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MICROMILLING – AN OVERVIEW

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Abstract : Recently, mechanical micro-milling is one of the most promising micro-manufacturing processes for productive and accurate complex-feature generation in various materials including metals, ceramics, polymers and composites. The micro-milling technology is widely adapted already in many high-tech industrial sectors; however, its reliability and predictability require further developments. In this paper, micro-milling related recent results and developments are reviewed and discussed including challenges in micromilling and micro tools. Finally, possible future trends and research directions are highlighted in the micro-milling areas.

Keywords **- Micromilling, Micro-tools, Machining**

I. INTRODUCTION

The micromachining process is the scale down process of conventional milling process which is being extensively used due to the increase in demand for micro products as well as high accuracy. Brinksmeier et al. [1] have categorized micro-manufacturing technologies into two types: microsystem technologies (MST) and microengineering technologies (MET). The MST is derived from electronic technology such as lithography and electroplating. The MET uses mechanical and physical material removal techniques such as milling and laser beam machining (see Table 1).

Table 1 Micro-manufacturing technologies [1]

Micro System Technologies (MST)	Micro Engineering Technologies (MET)	
Lithography	Mechanical process	Energy assisted process
Electroplating	Turning	Electro Discharge Machining
Lithography	Milling	Laser beam machining
Etching	Drilling	Ion beam machining
Polishing	Grinding	

The general principles for micromachining methods i.e. milling, turning, grinding and drilling are similar to that of conventional machining operations. Micromachining is a method of creating miniaturized products that range from tens of micrometers to a few millimeters in size by using the mechanical force of the micro tools to remove the excess material from the work material [1]. Micro-machining was derived from the motivation for manufacturing of higher quality, better performance, less expensive products. Alting et al [1] introduces a wide range of machining process for micro-scale parts and redefines the concept of microengineering.

Micro-milling is a cutting process that uses tools with diameters ≤ 1mm. The geometrically complex and micro products having a high aspect ratio can be machined easily using micro-milling process [2-4]. A variety of work materials such as composites, plastic metals, and nonmetals can be easily machined into complex and intricate shapes using micro-milling process [5-9]. The micro-milling processes are very cost-efficient as they do not require any expensive set-ups [1]. Micro-milling is also defined as the downscaling of the conventional milling process using miniaturized cutting tools [10].

II. CHALLENGES IN MICRO-MILLING

There are several challenges that come into the scenario while implementing micro-milling. The main factors are a miniaturization of the cutting tools, the irregular tool wear, non-uniformity of grain size in the workpiece, and errors/accuracy in a machine tool. The major problem in micro-milling process is unpredictable tool life and premature failure which are caused due to lower resistance to high stress [11-12]. The failure of the micro tool can further be worsened by inappropriate tool geometry design, defects in tool manufacturing, low coating quality, unsuitable cutting conditions and improper substrate material [13].
In micro-milling, the development of tool wear causes an increase in the ratio of cutting edge radius to uncut chip thickness and supports in the formation of burr [14, 15]. The burr generation damages the intricate features on the micro components and also

leads to rejection of the machined item due to the difficulties involved in burr removal process [16]. With the increase in cutting edge radius, the mechanics of tool-chip interaction changes and leads to a high negative rake angle and ploughing effects, this results in a significant increase in the axial force and surface roughness of work material [16-18].

The tool wear evaluation in micro-milling is still a major challenge due to limitations in various measurement techniques such as optical microscopy [19]. Using scanning electron microscopy (SEM) the necessary magnification and resolution can be achieved but the measuring technique is time-consuming and inefficient for multiple measurements that are required at frequent intervals. In order to maintain part tolerances and good surface quality of micro-component, the in-process monitoring of micro-milling is also a crucial factor, as micro end mills are prone to tool breakage and edge chipping [20].

Many researchers have proposed that the process of chip formation does not occur during micro-cutting when the uncut chip thickness is smaller than a critical minimum chip thickness as the work material experiences elastic deformation and ploughing which may cause cutting instabilities. The micro-milling of heterogeneous materials is highly affected by the different grain size of the work material. As the tool advances between the different metallurgical phases of the work material, the stresses and forces experienced can vary significantly and also cause high vibration, which in turn results in rapid tool failure [21].

