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Abstract: This paper presents an overview of the modern advancement of micromilling as pertained to the machining process from recent research and advancement perspective. The review starts by displaying the characteristics and micromilling contributions background, and later sets up the reader to difficult-to-cut materials. However, the fabricating process usually becomes complicated owing to these material's unique metallurgical properties. This paper brings to focus the micromilling of difficult-to-cut materials, especially materials that are currently the highlights of various industries. The discussion of research and attributes of difficult-to-cut materials are covered in further detail, which serves with opportunities for future developments.

Keywords: Micromilling; Hard to machine; High precision machining

1. Introduction

Nowadays, there are ever-increasing demands on mini-sized components along-side the advancement of much smaller and efficient innovation in many industries. On the technological side, their growth has inclined exceptionally fast, determined to produce smaller components with improved performances and capacity. Manufacturing fields for telecommunications, automotive, electronics, automotive, defense, and biomedical applications, widely used micromilling method to produce intricate 3-D micro-scaled units. In the medical field, it benefits from micro-production through micro scaled devices for medical equipments (pacemakers, analysis equipment, sensors, etc.), tissue engineered products and slightly intrusive accessories such as aneurysm clips, prosthesis, and stents. Therefore, there is a rising call for work with great resilience, distinct structures, and intricate details. The simplified and revised version of micro-products and its categories gained from L. Alting et al. review on micro-milling is shown in Table 1 below[1)]. The capability to fabricate a broad scope of materials, the best surface quality, and outstanding MRR (Material Removal Rate) are its main advantages[1-3)].

Various fields of dynamic research such as biomedical industry, aerospace, and optical industry require little metallic components sized lower than 1mm, which had features estimated to a few tens or hundreds of microns as their tolerances as precise as 0.1 microns. These incorporate devices that put as implants in the mortal body, microscopic lenses, accessories for learning the structures and behavior of the human body, and other mini sized parts. Aerospace manufacturing, for instance, uses alloys of steel, nickel, titanium and aluminium[4)]. Micromilling is a microscale machining process that can generate a large spectrum of small-sized parts, including advanced shapes and forms[5)].

Masuzawa, in his review, states that the 'micro' in micromachining shows 'micrometer' and suggests the range from 1µm to 999µm. He described micromachining comparative to components that are exceptionally small to be machined effortlessly[6)], while another paper elaborates forming technologies devoted to the construction of components which is considered as in the sub-millimeter range. However, Other researchers also suggested that the development of features or material removal in sub-millimeter range falls inside the micro-cutting domain [7-8)], while 1 to 10 mm is in the meso domain range[9)].

Micromilling procedure is represented by the relationship in the mechanical perspective of pointed tools with the element of the workpiece, leading to deterioration inside the component along established routes which, in due course contributing the impractical part of the workpiece eradicated in as chips. The tool's element has to be stronger than the workpiece's properties. There also should need zero thermally activated dispersion to occur between them to realize such a procedure. The tool edge radius should be in the cut's order, thickness's dimension,

Table 1. Micro-products and its categories[3,10)]

Product Group	Example
IT/Computers	Magnetic bearings
Medical Equipment	Pacemakers, Implants, Prosthesis, Aneurysm clips, Surgery devices,
Watches	Gear wheels, Micro transmission
Sensors	Gyroscopes, Accelerometers, Micro pumps, Micro total analysis systems
Actuators	Stick and slip actuators, Magnetic actuators, Piezoelectric elastic force motor, Micro motor, Electrostatic actuator
Optical Communication	Holographic memories, Lenses, Micro optics, Optical switching devices, Optical networks, Connectors
Displays	Micro mirror, Display devices
Electronic Parts	Ink jet printer nozzles, Colour printing, Hearing aids, Micro parts on circuit boards

or smaller. Down-scaling of conventional machining into micro milling creates difficulties for process stability and materials behavior. Applying the traditional viewpoint used to clarify the phenomena associated with macro machining by merely down-scaling is incomprehensible. It is challenging to reduce of the scale from macro to micro and to overcome its behavior. Although the general attributes do not change to a sensible limit, the size effects can affect the whole prospect of machining when the ratio of the workpiece and the tool size turns smaller[8)].

