1 INTRODUCTION

Despite the extensive research and development associated with blisk (bladed disk) manufacture and repair over the last two decades, the great majority of aeroengines, whether for commercial or military use, employ detachable rotating blades. These are typically located and held in position on a series of disks using either a fir tree or dovetail blade root design. The rotor assembly for the engine compressor and turbine, will, depending on size, contain many hundreds of blades of varying size and shape with similar variation in the scale of the root attachment. Figure 1 shows sample blade root mounting slots, the fir tree design being used where blade loading is high [1]. Figure 2 shows a selection of blade root configurations.

![Figure 1: Sample root mounting slot profiles.](10 mm 10 mm 10 mm)

The machining of axial / oblique root mounting slots in individual disks is almost universally accomplished using broaching, in some cases following a preliminary milling operation. The process is mature and consequently there have been few recent publications outlining equipment, technology or machinability, although commercial considerations are an additional factor. Broaching is able to provide complex slots of appropriate geometrical size (within ~ 10μm), quality (workpiece Ra ~ ≤ 2μm) and integrity, with roughing and finishing possible within one stroke. Broach design, accuracy and finish are however critical factors in maintaining acceptable performance and minimising tooth breakage, chip jamming and associated workpiece scoring / smearing etc. Furthermore, the use of different tooth / tool geometries at different positions on the broach produces variations in chip thickness and hence differences in wear rate, thus providing scope for process monitoring [2,3]. Major shortcomings of the process include the high capital cost and large size of machine tools together with their inflexibility, costly tooling, lengthy setup, validation and changeover times, high cutting forces (up to 10,000N) [2] and relatively long manufacturing times, with broaching speeds as low as 2m/min quoted in heat resistant alloys.

Feasible options for alternative processes to broaching for disk slot manufacture are limited, although significant changes have occurred in recent years in the way the equivalent root form is machined on the compressor or turbine blade. Here, broaching has largely been supplanted by creep feed grinding (CFG), involving the use of multi-axis, flexible machining centres equipped with porous conventional abrasive wheels, semicontinuous dressing and a high pressure / high flow rate fluid delivery system, aptly termed VIPER (Very Impressive Performance Extreme Removal) [4]. Solid carbide profiled milling cutters employing either a full or partial form, are also used in blade root manufacture and similar or indexable insert tooling is used in some machining of disk slots.

The re-entrant nature of disk slots appears to preclude the use of conventional grinding wheel arrangements for finishing the form. However, recently published details involving VIPER machining techniques [5], suggest that a modified arrangement is feasible at least for larger fir tree roots, although details are scant. A more versatile grinding arrangement with scope for machining a wide range of slot forms and sizes, involves the use of small diameter (≤ Ø25mm) single layer, electroplated superabrasive grinding wheels (sometimes referred to as grinding pins or points) employing either a full or partial form, see Figure 3. By necessity, rotational speeds are high, typically > 50k rpm in order to achieve even moderate peripheral cutting speeds, which will vary according to the shape of the blade fixing slot. High speed spindles of adequate power and stiffness are therefore required as is the machining of a preliminary or initial slot using either CFG / high efficiency deep grinding (HEDG)
or electrical discharge wire machining (EDWM). With the former, the slot cross section may typically resemble a stepped pyramid or quadrilateral with the widest feature at the periphery of the disk. In the case of EDWM, a shape more closely mirroring that of the root form, provides the possibility to obtain a more uniform wear pattern on the grinding wheel. A flow chart showing alternative manufacturing sequences is given in [6].

Figure 3: Electroplated superabrasive grinding wheels.

Root slot grinding reported in [6-9] essentially demonstrated the feasibility of the approach, using plain cylindrical diamond and CBN wheels and subsequently full form wheels, when machining two key nickel based superalloys; Inconel 718 and Udiment 720. Taguchi fractional factorial experiments were used to identify key operating factors and levels, with testing undertaken predominantly at 60k rpm, giving grinding speeds up to 45m/s. International interest in the approach may be gauged from the recent spate of patents [10, 11] dealing with preliminary / pre-cursor slot production, full form slot gauging from the recent spate of patents [10, 11] dealing with preliminary / pre-cursor slot production, full form slot and root machining. Such documentation provides methodology and boundary parameters but not their effect on performance. The following experimental work, which utilises a commercial fir tree root design (RR Trent), was undertaken to explore the effect of superabrasive type (diamond and CBN), grit size and cutting parameters on grinding wheel wear, workpiece surface roughness and cutting forces.

