Proceedings Paper:

Graves, A., Norgren, S., Crawforth, P. et al. (1 more author) (2020) Surface roughness response to drilling of Ti-5Al-5Mo-5V-3Cr using Ti-Al-N PVD coated and uncoated WC/Co tools. In: Arrazola, P.J. and Madariaga, A., (eds.) Procedia CIRP. 5th CIRP Conference on Surface Integrity (CSI 2020), 01-05 Jun 2020, Mondragón, Spain. Elsevier , pp. 170-175.

https://doi.org/10.1016/j.procir.2020.02.112

Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 87 (2020) 170–175

www.elsevier.com/locate/procedia

5th CIRP CSI 2020

Surface roughness response to drilling of Ti-5Al-5Mo-5V-3Cr using Ti-Al-N PVD coated and uncoated WC/Co tools

Alex Graves[a]*, Susanne Norgren[b], Pete Crawforth[c], Martin Jackson[a]

[a]*Department of Materials Science and Engineering, The University of Sheffield, Mappin Street, Sheffield S1 3JD, UK*
[b]*Sandvik Coromant R&D, Lerkrogsv. 13, 126 80 Stockholm*
[c]*Advanced Manufacturing Research Centre with Boeing; Advanced Manufacturing Park, Wallis Way, Catcliffe, Rotherham, S60 5TZ, UK*

* Corresponding author. *E-mail address:* agraves1@sheffield.ac.uk

Abstract

The surface response to drilling of the high performance titanium alloy Ti-5Al-5Mo-5V-3Cr (Ti-5553) with WC/Co tools cannot be assumed to similar to that of Ti-6Al-4V (Ti-64). Comparison of surface roughness for holes drilled in Ti-5553 with Ti-Al-N PVD coated and uncoated WC/Co tools at low and high cutting feed and speed was investigated. Cutting surface speed was shown to have more of an impact on surface roughness than that of feed, with high cutting speeds causing higher and more varied Ra value. In addition using coated tools at lower cutting speeds resulted in a lower average Ra. In most cases, the coated tools achieved lower Ra values compared to the uncoated tools. This is thought to be due to a difference in cutting edge radius and better stability associated with the coated tools. High variance in RMax was observed for all tested conditions and tools, in some cases RMax was above 10 µm. Alicona and SEM imaging identified re-adhered material pickup as the probable cause. A correlation between torque and surface roughness was identified for the drilling of Ti-5553 and further investigation is proposed for using torque measurement as an alternate way of quantifying surface roughness without probe measurement or image analysis.

Keywords: Type your keywords here, separated by semicolons ;

1. Introduction

Titanium alloys are essential in the aerospace industry for applications which require high specific strength, fracture toughness and corrosion resistance. Titanium machining is the most cost-intensive process required for the application of titanium alloy components. As drilling accounts for 40 – 60% of all material removal, improvements in drilling machinability would have significant cost saving implications [1,2].

High strength near-β alloys like Ti-5553 exhibit excellent fracture toughness and fatigue properties, as a result they are currently used in critical components like advanced structural landing gear components in single aisle commercial aircraft [3,4]. Currently, the cutting tools designed for the drilling of such high strength near-β titanium alloys are developed based on research conducted on the widely used α+β type alloy, Ti-6Al-4V (Ti-64) [5]. As a result of this and the elevated hardness and tensile strength of Ti-5553 compared to that of Ti-64, understanding of how such state-of-the-art tools can be improved for better tool life and surface integrity when machining near-β titanium alloys is required for alloy specific tool design and optimisation.

Currently tungsten carbide (WC/Co) tools are considered the optimal tool type when machining titanium alloys due to their

