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Hood, Richard; Johnson, C.M.; Soo, Sein; Aspinwall, David; Sage, C.

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R. Hood\textsuperscript{a}, C.M. Johnson\textsuperscript{a}, S.L. Soo\textsuperscript{a}, D.K. Aspinwall\textsuperscript{a} & C. Sage\textsuperscript{b}
\textsuperscript{a} Machining Research Group, School of Mechanical Engineering, University of Birmingham, Edgbaston, Birmingham, UK
\textsuperscript{b} Manufacturing Technology, Rolls-Royce plc, UK
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High-speed ball nose end milling of burn-resistant titanium (BuRTi) alloy

R. Hood*a, C.M. Johnsona, S.L. Sooa, D.K. Aspinwalla and C. Sageb

*Machining Research Group, School of Mechanical Engineering, University of Birmingham, Edgbaston, Birmingham, UK; bManufacturing Technology, Rolls-Royce plc, UK

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Following a brief introduction to aero-engine materials and the development of BuRTi alloy (Ti-25V-15Cr-2Al-0.2C), the paper details a statistically designed machinability experiment involving high-speed ball end milling. Testing utilised 8 mm diameter ATiN-coated carbide ball nose end mills in a Taguchi L8 fractional factorial design with six factors, each at two levels. Output measures related to tool life/wear, cutting forces, workpiece surface roughness, microstructure and microhardness. Main effect plots, tabulated ANOVA data, percentage contribution ratio (PCR) values together with graphical and SEM data are presented. Use of the lowest material removal rate, high-pressure (70 bar) cutting fluid and a workpiece orientation of 45° resulted in the longest tool life with a machining time of ~60 min; however, surface roughness was poor, and there was smeared/adhered material to a depth of 20 μm. Additionally, carbide fracture/pull-out was observed near the workpiece surfaces whereas microhardness depth profiles from sectioned, mounted and polished samples showed a moderate increase in surface hardness of ~80HK0.25 above the bulk value.

Keywords: titanium alloy; high-speed milling; Taguchi; surface integrity

1. Introduction
Since the mid-1940s, there has been continuous development of nickel-based superalloys and titanium alloys in order to meet the requirements for improved aero-engine performance, efficiency and reliability. Currently, the range of alloys is far more extensive than generally acknowledged, with over ~100 different superalloys and upwards of 60 titanium alloys/products (Reed 2006; Soo, Hood, Aspinwall, et al. 2011). The high strength to weight ratio and good corrosion resistance of titanium alloys makes them preferred candidates for aerospace structural parts. Temperature restrictions, however, typically limit their use to components subject to ≤550°C although the newer γ-TiAl intermetallic alloys are quoted as being capable of operating up to ~750°C (Boyer, Welsch, and Collins 2007; Soo, Hood, Lannette, et al. 2011). More familiar alloys such as Ti-6Al-4V have a tighter restricted range with an operational ceiling of ~315°C. Despite this the alloy accounts for around 50% of titanium alloy production. Modern commercial aero-engines typically employ some seven or eight different titanium alloys, which in the main are confined to the cooler, front end of the engine, involving the fan and low-pressure (LP) compressor sections, while nickel alloys dominate the hotter high-pressure (HP) compressor, combustion chamber and turbine sections (Elflinger and Helm 2004; Soo, Hood, Aspinwall, et al. 2011). In terms of engine weight in civil aircraft, it is estimated that around ~33% is due to titanium alloys whereas for Ni-based superalloys, the figure is quoted as 40–50%. In military engines, however, titanium use approaches ~50%.

