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Recent Trends in Manufacturing and Materials Towards Industry 4.0

Selected Articles from iM3F 2020, Malaysia

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Preface

The Innovative Manufacturing, Mechatronics and Materials Forum 2020 (iM3F 2020) is the first edition of the forum organized by the Faculty of Manufacturing and Mechatronic Engineering Technology, Universiti Malaysia Pahang (UMP). This forum is aimed at building a platform that allows academics as well as other relevant stakeholders within the region to share, discuss and deliberate their latest research findings in the domain of manufacturing, mechatronics and materials, respectively.

With the latest trend in manufacturing engineering that gearing towards Industry 4.0, iM3F provides an excellent avenue for the community to keep abreast with the current technological advancements. This volume hosts 89 papers from the manufacturing and materials tracks of the forum. The papers published in this proceedings have been thoroughly reviewed by the appointed technical review committee that consists of various experts in the field of manufacturing and materials.

A sincere thanks to all members of the organizing committee for making the conference a success. Not forgetting our sponsors, CREST and Cisco Webex, as well as our partners, Smart Manufacturing Research Institute, innovationlabs.my, SEAIC and BioMeC for their kind gesture and continuous support. We also would like to extend our appreciation to the authors for contributing valuable papers to the proceedings. Last but not least, we are grateful to publisher support especially to Mr. Prasanna Kumar N. and Dr. Loyola D'Silva. We hope this book will intensify the knowledge sharing among colleagues in the field of manufacturing and materials engineering.

Pekan, Pahang, Malaysia
August 2020

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Tool Wear Observation During Unconventional Low Speed Machining Using Low Cost Micromilling

Ainur Munira Rosli, Norlida Jamil, Ahmad Shahir Jamaludin, Mohd Nizar Muhd Razali, and Ahmad Razlan Yusoff

Abstract Nowadays, biomedical, aerospace, electronics, and military industries have high demand for miniaturized components due to their rapid technology development on high precision devices. Micro milling process is one of the processes that is expected to be able to produce micro-size 3-dimensional features onto workpiece. This process can be considered as costly and difficult due to dimensional effect and low cutting energy generated. It can be considered that one of its crucial components in the process is the micro size tool itself. The study challenges the capability of low cost micro milling tool during machining aluminum alloy 6065 and AISI 1045 steel material, where a 1.0 mm end mill tungsten carbide (WC) tool is chosen. The experiment is conducted using a different combination of machining condition. The surface roughness of the workpiece and size of wear length is measured using a 3D measurement laser microscope. It can be observed that the wear length increases proportionally with cutting length, resulting to the increment of the surface roughness. Machining process of higher strength material tends to wear the tool faster, shortening the life of the tool, although the machining process is possible. It is assumed that a proper selection of machining parameter is required to reduce tool wear rate and promotes a longer tool life.

Keywords Low cost tooling · Micro milling process · High precision machining

1 Introduction

In recent years, the increasing demand for micro-scale components and products give mold making industries with new and diverse challenges. Miniaturization brings new low-material-cost, high-precision and high-quality processes capable of producing miniaturized products to the forefront [1, 2]. These encourage ever-increasing attention to the process driven by miniaturization of devices, features, and components

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[1, 3–5]. Almost all of the conventional manufacturing methods have limited capabilities (geometric tolerances, shape complexity, and the material properties of the product in question) making them not suitable for micro manufacturing. Assessment on both geometrical attributes and overall process cost had been done, including other comparative studies of various machining processes [6]. The technical-economic assessment shows that the efficiency of the micro cutting process is closer to that achieved by lithography, in contrast with the other micromechanical approaches. In addition to this, it has the potential to resolve the problems faced by lithographic processes at the small (micron, sub-micron) scale.

The ability for precision machining in the manufacturing of workpieces had consistently increases, where the machining process had played a vital role. The advancement of the micromachining capability in terms of Taniguchi's unit removal is demonstrated by Taniguchi [7]. The inspiration for progressively smaller components where it matches the enhancements in cutting technology as laid out [7].

