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# MICRO MILLING OF METALLIC MATERIALS - A BRIEF OVERVIEW

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**Summary**

Micro milling is an important process of mechanical micromachining, with practical application in aerospace, automotive, mould and die, biomedical, military and micro-electronics packaging industries. This article will give a brief overview of the effects and conditions of micro milling with an emphasis on minimum chip thickness, size effect, cutting forces, cutting temperature, tool wear and tool failure, burr formation and surface quality. The case study presented in the present paper refers to the micro milling of an aluminium alloy.

*Key words:* *Micro milling; aluminium alloys; burr formation; surface quality*

## 1. Introduction

Micro milling, one of mechanical micromachining processes, 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. As the end milling process is scaled down from conventional sizes (100 μm/tooth feed rates, 1 mm depth of cut) to micro-end milling sizes (1 μm/tooth feed rates, 100 μm depth of cut), different phenomena dominate the micro-end milling process compared to those typically observed in conventional milling [1]. Dhanorker and Özel [2] stated that the fundamental difference between micro milling and conventional milling arises from the scale of the operation, in spite of being kinematically the same. However, the ratio of feed per tooth to radius of the cutter is much greater in micro milling than in 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 micro milling as opposed to the conventional milling.

## 2. Minimum chip thickness and size effect

In general, and according to a statement made by Dhanorker and Özel [2], the current manufacturing methods cannot fabricate micro end mills with sharp edges due to the limitation of structural strength of the tool at the edge. Currently, widely available micro tools have edge radii ranging from 1 μm to 5 μm. As the tool diameter decreases, the rigidity of the tool also decreases, which leads to tool deflections under heavy chip load and a sudden breakage of tool. This limits the chip load, especially in micro milling, to a few microns per tooth. Specific cutting forces also depend mostly on the ratio of the uncut chip thickness to the tool edge radius. The tool edge radius and small feed per tooth makes the phenomenon of minimum chip thickness highly predominant in micro milling [2]. The minimum chip thickness in micro milling is greatly affected by the radius of the cutting edge ($r_e$) which is usually greater than 1 μm. The chip is not formed and mostly elastic deformations are induced to the workpiece until the tool reaches a certain rotation angle where a minimum uncut chip thickness develops. A smaller edge radius causes early formation of minimum chip thickness, whereas a larger edge radius will result in ploughing of the workpiece.

The relationship between the process geometry and the workpiece microstructure, in addition to the relationship between the process geometry and the tool geometry, changes as compared to conventional end milling operations. When machining a multiphase material, such as steel, the grain size of the material is such that the tool is often cutting in only a few grains at any instant, as presented in Figure 1. Therefore, the workpiece material cannot be considered using average material properties as the length scales of the process and the microstructure dictate a heterogeneous nature of the workpiece. The heterogeneity in the workpiece microstructure leads to significant variations in the machining process as cutting moves from one phase to another. These variations affect the force system, leading to dynamic excitations of the tool workpiece structural system, and also affect the surface generation and chip formation processes [1].

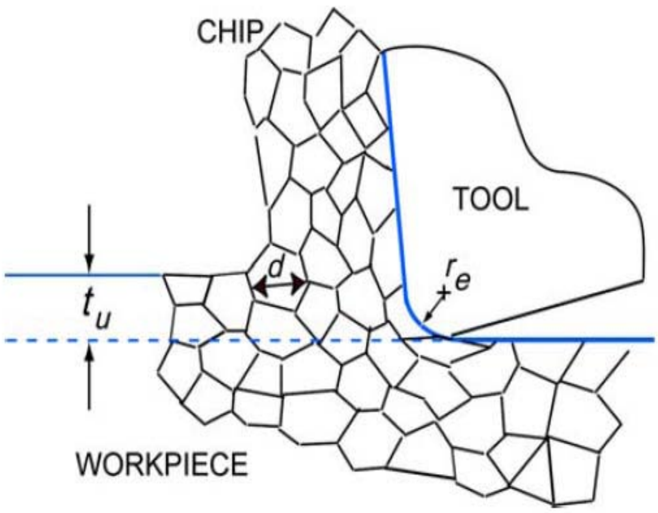


**Fig. 1** Size comparison in meso-scale orthogonal cutting [3]
*d* - average grain size of a polycrystalline aggregate
$t_u$ - uncut chip thickness, $r_e$ – radius of the cutting edge