Increasing the temperature threshold and burn resistance of titanium alloys would provide further scope for reducing engine weight/improving power to weight ratio, and none more so than in the intermediate pressure (IP) stage of the compressor, which is currently dominated by steel and nickel alloys, despite the operating temperatures being within the limits of several current titanium alloys. One of the main reasons for this is that conventional titanium alloys have a tendency to ignite and burn when subjected to IP conditions where ‘rubbing’ is a factor. Manipulation of alloy chemistry has, however, produced titanium alloys which possess superior burn resistance (Voice 2004). These are based on a titanium-vanadium-chromium system which was originally pioneered in the USA. Pratt and Whitney’s Alloy C (Ti-35V-15Cr) is an example (Loretto et al. 2000). An alternative to this is the burn-resistant alloy ‘BuRTi’ comprising Ti-25V-15Cr-2Al-0.2C (%wt), which is a proprietary titanium alloy developed in association with Rolls Royce Plc (Li et al. 2000), with a temperature ceiling of ~550°C. Aluminium is used both as a master alloy to V and Cr to limit the amount and cost of the raw materials (Voice 2004). The alloy’s burn resistance is due to the formation of oxides that help to extinguish flames; however, its higher than standard thermal conductivity is also a contributory factor. By adding a relatively high level of carbon (0.2%),

*Corresponding author. Email: R.Hood@Bham.ac.uk

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oxygen is scoured from the alloy matrix and tied to carbide precipitates which also constrain grain size during processing (Li and Blenkinsop 1999).

Compared to Ti-6Al-4V, BuRTi has ~37% higher thermal conductivity (10 W/mK) and ~8% greater tensile strength; furthermore, the alloy has high ductility (~20%) which is beneficial to foreign object damage and containment (Voice 2004). This contrasts sharply with γ-TiAl which while able to operate at significantly higher temperatures has a thermal conductivity of ~22 W/mK and has extremely poor room temperature ductility which is typically quoted as <1.5%. Despite BuRTi’s higher density than Ti-6Al-4V (5.1 as opposed to 4.43 g/cm³), the potential weight saving in the case of blade applications become attractive when comparing it with steel or nickel alloys having values of 7.87 and 8.30 g/cm³, respectively.

A few publications exist detailing the machinability of BuRTi alloy, hence the requirement for the current work; however, in the velocity–time curves detailed by Aspinwall, Dewes, and Mantle (2005) relating to the turning of TiAl and several burn-resistant titanium alloys, the data for BuRTi suggest it falls between standard titanium alloys such as Ti-6Al-4V and the titanium aluminide intermetallic alloys. A limited assessment of BuRTi machinability when high-speed ball end milling is presented by Novovic et al. (2003), which details results for coated carbide and PCD tooling. The coated tools significantly outperformed the PCD tools when machining at cutting speeds of 100–150 m/min and feeds of 0.05–0.20 mm/tooth. The presence of numerous brittle titanium carbides within the workpiece microstructure caused significant damage to the surface including material pull-out, workpiece smearing, fractured carbides and debonding.

Work comparing the performance of BuRTi against γ-TiAl when creep feed grinding using SiC abrasives was detailed by Hood et al. (2006). G-ratios for BuRTi were typically a tenth of those measured for γ-TiAl, and significant workpiece surface smearing together with laps and folds was present on most BuRTi surfaces. Often this layer showed cracks normal to the feed direction with the highest level of workpiece cracking occurring with the most severe operating parameters (i.e. highest wheel speed, feed rate and depth of cut), which resulted in intensive surface burn and the highest normal force.

Extensive carbide fracture and/or cavities due to lost carbides as previously reported (Novovic et al. 2003) were not found in ground specimens; however, the high level of smearing experienced made assessment difficult (Hood et al. 2006). Microhardness measurements showed in some instances an increased workpiece surface hardness of around 50–60HK0.025 above the bulk hardness of ~375HK0.025. More recently, work involving the use of vitrified bonded superabrasive wheels (cBN and diamond) for the creep feed grinding of BuRTi (Soo, Hood, Lannette, et al. 2011) has showed that a significant increase in G-ratio (~286) is obtainable when employing cBN grit compared to conventional SiC abrasives (<3), although the workpiece surface was similarly subject to intense burning and chatter, as well as defects including smearing, heat affected zones (HAZ) etc. Burn/chatter-free surfaces were only possible when utilising low operating parameter levels (wheel speed, feed rate and depth of cut) with diamond wheels, which produced relatively low G-ratios (between two and six).

