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Electrochemical superabrasive machining of a nickel-based aeroengine alloy using mounted grinding points

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ABSTRACT

Brief design and manufacture considerations are detailed for a hybrid electrochemical grinding unit adapted from a vertical machining centre using a 40,000 rpm spindle and 500 A DC generator. Subsequently, experimental work is presented on the influence of tool bond systems, superabrasive grit type and electrical parameters when simultaneous ECM/grinding Udimet 720 using 10–15 mm diameter plain points. Single layer electroplated CBN tools produced *G*-ratios and maximum normal cutting forces of ~451 and ~45 N, respectively, compared to ~128 and 557 N for equivalent diamond wheels. Data on workpiece roughness and overcut are also presented as are initial results for a fir tree shaped tool.

1. Introduction

The machining of complex turbine/compressor blade root mounting slots in aeroengine discs, is currently the focus of research involving several of the world's leading aeroengine manufacturers. It is aimed at identifying an alternative process to broaching [1,2], which will provide lower setup, validation and tool changeover times with increased productivity. While there are relatively few options for finishing slots, there are a number of viable possibilities when roughing [3], some of which are currently used in production and include conventional milling, creep feed grinding (CFG), abrasive waterjet cutting (AWJC) and electrical discharge wire machining (EDWM). Both AWJC, see Fig. 1(a) [4] and EDWM are able to produce profiled as well as plain slots, the former also being feasible with 'bell' or 'christmas tree' end mill cutters, involving either a solid WC arrangement or tool employing indexable inserts.

With grinding (CFG or otherwise) of the root form to finish size and specification with a cup wheel or similar as shown in Fig. 1(b) [5], the feasibility of the approach is dependent on root slot geometry and scale. This is not the case with point grinding or pencil grinding, involving the use of small diameter (<~35 mm Ø) superabrasive single layer electroplated grinding wheels, the rotational axis of which is radial with the disc [1,2], see Fig. 1(c). Here pre-slotting prior to finish point grinding is necessary and reported work has focused mainly on CFG with moderate size conventional abrasive wheels to produce either a 'v' shaped slot or modified trapezoidal slot or the use of EDWM to cut both plain and full form slots.

Depending on the shape and accuracy of the pre slot, subsequent machining may involve a single pass using a shaped grinding point in a creep feed mode with both sides of the slot machined simultaneously, or more realistically multiple single sided passes in a down grinding mode, in order to obtain the required workpiece integrity. This obviously necessitates using a grinding point or wheel which is smaller than the slot. In either event, use of a partial or full form grinding point to cut the slot from solid using only abrasion to remove material, is an unlikely scenario. A hybrid approach where two or more material removal processes act simultaneously offers more scope, if not to enable a single cut from solid, then as a means to increase productivity in completion of an intermediate (semi finishing) or finishing task. Typically such approaches involve the combination of different physiochemical actions [6]. Electrochemical/electrolytic point grinding (ECPG) appears as a potential hybrid candidate for disc blade root slot manufacture.

Over the past decade the level of ECM research has diminished, although there has been significant developments in relation to machining accuracy/overcut through pulsed operation, its use in microfabrication, surface finishing and related work in dressing together with bio-implant manufacture [7–9]. Hybrid ECM processes such as electrochemical grinding (ECG) have the advantage of employing an abrasive action (5–10% of material removal) to remove any oxide/passivated layer from the workpiece and so there is less need to utilise harsh/harmful electrolytes. Much of the publications on ECG date to the late 1970s and early 1980s and typically involve the use of large (150–250 mm Ø) conventional abrasive and superabrasive metal bond wheels. Although few in number, several recent papers detail the use of smaller diameter wheels under numerical control, for the machining of contoured surfaces [10]. The present work aimed to evaluate hybrid ECG with small wheels.

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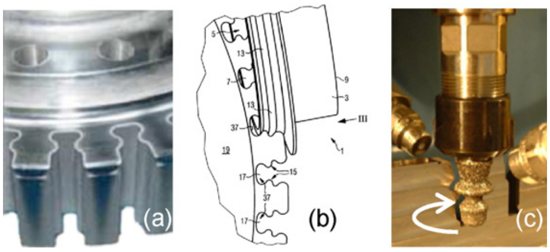

Fig. 1. (a) AWJC of blade mounting slots [4], (b) slot grinding using cup wheel [5] and (c) point grinding of slot.

2. ECPG machine design and manufacture

The ECPG unit developed for the present work was based on a commercial 3 axis CNC vertical machining centre. Modifications incorporated included the addition of an insulated retrofit high speed spindle (up to 40k rpm) and commutator assembly, laminar flow nozzles, control systems to provide machine interlocks, spindle control and accommodate a 500 A, 20 V DC generator, machine sealing with internal cavity protection against electrolyte ingress/contamination, the addition of a mist extraction system and electrolyte storage tank/filtration system, modifications to the table to incorporate a containment tank with in situ piezoelectric force dynamometer, insulated stainless steel vice and ECM power supply pickup, spindle power monitor device and data acquisition hardware.

The two schematics in Fig. 2 provide more detail of the spindle arrangement, in particular the copper commutator ring attached to the bottom of the unit which was balanced to *G* 2.5, together with the contact brush housing and assembly. In preliminary trials to test the effectiveness of the commutator over the full speed range, significant brush bounce and drift occurred with increasing rotational speed, although this was to some extent mitigated by the use of stronger springs; see continuity data shown in Fig. 3. As a consequence, spindle speed was limited to 20k rpm in subsequent experimental work.

