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Abrasive machining of advanced aerospace alloys and composites

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ABSTRACT

The aerospace industry has experienced significant growth over the past decade and it is estimated that nearly 30,000 new commercial passenger aircraft will be required by 2030 to meet rising global demand. Abrasive machining is a key material removal process utilised in the production of aeroengine components. Current industrial practice and perspectives relating to grinding in the aerospace sector are presented including general workpiece surface integrity standards/requirements, fluid delivery systems, wheel preparation options and machine tool designs/configurations. Corresponding academic research on the machinability of aerospace alloys and composites are critically reviewed together with recent developments involving novel/innovative grinding processes.

1. Introduction

The worldwide market for civil aircraft is rising in line with increasing global population and affluence. Growth in new airplane deliveries is expected to be at an average of 3.6% per annum up to 2030 [114]. This naturally translates to a greater demand for gas turbine engines, which places significant strains on current as well as future supply chain and production capacity.

Commercial pressures for continuous improvement in aeroengine performance and fuel efficiency have driven the development of materials with increasing temperature limits at affordable cost [65]. This is evident from the evolution of materials composition in engines, with the trend moving towards alloys with higher temperature capability (from steels to nickel and titanium alloys) and materials with lower density (aluminium to carbon fibre composites). Although not fully mature, ceramic and metal matrix composites (CMC and MMC) are showing evidence of replacing some of the high temperature alloys that dominated engines towards the end of the 20th century. The constantly changing state of aeroengine materials technology is another factor that will considerably stretch the limits/capability of established manufacturing processes and therefore further emphasises the critical need to develop more advanced and robust production techniques.

Despite the rapid development and increasing acceptance of non-conventional machining processes for the manufacture of turbomachinery parts [123], grinding is still one of the primary operations in the finish machining of critical gas turbine engine components. This is due to the strict requirement for achieving tight dimensional tolerances of $<10\ \mu m$ and superior surface finish with roughness in the order of $<0.5\ \mu m$ Ra together with acceptable workpiece quality/integrity.

The keynote will discuss the latest developments in academic research together with current state-of-the-art relating to abrasive machinability of key aerospace alloys and composite materials, fluid delivery and wheel preparation strategies, machine tool technologies and innovative process configurations, as well as example case studies and perspectives from practitioners in the aeroengine manufacturing sector. The paper complements a sister keynote to be presented in STC-C relating to the 'High performance cutting of advanced aerospace materials' as well as the keynote delivered last year (2014) in STC-E [123].

2. Workpiece surface/sub-surface integrity requirements

Aeroengine discs are categorised as critical components and are therefore subject to highly stringent dimensional accuracy, surface integrity and fatigue requirements. It is well documented that the functional performance of parts subject to machining processes is strongly affected by the resulting material surface/subsurface integrity conditions [111]. Publications detailing investigations relating to the influence of material removal processes on workpiece residual stresses initially appeared in the 1950s. However, Field and Kahles [66] were the first to define the concept of surface integrity and propose associated methodologies

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for assessment, with particular application to machining processes [67,68].

While specific standards of workpiece surface integrity and acceptance criteria for aerospace components exist, they are commercially sensitive and closely guarded, which precludes full disclosure in the public domain. Nevertheless, surface integrity/metallurgical assessment of the workpiece condition following grinding is typically undertaken to confirm the absence of various anomalies including cracks, amorphous/recast layers, re-deposited/foreign material, contamination and work hardening, none of which would be acceptable. In addition, the analysis can also encompass residual stress measurement and cyclic life assessment.

3. Abrasive machinability of aerospace materials

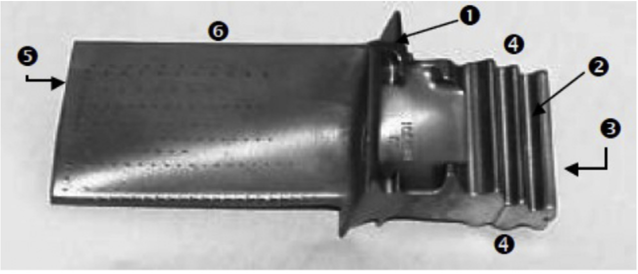
3.1. *Stainless steels*

Stainless steel is typically utilised for the manufacture of jet engine shafts and aircraft structural components such as fasteners and landing gears requiring elevated strength, high fracture toughness and exceptional ability to withstand stress corrosion cracking. The first stainless steels employed in the aviation industry were the low-alloy martensitic steels, AISI 4130 and AISI 4340 [245]. In 1978, Little and Machmeier [143] patented the secondary hardening ultra-high strength steel AF1410, which was based on HY180 but with increased toughness and corrosion resistance [245]. This was further improved through the introduction of AerMet 100 in the 1990s by Carpenter Technology Corporation, which is currently widely utilised in the aviation industry due to its superior fracture toughness and corrosion stress resistance [245].