2. Experimental work

2.1. Workpiece material, cutting tools and equipment

The workpiece material used in the experimental trials was forged BuRTi compressor blades produced by open die forging extruded ingots, see Figure 1(a). The β phase alloy, composition Ti-25V-15Cr-2Al-0.2C (%wt), was subject to a heat treatment cycle of 600°C for 2 hours. Prior to the start of tests, the root of the blade samples was initially prepared via a combination of face milling, side milling and electrical discharge wire machining to produce a rectangular section suitable for milling trials, see Figure 1(b). Microstructural analysis showed that the typical grain size was 30–50 μm with randomly distributed carbide particles having a length of up to 15 μm, see Figure 1(c). Bulk hardness was measured at ~330HV30.

The cutting tools were 4 flutes, 8 mm diameter solid tungsten carbide (WC), ball nose end mills employing a 30° helix angle. Two different WC substrate grades, IC900 and IC903, were evaluated with the latter having a smaller, ultra-fine grain size. Both were PVD coated with a single 5 μm thick layer of aluminium titanium nitride (AlTiN). A constant tool overhang of 28 mm was maintained for all tests with tool run-out restricted to less than 10 μm. All machining work was carried out on a Matsura FX-5 vertical high speed, with machining centre with a maximum spindle speed of 20,000 rpm rated at 15 kW with a feed rate of up to 15 m/min. Ancillary cutting fluid systems were connected to supply coolant at a pressure of 70 bar and a flow rate of 26 l/min via a twin nozzle.

Figure 1. (a) BuRTi blade in the received state, (b) BuRTi blade machined to produce flat section for tests and (c) bulk microstructure.
A bespoke fixture was produced for holding the BuRTi blades by the aerofoil section, see Figure 2.

Surface roughness Ra was measured using a Taylor-Hobson Form Talysurf 120 with a cut-off length of 0.8 mm and an evaluation length of 4 mm. The selected surface samples were hot-mounted in Buehler Epiomat Bakelite and subsequently ground/polished using SiC paper together with OP-s colloidal silica and etched using a solution comprising 8% HF, 10% HNO3 with the balance water. Machined surface and surface/subsurface workpiece microstructure was observed through a high magnification optical light microscope and scanning electron microscope (SEM), whilst workpiece microhardness was recorded using a Mitutoyo HM800 hardness testing machine with a Knoop indenter using a 25 g load and an indent time of 15 seconds.

### 2.2. Experimental design and assessment criteria

The main objective of the work was to provide an assessment of selected significant operating parameters when high-speed ball nose end milling BuRTi using coated carbide tools. An initial appraisal of the factors and levels that could be investigated produced in excess of 20 different operating parameters/conditions/tooling options that could be investigated. Due to limited workpiece material supply and the high cost of sample preparation, a fractional factorial experimental design employing a Taguchi L8 orthogonal array was used to investigate the effect of six factors, each at two levels, see Table 1. The levels of feed rate as well as axial and radial depth of cut were selected based on the work of Mantle and Aspinwall (2001) and Novovic et al. (2003) while cutting speed was kept constant at 100 m/min. Work performed by Ng et al. (2000) showed that the use of down milling in a horizontal downwards direction gave the longest tool life when machining Inconel 718; therefore, this was selected as the mode to be used when operating with a tilt angle/orientation of 45° and down milling used when operating with a tilt angle of 0°.

In order to ensure conditions were identical between tests, i.e. a constant depth and width of cut, entry into and exit from the workpiece was performed using a separate IC900 cutting tool. Peripherial cutting speed typically employed for titanium alloys was fixed for all tests while...
analysis of the results was restricted to the main effect rather than interactions between the factors. A confirmation trial to validate the results at the end of the experiment, detailed as Test 9 in Table 1, was performed.

