Rev. Adv. Mater. Sci. 30 (2012) 98-102

A BRIEF REVIEW ON MICROMACHINING OF MATERIALS

P. Cardoso and J.P. Davim

Department of Mechanical Engineering, University of Aveiro, Campus Santiago, 3810-193 Aveiro, Portugal

Received: December 05, 2011

Abstract. The demand for miniaturized devices with high aspect ratios and superior surfaces has been rapidly increasing in advanced industries. There is a growing need for fast, direct, and mass manufacturing of miniaturized functional products from metals, polymers, composites and ceramics. The current article presents a brief review on micromachining with special emphasis in micromilling.

1. INTRODUCTION

The miniaturization of devices is today demanding the production of mechanical components with manufactured features in the range of a few to a few hundred microns in fields that include optics, electronics, medicine, biotechnology, communications, and avionics, to name a few. Specific applications include microscale fuel cells, fluidic microchemical reactors requiring microscale pumps, valves and mixing devices, microfluidic systems, microholes for fiber optics, micronozzles for high-temperature jets, micromolds, deep X-ray lithography masks, and many more [1].

As a response to this demand, various micro-manufacturing techniques have recently emerged, such as X-ray lithography electrodeposition molding (LIGA), deep reactive ion etching, deep UV lithography, electrical discharge machining, laser machining and computer numerical controlled (CNC) micromachining. Most of these techniques require inaccessible, expensive, or time-consuming equipment [2], so one of the viable micro-manufacturing techniques for creating three-dimensional (3D) features on metals, polymers, ceramics, and composites is mechanical micromachining. Micromachining utilizes miniature milling, drilling and turning tools as small as 10 μm in diameter to produce micro-scale features. Although geometric and material capabilities of micromachining have been demonstrated by [3] industrial application of micromachining has been hindered by the lack of experience and knowledge on the micro-machinability of materials [4].

2. CHARACTERISTICS OF MICROMACHINING - MICROMILLING

Micromilling, one of the mechanical micromachining methods, is a process that utilizes end mills that typically vary in diameter from 100 to 500 μm and have edge radii that vary from 1 to 10 μm. Additionally, the micromilling process has several salient features that differentiate it from the macro-endmilling process. As the endmilling process is scaled down from conventional sizes (100 μm/tooth feed rates, 1 mm depths of cut) to micro-endmilling sizes (1 μm/tooth feed rates, 100 μm depths of cut), different phenomena dominate the micro-endmilling process compared to those typically observed in conventional milling [5]. Dhanorker and Özel [6] stated that the fundamental difference between micromilling and conventional milling arises due to scale of the operation, in spite of being kinematically the same. However, the ratio of feed per tooth to

Corresponding author: J. Paulo Davim, e-mail: pdavim@ua.pt

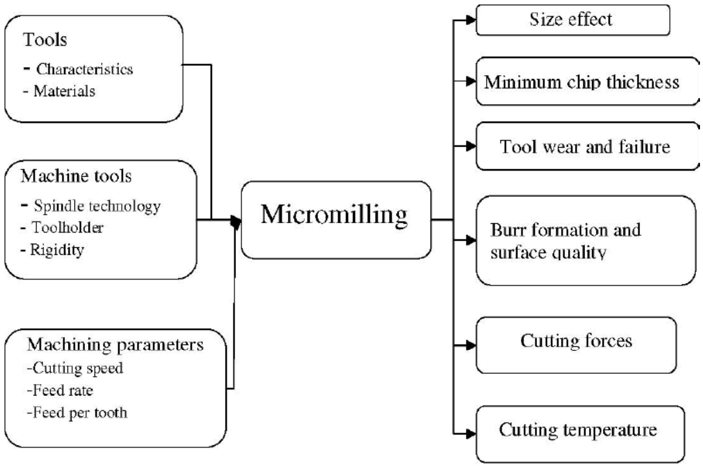


Fig. 1. Inputs and influences in micromilling.

radius of the cutter is much greater in micromilling than conventional milling, which often leads to an error in predicting cutting forces. Also, the runout of the tool tip, even within microns, greatly affects the accuracy of micromilling as opposed to the conventional milling.

