A Review on Capabilities and Challenges in Tool-Based Micro-milling Process

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Abstract. Micro-milling is a precision machining technique that holds a pivotal role in the manufacturing of miniaturised components and devices across various sectors, including aerospace, medical, aeronautical, etc. This review article provides a comprehensive overview of the micro-milling process, encompassing the latest advancements, challenges and applications. A detailed analysis of key aspects, including cutting conditions, cutting tools, process parameters and emerging trends in micro-milling, was carried out over the past 18 years. Investigation into the critical process parameters governing the micro-milling operation, encompassing spindle speed, feed rate, depth of cut, and toolpath strategies, was executed. The effects of material properties and workpiece fixturing on the quality and accuracy of micro-machined parts was also explored. Special attention has been given to the impact of environmental factors, such as temperature control and lubrication, on process stability and part quality.

Keywords: Part accuracy, Part geometry, Ti-6Al-7Nb, Tool life, Tool wear, Micro-milling

1 Introduction

Micro-milling, a precision machining method, has emerged as a critical technology in the manufacturing world, enabling the creation of miniaturised components with unparalleled accuracy and precision. This review explores the dynamic landscape of micro-milling, offering a comprehensive examination of the latest developments, challenges and applications in this field. As industries across the spectrum continue to push the boundaries of miniaturisation, the need for precise and reliable machining techniques has never been more pronounced. Micro-milling has risen to meet these demands, making it a subject of growing importance in research, development and industrial production. Even though methods for microfabrication have already been around for a long time, further advancements in precision machining methods have been made due to the strict requirements of having extremely close tolerances, dimensions, and surface properties [1], high milling efficiency and accurate machine positioning. A precise micromechanical cutting technique called micro-milling was created to meet the growing demands [2]. A highly effective and prosperous precision machining technique for producing components featuring microstructures, including intricate

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three-dimensional (3D) surfaces, on a microscale. The size of the micro-milling tool's cutting edge diameter, which typically ranges from 1 µm to 1000 µm, ultimately defines micro-milling [3]. Therefore, the following is a more technical way to characterise the micro-milling technique: a method of precise mechanical cutting that uses cutting-edge tool diameters smaller than 1,000 µm that can be determined geometrically, allowing for the precise form and dimensional precision of material chips with a tolerance of less than 1 µm to be removed.

However, when milling at the microscale, there are physical process limitations that are inherent and do not exist when machining at the macroscale. These limitations affect the micro-milling process. These limitations are associated with material removal methods at the microscale, such as process stability, size effect, and chip formation. Consequently, a detailed discussion of the primary physical procedures that restrict the accuracy and efficiency of the micro-milling process is given. These undesirable phenomena impacting the results of the machining process are taken into consideration and suggestions for reducing, if not eliminating, these effects are provided. The micro-milling process has garnered significant attention in research recently, with a lot of studies concentrating on the process variables, such as coolant, tool material and their microstructure, tool shape, material and effective toolpath generation. A clear picture of the modern micro-milling process may be obtained by looking at the most recent research on the effects of different process parameters on the a_p, R_a and tool wear in machining. To pinpoint aspects of the process that need further development, this study examines the theoretical, analytical and experimental research that has been published most recently.

Future advancements in hardness and more resistant materials will highlight the significance of these assisted procedures even more. These materials, which include hard and wear-resistant superalloy, refractory metals, structural ceramics, composites, polymers and magnesium alloys, are described as "hard-to-machine" materials [4]. It is taken into consideration that in the future, micro-milling might not be sufficient to overcome the actual process boundaries connected to the procedure, such as chip generation, size effect and process stability.

2 Workpiece Properties

Work material properties possess a profound impact on the path precision in geometry. It includes parameters such as material type, physical, chemical and mechanical properties [2]. Machinability of titanium alloys is always impacted by the variations in their microstructures and characteristics. the largest degree of strengthening was observed in α′ martensite, and that the columnar α + β microstructure is stronger than the equiaxed one [45]. Low-density materials like Ti alloys retain their hardness and strength even in really hot conditions up to 550°C, titanium has the highest strength-to-weight ratio of all common metals [5]. Face milling of EN-GJS-500-7 nodular cast iron and EN42CrMo4 steel and it was determined that the cutting force is highly influenced by the ductility and hardness of the workpiece. The size, shape, and microstructure of the crystal grains, in addition to the kind and quantity of impurities, ultimately affect the primary cutting force of the material.