The tool-life criteria selected in accordance with ISO standard 8688-2 was a maximum flank wear (VB_{max}) of 300 μm or a notch value of 600 μm (International Standards Organisation 1989). Cutting forces, Fx, Fy and Fz, were measured on selected cutting passes. A minimum surface integrity data set (Field and Kahles 1971) was performed to determine the effect of machining on surface texture, macrostructure, microstructure and microhardness. Following completion of all the trials, workpiece surface roughness (Ra) was measured both parallel and perpendicular to the feed. The surface and subsurface of selected samples were assessed to determine the extent/depth of damage. Finally, microhardness measurements were taken to a depth of 1 mm beneath the machined surface.

3. Results and discussion
3.1. Tool life/wear and material removed
The results of machining time (which ranged approximately from 2 to 60 min) against maximum flank wear are shown in Figure 3. The data suggest that a careful selection of operating parameters is necessary. Of the eight tests performed as part of the initial experimental design (excluding the confirmation test), Test 5 produced the best result.

Figure 4 details the main effect plot means for tool life measured in terms of machining time and material removed. Both output measures showed almost identical trends with the longest tool life produced using IC903 tooling, a feed rate of 0.06 mm/tooth, an axial depth of cut of 0.5 mm, a radial depth of cut of 0.25 mm, HP coolant and a workpiece tilt angle of 45°. These operating parameters were used for Test 5.

The coating and geometry on both the IC900 and IC903 tools were identical; therefore, the improved performance of the finer grain sized IC903 products can be attributed to the higher hardness and subsequent superior wear resistance at increased temperatures. The reduction in tool life observed when increasing both the feed rate and radial depth of cut was as expected, as a higher material removal rate would increase cutting forces and temperatures resulting in increased flank wear.

While mean tool life (see Figure 4) was less than 4 min when machining BuRTi under dry conditions, a near 5-fold increase (~20 min) was observed when high-pressure cutting fluid was utilised. In contrast, Che Haron, Ginting and Arshad (2007) reported a tool life of ~15 min when dry milling an α-β titanium alloy (Ti-6242S) at higher feed rates as well as axial and radial depths of cut of 0.15 mm/tooth, 2.0 mm and 8.8 mm, respectively. This suggests that BuRTi has a lower machinability compared to other titanium alloys. Extensive built-up-edge (BUE) and adhered material were observed when machining dry, see Figure 5, which was reduced but not eliminated by using high-pressure fluid application. This tendency of workpiece material ‘sticking’ to the cutting tool was also

Figure 3. Machining time against maximum flank wear.

Figure 4. Main effect plot – means for tool life.

Figure 5. Wear scar photographs showing built-up-edge (BUE) when machining dry.
highlighted by Su et al. (2006) when dry and wet milling Ti-6Al-4V. Operating with a workpiece tilt angle/orientation of 45° eliminated rubbing at the centre of the ball, caused by an effective cutting speed of zero when the tool axis is perpendicular to the workpiece surface. Figure 6 shows SEM images of cutting tools used in both workpiece orientations.

As the levels of factors that produced the ‘best’ tool life had been assessed in Test 5, a confirmation test (Test 9) was undertaken with the same parameters as Test 5 except that a 0.25 mm axial depth of cut was used as it was felt that the main effect plot favouring a higher depth of cut had been compromised by factor interactions. Figure 7 shows data for Tests 9 and 5, with the former giving a ~10% increase in the distance machined before the maximum flank wear criterion was reached. In terms of volumetric removal, however, almost twice as much workpiece material was removed by Test 5.

Analysis of variance (ANOVA) for both output measures is shown in Tables 2 and 3. As $F_{\text{calc}}(1, 1) = 111$, no factors were identified as being statistically significant at 5% level (Ross 1996), despite cutting environment having a percentage contribution ratio (PCR) of 17.2% (relative to machining time) and 17.4% (relative to material removed). Residual error levels were substantially higher than generally acceptable (~15%), suggesting that factors were omitted, measurement errors were present or most likely that there were interactions between factors not accounted for in the particular orthogonal array employed.

