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Exploring sustainable micro milling: Investigating size effects on surface roughness for renewable energy potential

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Abstract. Micromilling is a helpful process empowering the fabrication of small-scale components characterized by complex geometries, heightened precision, and superior surface integrity. Widely embraced across aerospace, biomedical, and electronics sectors, it characterizes efficiency and sustainability in modern manufacturing paradigms. However, fundamental instabilities emerge during the cutting phase, particularly when the size effect diminishes below a critical threshold termed the minimum chip thickness, a parameter linked to the cutting-edge radius and feed rate dynamics. The micro-milling process enables the production of small-scale parts with complex geometries, high precision, and optimal surface quality. It stands as a preferred production method not only in the aerospace, biomedical, and electronics industries but also in the renewable energy sector, where its ability to create intricate components with precise dimensions and superior surface quality is crucial for optimizing efficiency and sustainability in energy harvesting and storage technologies. Instabilities are observed in the cutting process when the size effect falls below a critical value known as the minimum chip thickness. This critical value is related to the cutting-edge radius and feed rate. This study investigates the effect of size on surface roughness in micro-milling of Al6061-T6 workpiece. The results show that surface roughness is high at feed rates below the minimum chip thickness due to the ploughing mechanism. The shear mechanism is active at feed rates above the minimum chip thickness, but the ploughing effect is still observed at the 100µm edge of the cutting channel. The study revealed that surface roughness and height differences were high at feed rates significantly below or above the minimum chip thickness. However, surface quality was optimal at feed rates near the minimum chip thickness. Nevertheless, the study highlights an optimal peak in surface quality achieved at feed rates close to the minimum chip thickness, explaining a relationship between operational efficiency and sustainability in micro-milling endeavours.

Introduction

The demand for precision and small-scale parts in various industries, including electronics, medicine, biomedicine, aerospace, automotive, and telecommunications, is on the rise [1]. Micro-mechanical machining methods have been developed to meet these demands and produce parts with high precision and small dimensions [2]. Among these methods, micro-milling stands out as a way to produce precise and complex parts at a micro scale [3]. The micro-milling method is commonly utilised in various applications, including precision integrated circuits, microelectronic and medical devices, biomedical implants, and optical components like micro mirrors, micro lenses, sensors, microchips, micro propellers, and blades [1]. The micro-milling process differs fundamentally from conventional milling due to the size effect [4]. When the feed rate per tooth (fz) falls below a critical value, which depends on the cutting tool and workpiece pair, instabilities occur in the cutting process and surface roughness increases. The optimal ratio between the cutting tool's edge radius (Re) and the feed rate per tooth determines the critical value. The ratio defining the minimum chip thickness is called h_{min} [5]. In micromachining, the uncut chip thickness (h) is kept below h_{min}, and the negative rake angle effect caused by the cutting-edge radius results in ploughing during the cutting process [6, 7]. Experimental studies have been conducted to determine the minimum chip thickness. According to the literature, the minimum chip thickness varies between 20% and 30% of the cutting-edge radius [8]. In titanium alloys, this ratio is 30% [9], while in aluminium alloys, it can go up to 35-40% [10, 11]. Wu et al. (2020) discovered that the minimum chip thickness is 17% of the edge radius [12]. It is a well-established fact that cutting forces display unstable behaviour at feed rates below the minimum chip thickness [13, 14]. This is attributed to the ploughing mechanism that becomes active at feed rates below the minimum chip thickness during the cutting process. Figure 1a provides a schematic representation of full slot machining in the micro milling process, while Figure 1b illustrates the variation of the chip thickness based on the position of the cutting edge and the feed rate per tooth. As is commonly understood, the thickness of the chip during milling varies depending on the position of the tool. Initially, when the tool first makes contact with the workpiece, the chip thickness is almost zero. As the angular position of the cutting edge (φ) increases, the value of h also increases. When φ=90°, h=fz. If $h<h_{min}$, ploughing occurs, which results in a decrease in the quality of the machined surface and an increase in the amplitude of the cutting forces [15]. This study aimed to establish a relationship between the angular position of the tool (represented by the symbol φ) and the ploughing length (wp) by examining the change in surface roughness on the machined slot surface (Fig. 1).