An earlier research stated that micromachining components with dimensions in the range of 1 μm could accomplish surface roughness, R_a values of approximately 5 nm. One critical aspect related to miniaturized components is the increment of the ratio between surface area to weight. For instance, there is a noteworthy reduction of 29% (from 6.2 to 1.8 kg) from 1989 to 2001 in the weight of an automotive ABS (anti-lock braking system) [7]. Micro turn-milling NC machine is used in a study to manufacture micro gears with 10 and 20 teeth with a thickness of 400 μm utilizing a gear milling cutter. At a cutting speed of 75.4 m/min and a feed rate of 0.083 μm/rev/tooth when performing milling operation, best results can be acquired [8].

Additionally, a later study states that the 'micro' in micromachining indicates 'micrometer' and indicates the range from 1 to 999 μm. That study characterized micromachining relative to parts that are "too small to be machined easily" [9]. However, several studies have suggested that formation of structures or removal of material in sub-millimeter range comes within micro-cutting range [1, 2] while 1 to 10 mm is in the meso-domain range [10].

Subsequently, applying the conventional approaches used to clarify the phenomena associated with macro machining in this case by merely downscaling the process is impossible. Decreasing the scale from macro to micro presents unique challenges that need to be overcome. Although the general characteristics of the process do not change to a sensible limit, when the ratio of the workpiece and the tool size turns smaller, size effects can impact the entire aspect of machining [2].

The size effect is an aftereffect of a diminished scale, as materials decline in size, the likelihood of finding a deficiency diminishes; therefore, the substance leans toward its theoretical power. Likewise, a small sized cutting tool is more averse to deformity. These implicates that an expansion in the material's strength in micromachining also could mean the cutting forces are elevated [11]. Size effects in materials associated with aerospace and biomedical fields are of particular interest since both depend solely on the utilization of small sized features. Mechanical micromachining of hard to cut materials (e.g. Titanium alloy), is perceived as a significant obstacle for manufacturing [2].

Micro milling applications require small-sized cutting tools, and research said that this small tooling should be run in high RPM to decrease the risk of tool breakage and optimized the quality of the end product. Schulz [11] addressed the upsides of high-speed machining; nevertheless, it is discovered that the undesirable impact of high-speed machining is the rate of tool wear frequently increases; this is due to an inclination in cutting zone temperature. There was also less research on micro milling using low-speed machining application, but it is a more cost-effective option if it can be improved. If the challenges during low-speed machining can be overcome, even machines with low-speed spindle can be used to produce a good quality micro milling product. Thus, a study on low-speed machining during micro milling is conducted to investigate the behavior of tool wear and tool life in the process. The scope of the study is limited to the machining process up to 3000 rpm, with a conventional milling lathe that commonly available in the workshop. It is expected that, the micro-milling tool is unable to do much due to low cutting speed, yet possibility of the process can be considered high if effective parameter is known.

2 Methodology

The experiment in this study involved the application of 1 mm tungsten carbide end mill tool, along with aluminium alloy 6065 and AISI 1045 steel plates that are chosen as the workpiece. A 3D measurement laser microscope is also used to analyze the surface roughness and wear length of the tool. The selection of material is conducted based on the availability of the material. Then, material of different hardness is chosen to compare the tool capability and behavior between the different hardness of material. The material properties of both Al-6065 and AISI 1045 steel is shown in Table 1. The plates, both with 1 mm thickness, is cut into a 10 mm × 50 mm workpiece using a shear cutter. Then, a jig is designed, and 3D printed using a 3D printer to act as a workpiece holder.

Initially, an experimental setup was developed, which then optimized through the full-factorial based design of experiments (DoE). During this experiment, a three-axis CNC vertical machining center (Makino KE55 CNC VMC) with 4000 max RPM is used. The machining operation used is side milling with tool overhang of 2 cm for every cutting condition. The fixed parameter and cutting condition is shown in Tables 2 and 3. In each cutting condition, the surface roughness and wear size is taken using the 3D measurement laser microscope, and analyzed with its software between each pass. The experiment is conducted until the tool wear reaches a significant wear size where the cutting process cannot proceed or the tool breaks.