Greater cutting speed and reduced cutting depth conditions led to higher corrosion resistance, While burr development and microparticle adhesion were enhanced by cutting depth and slower cutting speeds. The impact of cutting conditions on corrosion resistance during Ti-6Al-7Nb alloy micro-milling [6]. It was discovered that the lowest I_{corr} values were obtained with greater cutting speed and reduced cutting depth of cut conditions. Additionally, the study discovered that process variables have a major impact on surface properties [7].

3 Cutting Tool

A productive and effective precision machining technique for producing micro-structured components at the micro level, like complex 3D surfaces. The micro-milling is determined by the cutting-edge diameter of the tool, which usually varies from 1 µm to 1000 µm [3]. In addition to having a sharp cutting edge for minimal cutting force and UCT, appropriate geometry for little friction, the ability to create using a reliable manufacturing process for economic viability and the ability to form and remove chips from the machined zone are all desirable qualities in a cutting tool. The precision of tool-based micromachining is greatly influenced by many parameters, including tool geometry, shape, size, both physical and mechanical qualities, geometry, manufacturing processes and tool wear [8]. Micro-milling cutters, describe the cutting tool's uniqueness, compositions, structures, fabrication techniques and machining performances [9].

3.1 Tool material and geometry

The accuracy and quality of the surface of a micro-milled component are largely dependent on tool wear. About the tool wear image, Zhu and Yu suggested a tool wear surveillance technique. An algorithm based on morphological component analysis (MCA) was created to identify and excavate the wear region, in contrast to the conventional tool wear width criterion [13].

The creative tool image is broken down into target and noise images. The outcome of the experiment demonstrates that the MCA algorithm is capable of successfully extracting the wear condition and worn image indications. The tool wear rate is impacted by the amount of cutting fluid applied throughout the process of machining. According to Santos et al., the use of cutting fluid enhanced the development of the built-up edge (BUE) using TiN-coated carbide microtools while micro-milling UNS S32205 duplex stainless steel. Because BUE prevents the tool from wearing promptly, the tool wear rate decreases as a result.

In addition to affecting tool life, dimensions are also impacted by tool wear and surface quality of the workpiece and its unpredictable nature is a major process barrier in micro-milling. Tool wear progression in seven different coatings is monitored during high-speed micro-milling of hardened steel in a dry machining environment [14]. The breadth of the strip where the initial tool was manufactured process tracks were no longer visible has been defined as flank wear as shown in **Figure 1.[14].**

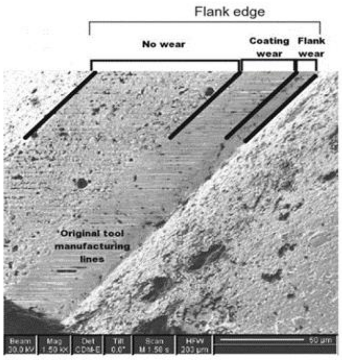

Fig. 1. Magnification of wear in flank edge[14].

There are three types of flank wear typologies: Wear land can be classified as uniform **Figure 2a [14].**and non-uniform **Figure 2b [14].** localized or occurring in a specific area of the flank. Uniform flank wear is typically uniform in breadth and covers the areas on the tool's flanks. adjacent to the active cutting edge. The profile created by the intersection of worn land and the initial flank varies at each measurement position. [14].