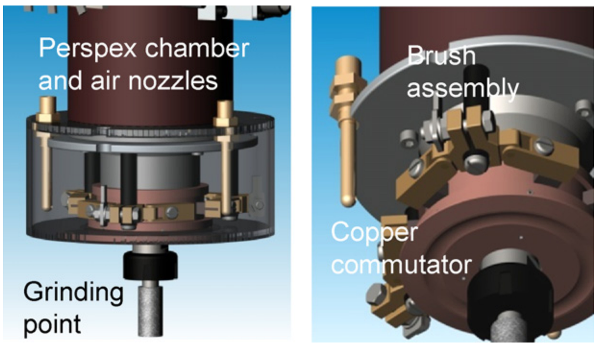

Fig. 2. Schematics of commutator ring, contact brush housing and Perspex chamber with compressed air input.

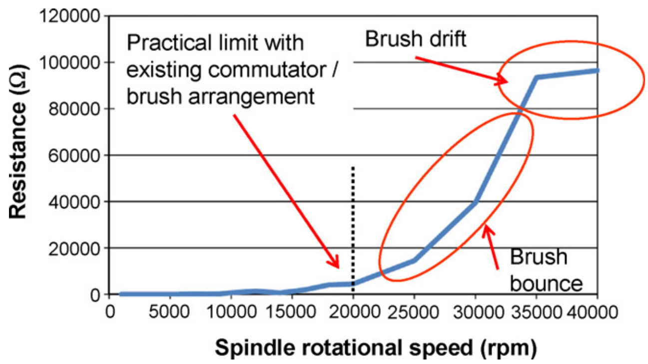

Fig. 3. Spindle continuity graph showing 20k rpm limit.

3. Experimental work

3.1. Workpiece material and experimental procedure

Workpiece specimens were flooded in an 11.5 wt% sodium nitrate ($NaNO_3$) solution in water during machining. The workpiece material was a solution treated and aged nickel-based superalloy Udimet 720, with a bulk hardness of ~44HRC. Grinding points employed were primarily plain wheels ranging between 10 and 15 mm diameter with up to 30 mm of abrasive of varying grit size, type and bond system (detailed further later in the paper).

The work reported here details tests to investigate: (i) the influence of grinding point bond system (resin, metal and single layer electroplated) and (ii) the effect of grit type (diamond/cBN). Three test strategies (multi-pass tests, stop tests and feed rate tests) were employed to evaluate the performance of the ECPG process against selected output measures. Multi-pass tests across the length of the workpiece were designed to ascertain the stability of the operation when machining using the 'baseline' tool feed rate over a pre-determined volume of material to be removed (~5400 mm^3 after 30 passes). This baseline feed rate represented here by f_{MRR}, was established in the same way as for a standard ECM process based on Faraday's Law, i.e. by equating it with the product of the specific dissolution rate of the workpiece material and current drawn (material removal rate, MRR) over the projected area of the tool. The process was assumed to achieve a current density of 116 A/cm^2, in accordance with the *Machining Data Handbook* [11] for the alloy–electrolyte combination used in this research. Stop tests involved machining (with feed rate f_{MRR}) over the pre-ground reference surface on the test piece across half its length, before rapidly retracting the tool away from the workpiece. This allowed the breakdown of material removed due to ECM and grinding respectively to be ascertained, together with measurement of any corresponding overcut. Feed rate tests were subsequently carried out to evaluate the effect of increasing tool feed rate on the ECM process and overall ECPG productivity. This was achieved by varying the grinding point feed rate during a cut between $0.33f_{MRR}$ and $1.66f_{MRR}$ mm/min at intervals of $f_{MRR}/3$ (5 levels of feed rate). The pass initially commenced with the ECM generator switched off (pure grinding) after which the current was applied and the feed rate cycled through the specified levels, each for a distance cut of ~7 mm.

As previously outlined, all tests were performed at a rotational speed of 20,000 rpm while a constant depth of cut of 0.5 mm was maintained throughout the experiments. Other fixed parameters included the flow rate (22.5 l/min) of the electrolyte which was supplied to the ECM gap through a laminar flow nozzle (aperture of 20 mm × 1.0 mm) at an operating pressure of 1.96 bar (4.41 bar maximum) giving a corresponding jet velocity of 18.75 m/s. An upper limit voltage was set but varied in operation between 4 and ~15 V based on the level of current drawn.

Tests were undertaken initially to determine the influence of the bond system. Here, a 15 mm diameter resin-bonded tool with copper binder and a bronze-based metal bond wheel both employing D76 grits were benchmarked against two variations of single layer, nickel electroplated (Type A and Type B) grinding points produced with slightly larger D91 sized abrasives. Unfortunately, the full bond composition of the tools cannot be disclosed due to commercial confidentiality. The baseline feed rate f_{MRR} was 10 mm/min. Diamond and cBN grits with similar morphology and particle size distribution (average diameter of 151 μm) were selected for trials to evaluate the effect of grit type. Grinding points supplied were plain nickel electroplated 10 mm diameter wheels. Due to the smaller tool size (hence difference in contact length), the f_{MRR} was 8 mm/min. Brief details are also presented of work involving ECPG with profiled tools.