Xu et al. [242] studied the abrasive machining of AerMet 100 using white Al_2O_3 vitrified grinding wheels. Tensile residual stresses were detected in the top surface layer, which crossed over to the compressive regime when moving deeper into the subsurface zones. The influence of single and white Al_2O_3 as well as cubic boron nitride (CBN) wheels on resulting force and temperature when surface grinding AerMet 100 (v_w = 8–14 m/min, v_s = 20–30 m/s, a_p = 5–25 μm) was assessed by Yao et al. [245]. Both grinding force (up to ~290 N) and temperature (up to ~735 °C) were highest when utilising the single Al_2O_3 wheel, while tests with CBN resulted in reduced forces and temperatures of up to ~75% and 100% respectively, as well as smaller heat affected zones. The superior performance was primarily attributed to the higher thermal conductivity of the CBN grain (133 W/m K) compared to Al_2O_3 (35 W/m K) abrasive. Subsequent trials also highlighted that compressive residual stresses up to ~1000 MPa extending to a depth of ~30 μm was obtained when surface grinding AerMet 100 using CBN wheels at a workpiece feed (v_w), wheel speed (v_s) and depth of cut (a_p) of 18 m/min, 14 m/s and 10 μm respectively [246]. In contrast, the majority of trials involving white Al_2O_3 wheels exhibited tensile residual stresses similar to that reported by Xu et al. [242]. The feasibility for creep feed grinding of AISI 420 stainless steel using a vertical high-speed machining centre was demonstrated by Dewes et al. [51]. Despite grinding forces of up to 650 N, no problems occurred with regard to spindle power or vibration/instability. The alumina-based wheel utilised achieved a maximum *G*-ratio of 41, with no apparent signs of workpiece burn.

3.2. *Nickel based superalloys*

Nickel based superalloys constitute 40–50% of engine weight in current commercial aircraft and are deployed particularly within the combustor and turbine sections where operating temperatures can exceed 1250 °C [189,201]. Turbine blades and nozzle guide vanes (NGV) are formed through complex investment casting processes capable of precisely controlling the grain boundary structure. Components that contain columnar grains fabricated through directionally solidified (DS) casting generally have a ~25 °C higher operational temperature limit compared to equiaxed parts. This is because the grain boundaries of DS blades are aligned along the principal stress direction parallel to the airfoil length [39]. A further 25 °C boost in allowable blade operating temperature can be achieved by single crystal (SX) airfoil castings, which do not contain any grain boundaries [189]. While modern high-pressure turbine airfoils are either DS or SX cast, the rear sections/cooler stages of the turbines are manufactured from equiax grained alloys. Structural components such as engine casings are similarly produced via investment casting while wrought processes involving cast ingots or consolidated superalloy powder preforms are applied to fabricate turbine discs [180].



1 Shoulder (convex & concave) 4 Front face
2 Fir tree profile 5 Blade top
3 Root end profile 6 Trailing edge

Fig. 1. Ground features on a high-pressure turbine blade [228].

Grinding is a key process for the manufacture of blades and vanes as economic machining of cast nickel-based superalloys using defined cutting edge operations is difficult. Depending on part design, up to 12 distinct abrasive cutting operations are required to machine a blade, see Fig. 1 [228], including face, plunge, profile and arc grinding. Arguably, the most important feature on a blade is the ‘fir tree’ shaped profile at the root that locates it into the rotor [86].

The process of turbine blade grinding in the aeroengine industry has seen significant evolution over the past 60 years. Use of creep feed grinding (CFG) at low table speeds and large depths of cut with soft and porous Al_2O_3 wheels at low cutting speeds (15–30 m/s) was predominant in the 1950s. Intermittent dressing using formed diamond rolls was the principal method for wheel preparation. The advent of continuous dress creep feed (CDCF) grinding in the 1980s allowed for much higher material removal rates, with roll dresser infeed levels of between 0.5 and 2.0 μm/rev preserving wheel profiles and keeping Al_2O_3 grits sharp. An alternative configuration when operating at wheel speeds of up to 80 m/s is high-speed continuous dress (HSCD) creep feed grinding. Infeed levels in HSCD are a factor of 5 to 10 larger compared to CDCF [166]. Unfortunately, the radically faster wear rate of grinding wheels and dressers when using HSCD has thus far prevented any widespread industrial application.

Fig. 2 shows a metallographic cross-section of an IN738LC workpiece following creep feed grinding using an intermittently dressed Al_2O_3 wheel. A 5 μm thick white etch layer is clearly

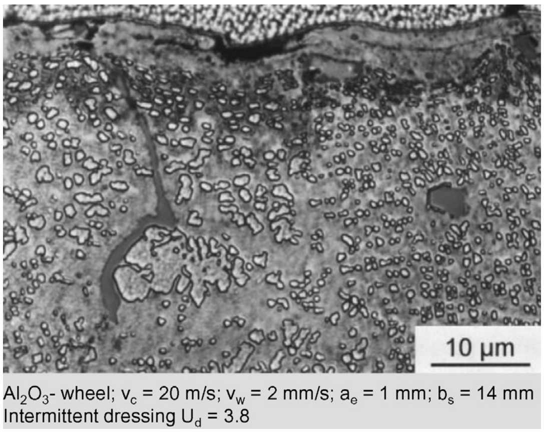


Fig. 2. Machined subsurface of IN738LC following CFG [173].