As shown in Table 2, it is decided to keep the cutting tool radius, the number of flutes, tool material and workpiece size fixed. The commonly utilized workpiece material is chosen, aluminium alloy Al-6065 and mild steel AISI 1045 steel. These acts as comparable parameters. In the study, cutting speed and feed/tooth parameters effect on tool wear and end product quality will be observed. The work specimens

Table 1 Material properties of both Al-6065 and AISI 1045

Material	Mechanical properties		Chemical properties	
Aluminium alloy (Al 6065)	Ultimate tensile strength (MPa)	310	Aluminium, Al (%)	97.1
	Yield strength, (MPa)	270	Silicone, Si (%)	0.6
	Modulus of elasticity (GPa)	68	Magnesium, Mg (%)	01.0
	Vickers hardness	107	Copper, Cu (%)	0.25
	Density (kg/m^3)	2800	Bismuth, Bi (%)	1.0 max
Mild steel (AISI 1045)	Ultimate tensile strength (MPa)	565	Iron, Fe (%)	98.51–98.98
	Yield strength (MPa)	310	Carbon, C (%)	0.42–0.5
	Modulus of elasticity (GPa)	200	Manganese, Mn (%)	0.6–0.9
	Vickers hardness	170	Phosphorus, P (%)	0.04 max
	Density (kg/m^3)	7870	Sulfur, S (%)	0.05 max

Table 2 Cutting tool and workpiece specification

Cutting tool radius size (mm)	0.5
Number of flute	4
End mill type	Flat end mill
Tool material	Tungsten carbide
Workpiece material	Aluminium Alloy 6065 AISI 1045 Steel
Workpiece initial dimension	10 mm × 50 mm × 1 mm

Table 3 Cutting condition

Spindle speed (RPM)	1000–3000
Cutting speed (m/min)	3.142–9.425
Feed per tooth per revolution (mm/tooth)	0.001–0.005

are mounted using the 3D printed jigs to ensure a secure hold of the small workpiece. The preparation of the experiment is shown in Fig. 1.

Additionally, all the measured data is collected and then tabulated into sets of graphs to compare the relationship and behavior of the variables.

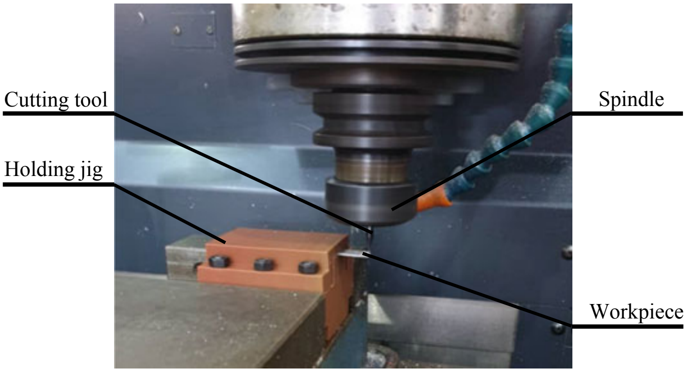


Fig. 1 Experimental preparation onto CNC milling machine

3 Result and Discussion

The experiment involves the combination of 3 different cutting speed with 3 different feed rate where the tool diameter is 1 mm with 4 flutes. The machining operation was performed, and the taken data, which, is then tabulated into a table.

3.1 Tool Wear

Figure 2 shows the relationship of wear size against the length of cut of aluminium alloy 6065 (Al-6065) and AISI 1045 steel (both at 0.001 mm/min feed rate). It can be observed that the wear size increases proportionally with the length of cut. In machining process of aluminium alloy Al-6065, cutting speed of 9.425 m/min, which is the highest possible generated by the machine, has the highest tool wear rate. Meanwhile in machining process of AISI 1045, the cutting speed of 6.283 m/min

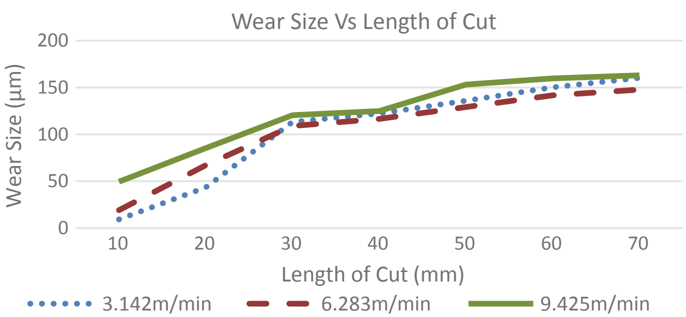


Fig. 2 Relationship of wear size and maximum cutting length of aluminium alloy Al-6065

shows the largest gradient of tool wear rate, but the process stops at 20 mm cutting length as the tool broke, similarly happens for machining process with 9.425 m/min. In Fig. 3, the machining process of AISI 1045 with 3.142 m/min shows the lowest inclination of wear size compared to the other cutting speeds parameter, and last longer than other chosen parameter.

