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An investigation into the challenges of the point grinding machining process

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Abstract

Point grinding is an abrasive machining process that utilises miniature single layer superabrasive tools to remove material. The use of such small diameter tools offers advantages in the manufacturing of small or difficult to access complex 3D geometries, however, in their current state, these tools suffer from several critical challenges preventing their successful implementation. An investigation into the use of a typical commercially available point grinding tool for machining of hardened steel components has been carried out, with the aim of identifying the critical process challenges. The requirement for high rotational speeds, high tool deflection, variation in grit protrusion heights and bond layer thickness, accelerated tool wear, increased sensitivity to runout, zero cutting speed at tooltip and high tool loading have been identified as the main issues affecting the point grinding process. It is crucial that these challenges are correctly understood to facilitate future tool development.

Keywords: Point Grinding; Grinding; CBN; Machining;

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1. Introduction

The global demand for air travel has been rising sharply over the last five years, with further growth predicted over the next 20 years [1]. In order to address this rising demand, aerospace component manufacturers are required to continuously refine the materials used, component design, and manufacturing techniques, with a focus on assuring quality and improving performance. Such requirements often lead to a push for new manufacturing techniques to be employed, in turn, meaning that manufacturing processes that were previously not suitable or affordable may now offer a promising solution to the arising manufacturing challenges. One example of such a process is point grinding.

Grinding, as a whole, is a machining process that utilises hard abrasive particles as a cutting medium to remove material. It is applied in the manufacturing of components that require a high-quality surface finish and fine tolerances as well as in machining of difficult to cut materials [2]. A wide range of grinding wheels with respect to their shapes, sizes, and types of abrasive exist, including single-layer superabrasive wheels. The latter, contain only a single layer of superabrasive grains (CBN or Diamond) secured to a metallic substrate via the electroplating or brazing processes [2,3,4].

The point grinding process is a subset of the broader group of grinding operations, which utilises miniature single layer superabrasive tools to accurately machine complex 3D surfaces. The term “point grinding”, as applied here, has been previously referred to using other terminologies such as miniature grinding [5], super abrasive machining (SAM) [6], and grinding with mounted points [7] to describe the same process. The key differentiating factor between conventional grinding and point grinding is the diameter of the grinding wheel. The conventional grinding process utilises large-diameter wheels, which typically range between 100-300mm,

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whereas point grinding operates at significantly reduced diameters of 15mm or below [8,9,10].

Following on from the first uses of point grinding tools and cutting parameter optimisation studies [7], the earlier work within the field, focused on assessing the viability of point grinding for machining of nickel superalloys, intending to apply the technology for grinding of root mounting slots in turbine discs [8]. Despite a series of issues with tool scarring as a result of runout, bond failure, and high roughness of machined surfaces, the early process proved capable of producing parts with improved fatigue resistance, as a result of beneficial compressive residual stresses [8]. Further studies considered the effect of superabrasive type, grit size, and cutting parameters on tool wear, grinding forces and surface roughness [11]. While parallel developments in the use of braze bonding in the conventional larger-scale single layer tooling were underway [12,13], point grinding research began to incorporate the same methodology, comparing brazed and electroplated type tools, while additionally studying the effect of various coolant environments on tool wear [14]. Similarly, with the growing understanding of surface integrity and its impact on the functional performance of machined components, research into the influence of process parameters on the surface and subsurface condition of steel [5], nickel, and titanium alloys [10] within a point grinding context was also carried out. Alongside root mounting slots in turbine discs, the process also naturally lends itself to the manufacturing of holes [8], and recently, work has been carried out to investigate the wear rates and grinding force response for brazed CBN point grinding tools [15]. The latest research in the point grinding field has focused on investigating the influence of abrasive grit size and cutting parameters on tool wear and efficiency of the grinding process [16].

The relatively small size of the point grinding tools offers a key advantage, allowing the grinding of small or difficult to access 3D geometries, where a conventionally sized wheel would not be suitable [16]. The use of superabrasive grains in single-layer configuration, is also advantageous, allowing the grinding of hardened materials at high removal rates while maintaining consistent part quality and profile accuracy [3,4]. Finally, when combined with a tool changeable attachment spindle, as applied in this study, the overall flexibility of the grinding operation is increased, potentially removing the need for large grinding machines and allowing integration with other machining processes.