2212-8271
10.1016/j.procir.2020.02.112

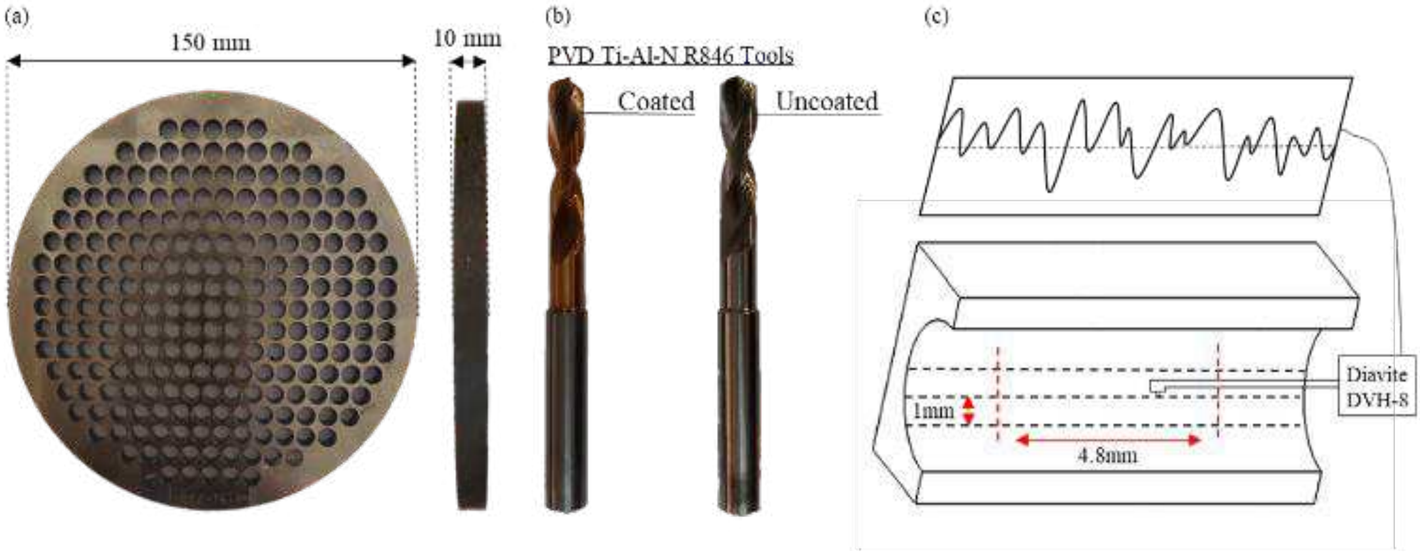

Fig. 1. (a) Dimensions of drilled Ti-5553 plates. (b) Ti-Al-N PVD R846 Coated and Uncoated Tools (c) Surface roughness line scan locations

high hardness, thermal conductivity and modulus of elasticity [6]. It has been identified that there is little difference between using coated and uncoated tools when turning or milling titanium alloys in terms of tool life and surface integrity. Investigations have shown tools are often considered the superior choice for most machining applications as they are cheaper to produce. Despite this it should not be overlooked that the application of coatings can significantly alter the cutting edge radius. Changes in the cutting edge radius have been found to alter the cutting forces and in some cases the surface roughness of the machined surface [7]. In drilling, less research has been carried out to determine the effectiveness of tool coating. However, one study has shown that Ti-Al-N PVD coatings have provided substantial benefits to tool life for drilling of Ti-64 [8]. Due to this, many of the WC/Co tools currently used to drill other $\alpha + \beta$ and near-β titanium alloys are coated with a Ti-Al-N or similar coating. As the application of such coating can be costly it is important to understand how they affect tool life and surface integrity when drilling near-β alloys like Ti-5553.

Surface integrity is an important component of alloy machinability for aerospace components as poor surface integrity can reduce fatigue life [2]. For this reason there are strict surface integrity standards in the aerospace industry. Unfortunately, to check parts against the criteria, is time intensive, often it adds another step to production and can result in the scraping of parts. If surface roughness could be characterised from data extracted from the cutting process there would be significant reductions in production time and cost.

Problems with titanium drilling machinability in terms of tool wear and surface integrity need to be addressed. Inadequate surface roughness, poor cylindricity and large hole exit burrs are associated with poor fatigue life and problematic assembly [9]. The effect of cutting forces and temperature can influence tool life and surface integrity [6]. High static cutting forces result in high mechanical stress. Thus rapid tool wear and breakage occurs on the tool cutting edge due to low chip tool contact and high resistance to deformation at elevated temperatures that titanium alloys exhibit. High dynamic cutting forces and chatter are caused by high deflection and adiabatic shear during chipping and result in poor surface quality [5]. One method of manipulating cutting force and temperature is to control the cutting feed and speed of the drilling operation [10]. One study has shown that for drilling with uncoated tools in Ti-64, high cutting speeds and resultant low cutting forces reduce surface roughness and have a positive effect on surface integrity [11]. Such findings were attributed to less material side flow on the machined surface and an absence of re-adhered workpiece material on the machined surface due to higher temperatures. Such material pickup has been shown to severely reduce fatigue life of Ti-5553 during milling by significantly increasing the amount fracture sites through the welding of material onto the machined surface [12]. Re-adhered material has also been used to explain poor roughness when testing the machinability of Ti-5553 at elevated temperatures in turning [13].