The chip formation in micromilling depends upon a minimum chip thickness and hence the chip is not always formed whenever tool and workpiece is engaged as opposed to conventional milling. The tool deflection in the micromilling greatly affects the chip formation and accuracy of the desired surface as compared to conventional milling. The tool edge radius (typically between 1–5 μm) and its uniformity along the cutting edge are highly important as the chip thickness becomes a comparable in size to the cutting edge radius [7]. Since the chip load is small compared to the cutting edge radius, the size effect and ploughing forces become significant on both surface and force generation in micromilling. Micromilling may result in surface generation with burrs and increased roughness due to the ploughing-dominated cutting and side flow of the deformed material when the cutting edge becomes worn and blunter.

There are several phenomena in micromilling that prevent the results of conventional milling from being applied to it directly. First, it cannot be assumed that the microstructure of the workpiece material is homogeneous [5]. As tool size becomes smaller, its effect becomes more important. In this work it was used an Ø 0.8 mm tool, and for simplicity this effect was not assumed. Second, the effect of the cutting edge radius is not negligible: it affects the chip forming mechanism. Minimum chip thickness is a function of this parameter, and determines the transition between two cutting conditions; where chips are produced and where ploughing takes place [6].

3. TOOLS – CHARACTERISTICS AND MATERIALS

Precision cutting tools and machine tools are critical to micro-mechanical cutting processes, since the surface quality and feature size of the micro-structures are dependent on them. Nowadays, the geometries of micromilling tools are created by scaling down macro tools but due to the increasing miniaturization of components, it is becoming ever more complex to produce the required tools. In addition, several researchers [8-9] have shown that micro tools respond to influences in a very different way than macro tools do.

Conventional milling tools vary widely in size and design for different applications. In end milling, the common issues are tool deflection and uneven distribution of cutting force among the cutting edges. The forces are concentrated on the side of the tool and cause the tool to bend in the direction of the workpiece feed. The extent of deflection also depends greatly on the rigidity of the tool and the distance extended from the spindle. In fact, the deflection is directly proportional to the cube of the extension [10]. Also, the smaller the tool diameter, the more prone it is to deflection and this is even more so in micromilling, as the tools diameters are ever so small.

Tungsten carbide cutting tools are generally used for the micro-mechanical cutting process, due to their hardness over a broad range of temperatures. In the early 1990s, use of coatings to reduce wear and friction became more common and most of these coatings are referred to by their chemical composition, such as TiN (Titanium Nitride), TiCN (Titanium CarboNitride), TiAlN (Titanium Aluminum Nitride) or TiAlCrN (Titanium Aluminum Chromium Nitride), among others. Advances in end mill coatings are being made, however, with coatings such as Amorphous Diamond and nanocomposite physical vapour deposition (PVD) coatings. In 2006, Arumugam, *et al.* [11] investigated the performance of polished CVD diamond tool carbide inserts in comparison with unpolished CVD diamond coated carbide tool inserts in the dry turning of A390 aluminum, a silicon hypereutectic alloy and concluded that polished chemical vapour deposition (CVD) diamond tool inserts improve tool life and reduce the cutting forces. However, the size of micro end mills makes coating deposition challenging especially around the cutting edges. The requirements on the coatings for micro machining tools are not only the desirable properties such as high hardness, high toughness and high chemical/erosive and abrasive wear resistance, but they must also be dense, have a fine microstructure and present a smooth surface to the workpiece, with a reduced coefficient of friction compared to that of the uncoated tool [7].

4. MICROMACHINING OF MATERIALS – CUTTING PARAMETERS

The most important machining parameters in micromilling are spindle speed, feed rate and feed per tooth. Literature shows that many studies have been done to show up to which extent these parameters influence the quality of the machined parts and the consequences on the tool. In Fig. 1 a diagram of the inputs and influences in micromilling is shown.

