Effect of Machining Parameters on Surface Roughness in Al 2618 Alloy Subject to Multi-axis Machining Process Using Ball Nose Cutting Tools

Md Shams E Tabriz
Turbocharger Research Institute
The University of Huddersfield
Huddersfield, United Kingdom
E-mail: Md.S.Tabriz@hud.ac.uk

Simon M Barrans
Turbocharger Research Institute
The University of Huddersfield
Huddersfield, United Kingdom
E-mail: S.M.Barrans@hud.ac.uk

Paul J Bills
Centre of Precision Technologies
The University of Huddersfield
Huddersfield, United Kingdom
E-mail: P.J.Bills@hud.ac.uk

***Abstract*— Recently multi-axis machining technology has improved significantly. It has become a widely accepted method of manufacturing components with complex, free form surfaces. Solid billet materials with negligible internal defects are used in this process. This provides increased durability and fatigue life over equivalent cast components. However, multi-axis machining using ball nose cutting tools leaves cusps as machining marks. The surface quality within the cusps can have a significant influence on the fatigue life and durability of a component. The main objective of this paper is to report the experimental investigation of the effect of different cutting parameters on surface roughness of Al 2618 alloy.**

This paper reports on an experimental investigation of the effect of different cutting parameters on surface roughness of Al 2618 alloy. A full factorial experimental analysis using four different levels of spindle speed, feed-rate and cutting-tool approach angle was carried out. The results indicate that higher spindle speed, lower feed rate and a cutting tool approach angle of approximately 25° generates a better surface finish.

Keywords- Multi-axis machining, cusps, machining marks, machining parameters, cutting speed, feed rate, tool approach angle.

I. INTRODUCTION

Multi-axis machining is a common manufacturing process widely used by automotive and aerospace industry. Ball nose tools are used on work-pieces with complex surfaces and for finishing operations. Multi-axis machining processes using ball nose cutting tools leave significant machining marks in the form of cusps. According to Vickers and Quan [1] , cusps form between adjacent cutter paths across the surface. Squires [2] pointed out that the depth of the cusp depends on the combination of tool diameter size and the distance between each pass of the machine tool head or step over. Cusps are extra material laying on top of the nominal geometry and this machined surface is typically a non-functional surface. Figure 1 shows an example of a machined nonfunctional surface with machining cusps. In this example the only purpose of the surface is to guide the flow of air through the compressor. The surface roughness does not impact on this function so is not an immediate concern.

Researchers have investigated the effect of the surface roughness of specimens machined by turning on stress, fatigue life and durability. Bayoum & Abdellatif [3], Javidi et al. [4] and Sasahara [5] have looked into the effect of surface roughness on fatigue life of aluminium alloy, nickel-molybdenum alloy and 0.45%C steel respectively and concluded that the fatigue durability reduces with increasing surface roughness due to the stress concentrations generated by the rough surface. Novovic et al. [6] state that surface roughness values over 0.1 µm influence the fatigue life on any component significantly. Schmid et al. [7] suggest using a Surface Finish Factor to include the effect of surface roughness on fatigue life. This surface finish factor is used to calculate the modified fatigue endurance limit as:

$$S_e = k_n \times k_f \times S'_e \qquad (1)$$

Here, S_e = Modified endurance limit
S'_e = Endurance limit in ideal condition
k_n = Size, temperature and other factors
k_f = Surface finish factor

The surface finish factor can be calculated by [8] :

$$k_f = eS_{ut}^{f} \qquad (2)$$

Here, k_f = Surface Finish Factor
S_{ut} = Ultimate Tensile Strength of Material, MPa
e & f = Empirical factors depending on the manufacturing process. For machining $e = 4.51$ nd $f = -0.265$.

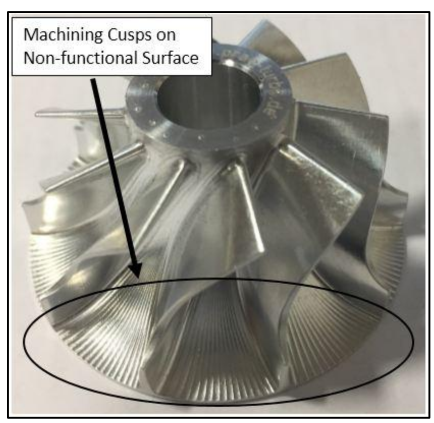

Figure 1:Non-functional Machined Surface on a Turbocharger Compressor Wheel.