Despite the advantages mentioned above, the process also suffers from several critical challenges. Some of these have been previously observed, such as the need for high cutting speeds and rapid wear of the abrasive grains, due to the small diameter of these grinding tools [8,15,17]. However, it is vital to gain a more detailed understanding of all the key process challenges that prevent the successful implementation of the point grinding tools, in order to facilitate any future development and optimisation work.

2. Experimental Methodology

In order to identify the critical challenges associated with the use of point grinding tools, grinding tests were designed and conducted on a DMG Mori NVX5080 three-axis vertical machining centre. Two combinations of feed rate (v_w) and cutting speed (v_s) were investigated, a slower approach (v_w=300mm/min; v_s=9.1m/s) and a more aggressive approach (v_w=700mm/min; v_s=7.6m/s), resulting in a larger undeformed thickness in the latter, at a constant 0.015mm radial depth of cut up to a 4000mm total length of cut over 52 grinding passes. The cutting speed was controlled by varying the position on the tapered point grinding tool, resulting in two nominal rotational speeds. The experimental setup can be seen in Fig 1(a). Based on a review of the typical commercially available point grinding tools, 6mm diameter tapered tools were selected for this investigation. The tools consisted of an M42 high-speed steel body, utilising a B76 CBN abrasive grain within a nickel electroplated bond (Fig.1 (b))

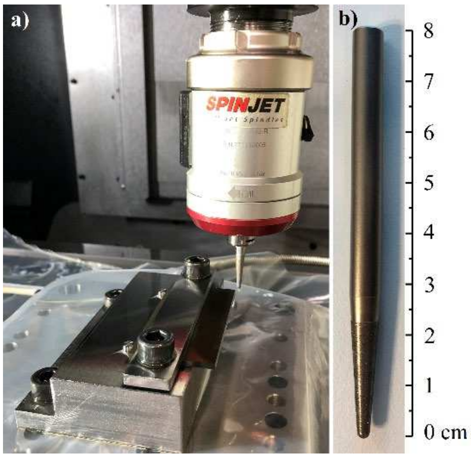

Fig. 1. (a) Experimental setup; (b) 6mm diameter tapered B76 CBN point grinding tool.

To achieve sufficient peripheral cutting speeds, a through tool coolant driven attachment spindle (Calibri SpinJet) capable of producing rotational speeds up to 42,000rpm was used. Through spindle emulsion coolant was supplied at 28bar pressure at the pump, resulting in the idle tool rotation speed of 40,700rpm, while the actual in-cut rotational speed was recorded using a wireless rpm monitor.

The material used for this investigation consisted of 3mm thick plates of D2 tool steel, heat-treated to achieve a through hardness value of 60HRC. The plates were cut into 77mm long sections and attached to a Kistler Type 9129AA Multi-Component Dynamometer to measure grinding forces at a sampling rate of 50,000Hz, equivalent to 75 data points per revolution of the tool. The roundness and total runout of the tool shanks were measured using the Talyrond 565 XL roundness tester. In addition, the point grinding tools were examined using Scanning Electron Microscopy (SEM) before and after the grinding operation, to gain a more detailed understanding of the abrasive surface topography.

3. Results and Discussion

3.1. Tool Roundness and Runout

A highly variable total runout of the tool blanks, ranging from 10.66μm to 21.76μm, with an average value of 18.01μm, was observed. This significantly exceeded the depth of cut used in this investigation. Furthermore, the measured roundness profiles showed high-frequency oscillations caused by roughness as well as low-frequency variations forming tri-lobed profiles. The latter could be linked to the manufacturing process of blanks, most likely caused by using 3-jaw chuck clamping systems. Fig. 2(a,b) shows representative examples of the results that were consistently observed in all tools. Such deviation of the tool geometry from an ideal circle would lead to an uneven engagement of the tool around its circumference when grinding, resulting in variable grinding forces, uneven tool wear, and dynamic issues.

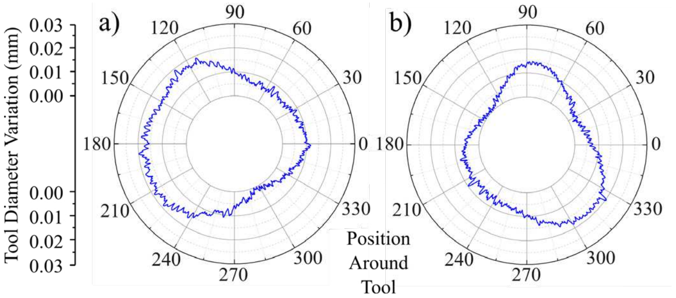

Fig. 2. Tri-lobed appearance of the ground M42 steel tool blanks.