In 2008, Filiz *et al*. [8] investigated the use of the mechanical micromilling process for fabrication of micro-scale piercing element from biocompatible materials. The authors used two custom made, special geometry, tools with cutting diameters 254 μm and 101.6 μm. To investigate the effects of feed, speed, and axial depth of cut on the performance of the tools, a design of experiments study was conducted on polymethyl methacrylate (PMMA). The investigation was done based on two spindle speeds (50000 and 100000 rpm), two feeds (1, 5 μm/flute), and two axial depths of cut (10, 20 μm). They concluded that the spindle speed has the most prominent effect for all force components, and increase in spindle speed caused an increase in forces.

Table 1. Workpiece and machining parameters [5].

Workpiece microstructure	Pearlite, Ferrite, Ferritic and Pearlitic
Cutting edge radius	2.0 and 5.0 μm
Axial depths of cut	50 and 100 μm
Feed rates	0.25, 0.5, 1, 2 and 3 μm/flute
Spindle speed	120,000 rpm

Also in 2008, Dhanorker and Özel [6] performed experimental and modelling studies on meso/micro-milling of AL 2024-T6 aluminum and AISI 4340 steel to predict chip formation and temperature fields. They also studied size effects and minimum chip thickness. To conduct this study, the authors used 2-flute tungsten-carbide on cobalt matrix WC-Co end mills with 30º helix angle, diameter 1.5875 mm and 3.175 mm and a fixed spindle speed of 60000 rpm. Cutting speed used was 22.62 m/min and 59.85 m/min and feed per tooth varied from 0.265 μm to 4 μm. Large force variations were observed as the diameter of the cutter decreased and the spindle speed increased.

In order to study the influence of the tool edge condition and the workpiece microstructure, Vogler and his colleagues [5] in 2004 performed experiments with 508 μm diameter end mills on workpiece materials with different microstructures over a range of feed rates. Four materials were selected for the experimentation; two specially prepared, single phase materials (pure ferrite and pearlite) and two multi-phase materials with different compositions of the two single phase materials. They performed 5 mm long full-slot endmilling cuts under several conditions in order to study the interaction between ploughing and process condition effects on the surface roughness of the slot floor. The conditions the authors used can be seen in Table 1.

In 2007, Filiz *et al.* [4] used a miniature machine tool to perform micromachining experiments on 99.99% purity Copper. This machine tool was equipped with a 160,000 rpm air-turbine, air-bearing spindle with a 3.125 mm precision collet. The spindle-axis runout was quoted by the manufacturer to be less than 2 μm. The micro end mills used during the experimentation were micro-grain tungsten carbide (WC) tools, fabricated by diamond grinding, two-fluted and with a 254 μm diameter and a 30° helix angle. This experimental study included full-immersion (slot) cutting with axial depth of cut of 30 μm. Four feed rates (0.75, 1.5, 3, and 6 μm/flute) and three cutting speeds (40; 80, and 120

