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3rd CIRP Conference on Surface Integrity (CIRP CSI)

## Evaluation of workpiece surface integrity following point grinding of advanced titanium and nickel based alloys

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### Abstract

Experimental results are presented following point grinding of Ti-6Al-4V, gamma-TiAl and Udimet 720 nickel based superalloy using plain 15 mm diameter electroplated superabrasive (CBN and diamond) wheels employing 46 µm grit. Surface roughness (Ra) was typically higher by up to ~36% on Ti-6Al-4V due to greater wheel wear and workpiece smearing/re-deposited material, corresponding to significant levels of wheel loading. While Udimet 720 exhibited minimal variation in microhardness parallel to the feed direction, strain hardened surfaces of up to ~100 HK<sub>0.025</sub> above the bulk value were observed for γ-TiAl. In contrast, ground Ti-6Al-4V workpieces showed minor softening at the surface. Sub-surface microstructural deformation was evident in both the Ti-6Al-4V and γ-TiAl samples, which extended to a depth of ~10 µm.

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*Keywords:* Grinding; nickel alloy; titanium

### 1. Introduction

Broaching is currently the industry standard technology for manufacturing blade root mounting slot features in gas turbine/compressor aeroengine discs made of advanced titanium and nickel based alloys [1,2]. The process has a long history and is capable of achieving good repeatability, high dimensional/geometric tolerance and acceptable workpiece surface/sub-surface integrity [3,4]. Furthermore, developments in optimising tool geometry together with the application of cemented tungsten carbide broaches instead of traditional high speed steel have enabled a 4-10 fold increase in operating speed (from 2-5 to 20 m/min) [5]. Nonetheless, key drawbacks of the process such as high capital and tooling costs, long setup/lead times, large equipment footprint, high cutting forces and poor machine/operational flexibility has driven the need to explore alternative solutions.

More recently, the point grinding operation utilising small diameter profiled electroplated grinding wheels (also referred to as grinding points) mounted on a high speed machining centre, has been suggested as a viable option to broaching.

Preliminary feasibility assessment by Burrows et al. [6] on Inconel 718 and Udimet 720 using plain grinding points on a high speed machining centre showed that forces when finishing were generally low (< 100 N) with workpiece surface roughness values down to 1.2 µm Ra. Corresponding experiments to evaluate workpiece integrity revealed minimal microstructural variation and surface compressive residual stresses down to -700 MPa, despite some minor softening of the material detected up to a depth of ~50 µm below the ground surface [7]. Additionally, the fatigue life of the point ground surface was considerably superior compared to equivalent milled and polished specimens [8]. The work progressed to investigate the performance of fir tree profiled grinding wheels, however all of the published research to date has mainly focused on nickel based superalloys [9]. The present paper details work to compare wheel wear/life and particularly the associated workpiece surface integrity following point grinding of 2 different aerospace grade titanium alloys and a nickel based superalloy. Machining characteristics for the titanium alloys have not been previously reported and point grinding has particular relevance in respect

of the  $\gamma$ -TiAl alloy due to its sensitivity to machining damage for operations other than grinding. The approach provides scope in relation to possible edge profiling and hole finishing.

## 2. Experimental work

The grinding trials were carried out on a 3-axis, linear motor vertical machining centre (Matsuura LX-1) with a spindle rated at 3 kW and a maximum rotational speed of 60,000 rpm. All of the grinding points employed unconditioned plain profiles being 15 mm diameter x 30 mm long steel cylinders brazed onto 10 mm diameter carbide shanks. The steel substrates were electroplated with either diamond or cubic boron nitride (CBN) superabrasive grits having an average grain size of 46  $\mu$ m. The balance specification of the tools was G2.5 at 60,000 rpm, each grinding point being held in a shrink fit toolholder that provided superior precision and stability compared to traditional collet systems at high rotational speeds, see Fig. 1.

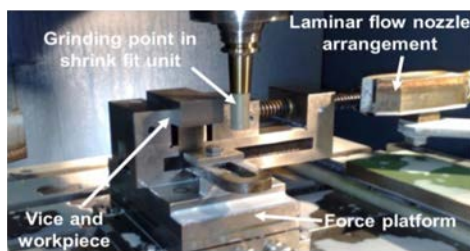


Fig. 1. Experimental arrangement.

