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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_{0.025} 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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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 γ -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 μ 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.

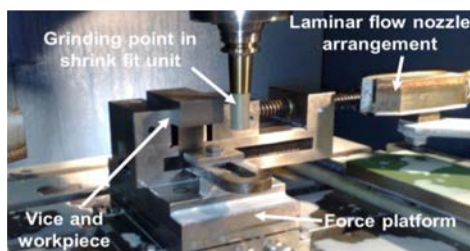


Fig. 1. Experimental arrangement.

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 (γ -TiAl) alloy (Ti-45Al-2Mn-2Nb-0.8TiB₂XD), 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 $\sim 46 \pm 3$, ~ 41 and ~ 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 μ m however results data shows traces only to 200 μ 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 ~ 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	γ -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 (~ 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 (~ 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 γ -TiAl in Test 5, which reflects its superior grindability compared to Udimet

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