Workpiece surface integrity when milling Udimet 720 superalloy

Hood, Richard; Morris, Jonathan; Soo, Sein

DOI:
10.1016/j.procir.2016.02.344

Document Version
Peer reviewed version

Citation for published version (Harvard):
Hood, R, Morris, J & Soo, S 2016, 'Workpiece surface integrity when milling Udimet 720 superalloy', *Procedia CIRP*, vol. 45, pp. 283-286. https://doi.org/10.1016/j.procir.2016.02.344

Available online at www.sciencedirect.com

SciVerse ScienceDirect

Procedia CIRP 00 (2016) 000–000

www.elsevier.com/locate/procedia

3rd CIRP Conference on Surface Integrity (CIRP CSI)

Workpiece surface integrity when milling Udimet 720 superalloy

R. Hood[a], J. Morris[a], S.L. Soo[a,*]

Machining Research Group, School of Mechanical Engineering, University of Birmingham, Edgbaston, Birmingham, B15 2TT, UK.

* Corresponding author. Tel.: +00 44 (0) 121-4144196; fax: +00 44 (0) 121-4144201. *E-mail address:* s.l.soo@bham.ac.uk

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.

Peer-review under responsibility of the scientific committee of the 3rd CIRP Conference on Surface Integrity (CIRP CSI)

Keywords: Milling; nickel alloy; cutting environment

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

2212-8271 © 2016 The Authors. Published by Elsevier B.V.
Peer-review under responsibility of the scientific committee of the 3rd CIRP Conference on Surface Integrity (CIRP CSI)

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.

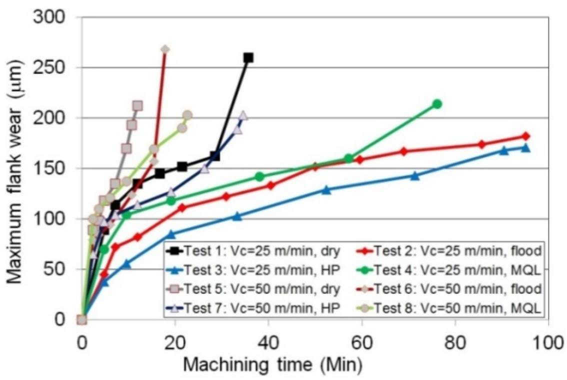

Fig. 1. Tool life measurements.

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 notch wear were observed at the higher cutting speed of 50 m/min with flood, HP and MQL.

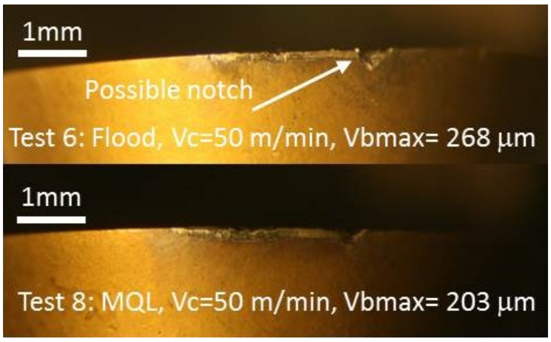

Fig. 2. Tool wear scar photographs.

Workpiece surface roughness Ra measurements ranged from a minimum value of 0.09 µm to a maximum of 0.25 µm as shown in Fig. 3. No discernible difference between measurements in the parallel or perpendicular to the feed direction was established hence only perpendicular measurements are shown. On average worn tools produced a 30 % lower surface roughness than new values and using a cutting speed of 50 m/min increased the surface roughness by ~30 %. Tests with MQL typically had the lowest roughness values whilst HP and flood coolant had the highest.

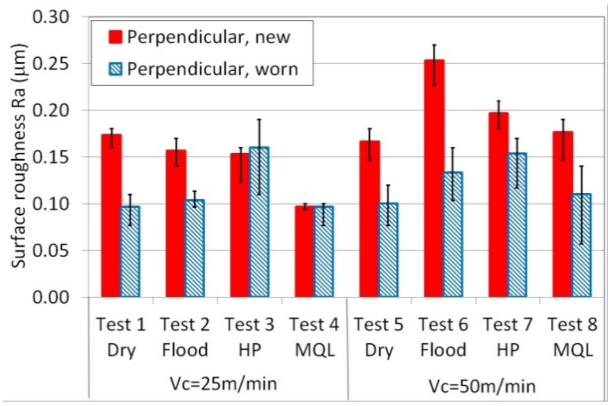

Fig. 3. Workpiece surface roughness measurements.

