers have reported hybrid ultrasonic assisted creep feed grinding (UACFG) with depths of cut $\geq$1 mm [9,10]. The present research aimed to investigate the effects of US vibration with regard to grinding productivity, wheel wear, cutting forces and workpiece integrity when CFG a γ-TiAl alloy using conventional and superabrasive wheels.

2. Experimental details

Blocks of Ti–45Al–2Mn–2Nb + 0.8 vol.%TiB$_2$XD (wt%) γ-TiAl alloy (100 × 55 × 7 mm) were used as the workpiece material. This was produced by casting followed by hot isostatic pressing (HIPing) at a temperature of 1480 °C and pressure of 148 MPa for 4 h and subsequently heat treated at a temperature of 1050–1080 °C, for 24 h, giving a bulk hardness of $\sim$365 HV$_{30}$. The material had a nearly fully lamellar structure with parallel plates of γ-TiAl and α_2-Ti$_3$Al, and a colony size of $\sim$100–130 μm, see Fig. 1(a). The workpiece was clamped onto a specially designed aluminium table sonotrode/horn connected to an ultrasonic transducer $\sim$20 kHz

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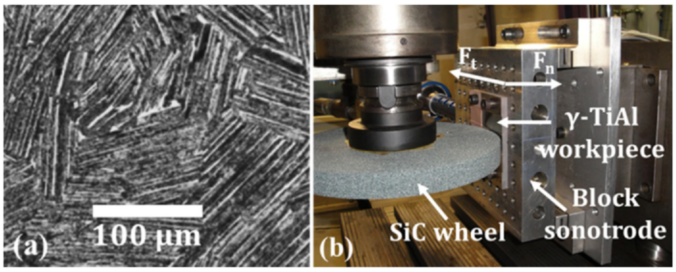

Fig. 1. (a) Microstructure of γ-TiAl; (b) wheel-workpiece-sonotrode assembly and force directions.

starting frequency linked to a multi-frequency, modulated ultrasonic generator rated at 1 kW. The primary direction of ultrasonic vibration was parallel to that of grinding feed (Y-axis). Under zero-load condition, a maximum amplitude of 8 μm was measured using a Laser Doppler Vibrometer.

All grinding trials were carried out on a Bridgeport FGC1000 flexible grinding centre, with a maximum spindle speed of 6000 rpm and power rating of 25 kW. Two high pressure pumping systems were utilised for delivery of grinding fluid via laminar flow nozzles with rectangular cross-sectioned outlets for cooling and cleaning the wheel during grinding [11]. The cooling nozzle orifice (2 × 20 mm) was directed towards the grinding zone at an angle and distance of 20° and 170 mm respectively, while the cleaning nozzle was aimed tangentially at the periphery on the opposite side of the wheel. Fluid pressure for cooling was 28 bar in order to match or exceed wheel velocity. In contrast, fluid pressure for cleaning was kept constant at 70 bar in all trials. The grinding fluid employed was a water based synthetic oil product with a concentration of ~8 vol.%. Plain profile vitrified bonded SiC and unconditioned electroplated (EP) diamond superabrasive wheels were utilised. Both wheels had similar average grit size of ~250 μm with an outer diameter and width of 220 mm and 20 mm respectively. An on-machine configuration of the SiC wheel-workpiece-sonotrode arrangement is shown in Fig. 1(b).

Phase 1 grinding trials involved the SiC wheel and a full factorial experimental array with 8 tests allowing variations in wheel velocity, v_s (15 and 30 m/s), table feed, v_w (150 and 600 mm/min) and ultrasonic vibration assistance (US ON and US OFF). Depth of cut per pass, a_e was fixed at 1 mm with all trials performed in a down grinding mode without spark-out. Wheel dressing was carried out prior to each trial using a diamond roller dresser with a 2 μm/rev infeed rate, 50 μm dressing depth and 0.8 dresser-to-wheel speed ratio. Phase 2 testing involved use of a superabrasive wheel to assess the influence of ultrasonic actuation. An initial series of 4 tests alternating between conventional CFG and UACFG were undertaken at fixed parameters v_s, v_w and a_e of 30 m/s, 150 mm/min and 1 mm respectively. Two additional tests (US ON and US OFF) were subsequently conducted at increased v_s and v_w of 40 m/s and 600 mm/min respectively. Each test in Phases 1 and 2 involved a single pass of the workpiece (55 mm cut length).