Researchers have investigated the effect of machining parameters during the turning process on surface roughness. Kilickap, Cakir, Aksoy and Inan [9] stated that for lathe turning of reinforced Aluminium metal matrix composite, the machining parameter with the greatest influence on surface roughness is spindle speed. Their experimental research suggests that higher cutting speeds and lower feed rates generate better surface finishes. Bhushan, Kumar & Das [10], Dwivedi, Kumar & Kumar [11], Patel & Patel [12] and Kumar & Chauhan [13] conducted similar research on turning with different composites and alloys as the test material and also concluded that higher spindle speeds and lower feed rates improve surface quality. Karabulut & Karakoc [14] suggested that feed rate is the most significant factor influencing surface roughness during milling. However, Pathak , Sahoo & Mishra [15] suggested both cutting speed and feed rate significantly influence the surface quality during end milling. Wojociechowski, Twardowski and Wieczorowski [16] suggested that with a tool approach angle of 45° surface roughness is significantly better than with an approach angle of 0° ball end milling of hardened steel. Figure 2 shows the tool approach angle and cusp area Wojociechowski et al. used for the analysis.

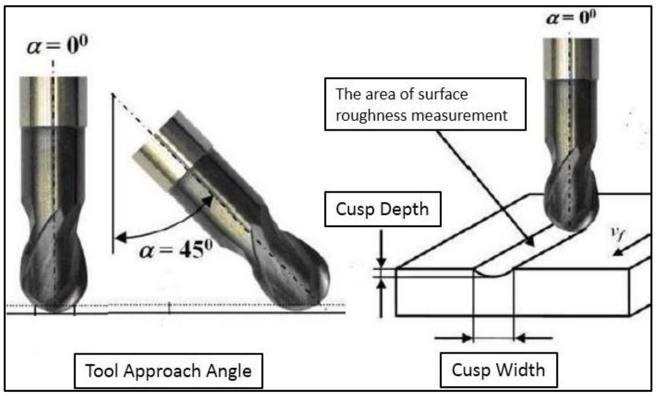

Figure 2: Tool Approach Angle and Cusp Area [16]

In the work discussed above, the majority has only looked at the effect of machining parameters on surface roughness in turning and end milling. These processes do not generates cusps on the surface. Wojociechowski et al. only investigated the effect of two different approach angles on surface texture; the effect of other machining parameters such as spindle speed and feed rate was not included. This paper presents a full factorial experimental analysis investigating the effects of spindle speed, feed-rate and tool approach angle on surface roughness within the cusps generated by a ball-nose milling tool.

II. Experimental Procedure

A. Work Material

The work material selected for the study was Aluminium 2618 Alloy in the form of a 140mm × 100 mm flat bar, as shown in Figure 3. Al 2618 is widely used in the automotive and aerospace industries due to its high strength to weight ratio, wear resistance and good machinability. Table 1 shows the mechanical properties of Al 2618 alloy.

Table 1: Mechanical Properties of Al 2618

Properties	Al 2618 Alloy
Density (g/cc)	2.76
Hardness (BHN)	115
Modulus of Elasticity (GPa)	74.5
Yield Strength (MPa)	372
Ultimate Tensile Strength (MPa)	441

B. Cutting Tool and Machining Equipment

A solid tungsten carbide ball nose tool with 4 mm tool diameter was used for this research work. This tool was used ina Hurco VM10U 5-axis machine. Figure 3 shows the 5-axis machine generating cusp at 75° tool approach angle.