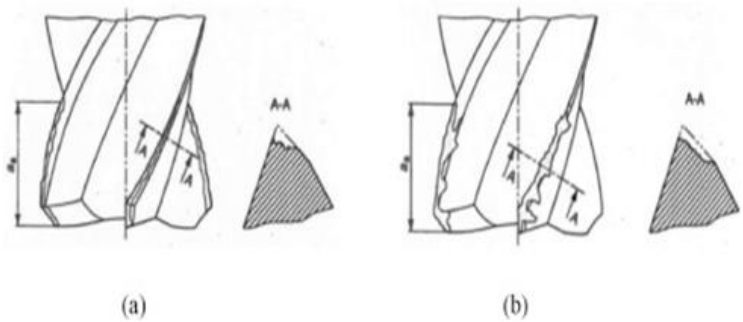

Fig. 2. Different typologies of flank wear: (a) uniform flank wear, (b) non-uniform flank wear [14].

Up and down milling is observed by Dehen et al. Up milling at high spindle speed and low feed rate. In down high feed rate and spindle speed milling. Up milling is the best strategy in terms of tool wear [15]. The shear angle is reduced and the shear zone is widened as a result of tool wear increasing the negative rake angle. Greater resistance to plastic deformation is achieved by larger shear zones, which also raise cutting temperatures, cutting forces and tool wear rates [16]. when the temperature gets to the point of melting. The abrasive wear, diffusion wear and oxidation wear occur. Oxidation wear causes the binder's failure and leads to tool particles peeling off [17].

4 Process Parameters

Process variables have significant effects on the precision with tool-based micromachining produces parts. Cutting speed, spindle speed, number of passes, feed rate, depth of cut, feature size, coolant and other processes [18]. To attain specific geometrical and surface finish requirements, unique process parameters need to be included for particular micromachining procedures. The highly effective optimum process parameters have improved the performance of micro-milling Ti-6Al-4V [19]. Artificial Intelligence (AI) and Genetic Algorithms (GA) are used in a CAPP system to optimize micro end-milling parameters for micromachining operations. For the creation of micro parts, polymethyl methacrylate is selected and micro features measuring 0.7 and 1 mm [20].

Higher spindle speed can cause rapid tool wear and deformation of the tool geometry. Increasing the cut depth and spindle speed can possess a profound effect on quality. In machining, surface roughness varies depending on feed rate, tool shape, and cutting edge radius. Additionally, the mechanical and physical characteristics of work equipment, as well as tool wear, and equipment vibration also affect the roughness. Increasing the spindle speed causes the surface quality to be negative and the R_a value to increase [12].

In machined components, the feed rate increases with increasing chip volume per unit time. In addition, it is observed that cutting force and stress values increase with increasing the feed rate [21]. Cutting parameters based on the empirical selection method, the optimal cutting parameters for micro-milling using the suggested optimization methodology would result in a 7.89% reduction in energy consumption [22].

5Cutting Phenomenon

In real machining circumstances, cutting phenomena are typically complicated and unpredictable. Among the variables are the development of chips, burrs, cutting force, friction, generation of heat, lubrication, size effect and consumption of energy. The latest predicament presents a significant amount of work. The machine tool parts' rigidity is crucial since it influences surface precision. As a result, DOC and cutting stability would be impacted. Appropriate quick-stop mechanisms should be taken into account to improve part accuracy [23]. variables include tool run-out, deflection, and cutting edge radius size-effect and tool flute path, the suggested analytical prediction model by forecasting three-dimensional cutting force components. It determines the immediate thickness of uncut chipsand computes varied angles of entrance and departure. Simulation results are confirmed by micro-slot end milling experiments conducted on Al6061 workpieces to validate the model [24].

5.1 Burr Formation

The burr formation are undesirable because they shorten life of tool and increases the possibility of a tool breaking, jamming and misalignment. Burr is typically produced during machining at the feature surface's entrance and exit of the workpiece. Plastic flow causes entrance burrs and work material protrusion at the exit surface causes exit burrs [25]. The major problem with micro-milling is the creation of burrs, which are collections of material that create a raised volume or edge on the workpiece's surface. The complex process of burr production involves both plastic and elastic deformation and it can be impacted by the geometry of the tool, the characteristics of the material and even process instabilities such as tool runout [26]. The removal of burr, which becomes extremely difficult in micro-milling, is called deburring. The burr size is influenced by variables such as material, tool wear, feed per revolution, and cutting speed.