It is important that the surface roughness resultant from using coated and uncoated drills in Ti-5553 is examined, as poor surface quality can lead to lower fatigue life which is highly undesirable in critical aerospace components [14]. Therefore, this work aims to provide understanding of the surface roughness response of the near beta titanium alloy Ti-5553 for drilling by measuring surface roughness for holes drilled with Ti-Al-N PVD WC/Co and uncoated tools. In addition to this, torque data will be used to investigate if measurements of surface roughness have any potential for predicting and measuring the surface roughness of holes.

2. Experimental Method

Ti-Al-N (50% Ti / 50% Al) PVD coated and uncoated WC-Co hard metal Corodrill R846 6.9mm drills were used (Figure 1b) to machine Ti-5Al-5Mo-5V-3Cr (Ti-5553) plates. The grade of the tools used was H10F which is a submicron cemented carbide containing 10% cobalt and 90 % tungsten carbide, its hardness is 1600 Hv. Each plate was milled before drilling using RCKT 16 06 MO-PM 1030 inserts at cutting speeds and feeds of 177 m/min and 124 mm/rev respectively. Figure 1a shows a typical drilled plate and includes the dimension and location of holes. The machine used through the investigation was a DMUmonoblock 60, the drills were held

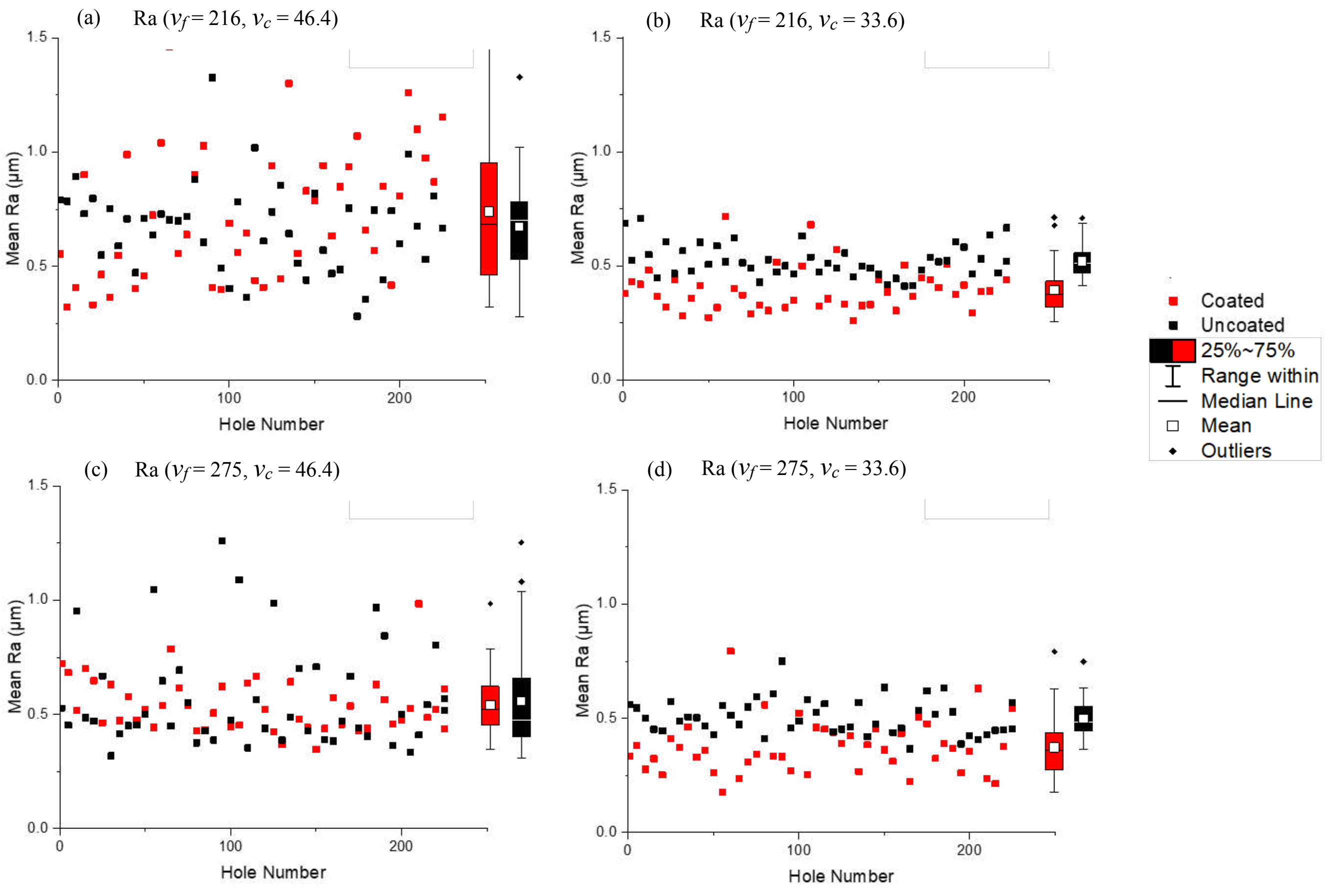

Fig. 2. Surface Ra probe results for each 227 hole set completed for the four speed and feed combinations (a,b,c,d).

using a hydraulic chuck and through tool Hocut 795 coolant of 7% (+/-0.5) was applied through tool for each hole. Tools were checked to be within specification (Table 1) using a Helicheck Pro. This hardware was also used to measure the cutting edge radius of each coated and uncoated tool near the outer corner. The average coated and uncoated edge radii were 34.4 μm and 29.8 μm respectively.