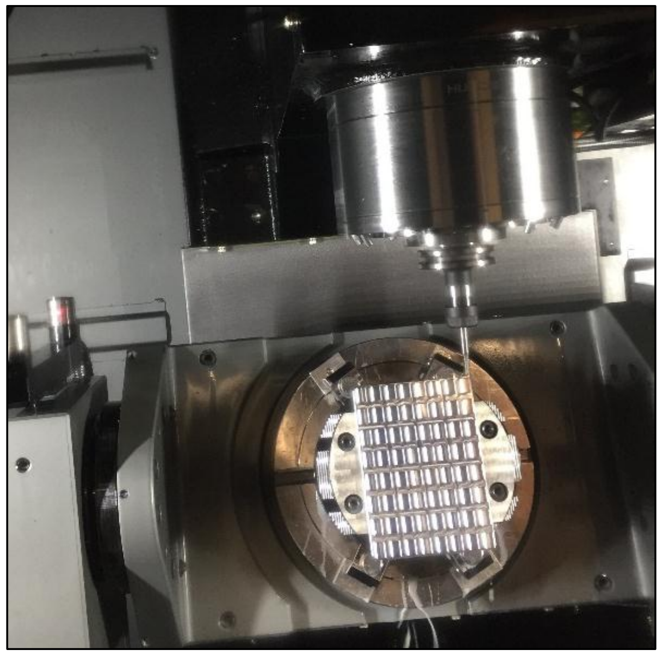
Figure 3: Hurco VM10U Machining Cusps at 75° Tool Approach Angle.

C. Experimental Plan

Three different machining parameters; spindle speed, feed-rate and tool approach angles were considered as factors for this experiment. Four levels were taken for each factor, as shown in table 2. To carry out a full factorial experiment, 64 (4^3) different machining surfaces were created.

Table 2: Factors Parameters and Levels.

Factors	Level 1	Level 2	Level 3	Level 4
Spindle Speed (rpm)	2500	5000	7500	10000
Feed Rate (mm/min)	250	500	750	1000
Approach Angle (°)	0°	25°	50°	75°

A 140mm×100mm solid bar was sub-divided in 64 10mm×6mm small segments. Two cusps were machined on each segment with same machining specification as shown in Figure 4. This figure shows the grid used to define cutting angle and spindle speed. The inset indicates the feed rate and cutting order.

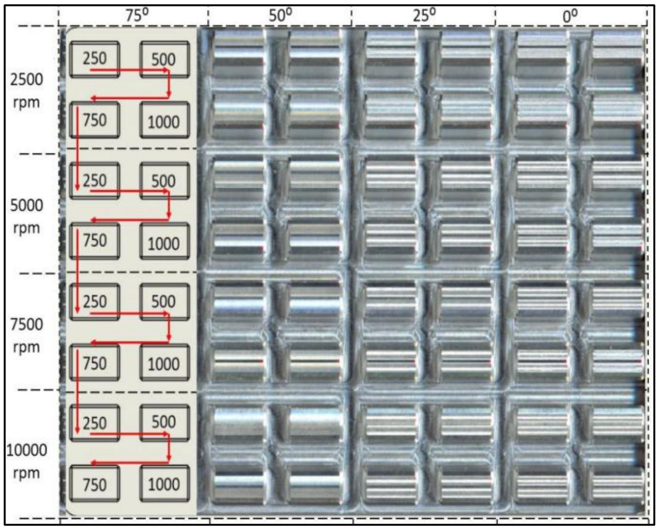

Figure 4: Machined Specimen and Machining Order.

D. *Surface Roughness Measurement*

Surface roughness measurements were taken using an Alicona Infinite Focus Measurement (IFM) machine. This optical 3D measurement device allows the acquisition of datasets at a high depth of focus. First, a stack of images from the lowest to the highest plane of the surface features is acquired. The positions in the stack where each image point is best in focus is then determined. This leads to an overall sharp image and a reconstruction of the surface, where a height value exists for each point on a ground plane. This method generates images with a lateral resolution of 400 nm and a vertical resolution of 20 nm.[17] The surface roughness parameter Ra was considered for this experiment, as recommended in [18]. Ra is the arithmetical mean of the absolute values of the profile deviations from the mean line of the roughness profile [19]. Figure 5 shows the reconstructed surface of a cusp measured by the Alicona and the surface profile in the feed direction.