Additionally, tools breakage often occurs during the cutting entrance of side milling process of the new pass in machining mild steel AISI 1045, compared to machining aluminium alloy Al-6065. It is assumed that at very low speed and low cutting power, surface integrity and hardness plays main role in tool as it is known that mild steel AISI 1045 has higher hardness and surface integrity compared to aluminium alloy Al-6065. This is also related to the force impact generated during entrance which also expected to be higher when the cutting speed increases [10].

Figure 4 shows the physical of worn tool observed during side milling of AISI 1045 steel. Since it is a side milling process, the wear is focused on the flank zone of the tool's flute. It is also observed during the experiment that the tool breakage

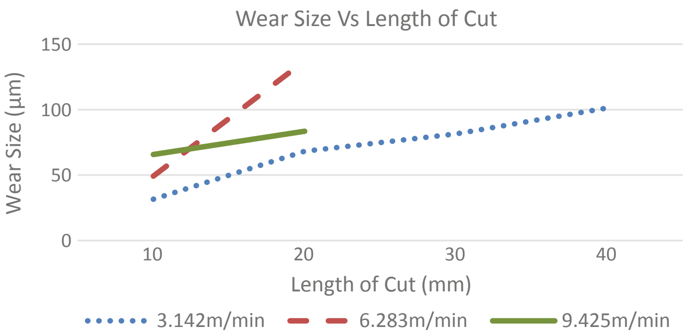
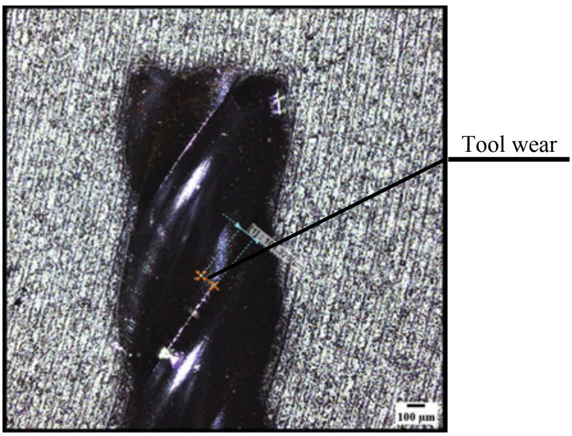


Fig. 3 Relationship of wear size and maximum cutting length of mild steel AISI 1045

Fig. 4 Generated tool wear (3.142 m/min, 0.001 mm/tooth on AISI steel)



more frequently occurs during tool entry and exit from the workpiece. It is assumed that higher forces are generated during surface penetration into the workpiece, as well as burr formation during exit from the workpiece [11]. One of the workpieces speciment which undergo this occurrence is shown in Fig. 5.

Figure 6 shows the relationship of feed rate and maximum cutting length for various cutting speed of aluminium alloy Al-6065. It can be observed that. the micromilling tool has the highest tool life (higher maximum cutting length) for the lowest feed rate of 0.001 mm/min, compared to the other tested feed rate parameter. However, the machining parameter using 0.003 mm/min as feed rate contributed to the lowest tool life (lowest length of cut). The tool life shows similar behavior in the lowest feed rate regardless of the cutting speed. However, only machining process with 3.142 m/min parameter shows the highest tool life for feed rate of 0.003 mm/min, and the variation of behavior spread even larger with the highest feed rate.

It is assumed that, the cutting load generated from the chosen feed rate might have a significant effect onto the process. Additionally, based on the overall results,

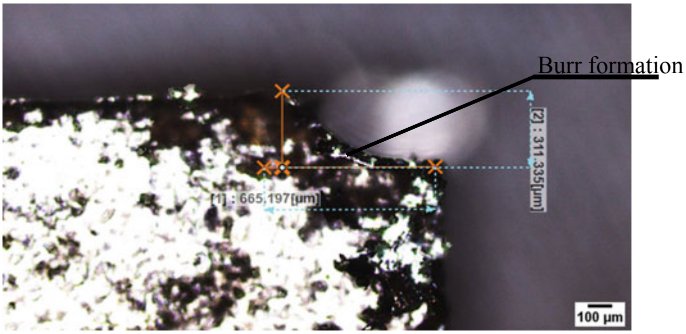


Fig. 5 Workpiece with broken tool during entry (AISI-1045)