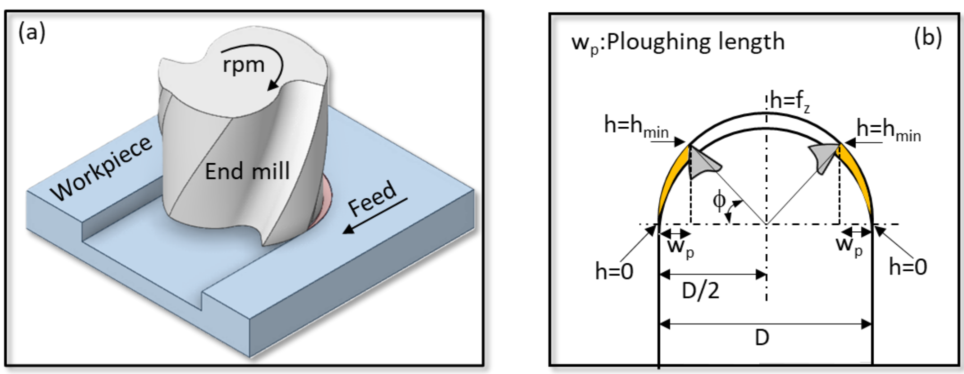

Figure 1. Relationship between uncut and minimum chip thickness.

The use of the ploughing mechanism instead of the shear mechanism during the cutting process has a negative impact on the surface quality of the workpiece. The high feed rate results in increased cutting forces, which in turn leads to a deterioration of the surface quality and an increase in surface roughness. To achieve the best surface quality during the cutting process, it is essential to use a feed rate that is large enough to prevent ploughing, yet small enough to keep cutting forces low. This study investigates the effect of size on surface roughness in the micro-milling process. Surface roughness measurements were taken from the cutting grooves of the micro-milled workpiece at different feed rates. The minimum chip thickness was determined, and the ploughing effect was identified.

Material and Method

This study used Al6061-T6 alloy, commonly used in the production of micro equipment in the defence, aerospace, and electronics sectors. Aluminium alloys are widely used due to their formability, light weight, high strength, and corrosion resistance. The T6 heat treatment improved the mechanical and physical properties of the alloy. Compared to other aluminum alloys, Al6061-T6 stands out due to its high toughness, superior corrosion resistance, low density, high thermal conductivity, and low cost [17]. Table 1 shows the alloy's chemical and basic mechanical properties, where 10 mm x 10 mm x 15 mm specimens were used in cutting tests.

Table 1. Chemical composition and mechanical properties of Al6061-T6 material [17].

	Chemical Composition							Mechanical Properties		
Elements	Al	Mg	Fe	Cu	Zn	Si	Mn	UTS (MPa)	YS (MPa)	%Elongation
Alloying elements(%	Rest	1.14	0.35	0.3	0.25	0.67	0.12	307	275	20

The cutting tests employed a 975 µm diameter, 2-flute tungsten carbide cutting tool with AlTiSiN coating. The tool has a helix angle of 30°, a helix length of 2 mm, an edge radius of 5 µm, a rake angle of 0°, and a clearance angle of 15°. The geometrical properties of the cutting tool were determined by measuring its features from scanning electron microscope images (Fig. 2).