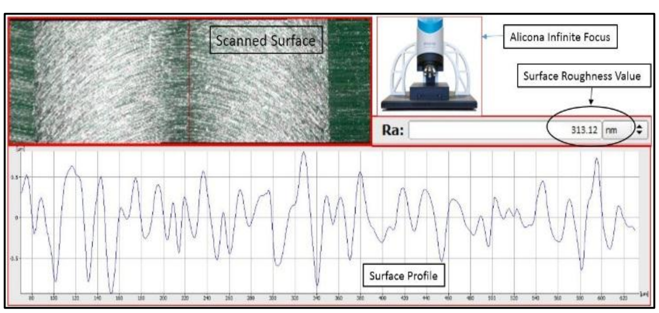

Figure 5: Alicona Measurement Technique

III. Results and Discussion

A. *Effect of Spindle Speed*

Figures 6, 7, 8 and 9 show the effect of spindle speed on surface roughness for different tool approach angles and feed rates. In general, the figures show that higher spindle speeds generate better surface quality. However, Figures 6 and 7 show that for tool approach angles of 75° and 50° the surface quality decreased significantly at the spindle of 10000 rpm. This was due to the excessive tool vibration with those particular tool-approach angles, which was noted during machining.

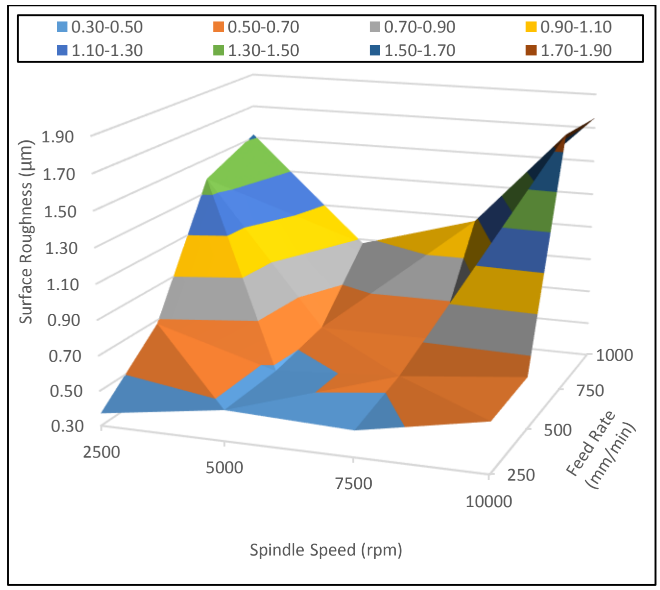

Figure 6: Impact of Spindle Speed and Feed Rate on Surface Roughness for 75° Approach Angle.

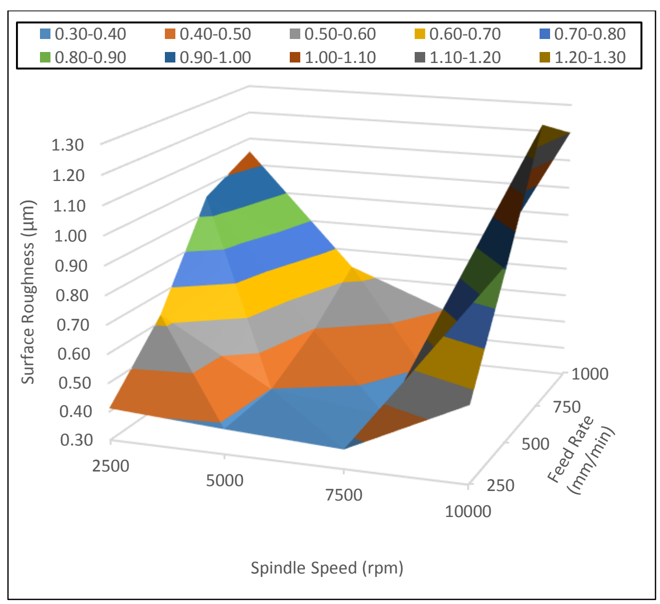

Figure 7: Impact of Spindle Speed and Feed Rate on Surface Roughness for 50° Approach Angle.

Figure 10 shows the overall impact of spindle speed on the surface roughness. This graph has been created by calculating the average surface roughness for a given spindle speed across all combinations of feed rate and tool approach angle. A spindle speed of 7500 produced the best surface quality.