Machine tool errors also have an important role in the efficiency of the micro-milling process. The factors such as the inappropriate design of machine tool, the environment in which the machining process is carried out to control vibrational and thermal effects, etc. are mainly responsible for machine tool error. Accurate tool and workpiece referencing are also critical to avoid errors in tool offset setting and control tool run-out to minimize the cutting forces [22]. Uriarte et al. [23] recommended that precision machine tools having positional accuracies in the order of ±0.1μm should be used for micro-milling to achieve the tolerances required in manufacturing with their corresponding applications.

III. MICRO TOOLS

The geometry of current micro endmill is mainly derived from macro endmill cutters as shown in Figure 2.1. Fabrication of micro endmill is a major challenge due to its small size. Geometric irregularities and poor resolution of the cutting edges are the typical defects related to the manufacturing of micro tools. Many researchers have studied the manufacturing of micro tools using focused ion beam (FIB) [24-26], wire electrical discharge grinding (WEDG) [27-29] and abrasive grinding processes [30-32]. A comparison of FIB, WEDG, laser ablation and grinding process in terms of fabrication of micro tools was presented by Schmidt et al. [33]. The conclusion of the study was that the tolerance control of the FIB process is better than the other fabrication processes but the material removal rates are relatively low with higher machining cost. A significantly lower error on the geometrical features of the cutting tool was observed when manufactured using used wire EDM operations [34].

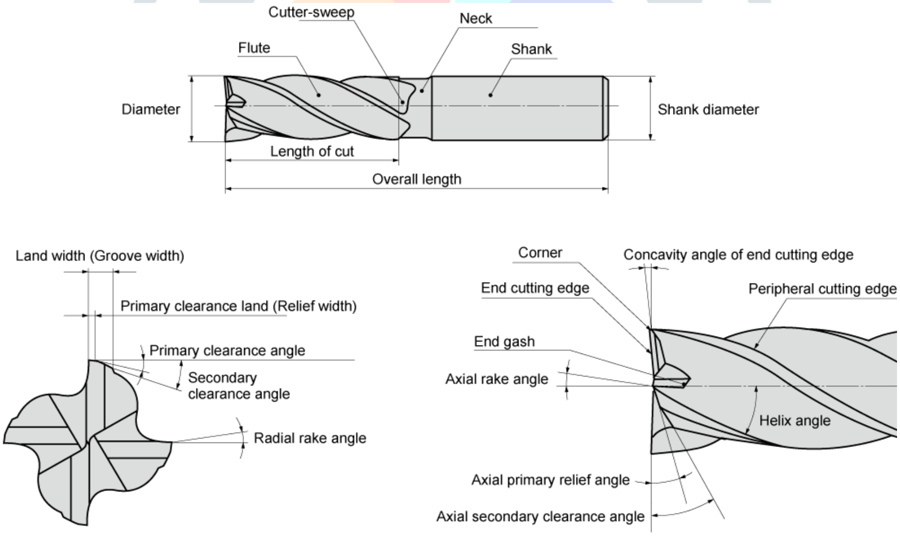

Figure 2.1: Geometry of endmill cutter [35]

Development of micro tools incorporates a number of factors. The cutting tool material should be harder than the work material. The thermal deformations between the tool and workpiece should have an important role in cutting performance. The tool edge radius should be smaller than the chip thickness [36, 37].