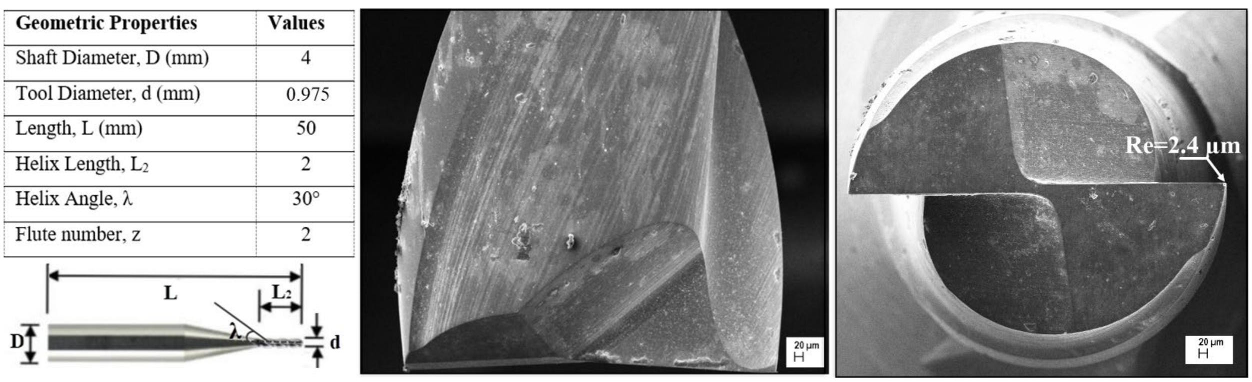

Figure 2. SEM image of the diameter and edge radius of the cutting tool used in cutting experiments.

Cutting tests were conducted at various feed rates under dry cutting conditions using a triaxial test rig to determine the minimum chip thickness. The cutting tool was secured to the IMT spindle with a collet, and axis movements were set using Thorlabs software. The workpiece was held in place with a Kistler-9119AA1 mini dynamometer to measure the instantaneous cutting forces. The cutting force signals were transferred to the computer via an amplifier and converted into force measurements using Dynoware software. The cutting tool movements and cutting zone were observed using a USB microscope during the cutting process (Fig. 3).

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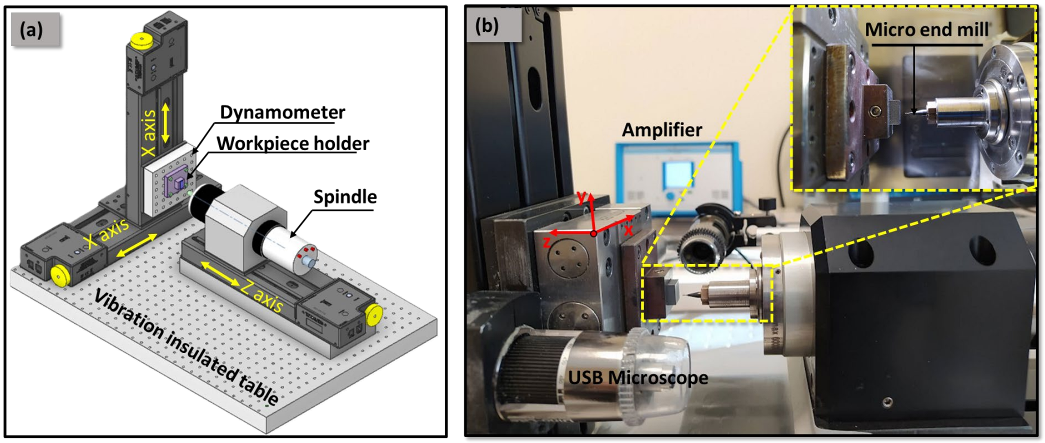

Figure 3. a) Schematic representation of the experimental setup used in cutting experiments, b) a general view and positioning of the cutting tool-workpiece on the experimental setup.