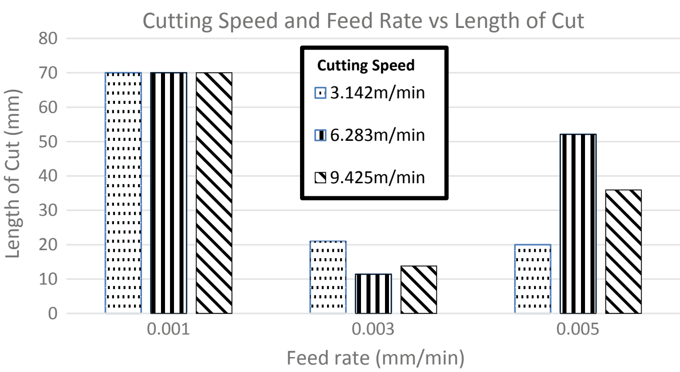


Fig. 6 Relationship of feed rate and maximum cutting length of aluminium alloy Al-6065 at various cutting speed

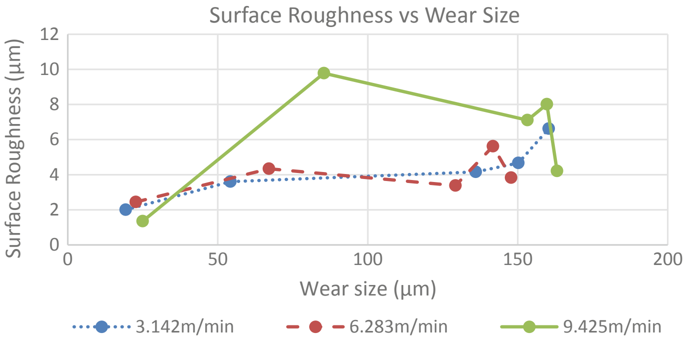


Fig. 7 Graph of surface roughness versus wear size of aluminium alloy 6065 at feed rate, 0.001 mm/min

machining with the lowest feed rate in the experiment (0.001 mm or 1 micron) have higher tool life during cutting of Al-6065. At 0.005 mm/min, machining process with the cutting speed of 6.283 m/min have the highest tool life, and the lowest cutting speed has the lowest tool life. The separated variation of tool life during the machining process might be affected by the entrance and exit process of the micromilling tool as well as the micro geometry itself [12, 13].

3.2 Surface Roughness

Figure 7 shows the relationship of surface roughness (Ra) against the tool wear propagation of machining process aluminium alloy Al-6065. It can be observed that as the wear size of the tool increases, the surface roughness also increases. Both cutting speeds of 3.142 and 6.283 m/min have quite a similar trend of surface roughness generation against wear size. However, at 9.425 m/min there is an entirely unexpected spike on the surface roughness when the wear size is 85.39 µm. It is assumed that higher cutting speed leads to higher cutting forces that increase the wear at a much higher rate, thus making the surface roughness spikes. It is noticed that there are irregularities in the trend, where it is expected that surface roughness supposed to increase along with the wear size [10, 11]. The trend increases until 85.39 µm before it starts a decreasing trend. This could be caused by the worn edge of the tool, where the tool is unable to cut effectively anymore, but more towards grinding action on the workpiece lead to the reduction of surface roughness.

4 Conclusion

This study is carried out to observe tool wear propagation behaviour during low cost micromilling of both aluminium alloy 6065 and AISI-1045 steel. From the result obtained, it can be understood that cutting higher hardness material needs more cutting energy to be machined. Thus, explaining the shorter tool life during cutting of mild steel AISI 1045 which has 170 Vickers hardness compared to Al-6065 material that has 107 Vickers hardness. Selection of cutting speed and feed rate also affects the rate of tool wear and tool life. Lower feed rate is preferable while cutting with 3.142 m/min cutting speed is found the best between the others for current experiment. Additionally, due to the size effect of the tool, the entry and exit force during micromilling also plays a vital role in causing tool breakage. Thus, finding a way to reduce the entry and exit force could contribute to more extended tool life. More study needs to be done on finding the optimum machining parameter for low-speed machining of micromilling, especially increasing the cutting speed for micro size machining.

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