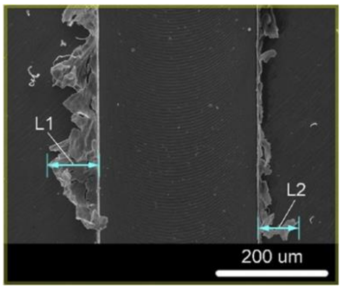

Fig. 3. SEM 500 X magnification of a machined slot for burr width measurement [1].

Micro-milling optimization, the parameters for cutting can be reduced to a height of less than 25 nm. UCT and tool sharpness rank among the most crucial variables, demonstrating the need for an ideal tool geometry to minimise burr formation**Figure.3.[1]**. Developing tools with the right geometry, selecting the right machine parameters and optimising the toolpath to reduce and eliminate burr formation during the micro-milling process [27]. At higher air pressure burr formation is increased. Under the air-fluid, the burr size is small at higher pressure large burr is formed, and the larger burr size is 0.45 MPa [28].

5.2 Size Effect

The size impact is important for improving accuracy in micromachining as the unit material changes, grain size, tool size and orientation become more important variables [17]. The ratio of the cutting edge radius to the undeformed chip thickness is a crucial control parameter in micro-milling. When the ratio of the cutting edge radius to the UCT less than one, the size effect becomes substantial. The results of the experiment showed that when the unreformed chip thickness is chosen to be the same magnitude as the tool edge radius, the best surface polish can be achieved while micromachining tool steel [29]. The size effect is affected while the plastic deformation zone surrounding the tool-workpiece contact, by surface machining. It is affected in both macro and micro-milling, with micro-milling predominating. The surface finish is achieved by lower tool feed without breaking the tool [30]. The reduced ratio of the cutting edge radius of the tool and cutting chip thickness produces ploughing force instead of cutting force. The micro-milling process makes the size effect more apparent. Feed per tooth makes a great contribution to a specific cutting force. The relation between feed per tooth and tool edge radius plays a vital role in the size effect [31]. Reducing the tool diameter in milling processes while keeping cutting settings constant was experimented with different tool diameters (0.2, 0.4 and 1 mm) to assess its influence on tool deflection [32].

5.3 Heat Generation

In micro-milling, heat generated because of the way the tool and workpiece interact has a significant impact on machining accuracy. Therefore, more care needs to be taken to reduce production of heat. According to Moriwaki et al., the direction of tool feed determines the pattern of temperature rise and machining oversight. Temperature changes abruptly when the workpiece is the source of the feed direction periphery to its center. The temperature increases gradually if the tool is moved in the opposite way. Replacing tools on a regular basis will lower heat generation [2]. During machining, the temperature affects the tool wear and influences the residual stress and also the accuracy of micro parts [33]. Due to localized heating, the burr is welded to the machined surface and deposited, resulting in a poor surface finish [6].

5.4Cutting fluid

The quantity of cutting fluid utilized greatly affects the machined surface quality in terms of burr generation as well as machined surface quality. Tool life and surface finish are affected by built-up edges on cutting tools [34]. Cutting fluids can be sprayed over the work surface in several methods, including at high and low pressure in a flooding process and using compressed air as a minimum quantity mist [35]. Chips that are irregular in shape and were removed by mist cooling occur when there is a high cutting feed rate and speed. The prevention of burr formation and groove formation [6]. MQL can enhance the cutting fluid's ability to enter the cutting region, potentially greatly enhancing the lubricating and cooling effects. MQL is generally a very effective and affordable cutting fluid method [36].