Examination of the machined surface under a microscope generally revealed a positive result with limited visible damage see Fig. 4 (a) and (b). Surfaces appeared free of defects with only the cutting marks observed. Burring with a depth of ~100 µm was experienced at the exit location of the sample when using MQL with a worn tool at 50 m/min only as shown in Fig. 4 (c). This was the only difference found between surfaces produced in the new and worn condition. All other samples showed low levels of burr formation. Adhered material was present on many surfaces with the highest level found on the dry samples. These included a couple at approximately 1 mm in length; see Fig. 4 (d). Only a small amount of adhered material was found on any of the flood condition test samples and none was found when using higher pressure cutting fluid. This lack of adhered material observed when using higher pressure coolant is in contrast to the similar studies on nickel base superalloys carried out by Soo et al. [8] and Hood et al. [7], where adhered material was found on all samples, but this could be due to slot milling used in the previous studies causing less efficient chip evacuation.

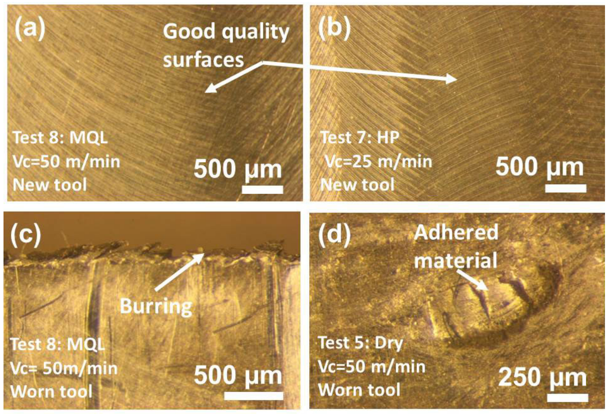

Fig. 4. Images of the workpiece surface.

No significant variation between the different machining parameters for the workpiece subsurface cross-sectional analysis was observed. Grains near the surface had no difference in size or structure to the bulk material and were not swept in the direction of the feed. Fig. 5 (a) produced using MQL at a cutting speed of 50 m/min in the perpendicular direction is indicative of all surfaces produced. This corresponds with the research done by Soo et al. [8] on RR1000, where no subsurface damage was observed for the tests with a feed rate of 0.1 mm/tooth. Li et al. [9] suggest that the interrupted nature of the milling process usually results in lower cutting temperatures and better surface integrity when compared to continuous tool/work contact processes such as turning. Small amounts of smeared/adhered material were observed only under dry conditions. A single instance of plucking was found; see Fig. 5 (b) for Test 4 using MQL at a cutting speed of 25 m/min on the parallel sample.

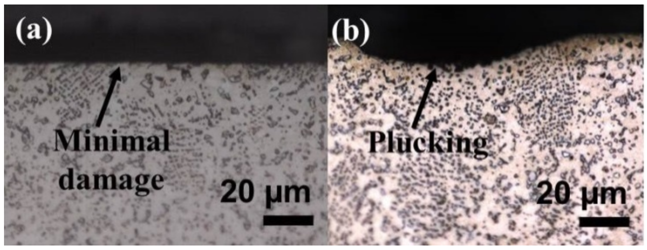

Fig. 5. Workpiece surface/subsurface images.

Microhardness depth profile measurements for the parallel to the feed direction are shown in Fig. 6. Similar values and trends were obtained for the direction perpendicular to the feed direction. The clearest trend appears to be for the difference between new and worn tooling. For each cutting speed there is an increase in the hardness of up to ~100 HK from a new tool to a worn tool. No discernible trend could be identified for the differences between the operating conditions. Trends were similar for either cutting speed suggesting that the range chosen provided a limited difference.

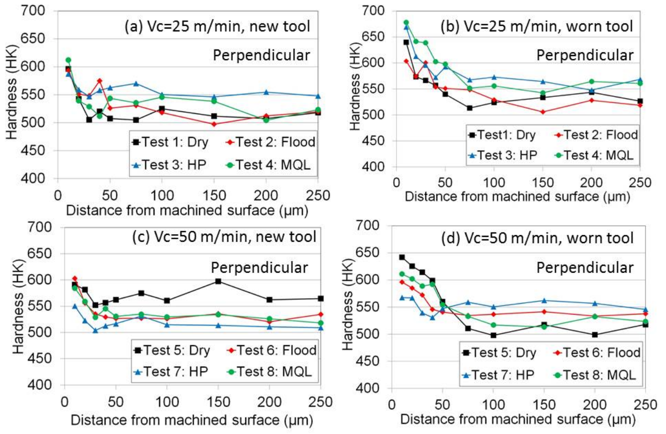

Fig. 6. Microhardness depth profile measurements.