To compare the surface roughness response for coated and uncoated tools, four different cutting feed (v_f) and cutting surface speed (v_c) combinations were investigated. Two v_f were investigated, 216 mm/min and 275 mm/min, at each of which a test at v_c of 46.4 m/min and 33.6 m/min was carried out. For each combination a coated and uncoated tool were used to drill a plate of 227 holes to investigate if any changes in surface quality would be observed as tool wear developed. The lowest v_f and v_c were selected to be below the recommended industrial v_f (268 mm/min) and v_c (41.1 m/min) for drilling Ti-5553, whilst the highest v_f and v_c were above [15].

A Kistler spindle dynamometer measured the force and torque for each hole drilled. Tool wear measurements were obtained using an Olympus SZX 10 light microscope and Clemex vision software. Hole roughness (Ra and RMax) measurements were made using a Diavite DH-8 instrument with a CLA-400 2 μm measuring head for every fifth hole drilled. In this case RMax was the maximum distance measured between the highest peak and lowest trough from the mean line. For each surface roughness data point three line scans were made at three locations 1 mm apart in each hole as detailed in Figure 1c. Each line scan sample length and cut off wavelength were 4800 and 800 μm respectively, providing a vertical resolution between 0.1 and 2 μm. Validation and further surface assessment were undertaken through 3D surface imaging of inner hole and hole burs using an Alicona Infinite Focus machine. A scanning electron microscope was used to obtain micrographs of the polished surface and subsurface of drilled holes to identify features found on Alicona scans. MATLAB and Origin Pro were utilized for statistical analysis and presentation of the data.

Table 1. WC-Co Corodrill R846 6.9mm Specification

	Specification	+/-
Point Angle	140 ˚	1 ˚
Point Length	29.2 ˚	0.5 ˚
Helix Angle	1.2mm	0.01mm
Diameter (D)	6.9mm	0.01mm
Useable Length	21.9mm	NA
Coating Thickness	3 μm	1 μm

3. Results and Discussion

The Diavite DH-8 Ra results for each of the v_f / v_c combinations tested are shown in Figure 2 (a,b,c,d). Each graph includes the average Ra for every fifth hole in the 227 hole data set. Since there was no significant increase or decrease of the

