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# Workpiece surface integrity when milling Udimet 720 superalloy

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## Abstract

The paper details a comprehensive investigation into the surface integrity of Udimet 720 following end milling under different environment conditions (dry, flood, higher pressure and MQL) and cutting speed (25 and 50m/min). Surface roughness (Ra) was < 0.25 μm regardless of tool condition with no white layers detected on any of the samples analysed. Residual stress measurements indicated surface compressive stress of 120 MPa on workpieces milled using new cutters under MQL environment. In contrast, worn tools produced surface tensile stresses of ~80 MPa, with subsurface compressive residual stress of up to ~400 MPa at a depth of 80 μm.

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*Keywords:* *Milling; nickel alloy; cutting environment*

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## 1. Introduction

Nickel based superalloys such as Udimet 720 are a group of materials that are key to the aerospace industry and often contribute to over half the weight of gas turbine aero engines [1, 2]. Udimet 720 has good resistance to creep, corrosion, and mechanical and thermal fatigue, making it suitable for use in extreme environments [2]. It's ability to maintain high strength at elevated temperatures means they are utilised mainly in the turbine end of the engine, where temperatures can exceed 1650 K [2]. This along with a strong chemical affinity to many tool materials, high work hardening rates when subjected to high strain rates and relatively poor thermal conductivity (typically < 20 W/m.K) means that nickel based superalloys are notoriously difficult to machine [1]. This poor machinability means that meeting the high level of surface integrity required from the aerospace sector can be a costly and time consuming process [1]. A recent literature review on the machining of nickel based superalloys suggests that only turning investigations have been reported for Udimet 720 alloy, with no milling studies published [3]. This is surprising given that milling is a key process for the production of aerospace casings, discs and other components.

Cutting fluids and often their method of application play a vital role in resulting surface integrity when milling difficult to machine materials as they have a large influence on the frictional forces, cutting temperatures and chip evacuation [4]. They are also closely linked with tool life as well as being an expensive part of the process themselves. Improvements in how fluid is utilised can thus provide many economic benefits. These benefits include but are not limited to: reduced machining time; reduced cost of fluids and tooling and reduced strain on machines [5]. Typically for milling of aerospace alloys copious quantities of fluid are used either in a flood form or at high pressure though directed nozzles. Minimum quantity lubrication (MQL) or near dry machining also shows potential for application because of the reduction in coolant volume [5] thus reducing the environmental impact.

The need for reliable and predictable processes in the aerospace industry means that extensive data is required to make any change viable, but due to the high cost and limited accessibility of the materials, few studies on the machining of Udimet 720 have been completed [1, 3]. The current study addresses the lack of machinability data for this alloy when end milling. In particular it focuses on the effect of operating parameters and cutting conditions on tool life and workpiece surface integrity including microstructure and residual stress.

## 2. Experimental work

The workpiece material used was Udimet 720 nickel based superalloy that was treated and aged to HV490-510. Trials

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were performed on a Mazak VCS430A vertical CNC machining centre with a maximum spindle speed of 12,000 rpm and maximum feed rate of 42,000 mm/min. A single circular 8 mm diameter tungsten carbide insert with a TiAlN PVD coating (product code: RDHW 0803MO-MD03-F40M) was held in a 20 mm diameter tool (product code: R217.29-1020.RE-04.3A), both produced by Seco. A single insert configuration was chosen to conserve workpiece material. Cutting environments including dry, flood (1 bar), higher pressure-HP (15 bar) and MQL were tested at cutting speeds of 25 and 50 m/min. Table 1 details the full test matrix. The feed rate was 0.1 mm/tooth, axial depth of cut was 0.5 mm and radial depth of cut 5 mm with down milling was used for all trials. These were chosen based on typical finishing conditions [6] and parameters used in previous work when end milling Haynes 282 superalloy [7]. No tests replications were performed due to time and resource limitations.