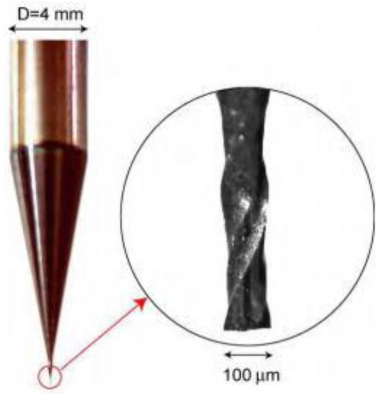

Figure 2.2 Tungsten carbide micro-end mill with two flutes [38]

Diamond tools are often used in micromachining but it is having a limitation in the machining of ferrous materials. During machining of ferrous materials with diamond tools, high chemical reaction causes tool wear [38]. Tungsten carbide tools are having high hardness and strength at elevated temperatures. For this reason they are generally used in micromachining. Tungsten carbide micro endmill with two flutes is shown in Figure 2.2. To improve the tool wear resistance, small grain size tungsten carbide (less than 600nm) is used to fabricate the micro tools. The zero helix angle is considered in many micro-tools having diameter <50µm to enhance their rigidity and also reduces the drawbacks of the machining process [39]. For fabrication of 11µm diameter micro carbide, tool ultrasonic vibration grinding was used by Onikura et al. [31]. The manufacturing technique reduces the grinding forces generated during fabrication using conventional technique. Fang et al. [40] investigated geometries of different micro-carbide tool using finite element method and verified them experimentally. They have concluded that the end mills having semi-circular geometry shows better result than triangular or conventional 2-flutes end mills. One of the major concerns of micromachining tool is their unpredictable and premature tool life. While machining hard materials, such as hardened tool steels, after various cutting tests, the tool life becomes very unstable [41].

Bissacco et al. [13] investigated the effect of working fluid on the accuracy of micromachining. Nowadays many ultra-precision machine tools are commercially available which are having a position resolution up to 1 nm with high-speed spindles up to 100,000 rpm. The practical accuracy of these machine tools decreases while considering thermal deformation. A minute offset caused by thermal deformation causes a significant error. The temperature difference between the cutting fluid and spindle during machining is also a source of error.

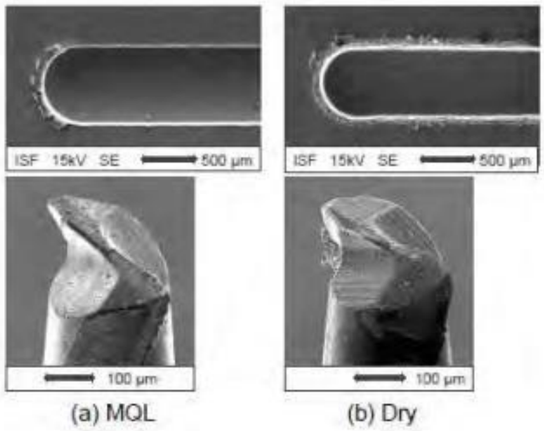

Figure 2.3 Micro-end milling using MQL and dry condition [43]

Figure 2.3 shows the surface and edge quality of micro products machined using two lubrication conditions i.e. minimum quantity lubrication (MQL) and dry condition. Burrs formation is observed only at the end of the slot when MQL is used while a burr is present along the entire slot length under dry conditions. Under MQL conditions, it is also seen that the tool wear is much lower and surface finish of the side walls are much better. It can be concluded that the performance of micro-end milling is much better when MQL is used while machining of NiTi materials [42].

IV. CONCLUSION

In the present paper, current studies dealing with micro-milling technologies were reviewed with particular attention to the discussion of the influences of the process parameters on the cutting force, temperature, vibration and surface roughness. Based on the present review, the following conclusions can be drawn.
Micro-milling is suitable for producing complex 3D geometries in several materials; however, its application still meets many challenges and difficulties such as high tool wear, removal of micro burrs, inappropriate vibrations, etc.
Chip removal and burr formation mechanisms of micro-milling significantly differ from the mechanisms known in macro-sized machining if the size of the theoretical chip thickness is comparable to the size of the minimum chip thickness. The ploughing effect often dominates the process, and the shearing mechanism is only secondary.

Although current micro-milling technologies are often able to generate high-quality micro-features in several materials, it is highly encouraged to increase material removal rate, tool life, cost-effectiveness, and flexibility; and decrease operation time, burr formation and surface roughness. These issues could be partly improved by using hybrid micro-milling technologies, green or sustainable micro-milling, smart micro-milling or artificial intelligence controlled technologies.

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