Three different workpiece materials were investigated, comprising cast/wrought Udimet 720 nickel based superalloy in the solution treated and aged condition, solution annealed Ti-6Al-4V titanium alloy and hot isostatic pressed (HIP-ed) gamma titanium aluminide ( $\gamma$ -TiAl) alloy (Ti-45Al-2Mn-2Nb-0.8TiB<sub>2</sub>XD), which was HIP-ed at 170 MPa and 1260°C for 4 hours, with subsequent heat treatment at 1010°C for 50 hours. The workpieces were supplied in the form of rectangular blocks (20 mm height) having bulk hardness values of  $\sim 46 \pm 3$ ,  $\sim 41$  and  $\sim 32$  HRC respectively. Test blocks were clamped in a vice, mounted on a 3-component Kistler 9257A platform dynamometer fixed to the machine bed to allow grinding force measurement.

Wear of the grinding points was determined using a coordinate measuring machine (CMM), equipped with a touch trigger probe having a 4 mm diameter ruby stylus. The diameter was measured at regular intervals by probing 20 locations around the circumference of the grinding point, which was repeated 3 times at different axial positions over the worn region and averaged. Ground workpiece 2D surface roughness was assessed using a TH Form Talysurf 120L with cut-off and evaluation lengths of 0.8 and 4.0 mm respectively.

Selected workpiece surfaces were cross sectioned both parallel and perpendicular to the feed direction using wire electrical discharge machining (WEDM) and subsequently mounted in edge retentive bakelite. The specimens were then ground and polished using appropriate routes for each of the alloys with typically 0.5-1.0 mm of stock material removed to

ensure complete elimination of any thermal damage due to WEDM. Workpiece microhardness depth profile evaluation was undertaken with a Mitutoyo HM124 hardness tester using a Knoop indenter at a load of 25 g applied for 15 s. Three measurements were recorded at each depth level and the results averaged. Assessment was undertaken to a depth of 500  $\mu$ m however results data shows traces only to 200  $\mu$ m. Polished specimens were etched using industry standard etchants and microstructural analysis undertaken with a Leica DMLM optical microscope connected to a digital camera. A similar setup was also utilised for capturing images of the machined workpiece surfaces and grinding points. In addition, high resolution micrographs of ground surfaces were captured using a JEOL JSM-660 scanning electron microscope (SEM).

A total of 6 tests were performed according to the operating parameters and factor levels detailed in Table 1. Tests 1-5 are representative of preferred finishing conditions based on results from previous research [10], while Test 6 was carried out to assess performance at higher material removal rate (MRR). Plunge down grinding was employed in all trials with rotational speed kept constant at 60,000 rpm to provide a grinding speed of  $\sim 47$  m/s. A water based emulsion containing  $\sim 5\%$  oil concentration was used, which was delivered at a flow rate of 135 l/min and pressure of 3 bar via 2 laminar flow nozzles (20 x 2 mm aperture) attached on specially designed linear rails that were bolted onto the machine worktable.

Table 1. Test matrix.

Test no.	Workpiece material	Abrasive type	Feed rate (mm/min)	Depth of cut (mm)
1	Udimet 720	Diamond	100	0.1
2	Udimet 720	CBN	100	0.1
3	Ti-6Al-4V	Diamond	100	0.1
4	Ti-6Al-4V	CBN	100	0.1
5	$\gamma$ -TiAl	Diamond	100	0.1
6	Ti-6Al-4V	Diamond	2000	0.02

## 3. Results and discussion

Wear progression of the grinding points in each test against volume of workpiece material ground is detailed in Fig. 2. Results from Tests 1 and 2 indicated that the calculated G-ratio of the diamond wheel was  $\sim 20\%$  higher compared to that of the CBN ( $\sim 22$  vs. 18). This was in contrast to trends observed when machining Udimet 720 with an oil fluid using fir tree profiled grinding points, where the CBN significantly outperformed the diamond grits [9]. The diametrical wear rate was somewhat higher when grinding Ti-6Al-4V, although calculated G-ratios of the diamond and CBN wheels (Tests 3 and 4) were approximately equivalent at trial cessation ( $\sim 16$ ). When considering Tests 1-4 as a full factorial experiment, an analysis of variance (ANOVA) highlighted that neither workpiece material (Udimet 720 and Ti-6Al-4V) nor abrasive type (diamond and CBN), had a significant effect on G-ratio at the 5% level, despite the former exhibiting a relatively high percentage contribution ratio (PCR) of 55%. The highest G-ratio of 33 was achieved when machining  $\gamma$ -TiAl in Test 5, which reflects its superior grindability compared to Udimet

720 and in particular Ti-6Al-4V, which was also outlined in previous publications [11,12]. Typically, the room temperature ductility of  $\gamma$ -TiAl is < 2% compared with that for Ti-6Al-4V of ~15% in the annealed condition. Grinding Ti-6Al-4V at the elevated feed rate of 2000 mm/min with diamond abrasive in Test 6 however led to higher wear rates and reduced G-ratio of ~11, which was mainly due to the larger undeformed chip thickness. In general, normal forces peaked at ~ 1000 N in Test 6 at trial cessation. Nevertheless, a t-test carried out between results from Test 3 and Test 6 revealed no significant difference in wear progression at the 2.5% level.