### 3.2. Workpiece surface roughness

The main effect plot (means for workpiece surface roughness), see Figure 8, shows the workpiece surface roughness Ra was on average 33% higher when assessed perpendicular to the feed direction rather than parallel. For both directions, the two cutting tool grades showed limited difference. This was expected as the cutting tool geometry and coating were identical for both tool types. Workpiece orientation and feed can be seen to have had the greatest influence on roughness. Tests which were carried out with the workpiece horizontally mounted showed higher surface roughness (average of 3.89 μm Ra over four tests) when compared against those performed with a 45° tilt angle (average of 1.45 μm Ra). Mantle and Aspinwall (2001) report a similar trend with the workpiece orientation having a greater effect on the workpiece surface roughness in a direction perpendicular to the feed direction rather than parallel. Analysis of variance for workpiece surface roughness perpendicular to the feed direction showed the largest percentage contribution of ~58% for workpiece orientation, yet the result was not statistically significant at 5% level. Similar
analysis in respect of measurements made parallel to the feed direction identified feed rate and environment as being statistically significant at 5% level, with the former having a PCR of ~89% and residual error within acceptable limits.

3.3. Cutting forces

The main effect plot – means for maximum resultant force – is given in Figure 9 with results for both new and worn tooling. Using worn tools caused the resultant force on average to increase by 160%. Not surprisingly, increasing the material removal rate by changing the feed rate, axial and radial depth of cut caused a rise in the resultant force by up to 60N for a new tool and 160N for a worn tool. Workpiece orientation showed a similar trend with lower resultant forces measured with the workpiece tilted at 45°. This was probably because of the reduced level of smearing at the centre of the cutter ball caused when operating with the workpiece at 0°. With a new tool, changing the cutting tool and environment had little effect on the resultant force; however, with worn tools the two factors had a much greater effect on the resultant force. A worn IC903 produced a 150N lower value than that of a worn IC900 end mill.

Analysis of variance for maximum resultant force using new and worn tools (VBmax = 300 μm) identified all factors as non-significant at 5% level. A comparison of the cutting force components Fx, Fy and Fz measured for Tests 5 and 9 (confirmation experiment) is shown in Figure 10. The data show all three components increasing by up to 400% as tool wear progressed to test cessation. Increasing the axial depth of cut from 0.25 mm to 0.5 mm caused only a moderate increase (~10%) in the Fx and Fy force components with a new and worn tool. Fz forces showed a greater difference; however, all the three components showed similar values for the forces at intermediate flank wear levels (VBmax = 50–250 μm).

3.4. Machined workpiece surface

Figure 11 shows examples of surfaces produced using worn tools. Adhered material of varying size was found on all surfaces, in some cases to a width of up to 1 mm, depending on operating parameters. This is typical when machining titanium alloys (Ulutan and Ozel 2011) and can result in underlying surface damage being obscured as well as geometrical accuracy errors. Surfaces generated in tests employing high-pressure cutting fluid had reduced levels of adhered material and smearing as had tests at 45°, as a consequence of the improved cutting speed distribution over the cutting edge. Cavities/material pull-out due possibly to fractured/removed carbides were evident whilst possible micro-cracks were found on the worst surfaces (Tests 3 and 8) promoting the adhesion of material on the crack edge, see Figure 11(c). The confirmation test, Test 9 showed the ‘best’ surface with smeared/adhered material only ~20 μm in size, see Figure 11(d). It would be expected that surfaces produced using new tools would show lower levels of surface damage; unfortunately, limited material availability made it unrealistic to assess this aspect. Having said this, burring was observed on the exit from the workpiece of each pass even with new
tools, although high-pressure cutting fluid reduced the severity.