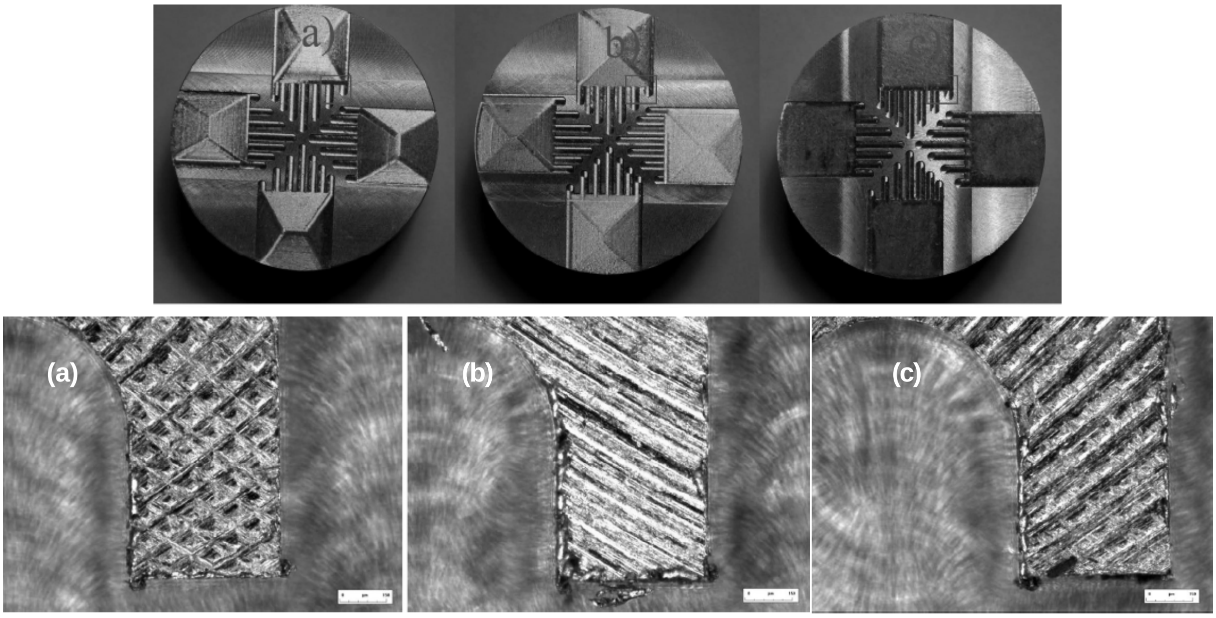
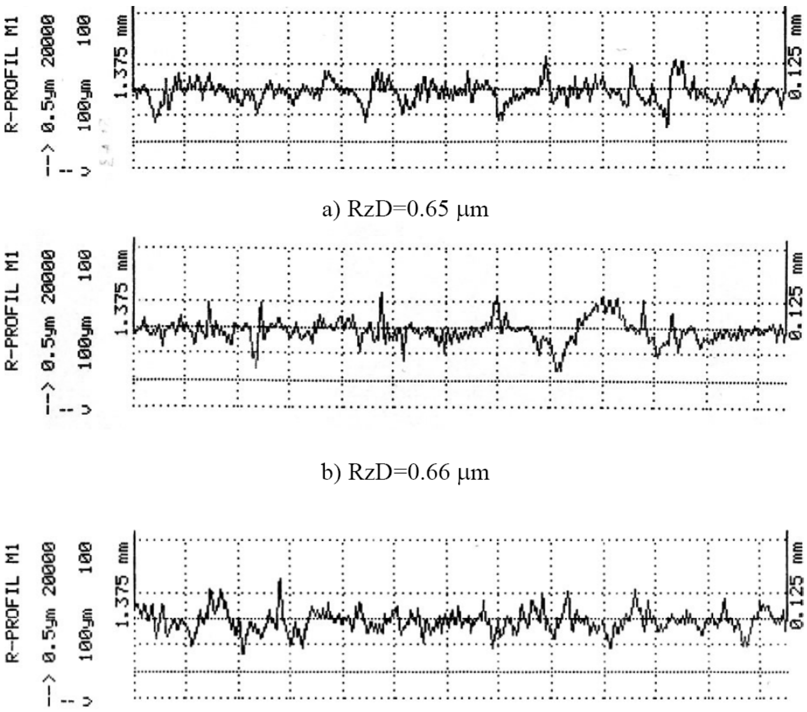


Fig. 2. Comparison of strategies for the same 6μm/tooth feed rate: (a) constant overlap spiral, (b) parallel spiral and (c) parallel zigzag.



a) RzD=0.65 μm

b) RzD=0.66 μm

c) RzD=0.73 μm

Fig. 3. Surface profile comparison between strategies for the same feed rate of 6 mm/tooth: a) constant overlap spiral, b) parallel spiral and c) parallel zigzag.

m/min) were considered in this experimentation. The range of feed rates was selected to include the ploughing, indentation, and minimum chip thickness effects in the data. The spindle speed varied according the feed rates: 50,000 rpm for 0.75 μm/flute, 100,000 rpm for 3 μm/flute and 150,000 rpm for 6 μm/flute.