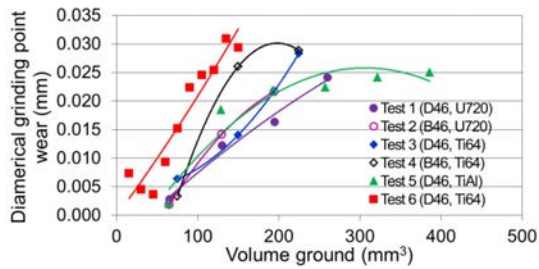


Fig. 2. Grinding point wear against volume ground.

Workpiece surface roughness ( $\mu\text{m Ra}$ ) following the end of each trial is detailed in Fig. 3. Surface roughness of the Ti-6Al-4V samples was typically higher by up to ~24% compared to Udimet 720, which further increased to ~36% when compared with the  $\gamma$ -TiAl workpiece (Test 5). This was most likely due to the greater levels of wheel loading and workpiece smearing/re-deposited material on the Ti-6Al-4V surfaces. Lower surface roughness was also generally achieved with the diamond abrasives as opposed to CBN, most likely due to the ‘blockier’ shape of the former [13], which is consistent with previously published results [9]. Although the corresponding ANOVA indicated that workpiece material had a relatively high PCR of 73% with respect to Ra, none of the factors were significant at the 5% level.

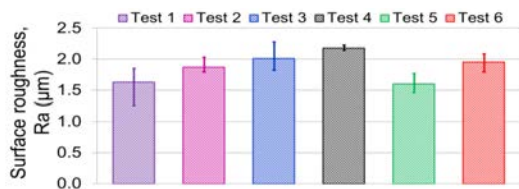


Fig. 3. Workpiece surface roughness at test cessation.

Sample optical micrographs of the particular grinding point surfaces after each test are detailed in Fig. 4. While workpiece adhesion/wheel loading was observed on all the tools, this was especially prevalent on diamond grinding points used to machine Ti-6Al-4V workpieces regardless of operating parameters (Tests 3 and 6). Somewhat surprisingly, severe wheel loading was also encountered when grinding Udimet 720 with CBN (Test 2), which was not apparent in any of the previous experiments undertaken by the authors [10]. A possible reason for this would be a greater than expected run-out for the grinding point used.

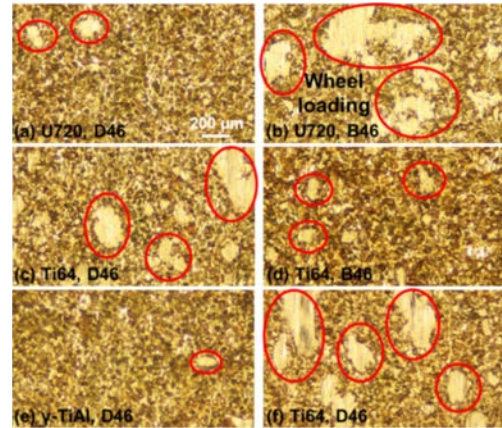


Fig. 4. Grinding point surface at test cessation; (a) Test 1, (b) Test 2, (c) Test 3, (d) Test 4, (e) Test 5, (f) Test 6.

Workpiece smearing/material ploughing was evident particularly on the Ti-6Al-4V surfaces ground using diamond abrasives, see Fig. 5(a) and Fig. 5(b). Black spot formation was also clearly visible, which is characteristic of re-deposited or smeared material. This can be attributed in part to the relatively high ductility and chemical reactivity of Ti-6Al-4V. Evidence of possible chatter during machining in Test 3 was detected in Fig. 5(c), which shows a ‘discontinuity’ in grinding marks on the workpiece surface. This is generally indicative of the grinding wheel ‘lifting off’/disengaging and then reengaging with the workpiece surface during operation. Conversely, the surface generated using the CBN wheel exhibited uniform grit tracks together with minimal smearing, see Fig. 5(d), which corroborates earlier observations of grinding point wear patterns in Fig. 4.

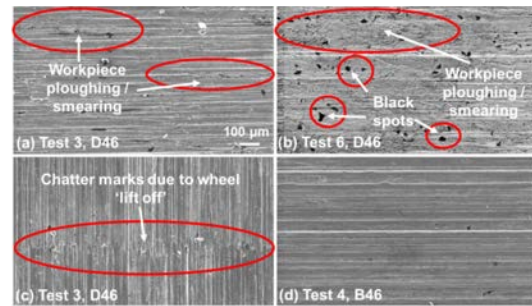


Fig. 5. SEM micrographs of ground Ti-6Al-4V surfaces at test cessation.