3.2. Grinding Forces

Fig 3(a) shows the evolution of the normal grinding forces throughout the grinding operation, wherein the normal force increases rapidly during the early stages of the process followed by a steady rise up to the end of the experiment. Such behaviour is typical of unconditioned single layer grinding tools, as previously reported in the literature, and has been attributed to a change in the wear mechanism of the grains [18,19]. The initial transient increase in grinding force is likely caused by wear as a result of pullout and macro fracture of the outermost and weakly held CBN grains, while the steady-state region of increase in force is most likely dominated by wear through attrition and microfracture leading to increasing forces [4]. Additionally, the normal grinding forces over the final 20 revolutions of the tool during the final pass are plotted on the radial-axis against the angular location on the tool (Fig. 3(b,c)). The tri-lobed appearance of the tool shanks can be seen replicating in the grinding forces, resulting in low-frequency cyclical variation or lobing around the tool periphery. Furthermore, as the aggression of the grinding parameters increased, through combinations of increasing feed and decreasing cutting speed, high-frequency vibration of the grinding tool was observed (Fig. 3(b)).

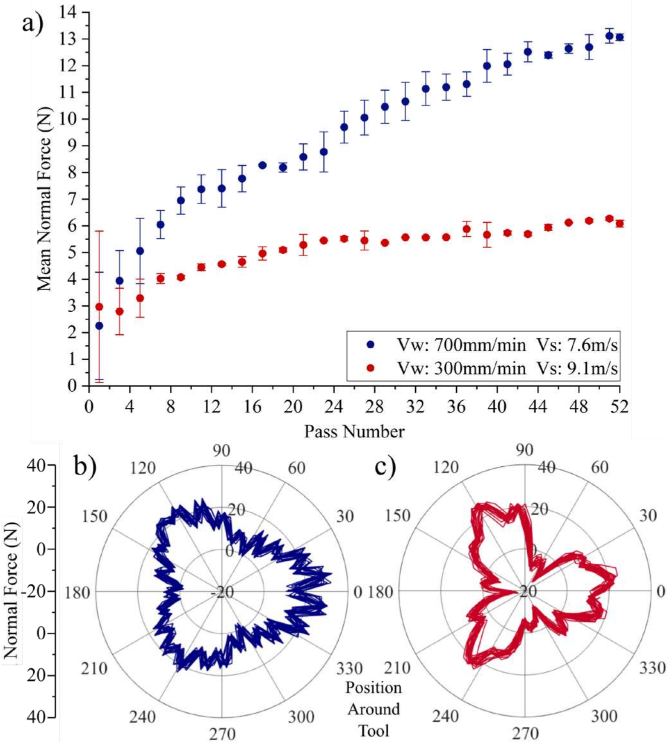

Fig. 3. (a) Mean normal force evolution and standard error (a_e=0.015mm); (b,c) unfiltered normal grinding force during the final 20 revolutions.

3.3. Tool Surface Assessment

A qualitative assessment of a representative point grinding tool surface was carried out using Secondary Electron (SE) micrographs before and after grinding. As can be seen from Fig. 4 (a,b), the CBN grains have an angular or irregular morphology, in most cases, orientated with a sharp edge protruding upwards. It is also evident from these images that a significant range of grit protrusions above the bond layer exists. Some abrasive grains appeared securely held on the surface of the tool. However, a large number of grains also appeared as barely protruding or completely submerged below the plating layer. These grains are unlikely ever to become active and, therefore, will not participate in material removal. Other grains were seen to over-protrude, appearing loosely bonded to the surface with only a small portion of the grain held by the bond, and would likely be immediately pulled-out from the tool surface upon contact with the workpiece. This large variation in the grit protrusion heights above the bonding layer is consistently reported in the literature and presents a challenge that leads to a significant reduction in the life of such point grinding tools [4,18]. Several grain failure mechanisms can be observed on the surface of the worn tool, including pullout and macro fracture (Fig. 4(c,d)). However, the majority of the observed grains contained signs of flattening of the most protruding tips, where fracture like surfaces are visible as opposed to the striation marks, which are typical of attrition wear. This suggests that the dominant wear mechanism leading to their formation is microfracture. Additionally, it was found