2 EXPERIMENTAL WORK

2.1 Equipment, test procedures and operating parameters

Laboratory testing was undertaken on two high speed machining (HSM) centres. The first was a 20k rpm unit equipped with two separate retrofit high speed spindles, one rated at 3kW operating at up to 60k rpm and another rated at 4.5kW able to operate at up to 90k rpm, together with ancillary cooling, lubrication and control equipment. Mounting of the spindles necessitated the manufacture of two manifold units due to the different arrangement of supply connections. The second HSM centre was a linear motor machine which utilised its' own 60k rpm spindle (3kW) and was equipped with laser tool setting. Modifications were made to both machines to incorporate high pressure, high flow rate fluid supply, mist extraction and CO₂ fire suppression systems for use when machining two key nickel based superalloys; Inconel 718 and Udiment 720. Taguchi fractional factorial experiments were used to identify key operating factors and levels, with testing undertaken predominantly at 60k rpm, giving grinding speeds up to 45m/s. International interest in the approach may be gauged from the recent spate of patents [10, 11] dealing with preliminary / pre-cursor slot production, full form slot and root machining. Such documentation provides methodology and boundary parameters but not their effect on performance. The following experimental work, which utilises a commercial fir tree root design (RR Trent), was undertaken to explore the effect of superabrasive type (diamond and CBN), grit size and cutting parameters on grinding wheel wear, workpiece surface roughness and cutting forces.

Figure 4: 90k rpm retrofit spindle and experimental setup. Workpiece blocks typically 15mm and 36mm thick were mounted in purpose made clamping units fitted to a vibration damping palletisation (VDP) system. Force measurement involved a piezoelectric 3-component force dynamometer, associated charge amplifiers and analysis software on a desktop computer.

Figure 5: Experimental setup on 60k rpm linear motor unit.

Tool inspection was principally undertaken using a shadowgraph set to 10x magnification which was fitted with an X-Y digital readout. Tool wear was monitored using graphite replicas (3mm thick), which were cut at predetermined times throughout the tests and measured on the shadowgraph (diametric wear results detailed which were averaged from measurements between all fir tree turning points / lobes). Workpiece surface roughness and grinding wheel roughness were assessed using stylus profilometry equipped with 3D analysis software. When measuring grinding wheel roughness (lobe side), a synthetic rubber replicating compound was employed to produce a negative replica after which a fast curing polymerising resin was used to produce positive, hard replicas suitable for stylus measurement. Cut off was 0.8mm. A digital camera arrangement connected to a laptop computer was used for recording low magnification micrographs, while a scanning electron microscope (SEM) was used for analysis of grinding wheel / superabrasive grit wear.

Figure 6 details the single sided slot configuration used throughout the present work, a machined graphite replica and a sample B91 (preconditioned) grinding wheel. Testing involved diamond; D46 and CBN; B46, B76 and B91 grit sizes respectively.

Figure 6: (a) Single sided slot, (b) machined graphite replica, (c) sample B91 grinding wheel.

All tests employed down grinding, a feed rate of 2mm/min and 20μm depth of cut per pass. Peripheral cutting speed
varied according to the spindle rotational velocity and shape of the fir tree root form, but ranged up to ~ 90m/s. Both B91 and B76 grinding wheels were subject to a preconditioning or pre wearing regime by the wheel manufacturers which was intended to truncate the wear response and reduce workpiece roughness. Typically, fluid pressure at the nozzle was ~ 3bar with a combined flow rate of ~ 135l/m.

2.2 Results and discussion

Differences in diamond and CBN abrasive wear and associated workpiece roughness are shown in Figure 7 for D46 and B46 products when operating at 60k rpm on the second HSM machine. Statistical analysis (two sample t-Test) suggests there is a significant difference in means at the 5% level, with the CBN grit providing a lower wear rate. The results for workpiece surface roughness (measured at a point corresponding with the lobe side) between the different grit types provided similar trend results, with diamond (D46) producing the lowest roughness, despite higher Sa values for the diamond grinding wheel at the cessation of the tests (start and finish Sa results for D46=4.85 / 3.58μm and B46=4.95 / 2.78μm). In view of the fact that the operation was essentially plunge grinding with no vertical oscillation, it is likely that the result relates in part to replication inaccuracies (synthetic rubber compound accurate to 0.1μm, for the hard polymerising resin, 1μm is given).