Residual stress depth profile measurements undertaken using the blind hole drilling technique for Test 4 using a cutting speed of 25 m/min and MQL are shown in Fig. 7. The parallel and perpendicular profiles for each tool condition (new and worn) were almost identical. With a new tool, compressive stress of ~120 MPa was measured at a distance of 16 μm from the workpiece surface. This stress became neutral at a depth of ~75 μm from the workpiece surface. For a worn tool a tensile stress of 50-75 MPa was measured at a distance of 16μm from the workpiece surface. The stress then decreased almost linearly until a compressive stress of ~400 MPa was measured at a distance of ~80 μm from the workpiece surface. The stress then became neutral at a depth of ~225 μm from the workpiece surface. It is likely that higher cutting temperatures from the worn tool and greater surface burnishing was responsible for the tensile residual stress on the surface and the large compressive stress below the surface. Measurement uncertainty was ±85 MPa at a depth of 16 μm, ±19 MPa at a depth of 512 μm and ±23 MPa at a depth of 1024 μm.

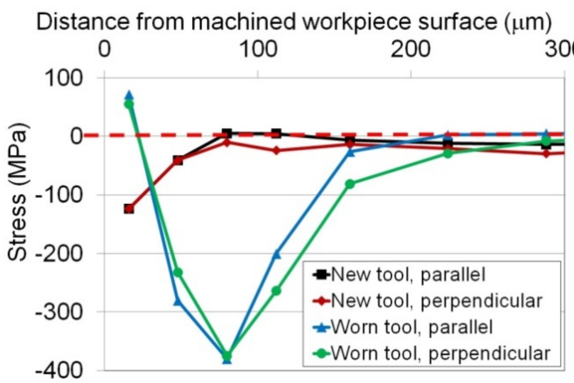

Fig. 7. Residual stress measurements for Test 4: v=25m/min, MQL.

4. Conclusions

- Assessment of tool life and workpiece surface integrity when end milling Udimet 720 using a variety of operating conditions and cutting speeds has been achieved.
- Higher pressure (15 bar) cutting fluid showed the best performance with the longest tool life of over 90 min at a cutting speed of 25 m/min. MQL showed a similar performance to flood with a tool life of over 20 min at a cutting speed of 50 m/min.
- Workpiece surface roughness values were <0.25 μm Ra, which is well within the required standard for aerospace applications. MQL cutting conditions generally produced the lowest levels with a value of Ra <0.1 μm obtained.
- No traces of thermal based damage such as white layers or heat affected zones were found on any of the surface/subsurface cross-sections analysed. This suggests that cutting temperatures were most likely low.
- Using MQL at a cutting speed of 25 m/min, compressive residual stress of ~120 MPa was measured with a new tool. For worn tools, tensile stress of 50-75 MPa was measured close to the surface, which became ~400 MPa compressive at a distance of ~80 μm from the workpiece surface.

Acknowledgements

The authors would like to thank Yamazaki Mazak UK for the loan of the machine tool, Airbus UK for the loan of the MQL unit and Houghton for supply of the V30ML oil.

References

[1] M'Saoubi R, Axinte D, Soo SL, Nobel C, Attia H, Kappmeyer G, Engin S, Sim WM. High performance cutting of advanced aerospace alloys and composite materials, CIRP Annals - Manufacturing Technology 2015; 64/2:557-580.
[2] Ezugwu EO, Bonney J, Yamane Y. An overview of the machinability of aeroengine alloys. Journal of Materials Processing Technology 2003;134:233-253.
[3] Thakur A, Gangopadhyay A. State-of-the art in surface integrity in machining of nickel-based super alloys. International Journal of Machine Tools and Manufacture 2016;100:25-54.
[4] Dudzinski D, Devillez A, Moufki A, Larrouquère D, Zerrouki V, Vigneau J. A review of developments towards dry and high speed machining of Inconel 718 alloy. International Journal of Machine Tools and Manufacture 2004;44:439-456.
[5] Weinert K, Inasaki I, Sutherland JW, Wakabayashi T. Dry machining and minimum quantity lubrication. CIRP Annals - Manufacturing Technology 2004;53(2):511-537.
[6] Jawaid A, Koksal S, Sharif S. Cutting performance and wear characteristics of PVD coated and uncoated carbide tools in face milling Inconel 718 aerospace alloy. Journal of Materials Processing Technology 2001;116:2-9.
[7] Hood R, Soo SL, Aspinwall DK, Andrews P, Sage C. Radius end milling of Haynes 282 nickel based superalloy. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 2012;226(10):1745-1753.
[8] Soo SL, Hood R, Aspinwall DK, Voice WE, Sage C. Machinability and surface integrity of RR1000 nickel based superalloy. CIRP Annals – Manufacturing Technology 2011;60/1:89-92.
[9] Li W, Guo YB, Barkey ME, Jordon JB. Effect tool wear during end milling on the surface integrity and fatigue life of Inconel 718. Procedia CIRP 2014;14:456-551.