5.5 Chip morphology

The minimum chip thickness is the crucial limit that determines whether material flows along the flank face, where it causes plastic or elastic deformation depending upon the material, in the ploughing mode, or along the rake face, where it forms chips in the shearing type of material removal [37]. The lowest UCT below which a defined chip cannot form steadily. The parameters of the process, the material's characteristics and the microstructure will determine this critical value [38]. In cases when the UCT falls below the minimal value, chips originating from the ploughing-dominant technique of material removal will not form. On the other hand, if the UCT exceeds the minimal value, a specific chip will be produced and the procedure is analogous to traditional milling as in **Figure 4 [39].** When the minimum UCT becomes close to a After a certain threshold is reached, the material removal process will begin to transition from shear chip to plastic deformation, creating with a continual increase in the depth of cut. As a result, chips can only be created and removed when the cut depth is greater than the minimum UCT [40].

5.6 Surface morphology

Micro-milling is a useful machining method that produces surfaces, features, and structures in the microdomain with exceptional accuracy and precision. In micro-milling, the burr size and surface polish are greatly influenced by the cutting-edge shape. It was found that chamfered geometries or rounded cutting edges were more advantageous for producing a fine surface finish [41]. The vibration support improved the glass brittle-ductile transition, which lessened surface damage. A higher vibration frequency improved the surface quality by reducing the surface waviness [42]. Compared to traditional micro-milling, the size effect exhibited at significantly lower input rates. They suggested that a modification in the material removal mechanism was brought about by vibration-assisted machining in the microdomain.

5.7Built-up edge

The creation of built-up edges (BUEs) has a major effect on surface quality. Surface finish is influenced by free particles produced by BUE generation. When BUE is stable, the tool can be shielded from wear that would otherwise make micromachining difficult. This is caused by material or chips adhering to the face of the tool, which has a detrimental influence on the roughness of the surface and has a major impact on process outputs. It also results in issues such as reduced tool life and increased cutting forces, as seen in **Figure. 4**[43].BUEs are visible on the tool's rake face during the micro-milling process used to produce ductile materials like steel, aluminum and even some titanium alloys [43].

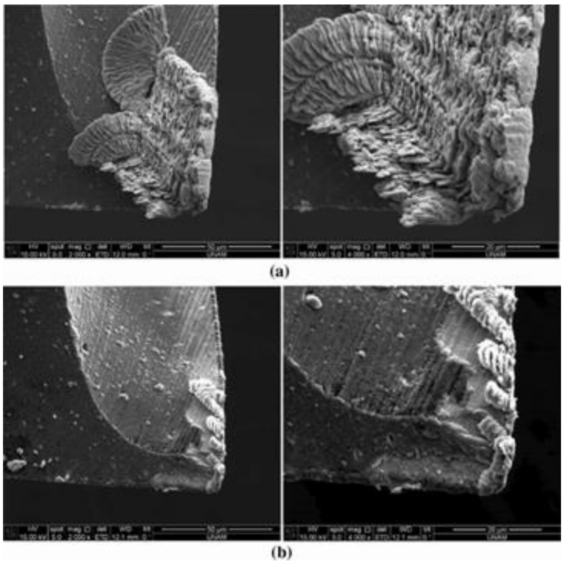

Fig.4 Scanning Electron Microscopy (SEM) images of both flutes of a micro-milling tool rake face exhibiting uneven BUE on each flute a Edge1 and b Edge 2 [43].

Oliaei and Karpat examined the connection between BUE and Ti–6Al–4V alloy micro-milling. It was examined how cutting force, surface finish and tool geometry relate to one another. It implies that choosing the right feed and "ap" condition is crucial for stable BUE generation. Optimising surface quality, enhancing machining efficiency and extending tool life can all be greatly impacted by steady and consistent BUE formation [44].

6Challenges and Future Directions

This new work provides valuable insights into the rapidly evolving field of micro-scale machining. Micro-milling offers precision and versatility in the fabrication of intricate components and structures with dimensions at the sub-micron and micron scale. The future of micro-milling lies in overcoming current challenges and pushing the boundaries of precision manufacturing. Advancements in tooling, materials and monitoring control will continue to drive innovation and open up new opportunities for creating smaller, more intricate and functional micro-scale devices for a wide range of industries. Micro-milling faces a few challenges related to tool wear, surface quality and process stability. Future research should focus on developing innovative solutions and pushing the boundaries of tool based micromachining capabilities.

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