Data when operating with the 90k rpm spindle for B46, B76 and B91 grinding wheels are shown in Figures 9 and 10 which details wheel wear and workpiece Ra respectively. The effect of ‘preconditioning’ for the B76 and B91 wheels is clearly visible when compared with the unconditioned B46 wheel, which displays an initial step change in wear levels. Additionally, the workpiece Ra for the B76 and B91 display a far shallower response than for the B46. The disposition of the Ra plots is as expected with finer grit producing a lower surface roughness. Trials with B76 and B91 were discontinued at ~35000mm² as the required workpiece surface roughness was not achieved.

Figure 7: Wheel wear and workpiece Ra at 60k rpm.

Figure 8 gives 3D topographic maps (curvature compensated) taken from the hard replicas of a B46 grinding wheel when new and worn (~7500mm³ material removed). Although mean grit size and concentration were approximately the same, the morphology of the diamond and CBN abrasives was different, with the former having a more ‘blocky’ shape. No significant loading of the wheels was observed, neither was there any obvious discoloration / burning of the workpiece surface.

Figure 8: 3D topographic maps of (a) new B46 and (b) worn B46.

Figure 11 shows the uniform distribution of abrasive grit on a worn (~ 35000mm² material removed) B91 grinding wheel at the indicated position, with details of the same area at higher magnification when new and worn, no special cleaning was undertaken following use. No obvious loading or grit blunting is evident although there appears to be some grain pullout as indicated.

Figure 11: SEM micrographs of grit distribution and wear.

Maximum normal cutting force when operating at 60k rpm on the first HSM machine using B46 wheels was ~ 45N.
Total spindle power levels recorded on the second machine at 60k rpm for both B46 and D46 wheels were 1.03kW (stable) and 1.03 to 1.59kW (over the duration of the test) respectively. The actual grinding power component within these figures was calculated to be 94W and 94 to 656W respectively, with corresponding specific grinding energies of 6.54J/mm³ for the CBN and up to 45.79J/mm³ for the diamond wheel. The very low values of force and power reflect the nature of the operation (finishing).

A comparison of wear performance for B46 grinding wheels when operating at 60k and 90k rpm is illustrated in Figure 12. Lower wear was observed at 90k rpm as a result of the smaller undeformed chip thickness and the anticipated effects on forces and power. There are however practical considerations relating to the use of such high speeds in any potential industrial application (spindle life, reliability, tool fabrication / balancing etc.).

Figure 12: Effect of cutting speed on wheel wear.

Figure 13 details entry burr formation in the lobe region of the workpiece when operating at 90k rpm for worn (~3500mm³ material removed) B46 and B91 wheels. The preconditioning of the B91 is considered to be the main factor controlling burr size, which was up to 4mm long. Similar burrs were observed with the preconditioned B76 wheels.

Figure 13: Entry burrs at 90k rpm for B46 and B91.

The testing raised a number of concerns relating to the suitability of machine tool configurations, fluid supply etc. The different spindle arrangements necessitated different tool adaptors which produced unavoidable variations in tool overhang and runout, the latter ranging from 2μm to 10μm. Such aspects will impact directly on slot accuracy, wheel wear and workpiece roughness.

3 CONCLUSIONS

Lower absolute wear values were recorded for CBN rather than diamond abrasive, however it was not possible to assess the influence of grit morphology. Wear rate following preconditioning was significantly reduced however the 'pretreatment' had an effect on burr formation which was evident to a greater extent. Lower workpiece surface roughness was obtained using diamond superabrasive, most likely as a result of the 'blocky' morphology of the diamond grit and possibly the higher wear rate. The use of higher rotational speeds and hence cutting speed produced lower grinding wheel wear. Under the conditions tested, no obvious wheel loading was observed, however there was wholesale grit pullout.

No workpiece burning or surface discolouration was evident in any of the tests undertaken.

4 ACKNOWLEDGMENTS

We wish to thank Rolls-Royce plc., Saint-Gobain Abrasives (Chris Davis & Andreas Grimm) and Matsuura Machinery (David Edwards) for the provision of funding, tooling and technical support. Additional thanks go to Faemat & Dick Langley of High Gain Technology for technical support in relation to high speed spindle installation and use, together with Peter Lampitt at System3R for provision of the vibration damped workpiece pallet system. Finally we are indebted to Dr. John Webster of Cool Grind and staff at Pumps & Equipment (Warwick) Ltd. for technical support / advice in relation to fluid supply and in particular laminar flow nozzle technology.

5 REFERENCES