L. Alting et al., in his review, mentioned that the lowered deformation of heat on the machine tools are the primary reasons behind the minimisation of machining tools. A cutback of material expenditure for machine tool manufacturing provides the opportunity for the usage of more expensive, enhanced materials, a drop on sizes and vibration amplitudes, and light weighted products which is caused by diminished space effect and energy expenditure farther contributes to reasons for downscale components[1)]. The minimisation and reduce in weight and prime function density will make micro products to be more competitive[11)]. Other than that, the micromilling process allows the usage of any machinable material, brisk process planning, and material removal. The machine and tools used also limits the three- dimensional geometry. Often, producing the prototypes or individual components within one day of the design is possible because of quick and inexpensive total cost[12)]. However, there are possibility of tool breakage and deflection from forces that reacts on the micromilling tools. Deflection diminishes machining accuracy, and tool breakage results in having to repeat the cutting process, slower production, and more imperfect tolerances[13)]. Several wear mechanisms that are important to consider during machining are adhesion, diffusion, and abrasion [14-16)]. Friction induced temperature generation at the cutting zone also affects the surface roughness[17)]. Lowering surface roughness or enhancing surface quality had been a prime aim of many researchers[18-22)]. These difficulties serve as a motivation to do more research on the micromilling process and enhance it, specifically on its advanced application and machining of difficult-to-cut materials.

2. Micromilling of hard to machine material

Difficult-to-cut material has unique properties such as poor thermal conductivity, ductile and high hardness brittleness materials (e.g., superalloy, pure nickel, and ceramics). Hard to machine materials also referred to production of excessive wear, heat or cutting forces during machining operation and poor surface roughness during machining of a material[23)]. They also are often not cost effective to machine[24)]. These characteristics have an immense impact on the selection of machining methods, equipment, and conditions[25,26)]. The production of materials such as titanium, steels, and other superalloys which can tolerate the demands of extreme applications is done to occupy the voids in various industries such as aerospace, telecommunication, and biomedical industries[27]. The materials are made harder, more robust, stronger heat resistance, and further invulnerable to corrosion and fatigue however this also caused them to became more challenging to machine[28,29].

Adams et al. have machined linear channels in PMMA and brass. He also machined linear channels, wide concentric channels and helical channels on cylindrical Al6061 workpieces which achieved Ra (average roughness) less than 0.30 pm.)[30,31]. Aluminium alloy has exceptional corrosion resistance and strength to weight proportion[32]. It also can be heat treated to precondition for aging and increase phase structure quality without precipitation and have very good wettability with reinforcement[33]. Aluminium alloy had been used in the manufacturing of aircraft components and automobile industry[34-36]. Because of the hardness of the material, it makes it hard to machine[37]. There are results of increased hardness and tensile strength when aluminium alloy is strengthened using eggshell composite, Nano-SiC particles, and Al2O3[38-40]. Assis et al. also had investigated the micromilling of aluminium, mild steel, and stainless steel[41]. Another research had studied the usage of tapered geometry micromilling tool on machining of aluminium alloy[18] while Soffie et al. had used 17 micro v-groove samples to investigate the morphological and surface quality on AISI 6010 using magneto-rheological polishing method[42]. Alting et al., stated that micro-cutting of steel using tungsten carbide tools has been done by other researcher and leads to a fully 3-dimensional micro mold for plastics fabrication (SAE H13), accomplishing 0.5 pm Rz[1]. Stainless steel is also another material that is high corrosion resistance that is used by Wulan et al. in her research on carbon nanotube because that characteristic[43].