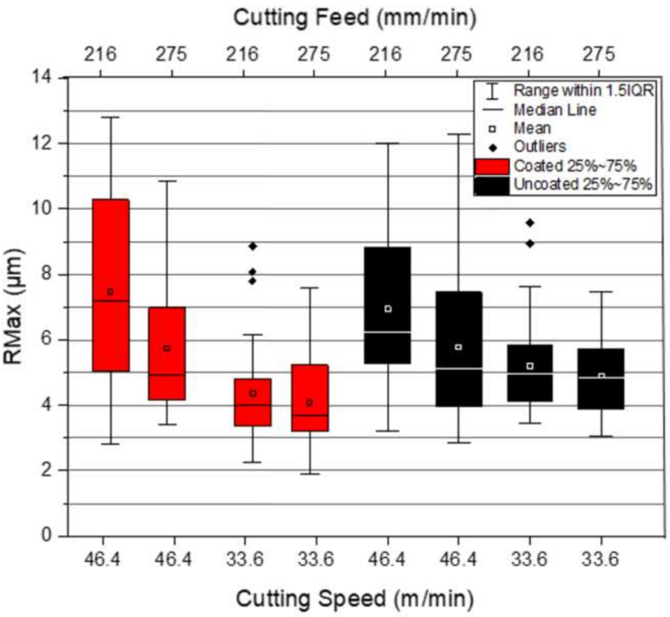

Fig. 3. Surface RMax at various v_f and v_c for coated and uncoated tools.

Ra value with respect to hole number, the data has been consolidated into box and whisker diagrams within Figure 2. This makes it easier to compare the mean, median, spread of data and associated outliers for each coated and uncoated tool. The highest mean for coated and uncoated tools were 0.73 µm and 0.67 µm respectively, and were recorded at the lowest v_f (216 mm/min) and highest v_c (46.4 m/min) (Figure 2a). The lowest Ra values, 0.37 µm and 0.50 µm for coated and uncoated tools respectively, were measured at the highest v_f (275 mm/min) and lowest v_c (33.6 m/min) (Figure 2b). The variation associated with Ra was much higher at the high cutting speeds (Figure 2a and 2c) and was most extreme for the low feed tests. The reason for higher mean Ra and larger variation could be attributed to one or both of the following; 1) to chatter and instability as a resultant of titanium's low modulus of elasticity, although this often occurs at the lower cutting speeds [3]. 2) To higher temperatures associated with higher cutting speeds promoting an increase in the amount of re-adhered material on the machined surface [13]. Compared to drilling studies on Ti-64 and other α + β alloys which identify higher Ra values at low cutting speeds the results of this experiment show Ti-5553 to have higher and more varied Ra values at higher speed [7, 10]. As Ti-5553 has previously been identified in other machining practices to have large amounts of re-adhered pickup on the machined surface and BUE on the tool, it is probable that increased temperatures are causing large amounts of pickup [3].

Also of interest is the higher mean roughness observed for uncoated tools at the lowest v_c, 33.6 m/min at both v_f tested (Figure 2b and 2d), demonstrating that the coating is in some way beneficial in improving roughness levels at such speeds. This correlation has previously been identified for the Ti-64 alloy by Sharif and Rahim [8]. They stated that the disparity was due to increased wear on the uncoated tools. This was a highly probable conclusion considering their tools sustained extensive wear and they only measured Ra for the final hole drilled. The results in Figure 2 were not just for the final hole but included roughness across all the drilled holes. When this is coupled with the fact that tools in this investigation were all measured to have wear equivalent to 20% (0.05) and 40% (0.1) of the max flank wear limit (0.25mm) these results show the values of Ra to remain static with the progression in life of the tool. This means it is likely that at least in the case of Ti-5553 and for the first 40% of the tools life it is not tool wear causing increased Ra. The slightly lower Ra measured for coated tools is likely due to the significant difference in the edge radius of the coated and uncoated tools which was measured to be 4.6 µm (15%) [7]. There could also be some influence of a different tool coating work piece interaction taking place, other researchers have suggested that the formation of an Al_2O_3 layer can form at the interface of Ti-Al-N tools reducing friction and improving surface finish [8].

The maximum measurements of roughness from peak to trough (RMax) are shown in Figure 3. The mean RMax over the 227 holes is slightly lower for the higher cutting feeds and considerably lower for the lower cutting speeds. The trends observed in these results are similar to that of the Ra results, but the RMax measurements are larger than expected for all tested v_f and v_c combinations, in many cases. The RMax results in Figure 3 supports the hypothesis that re-adhered material