Micro milling experiments were conducted at a constant depth of cut (100 µm) and speed (30000 rpm) to determine the minimum chip thickness and observe the effect of feed rate differences per tooth on surface roughness. Ten different feed rates (0.1, 0.25, 0.5, 0.75, 1, 2, 4, 6, 8, 10 µm/tooth) were used to determine the dominant cutting process mechanism between shear and ploughing. The Nanovea 3D ST400 optical surface profilometer was used to take measurements by scanning the cutting grooves. The scanning distance was 1.2 mm x 0.6 mm with a scanning step of 3 µm. Measurements were taken from the inside of the channel at a distance of 970 µm x 600 µm. The resulting Sa (areal average surface roughness) and Sz (areal maximum surface roughness) surface roughness values were compared at different feed rates. Additionally, Ra measurements were taken parallel to the feed direction across the width of the machined channel. This revealed the impact of differences in feed rate on surface roughness for two distinct levels of roughness.

Results and Discussion

Sa and Sz values were determined at different feed rates through cutting tests and surface roughness scanning. Measurements were taken from at least three different areas of the cutting grooves, and the averages of these measurements are presented in Figure 4. A detailed graph for fz=2µm/tooth is also provided in Figure 4. The results indicate a significant increase in both Sa and Sz values for fz<0.5µm/tooth, which is defined as the Ploughing zone in both graphs. In micro milling, a negative rake angle effect occurs at the cutting edge when the feed per tooth is smaller than the minimum chip thickness. This effect makes the cutting process difficult, increases cutting forces, and causes deterioration of the machined surface quality and burr formation. Figure 4 shows a significant difference between the error bars for 0.1 and 0.25 µm/tooth, indicating a high degree of surface variability. For fz greater than 0.5µm/tooth, the milling process achieves cutting through a shear mechanism. Similar to conventional milling, increasing the feed rate results in an increase in surface roughness. As the cutting edge radius measures 2.4 µm (Fig. 2), the minimum chip thickness corresponds to 21% of the cutting edge radius, based on the surface roughness results. The Sa and Sz values at the minimum feed rate (0.1 µm/tooth) are higher than those at the maximum feed rate (10 µm/tooth), indicating that the ploughing mechanism has a significant effect on surface roughness.

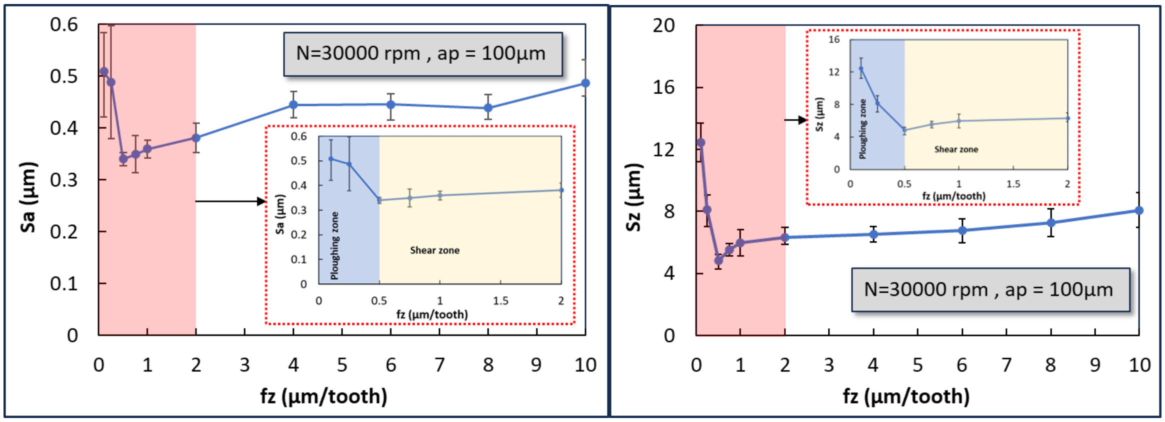

Figure 4. Variation of Sa and Sz surface roughnesses as a function of feed rate.