Researchers have identified titanium alloy Ti6Al4V as one of the most extensively applied materials in biomedical engineering and in alternative fields[44,45]. The most used type of titanium alloy is Ti-6Al-4V α-β reaching more than half of global production[48]. It is popular because of its strong fracture resistance, and corrosion resistance and high temperature strength[49-52], utilizable at places that have high operating temperatures[53,54]. However, micro cutting often leads to heat inclination in the cutting region because of high spindle speed causing rise on chip load and cutting forces[17], which will then affect the machining process negatively particularly for low thermal conductivity materials[55] (e.g. titanium alloys) by causing excessive tool wear[2]. Poor thermal conductivity and high specific heat capacity (c) causes inefficiency on dissipation of heat effectively during machining[56,57], as well as poor surface quality and reduced tool life[58]. Mohid et al. had studied micromilling of titanium alloy, laser assisted, with micro ball-end mill and had reduced approximately half of the maximum flank wear[59]. Additionally, a study on investigating the application of coatings effect on micromilling tools in micromilling process of Titanium alloy had been done[30]. The experiments run at a high cutting speed (50000 rpm), a varied cut depth with different coating conditions. They correlated the cutting pressures for machining with various types of coatings and without coatings with the cutting forces. He founds that a noteworthy cutback in the machining forces which occurred in dry lubricant coating of WS2 when applied with TiAIN. The usage of solid lubricant coatings shows an improvement on the machined surface finish[30].

Other than that, Mittal et al. studied the instability in dynamic perspective in HSM of Titanium alloy and lubrication's effect on micromilling results. He chooses the dependent cutting force coefficients to represent the behavior of the workpiece material, chip load, and spindle speed for different machining conditions on high speed machining (HSM) of Titanium alloy. Fig. 1 and 2 below presents the comparison spindle speed against forces in both x and y-axes paths at a specific feed rate of 4 m/flute and 20 m depth of cut (DOC). The cutting forces is minimised at higher spindle speeds, in lubricated machining, but Fx stays constant at lower speed region while Fy increases. He noticed that lubrication's effect is enhanced on decreasing cutting forces and quality of surface finish. Stability limits also increase when the rotational speed is above 47000rpm, which is critical rotational speed in this experiment[2].

Another researcher also analyzed the impact of traditional cooling conditions and MQL during micromilling of Ti6Al4V by analyzing wear rate of tools, formation of burr, precision, R_a, and geometrical characteristics of the tool. He claimed that a moderate amount of lubrication during micromilling in direction of the feed have higher performances than conventional cooling methods[3]. Sandip et al. had micro-machined through microgrooves successfully on pure commercial titanium[60]. Finally, microcutting tools wear experienced using HSM of Ti6Al4V has been elaborated on another study[61]. Fatigue cracks, notch wear, and micro chipping were affirmed to be the primary cause of breakage. Titanium is one of the difficult-to-cut material that is widely studied by researches because of its famous role in various fields.

Researchers also view Inconel 718 superalloy as demanding to machine because of its superior mechanical attributes. It has higher strength during extreme temperatures, and poor thermal conductivity[62]. It has a chemical resistance up to 700°C and possible for precipitation hardening. The alloy is frequently applied for unusual demands in various fields such as oil or gas, aerospace, and nuclear fields. The rapid cooling of SLM from high melting temperature of Inconel brings about complicated surface texture and unpreventable residual stresses, reaching a temperature of more than 1000ºC with high stresses speeds up flank wear, craters, and notch[63]. Porosity, solidification shrinkage, micro-cracks, high residual stress, poor quality finishing, noticeable distortion, and unwanted microstructure are among