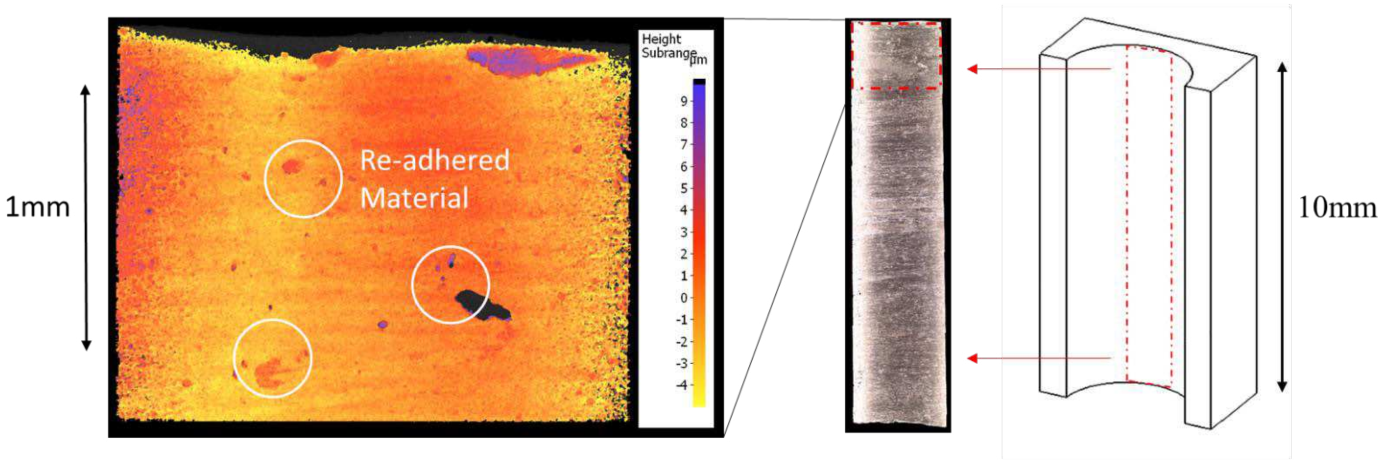

Fig. 4. Alicona image showing Re-adhered material on the machined surface of a 6.9 mm hole that was drilled using a coated tool at v_f 275 and v_c 46.4.

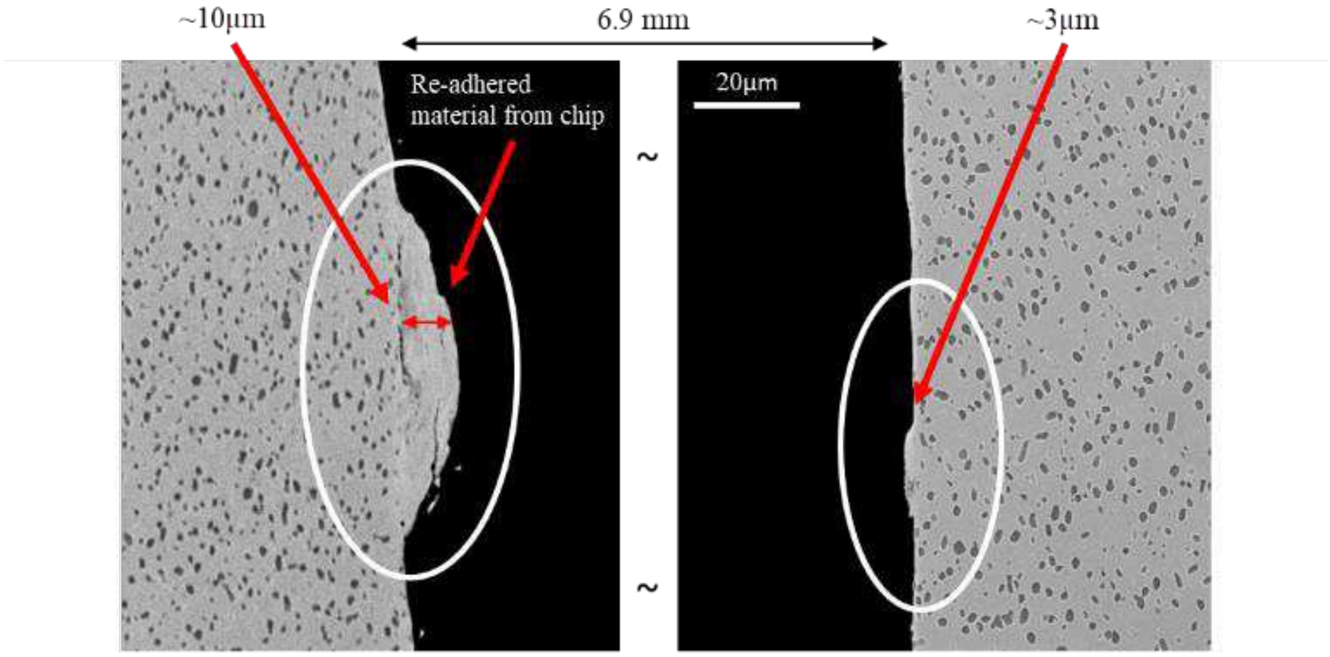

Fig. 5. SEM Electron Backscatter micrographs of the machined surface on either side of a 6.9mm hole drilled using a coated tool at v_f 275 and v_c 46.4.