Recently, Cardoso and Davim [12] in order to perform a comprehensive study on surface roughness of the machined surfaces, cutting parameters such as feed rate as well as machining strategies were varied to optimisation micromilling. In this research, Al 2011 aluminium alloy was used. It is an Al-Cu-Bi-Pb age-hardened alloy noted for its free-machining characteristics and good mechanical properties. The tool used to machine the workpiece was a cemented carbide K10, 0,8 mm diameter endmill. Four feed rates (2, 4, 6, and 8 μm/flute) and one spindle speed 6,500 rpm were considered in this experimentation. Three machining strategies were used: constant overlap spiral, parallel spiral and parallel zigzag. Fig. 2 shows the comparison between the three different strategies. The burrs produced with the second strategy (parallel spiral) are much pronounced. The constant overlap spiral strategy was the one that presented the best result. Surface roughness profiles and the value of RzD (Mean peak-to-valley height- DIN 4768) comparison are shown in Fig. 3. Also the constant overlap spiral strategy was the one that presented the best result to RzD (Fig. 3a).

5. CONCLUSIONS

The most relevant inputs in the micromachining process can be said to be the tools (characteristics and materials), machine tools (spindle technology, toolholder, rigidity) and, not least importantly, machining parameters (cutting speed, feed rate and feed per tooth). On the other hand, the issues addressed with micromachining are the minimum chip thickness and size effect, the cutting temperatures and cutting forces, which influence the tool wear and its failure, which, in turn, influence the burr formation and, consequently, surface quality.

REFERENCES

[1] X. Liu, R.E.DeVor, S.G. Kapoor and K.F. Egmann // *Journal of Manufacturing Science and Engineering* **126** (2004) 666

[2] S. Mecomber Justin, Hurd Douglas and A. Limbach Patrick // *International Journal of Machine Tools & Manufacture* **45** (2005) 1542.

[3] J. Chae, S. S. Park and T. Freiheit // *International Journal of Machine Tools & Manufacture* **46** (2006) 313.

[4] Filiz Sinan, Caroline M. Conley, B. Wasserman Matthew and O. B. Ozdoganlar // *International Journal of Machine Tools & Manufacture* **47** (2007) 1088

[5] Michael P. Vogler, R.E DeVor and S.G. Kapoor // *Journal of Manufacturing Science and Engineering* **126** (2004) 685

[6] A. Dhanorker and T. Özel // *Int. J. Mechatronics and Manufacturing Systems* **1** (2008) 23.

[7] A. Aramcharoen, P.T. Mativenga, S. Yang, K.E.Cooke and D.G. Teer // *International Journal of Machine Tools & Manufacture* **48** (2008) 1578.

[8] Filiz Sinan, Xie Luke, E. Weiss Lee and O.B. Ozdoganlar (2008) // *International Journal of Machine Tools & Manufacture* **48** (2008) 459

[9] H. Pérez, A. Vizán, J. C. Hernandez and M. Guzmán (2007) // *Journal of Materials Processing Technology* **190** (2007) 18

[10] R. Jalili Saffar, M. R. Razfar, O. Zarei and E. Ghassemieh // *Simulation Modelling Practice and Theory* **16** (2008) 378

[11] U. Arumugam Prabhu, A.P. Malshe and S.A. Batzer // *Surface & Coatings Technology* **200** (2006) 3399.

[12] P. Cardoso and J.P. Davim // *Materials and Manufacturing Processes* **25** (2010) 1125.