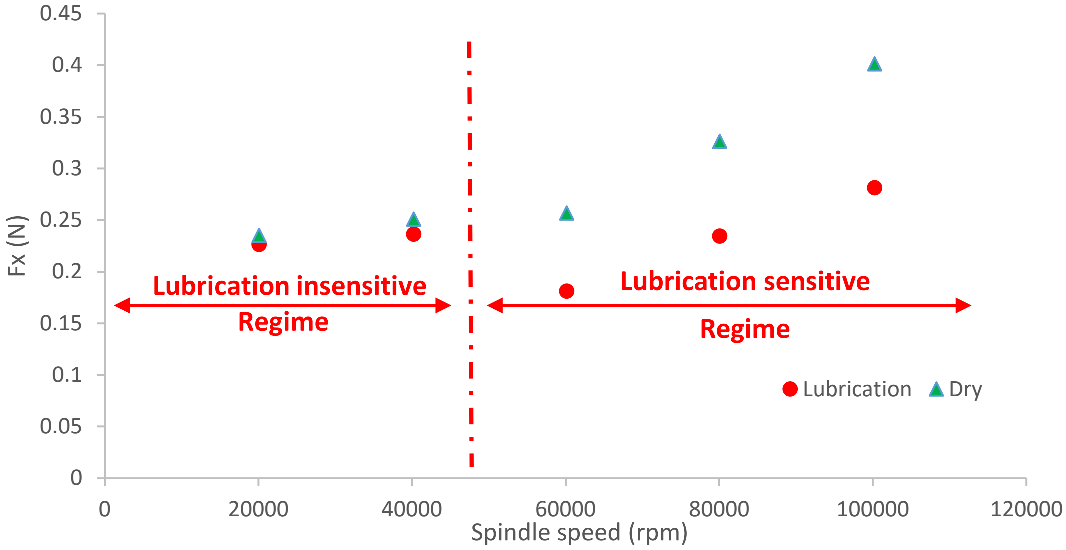

Fig. 1: Spindle speed against forces in x direction[2)]

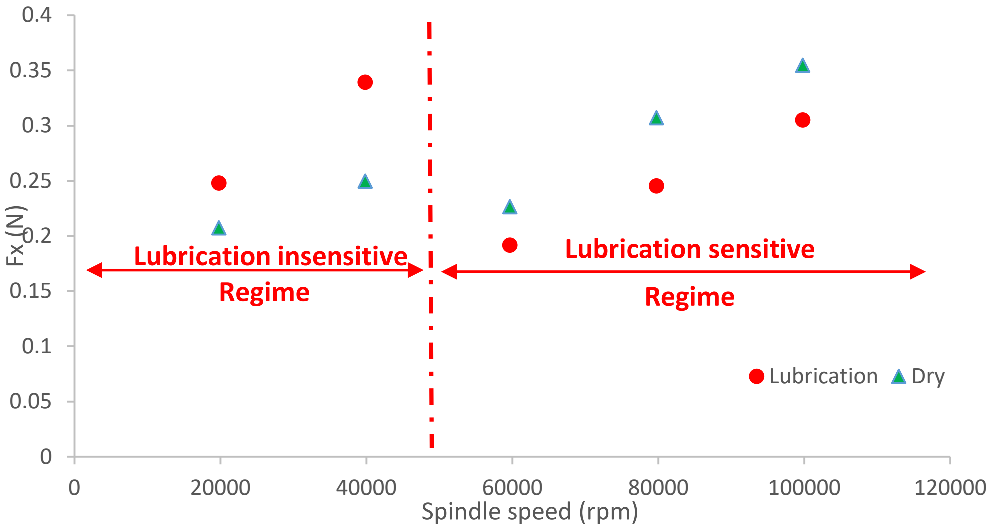

Fig. 2: Spindle speed against forces in y direction[2)]