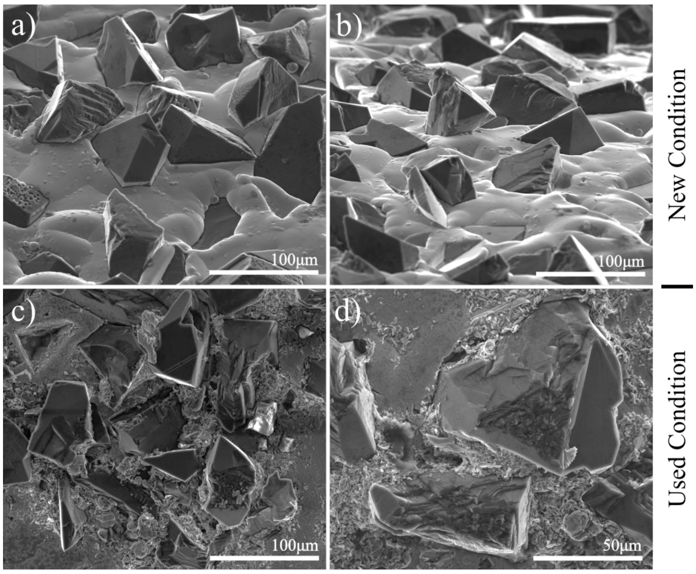

Fig. 4. SE SEM micrographs of a representative (a,b) unworn and (c,d) worn single layer electroplated CBN point grinding tool surface at (a-c) 1000x and (d) 2000x magnifications.

that loading of the tool surface occurred, especially in regions where clusters of abrasive grains were present, as shown in Fig. 4(c). Although flood cooling was supplied during grinding through the attachment spindle, it had a minimal scrubbing effect on the wheel surface. This presents another challenge for the application of point grinding on conventional machining centres, as high-pressure external coolant supply is required to evacuate chips from the wheel's surface [16].

3.4. Other Challenges

Previously conducted point grinding research has revealed high rates of tool wear, which was also highly uneven around the wheel periphery as a result of runout [8,16]. Similar observations were also made in this investigation. Due to the small size of the point grinding tool, the quantity of abrasive grains within the active grinding region is significantly reduced. When combined with the high hardness of the workpiece material, this leads to accelerated wear rates. The problem is aggravated further in the case of variable diameter tools. As the tool diameter decreases, the peripheral cutting speed tends towards zero, and the abrasive quantity decreases further. This results in a rapid increase in chip thickness and cutting forces, in turn leading to localised accelerated wear. In extreme cases, abrasive grains have even been completely stripped from the surface [8].

The accelerated wear rates also have a progressively more significant impact on rotational speed when utilising a coolant driven spindle. As such spindles operate at a constant supplied coolant pressure, a drop in rotational speed is observed when the tool engages. As the power demand on the spindle increases, through wear and loading, the in-cut rotational speed decreases further. Although a small level of control is possible by adjustment of the supplied coolant pressure, the spindle is limited by a maximum allowable pressure, making this more challenging when utilising more aggressive cutting parameters.

Tool deflection is also a more significant issue when compared with conventional grinding wheels. Caused by a combination of high cutting forces and small diameter of the tools, deflection leads to incorrect actual depth of cut, part dimensional inaccuracies and tapers [2]. In this investigation, a large and highly variable undercut was observed on all samples following grinding as a result of deflection. Others have previously reported tool deflection as a challenge for the application of point grinding [17].

4. Conclusion

Based on the results of the investigation summarised here, and a review of the previous work conducted using point grinding tools, it is clear that several critical issues with the current technical state of the point grinding tooling exist. These present a substantial obstacle preventing their successful implementation for the manufacturing of high-value aerospace components. A list of the key process challenges identified here is as follows: a requirement for high rotational speeds, high tool deflection, variation in grit protrusion heights and bond layer thickness, accelerated tool wear, increased sensitivity to runout resulting in vibrations and uneven tool wear around circumference, zero cutting speed at tooltip and high tool loading. Some of the key point grinding challenges, such as high wear rates and deflection, can to an extent be controlled by optimisation of the cutting parameters, and additional studies investigating this are required. However, more significant tool development work may be necessary to successfully address the majority of the issues, allowing the full utilisation of the advantages of the point grinding process, paving the way for its wider application.

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