3.5. Surface/subsurface analysis

A range of surface/subsurface cross-sectional micrographs in a direction parallel to the feed is shown in Figure 12. As with the analysis of the machined workpiece surface, adhered material up to a depth of ~20 μm was seen on the surface of every cross-section, the depth and frequency of which depended on the operating parameters used. In general, an orientation of 45°, use of cutting fluid and the lowest feed rate, depth of cut and step-over produced the lowest levels. Material pull-out on the surface and voids were found in ‘reformed’ material. Carbide fracture or removal was also observed. Figure 12(c) details a sample cross-section from Test 5, showing fracturing of a carbide as well as material with voids adhered to the workpiece surface. Comparative levels of damage to the surface/subsurface were found by Novovic et al. (2003), including fractured carbides near to the surface. It has been reported that defects such as carbide cracking can severely compromise fatigue life of the material as well as accelerate failure of the component (Ranganath, Guo, and Holt 2009).

3.6. Microhardness

Microhardness depth profiles were taken for all samples perpendicular to the feed direction, see Figure 13. Most samples showed an increased hardness of up to 80HK0.025.
higher than the bulk hardness of ~370HK_{0.025} to a depth of up to 500 μm. It was found that samples for Tests 3, 5 and 8 had increased hardness for the entirety of the depth measured. The presence of non-uniformly distributed carbide particles of up to ~12 μm in size made the measurement of microhardness difficult. A comparison of results between Tests 5 and 9 surfaces is given in Figure 14. As previously outlined, axial depth of cut was the only operating parameter that was varied between these two tests, and it can be seen that the higher depth of cut produced an increase in microhardness of up to ~100HK_{0.025} higher than the bulk value to a depth of around 300 μm. Novovic et al. (2003) also found that lower axial depth of cut produced limited change in the microhardness variation.

**Figure 14.** Microhardness profiles for Tests 5 and 9.

### 4. Conclusions

This paper presents a comprehensive assessment of the tool life, surface roughness and surface integrity when milling a newly developed and novel titanium alloy with improved burn resistance. The main results and conclusions are summarised as follows:

- Burn-resistant titanium alloy Ti-25V-15Cr-2Al-0.2C (BuRTi) was generally more difficult to machine compared to standard titanium alloys such as Ti-6Al-4V, despite its higher thermal conductivity (10 vs. 7 W/mK) and ductility (20 vs. 14%) compared to the latter. Experimental results from the high-speed milling trials showed that relatively low tool life, high workpiece surface roughness (Ra) levels and poor surface integrity were prevalent, which was principally caused by the presence of carbide particles up to ~15 μm in size.
- The main effect plot – means for tool life – showed that ‘best’ tool life was achieved using an IC903 tool, a feed rate of 0.06 mm/tooth, an axial depth of cut of 0.5 mm, a radial depth of cut of 0.25 mm, HP (70 bar) cutting fluid and a workpiece orientation of 45°.
- High feed and material removal rates were found to cause increased surface roughness. Tests showing the longest tool life and lowest forces tended to produce surfaces with the lowest surface roughness.
- An increase in force component level of up to 400% from a new tool to a worn tool was observed. Increasing the axial depth of cut from 0.25 mm to 0.5 mm caused a slight increase (~10%) in the Fx and Fy force components with both new and worn tools.
- Poor surface finish was achieved with smeared/adhered material; however, the application of high-pressure cutting fluid reduced the levels of this damage but did not eliminate it. Surfaces were subject to burring at the exit of cut which could be reduced but not eradicated by the application of cutting fluid.
- Workpiece surface/subsurface damage was experienced in all the tests. This included carbide pull-out or fracture, smeared material and micro-cracks. The severity of these features depended on the operating parameters used with higher levels, in general yielding more damage.
- The large number, size and non-uniform distribution of carbides within the workpiece material impaired the measurement of microhardness; however, increased microhardness was evident with all tests within 300 μm of the surface. A larger depth of cut significantly increased workpiece hardness up to ~100HK_{0.025}.

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