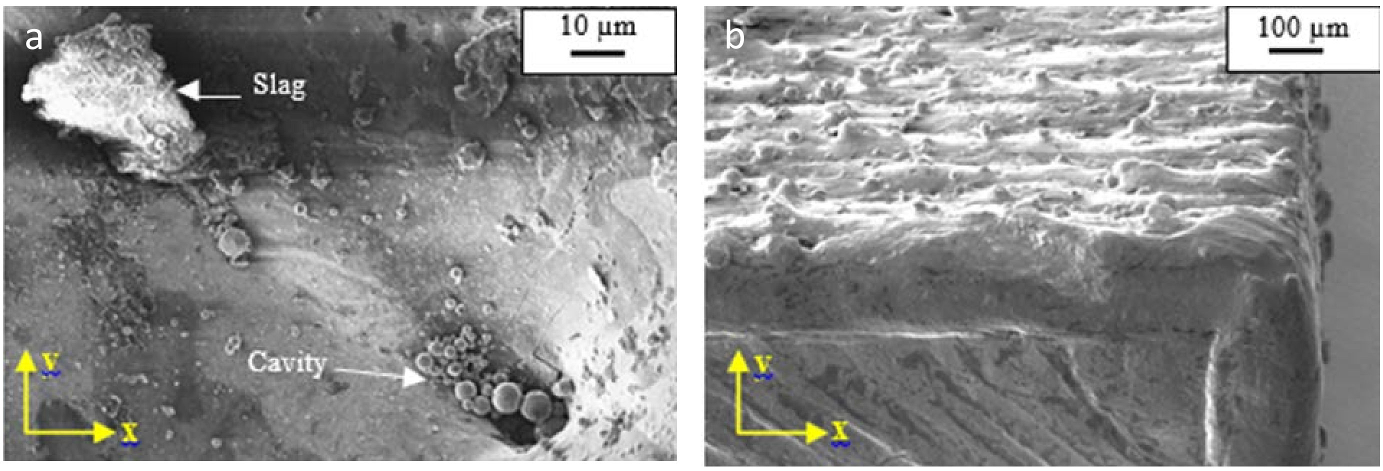

Fig. 3: a) Common surface deformities such as slag, shrinkage hole, microcrack on xy view b) Poor surface quality due to incomplete welded powder and imperfect layers from z axis view[38)]

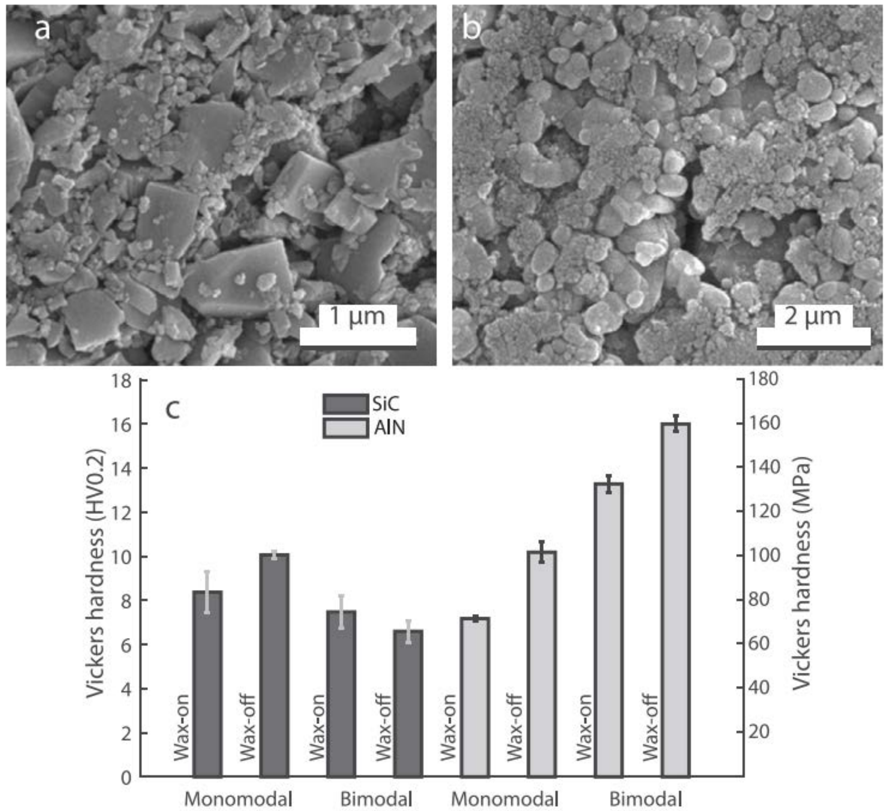

Fig. 4: SEM pictures of bimodal ceramic powders: (a)Silicon Carbide (b)Aluminium Nitride. (c) The Vickers hardness value of PIM green state ceramic workpieces[73].

crucial problems with selective laser melting[64].