pickup is evident on the machined surface of the drilled holes, as the pickup is scattered inconsistently within each hole it would have a much lower impact on Ra than RMax.

To further investigate if high values and variation in RMax was due to re-adhered pickup on the machined surface, Alicona variable focus scanning and backscatter electron imaging was used to investigate the machined surface and subsurface at the wall of a hole drilled at v_f = 275 m/min and v_c = 46.4 m/min. The Alicona scan in Figure 4 shows the inconsistent scattering of re-adhered pickup on the machined surface which is of similar magnitude to the measured RMax results. Figure 5 shows two SEM backscatter micrographs which further proves the existence of re-adhered pickup on the surface of the hole. The features on the left and right of the figure are around 10 µm and 3 µm in width, respectively. In the milling of Ti-5553 such features were severely detrimental for fatigue life due to the welding of high oxygen fractures sites onto the machined surface [12]. As the pickup could be expected to have a similar effect on fatigue performance in drilling, these observations are concerning for aerospace Ti-5553 components.

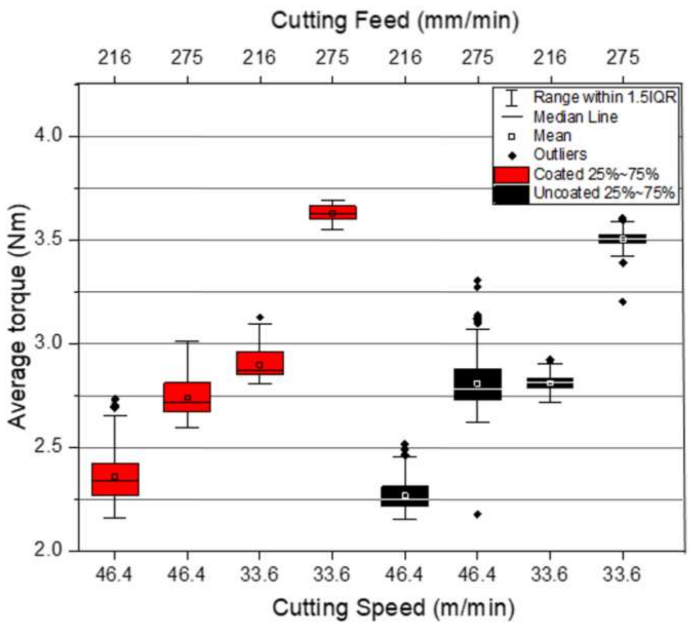

Fig. 6. Box and whisker plot showing variation of average torque data for each of 227 holes for 1 second of cutting for all v_f / v_c.

As torque on a drill in cut is mostly influenced by the workpiece tool interaction on the outer corners, torque was measured in this study [16]. The torque results in Figure 5 consist of box and whisker plots made from the average torque over one second of the steady state cutting region. In all but the v_f = 275 (mm/min) and v_c = 46.4 (m/min) case, the torque on the uncoated tool is slightly lower than the coated tool. This result is likely due to the larger edge radius measured for coated tools [7]. The trend that increasing cutting feed and/or decreasing cutting speed causes an increase in torque should be expected as the chip thickness is being increased. The increases in torque shown in Figure 6 are correlated to better surface roughness, probably because at the higher torque there is more stability in the cutting process. This would also go some way to explain why lower variance of Ra and Rmax is correlated to lower variance in the torque results. As there is a requirement for quick efficient surface profiling of hole quality, the correlation in variance may highlight a key area for further research. If individual measurements of torque correlate with features on the surface finish then an element by element analysis of torque may allow prediction or measurement of certain features on the machined surface and even the Ra.

4. Conclusions

The drilling of Ti-5553 has been shown to have different characteristics compared to previous work on Ti-64.