Microhardness depth profile plots measured both parallel and perpendicular to the feed direction are detailed in Fig. 6 and Fig. 7 respectively. In the parallel direction, the near surface microhardness of the  $\gamma$ -TiAl workpiece increased up to a maximum of ~461  $\text{HK}_{0.025}$ , which suggests strain hardening occurred, while marginal softening (up to ~13% below bulk hardness) was observed for the Ti-6Al-4V samples. In contrast, no apparent variation in microhardness was evident for the Udimet 720 specimens. Changes in microhardness perpendicular to the feed direction however were less pronounced in the both the Ti-6Al-4V and  $\gamma$ -TiAl workpieces. Some limited surface softening (~60  $\text{HK}_{0.025}$

below bulk value) of the Udimet 720 workpiece ground with CBN was however evident to a depth of 20  $\mu\text{m}$ .

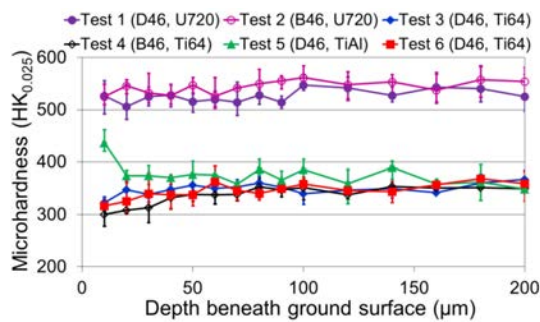


Fig. 6. Microhardness profiles measured parallel to feed direction.

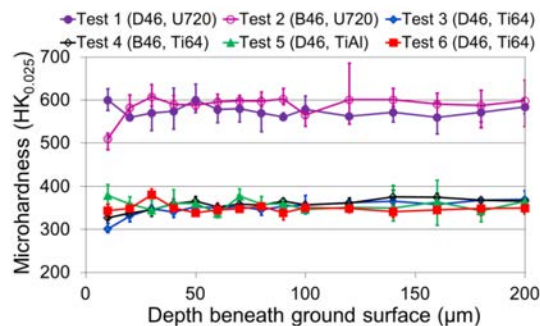


Fig. 7. Microhardness profiles measured perpendicular to feed direction.

Cross-sectional micrographs showing the sub-surface workpiece microstructure from selected tests are detailed in Fig. 8. Considerable workpiece smearing and microstructural deformation to a depth of  $\sim 10 \mu\text{m}$  was visible on the Ti-6Al-4V samples parallel to the feed direction when operating at the higher feed rate level in Test 6, see Fig. 8(a).

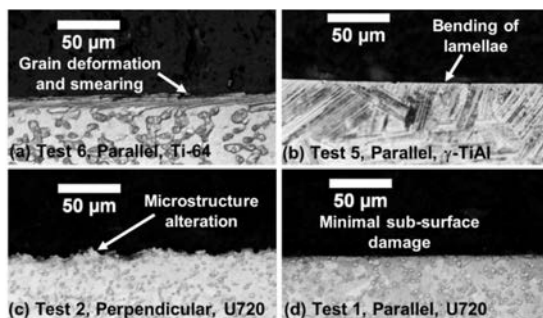


Fig. 8. Workpiece cross-sectional micrographs from selected tests.

Similarly, bending of lamellae in the  $\gamma$ -TiAl specimens (Test 5) along the feed direction was apparent, which led to strain hardening of the material as observed in the microhardness results, see Fig. 6. Signs of microstructural alterations were evident on the Udimet 720 sub-surface cross sectioned perpendicular to the feed in Test 2, see Fig. 8(c). In contrast, there was minimal damage detected in all of the

other Udimet 720 specimens assessed, such as that detailed in Fig. 8(d).

#### 4. Conclusions

- Longest tool life was obtained when grinding  $\gamma$ -TiAl using D46 abrasive with a corresponding wheel G-ratio of  $\sim 33$ .
- Workpiece surface roughness was highest on the Ti-6Al-4V samples regardless of grit type or grinding parameters.
- Severe workpiece smearing was evident when grinding Ti-6Al-4V due to higher grit wear, wheel loading and material ductility. In contrast, minimal workpiece adhesion was seen when grinding  $\gamma$ -TiAl but surface strain hardening up to  $\sim 461 \text{ HK}_{0.025}$  and bending of lamellae to depth of  $\sim 10 \mu\text{m}$  occurred.
- Least workpiece damage occurred when grinding Udimet 720 with diamond grits.

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