Ezugwu et al.[65] combined high pressured air into flood coolant during the turning process. This technique improves the tool life with decreased cutting force, Ra (surface roughness) and burrs. He also invented a unique tool holder for minimum quantity lubrication (MQL) with an internal channel to turn IN718 rods[64].

Even though IN718 had been increasingly on demand, there had been a deprived number of researches on the topic. Ucun et al. investigated on cutting performances of IN718 using various types of coatings[64]. In another paper, he micro milled IN718 with DLC coated tools which achieve the end surface finish of 0.1-0.2 µm. He also lowered the cutting force, reaching towards 6 N when using the DLC coated tool[66]. Another study correlated micro cutting of Ti6Al4V and IN718 through dry machining procedure experimentally and got resulting surface finish less than 0.25 µm Ra when micromilling IN718[67].

A paper studied selective laser melting (SLM) additive cutting of micromilling of IN718. They set its focus on the resulting wear on the tool, and Ra influenced by the tool coating. He found out that coated tools show positive results but had to run at lower cutting speeds and improved the surface finish from 17 to 1-2 µm Ra through micromilling, and found that limited quality finish is caused by surface deformities such as pores and slags. Fig. 3 above shows the common surface deformities occurred on IN718 after SLM[38].

The modern adaptation of ceramics at the miniaturized level has been inhibited because of the lack of workable ceramic micro-cutting means, even though the distinctive characteristics of the materials are making them the optimal elements for various applications relating to micro-component features. Industries used ceramics for an expansive variety of industrial applications for their exclusive physical and chemical attributes, incorporating high resistance to corrosion, outstanding extreme temperature stability, biocompatibility, and principal metallurgical attributes as stated by Campbell et al.[68,69]. There is a booming request for higher accuracy ceramic parts with micro-component scale[70]. It has been used in high-temperature ceramic reactors[71], heat exchanger, tissue scaffold[72], energy, environment, and transportation systems[73]. Although its demands are increasing, the lack of conceivable fabricating methods has limited the utilization of miniaturized ceramic products.

Recep et al. administered an investigation that includes micromilling tests with 254µm diameter micromilling endmill tools at varying machining speeds (RPM) and feed rates. Figure 4 shows the SEM pictures of the bimodal powders used in the research. The silicon carbide components has powder particles with irregular shapes AlN workpieces mainly contain spherical powder particles. The material characteristics of his green-state workpieces also observed by Recep, where he conducted micro-indentation at 20 different locations using Vickers indenter[73)]. Dhara et al. then elaborated the green machining method[65)].

3. Conclusions and future recommendations

As described previously, difficult-to-cut materials are materials that are challenging to machine because of their unique metallurgical attributes[74,75)]. Because of their resilience and ability to withstand extreme conditions, there had been increasing demands in their application in miniature components, particularly in demanding fields and increasing amount of research study had been done on micromilling of difficult-to-cut materials by diligent researchers. However, there are still limited research on each type of materials and more studies need to be done to develop and bring our micromilling technology to gain one more step forward in manufacturing and innovation field.

The suggestions for prospective research and development comprises the following:

- Establish the part played by lubrication in micro cutting of difficult-to-cut materials because of their unique properties from each other.
- Enhance the effectiveness of difficult-to-cut materials micromilling process, specifically on tool wear and surface quality since the issue on tool wear is a crucial issue in micromilling process especially in difficult-to-cut materials.

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