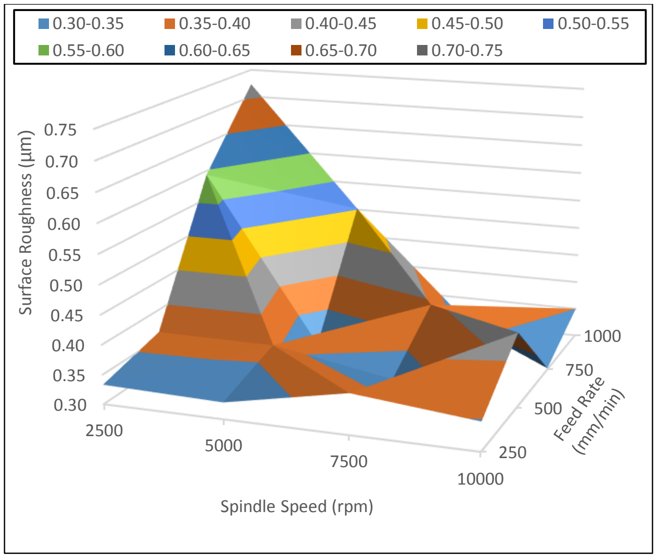

Figure 8: Impact of Spindle Speed and Feed Rate on Surface Roughness for 25° Approach Angle.

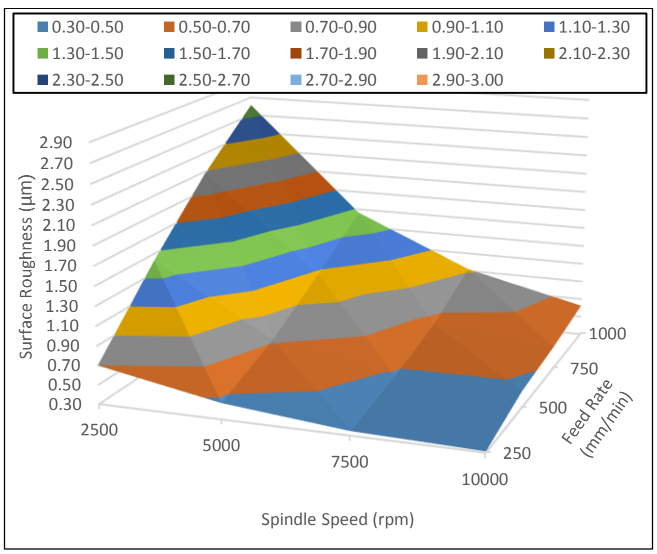

Figure 9: Impact of Spindle Speed and Feed Rate on Surface Roughness for 0° Approach Angle.

B. *Effect of Feed Rate*

Figure 11 showing the overall impact of feed rate on surface quality, shows that increasing feed rate increases surface roughness. However, as shown in Figures 8 and 9 the detrimental effect of increasing feed rate can be partially mitigated by increasing spindle speed. For all tool approach angles, a combination of lower feed rate and higher spindle speed generated better quality surfaces.

C. *Effect of Tool Approach Angle*

The marked difference between the peak surface roughness shown in Figures 6 to 9 demonstrates the significant effect that tool approach angle had on surface quality.

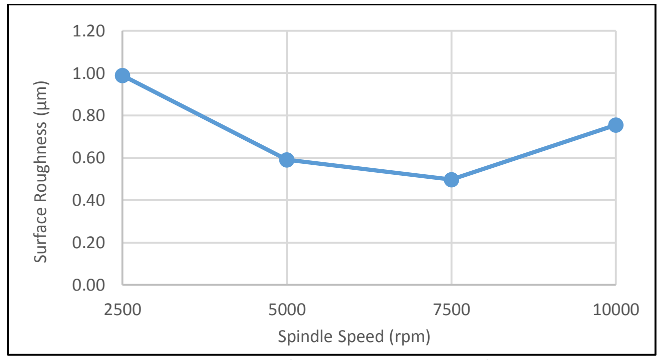

Figure 10: Overall Impact of Spindle Speed on Surface Roughness

The highest level of surface roughness is shown in figure 9 for a tool approach angle of 0°. At this approach angle the cutter's axis, where the cutting speed is close to zero, is in contact with the surface. Therefore, cutting does not occur. This leads to material removal by ploughing which generates the high surface roughness. [16]

Figure 12 shows the overall impact of tool approach angle on surface roughness. 25° is the optimum tool approach angle.