Figure 5 displays the surface topographies of the machined slots, illustrating the impact of the ploughing and shear mechanism on the surface in micro milling. Additionally, the two-dimensional variation plot along the slot width is presented. When the feed rate is below the minimum chip thickness (0.1 µm/tooth is provided as an example), a non-uniform surface topography is observed. The cutting marks of the cutting tool are faint and only located in the center of the slot, across its width. The surface irregularity and height difference increase towards the edges of the slot, as shown in the linear variation plot. When using fz=1 µm/tooth, the cutting marks on the surface are more pronounced, and the height difference (hpv) at the edges of the slot is smaller compared to fz=0.1 µm/tooth. Additionally, the height difference (hpv) of the surface marks between the edges and the middle region of the slot is also smaller for fz=1 µm/tooth. At a fz of 1 µm/tooth, the cutting in the middle region of the slot (100µm<ws<800 µm) is achieved through shear mechanism. However, there is a height difference between the edges and the center of the slot, indicating ploughing occurs at the edges. At a fz of 10 µm/tooth, the cutting process is also achieved through shear mechanism. The high feed rate resulted in an increase in surface roughness. Figure 5 shows that the hpv values for 0.1 and 10 µm/tooth are similar, indicating a deterioration of surface quality caused by milling with ploughing.

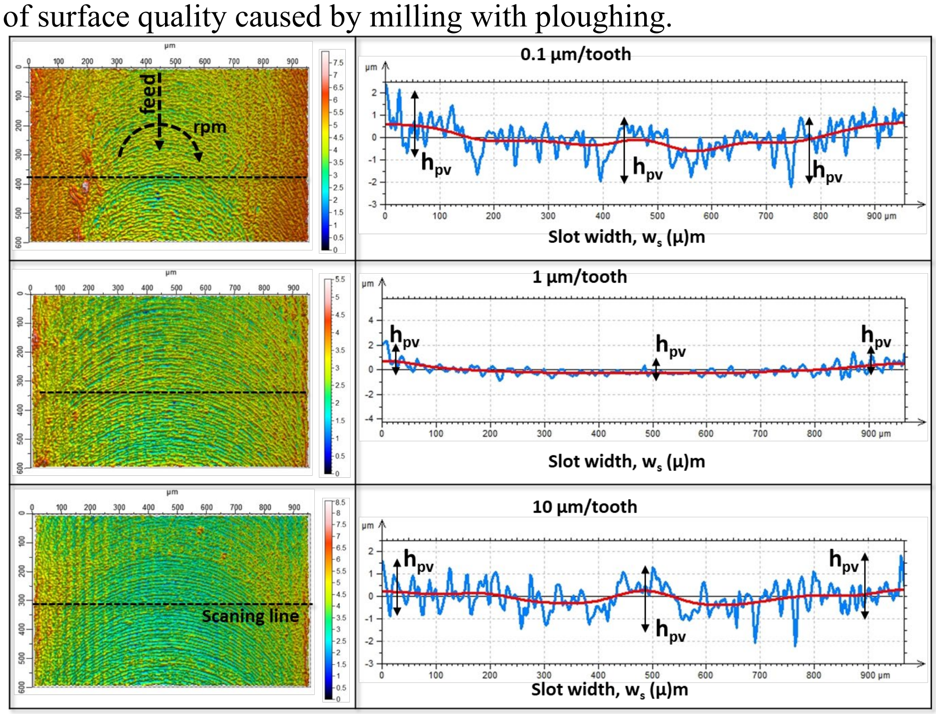

Figure 5. 3D surface topographies from the optical profilometer.