- No evidence of increasing or decreasing Ra over the 227 holes at any tested feed or speed was apparent. Therefore, for this portion of the tools life (20 % – 40 %), wear is not responsible for changes in Ra values.
- Higher magnitude and variation in Ra values when drilling Ti-5553 at 48 m/min than 33.6 m/min has been attributed to lower stability and increased re-adherence of material to the machined surface. Such pickup was also confirmed using SEM imaging of the machined surface.
- With the exception of low feed and high speed test coated tools generally achieved superior Ra values compared to uncoated tools. This was likely due to the larger edge radius of coated tools and better stability in the cutting process indicated by smaller range shown for torque results of coated tools.
- Torque data show a similar trend to the surface roughness data. Despite the highest torque being higher where lower roughness was measured, the variance is significantly lower which indicates a more consistent stability within the process. As variance in torque and variance in roughness were correlated there is the possibility of using torque measurement and manipulation as an in-line process NDE method for predicting and measuring surface roughness.

Acknowledgements

This work is funded through the ESPRC grant EP/L016257/1. The authors thank Sandvik Coromant for providing the tools, machine and operators that made this work possible.

References

[1] Brinksmeier, E. Prediction of Tool Fracture in Drilling. *CIRP Ann. - Manuf. Technol.* **39,** 97–100 (1990).

[2] Abdelhafeez, A., Soo, S., Aspinwall, D., Dowson, A. & Arnold, D. Burr Formation and Hole Quality when Drilling Titanium and Aluminium Alloys. (2015). doi:10.1016/j.procir.2015.08.019

[3] Sun, Y., Huang, B., Puleo, D. A. & Jawahir, I. S. Enhanced machinability of Ti-5553 alloy from cryogenic machining: Comparison with MQL and flood-cooled machining and modeling. Procedia CIRP 31, 477–482 (2015).

[4] Veeck S, Lee D, Boyer RR, Briggs RD. The microstructure and properties of cast titanium alloy Ti-5553 were evaluated in a joint program by Howmet and Boeing. Advanced Materials & Processes (2004); October: 47-49.

[5] Arrazola, P. J. et al. Machinability of titanium alloys (Ti6Al4V and Ti555.3). J. Mater. Process. Technol. 209, 2223–2230 (2009).

[6] Ezugwu, E. O. & Wang, Z. M. Titanium alloys and their machinability. *J. Mater. Process. Technol.* **68,** 262–274 (1997).

[7] Wyen, C. F., Jaeger, D. & Wegener, K. Influence of cutting edge radius on surface integrity and burr formation in milling titanium. *Int. J. Adv. Manuf. Technol.* **67,** 589–599 (2013).

[8] Sharif, S. & Rahim, E. A. Performance of coated-and uncoated-carbide tools when drilling titanium alloy-Ti-6Al4V. *J. Mater. Process. Technol.* **185,** 72–76 (2007).

[9] Che-Haron, C. H. & Jawaid, A. The effect of machining on surface integrity of titanium alloy Ti-6% Al-4% v. J. Mater. Process. Technol. 166, 188–192 (2005).

[10] Armendia, M. & Osborne, P. Comparison of the machinability of titanium alloys. *Proj. ADG006 - Timet Mater. characterisation* (2009).

[11] Rahim, E. A. & Sharif, S. Investigation on Tool Life and Surface Integrity when Drilling Ti-6Al-4V and Ti-5Al-4V-Mo / Fe ∗. **49,** 340–345 (2006).

[12] Cox, A., Herbert, S., Villain-Chastre, J., Turner, S. & Jackson, M. The effect of machining and induced surface deformation on the fatigue performance of a high strength metastable β titanium alloy. *Int. J. Fatigue* **124,** 26–33 (2019).

[13] Baili, M., Wagner, V., Dessein, G., Sallaberry, J. & Lallement, D. An experimental investigation of hot machining with induction to improve Ti-5553 machinability. Appl. Mech. Mater. 62, 67–76 (2011).

[14] Sun, D. *et al.* Hole-making and its Impact on the Fatigue Response of Ti-6AL-4V Alloy. *Procedia CIRP* **56,** 289–292 (2016).

[15]CoroPlus ToolGuide (2019). Retrieved 9 December 2019, from https://www.sandvik.coromant.com/en-gb/products/Pages/toolguide.aspx

[16] Nayebi, A. & Vag hefp our, H. Thermoviscoplastic modelling of drilling : twist drills. **222,** 403–411 (2016).