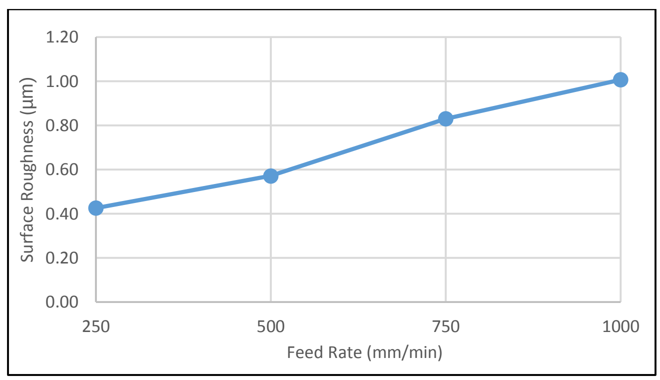

Figure 11: Overall Impact of Feed Rate on Surface Roughness

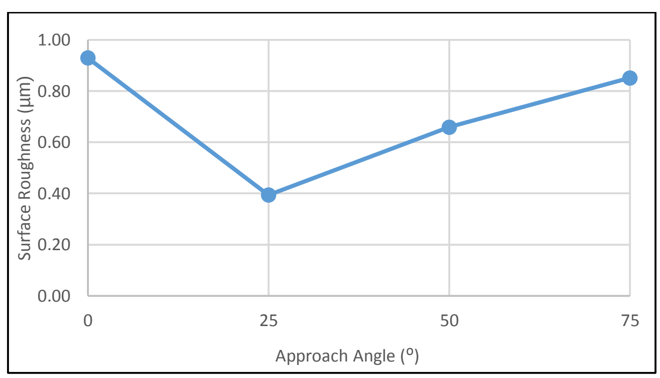

Figure 12: Overall Impact of Tool Approach Angle on Surface Roughness

Surface plots shown in Fig 6 to 9 can be used to determine the combination of spindle speed and feed rate that minimises surface roughness.

IV. CONCLUSIONS

In this work, the effects of spindle speed, feed rate and approach angle on the surface roughness within cusps produced by a ball nose cutter were investigated experimentally. The experimental results showed that:

- Spindle speed, feed rate and tool approach angle all have a significant effect on the surface roughness.
- Generally, higher spindle speeds generate better surface quality. However, at some tool approach angles, high spindle speed can generate tool vibration and hence reduce surface quality.
- Lower feed rates produce surface with lower surface roughness.
- A 0° tool approach angle causes a ploughing mechanism due to zero cutting speed on the cutting axis; hence, surface quality deteriorate s.
- A 25° tool approach angle generates the best quality surface.

ACKNOWLEDGEMENT

The authors would like to acknowledge and thank UK Government (Regional Growth Fund Grant Award 01.09.07.01/1789C) for the financial support and Centre of Precision Technologies for providing machining and Optical Surface Measurement facility.

NOMANCLATURE

S_e	Modified Endurance Limit, MPa
S'_e	Endurance Limit in Ideal Condition, MPa
k_n	Size, Temperature and other Factors
k_f	Surface Finish Factor
S_{ut}	Ultimate Tensile Strength of Material, MPa
e & f	Empirical Factors Depending on The Manufacturing Process

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AUTHORS' BACKGROUND

Your Name	Title*	Research Field
Mr Md Shams E Tabriz	PhD Student	Finite Element Analysis Structural Analysis Low Cycle Fatigue Multi-axis Machining Turbo-machinery
Dr Simon M Barrans	Reader in Turbo-machinery	Structural Integrity of Turbo-machinery Structural Analysis Finite Element Modelling V-bands Fatigue Multi-axis Machining Application of Air Bearings
Dr Paul J Bills	Senior Lecturer in Automotive and Mechanical Engineering	Surface Metrology Precession Measurement Mechanical Wear µCT Scanning Additive Manufacturing