Table 1. Test matrix with operating parameter levels.

| Test | Cutting environment | Cutting speed (m/min) |
|---|---|---|
| 1 | Dry | 25 |
| 2 | Flood (1 bar) | 25 |
| 3 | HP (15 bar) | 25 |
| 4 | MQL | 25 |
| 5 | Dry | 50 |
| 6 | Flood (1 bar) | 50 |
| 7 | HP (15 bar) | 50 |
| 8 | MQL | 50 |

The fluid used for flood and higher pressure coolant application was Hocut 3380, supplied at 1 bar (28 l/min) and 15 bar (20 l/min) respectively. Flood coolant was supplied through 4 external nozzles whilst HP was delivered internally via the tool. Houghton V30ML ester based oil was supplied by an Accu-Lube MQL system. Air flow was regulated using an adjustable valve with a pressure of ~ 5 bar while oil flow was controlled according to the pump frequency cycle set at ~100 strokes/min, giving a lubricant flowrate of ~50 mL/hour. A single nozzle supplied the MQL oil at a distance of 50 mm from the point of cut entry.

Tool wear criteria were a maximum flank wear of 200µm with a machining time limit of ~90 minutes also applied to conserve workpiece material. This low tool wear criterion was chosen to represent practices common in the aerospace industry. For each set of machining parameters, a block (119 mm long) of Udimet 720 was machined with the tool wear measured and photographed periodically. The test was continued until the 200 µm wear criterion was passed or the maximum time was reached. A small workpiece block measuring 34 mm long was machined using the same parameters at the start of the test with the new tool and after the test with the worn tool to provide samples for analysis.

A Wild microscope combined with a toolmakers table and digital micrometre heads was used to measure tool wear, and a Canon EOS 400D digital camera used to capture images of the tool wear. The analysis completed was based on the minimum surface integrity data set [1]. A Taylor Hobson Form Talysurf 120L was used to measure the surface roughness, using a cut-off length of 0.8 mm and an evaluation length of 5 mm. The average of three measurements was recorded. Surface topographical defects such as adhered material were photographed using the same setup used to document tool wear. Small specimens were cut from the samples to analyse the subsurface microstructure both parallel and perpendicular to the feed direction. Specimens were cut to size, hot mounted in bakelite, ground using SiC paper, polished and etched using Kalling's reagent for 12 seconds. Microhardness depth profile measurements were obtained using a Mitutoyo HM 124 fitted with a Knoop indenter (25 g load and indent time of 15 seconds). Measurements were recorded at 10 µm increments from the surface until bulk hardness was achieved, with two more repetitions taken and the average calculated. Microstructure was analysed using the Leica microscope and Alicona Infinite Focus system.

Residual stress depth profile measurements were undertaken using the blind hole drilling technique. Target sites were prepared by thorough degreasing with acetone. Strain gauge rosettes type CEA-06-062UL-120 (Vishay Precision), were bonded to the workpiece surface using Loctite 407 adhesive. Each rosette was drilled using a PC-controlled 3-axis drilling machine. Depth increments were set at 32 µm (four times), 64 µm (four times) and 128 µm (eight times), providing a completed hole depth of 1.41 mm for the determination of stresses up to 1024 µm below the machined surface. Results from the individual target gauges were recorded in the form of relaxed strains, which were subsequently converted into stress values.

## 3. Results and discussion

Tool life measurements for the eight tests are shown in Fig. 1. As expected the higher cutting speed resulted in a lower tool life of approximately one third of the lower speed. Higher pressure (HP) cutting fluid provided the longest tool life for each cutting speed. At 25 m/min the maximum flank wear criterion of 200 µm was not reached after machining for 90 minutes whereas for 50 m/min the maximum flank wear criterion was reached after ~32 min. At the lower cutting speed of 25 m/min flood coolant outperformed MQL however for the higher cutting speed of 50 m/min the opposite was true. MQL reached the wear criterion after ~22 min and flood after ~14 min. Not surprisingly, dry cutting performed the worst with the shortest tool life for either cutting speed.

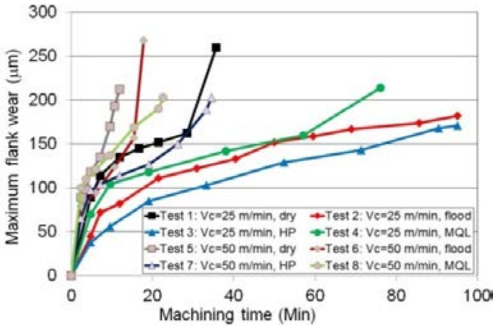

Fig. 1. Tool life measurements.

Images showing the tool wear at test cessation for tests 6 and 8 are provided in Fig. 2. The tool wear observed was generally uniform and similar for each type of operating condition and was very similar to the previous work performed when using a similar tool to mill the nickel based superalloy Haynes 282 [7]. The higher speed caused slightly less uniformity in the wear profile and possible instances of

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