Grinding forces F_t and F_n, see Fig. 1(b), were measured using a Kistler 9257A dynamometer. Grinding-ratio was determined by measuring the wheel diameters before and after each test using a coordinate measuring machine. The wheels were assessed at 30 different points around the periphery, each at 5 different levels of the wheel width. Roughness of the ground workpieces (average of 3 measurements at start, middle and end of slot) was recorded using a stylus based profilometer, with 0.8 mm cut-off and 4 mm evaluation length. Wheel surface topography was assessed with a JEOL 6060 SEM by producing positive replicas using a synthetic rubber and resin replicating compound (Microset).

Knoop microhardness depth profile measurements of the γ-TiAl workpieces were taken using a 25 g load and indent time of 15 s. Three measurements were recorded, both in the transverse feed (TF) and longitudinal feed (LF) directions, each set at 10 μm depth intervals. In order to reveal workpiece microstructures, γ-TiAl samples were immersion etched in a solution of 2% hydrofluoric and 10% nitric acid with balance water for 5 s and were analysed using a Leica DMLM optical microscope.

3. Results and discussion

Fig. 2(a)shows that the maximum F_n varied from ~1450 to 2300 N for the vitrified SiC wheel, with values increasing with cutting speed, the data being comparable to that reported by Hood et al. [4] when creep feed grinding γ-TiAl at similar process parameters. Analysis of variance (ANOVA) highlighted v_s as a significant factor at the 5% level with a percentage contribution ratio (PCR) of 83%, which was in line with previous work [4,12]. This was attributed to an increase in the sliding length per unit volume of material removed when grinding at higher v_s, which resulted in greater attritious wear and dulling of the abrasive grits leading to higher rubbing and ploughing. Operation under UACFG generally led to lower F_n, while variation in v_w from 150 to 600 mm/min had minimal influence (based on tabulated data and corresponding main effects plots not shown here). Conversely, mean F_t, decreased with an increase in v_s and use of ultrasonic vibration (statistically significant with PCR of 64.5%). The application of US actuation generally led to reductions in both F_n and F_t by up to 19% and 35% respectively, possibly due to self-sharpening of the abrasive grains. Similar results were also presented by Nik et al. [13] when surface grinding Ti–6Al–4V alloy with a vitrified alumina wheel.

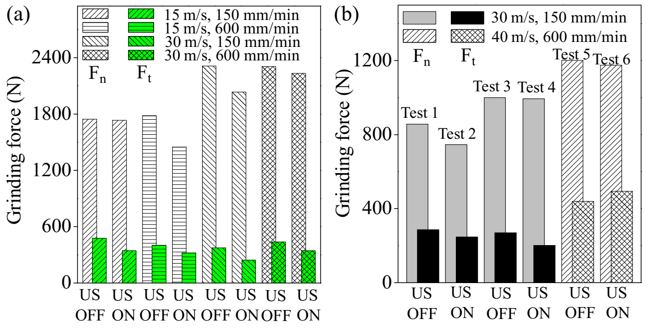

Fig. 2. (a) Grinding forces (F_n, F_t) when grinding with SiC wheel; (b) grinding forces when using the EP diamond wheel.

In CFG tests with the superabrasive wheel (Tests 1, 3 and 5), F_n increased from 857 to 1200 N, the rise of ~150 N occurring between Test 1 and Test 3 due to cumulative wear of the wheel, see Fig. 2(b). A further increase of ~200 N between Tests 3 and 5 was attributed to the elevated operating parameters (40 m/s and 600 mm/min). Despite the 13% reduction in F_n between Tests 1 (US OFF) and 2 (US ON), the application of ultrasonic vibration appeared to have minimal effect in succeeding tests, possibly due to the different dynamic/mass characteristics of the EP diamond wheel (steel hub) compared to the solid SiC wheel structure. Similarly, it is likely that the variation observed in F_t was due to both wheel wear and operating parameter variation rather than application of US assistance. With regard to the latter, Zhang and Zhang [14] reported that there is a critical value of feed rate above which the effect of ultrasonic vibration is diminished.

Fig. 3(a)shows that the G-ratio of the SiC wheel varied from 3.2 to 8. This was similar to results by Hood et al. [4] where G-ratios between 2 to 15 were obtained when CFG a slightly different γ-TiAl alloy of Ti–45Al–8Nb–0.2C wt% using conventional SiC abrasives. Except for trials using the highest operating parameters (30 m/s and 600 mm/min), wheel wear increased (G-ratio reduced) with the rise of both v_s and v_w, while use of UACFG reduced wheel wear. This was most likely due to an increase in attritious wear at a higher cutting speed coupled with larger undeformed chip thickness, h_m at a greater table feed leading to more frictional forces. The increase in G-ratio (~30–75%) when using US

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