Figure 6 illustrates the variation of two-dimensional surface scanning results parallel to the feed direction with slot width. The surface roughness is high at the edges and in the middle regions in cutting processes with fz=0.1 and 0.25 µm/tooth due to the ploughing mechanism effect since h<hmin along the cutting channel. However, in cutting processes with feed rates of 0.5, 0.75 and 1 µm/tooth, Ra is minimum in the middle region of the cutting channel (100µm<ws<800 µm). In contrast, Ra increases near the starting (ws<100µm) and ending edges (ws<900µm) of the slot due to ploughing. The chip thickness is initially close to zero and increases with the rotation of the tool during cutting, even for fz=0.5 µm/tooth, where the surface roughness is minimum. However, the chip thickness at the beginning and end of the cutting process is less than the minimum chip thickness, causing ploughing. Figure 6 shows that the length at which ploughing occurs is about 100µm. At fz=0.1 and 0.25 µm/tooth, the Ra value varies across the entire width of the groove, with the maximum Ra value being at the edge and in the center of the groove. At higher feed rates (fz=8 and 10 µm/tooth), the Ra value is higher in the center of the slot (200µm<ws<800µm). However, the Ra value is low at the beginning (ws<100µm) and end edges (ws<900µm) of the slot.

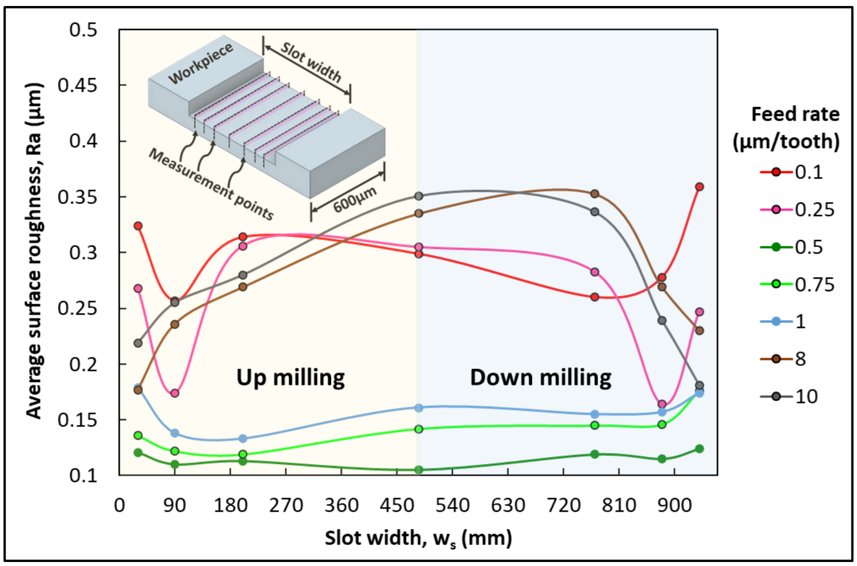

Figure 6. Two-dimensional surface topographies from the optical profilometer.

Conclusion

This study observes the size effect in the micro milling process and investigates the impact of different feed rates on surface roughness due to ploughing and shear mechanisms. The obtained results are listed below.

- Based on the surface roughness results obtained at different feed rates, it was determined that the critical feed rate was approximately fz=0.5 µm/tooth.
- It was observed that when feed rates fall below the minimum chip thickness, the ploughing mechanism significantly increases surface roughness.
- At feed rates higher than the minimum chip thickness, the surface roughness increases linearly with the feed rate because the shear mechanism is active.
- At feed rates where the shear mechanism is active, the surface roughness is higher at the starting and ending edges of the 100 µm slot than in the middle regions due to the ploughing effect.
- At high feed rates, the surface roughness in the middle regions of the slot (200µm<ws<800µm) is higher than the edge regions (ws<100µm). The Ra value increases

with increasing feed rate, which is more effective than the increase due to ploughing in the edge regions.
- At feed rates lower than the minimum chip thickness and at high feed rates, there are greater height differences in the surface topography.

Moreover, these findings hold promising implications for renewable energy applications. Understanding the interaction between feed rates and surface roughness enhances manufacturing efficiency and has significance in the fabrication of micro-components crucial for renewable energy technologies. Manufacturers can achieve smoother surfaces and improved energy conversion efficiencies in micro-devices utilized in solar panels, wind turbines, and other renewable energy systems by optimizing milling parameters to minimize plowing effects and maximize shear mechanisms. This emphasizes the pivotal role of micro-milling in advancing sustainable energy solutions.

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