In 2007, Özel and Zeren [3] stated that in micromachining, cutting is performed within the grains of the material because the uncut chip thickness ($t_u$) in meso-scale machining (usually less than 100 μm) is comparable to the average grain size of a polycrystalline aggregate -d- (e.g. between 1.5 and 150 μm for ferritic steels). The polycrystalline material, which can be considered as an isotropic and homogeneous continuum in conventional analysis, must be treated as a series of single crystals with random orientations. Single crystals are known to be highly anisotropic in their physical and mechanical properties. These authors [3] also inferred that the crystallographic orientation of the substrate material will influence significantly the micro scale machining process.

## 3. Cutting forces

During the milling operation, the cutting forces will induce vibration on the cutting tool, the workpiece and the fixtures, which will affect the surface integrity of the final part and, consequently, the product quality. When cutting conditions are not appropriate, tools are easily fractured, which wastes time and money. In addition, it is not easy for the operator to detect tool wear or fractures [4-5]. Accordingly, in micro end milling, the cutting force analysis plays an important role in the determination of the characteristics of cutting processes, such as tool wear and surface texture, the establishment of cutting plans, and the setting of cutting conditions. An analytic cutting force model of micro end milling was first introduced by Bao *et al.* [6]. This model took into account the differences in the tool tip trajectories between micro end milling and conventional end milling. Unlike conventional macro cutting, micro cutting with a micro depth of cut cannot ignore the effect of the tool edge radius.

A considerable number of studies that consider the tool edge radius in two dimensional orthogonal cutting have been conducted but studies that take into consideration the tool edge radius in end milling are very limited in number.

Machining forces contain important information on the mechanics and dynamics of machining processes. The quality of the machined surfaces is dictated by the static and dynamic characteristics of machining forces. In addition, machining forces are critical in designing tooling and machine tools, as well as in determining power consumption and process productivity. Although the characteristics of machining forces for conventional milling have been thoroughly investigated, micro-milling forces are not yet fully understood. In addition to the factors that affect milling forces at the macro scale, such as vibrations, repeated entry and exit of the cutting flutes and runout of the tool tip, the effects of minimum chip thickness, ploughing, indentation, and elastic recovery become controlling factors in micro milling. Furthermore, both the static and the dynamic tool-tip runout have greater influence in micro milling as they could be comparable in size with the feed rates [7-9].

In 2007, Filiz *et al.* [10] conducted a study on the micromachinability of copper and concluded that, at low feed rates, the cutting force signatures show erratic behaviour. At feed rates larger than the edge radius of the tool, the increased feed rate produces cutting force signatures similar to those seen in conventional machining and the tool-tip runout is an important contributor to the cutting force fluctuations. They also concluded that average peak-to-valley forces exhibit big changes with the cutting speed for feed rates close to the cutting edge radius. At higher feed rates, the effect of cutting speed is considerably reduced.

## 4. Cutting temperature, tool wear and tool failure

Cutting temperature is one of the most important factors to be considered in metal machining because it influences the tool wear immensely. Tool wear, in its turn, must be taken into account because one wants to maximize the tool life in all machining processes.

In applications such as machining, substantial amounts of heat may be generated due to plastic deformation and friction at the tool-chip interface. The temperature attained can be quite high and has a considerable influence on the mechanical properties of the material. In 2005, Liu [11] observed that the strength of the material is usually lowered by an increase in temperature and vice-versa. From dislocation mechanics, material strength in the plastic deformation of metal crystals is determined by the motion of dislocations and their interactions. A rise in temperature increases the thermodynamic probability of dislocations achieving a sufficient amount of energy to move past the peak in the potential, thereby producing a softening effect on the flow stress. It was also found by Liu [11] that the temperature gradient within the chip changes with the uncut chip thickness.

Cutting speed, among all machining parameters, is regarded as having the strongest effect on tool wear because higher cutting speeds tend to generate more heat, resulting in more wear. Tool wear is influential in several areas: increased cutting force, changes in dimensions and the need to change tools, with the consequent loss of accuracy. Uriarte *et al.*

[8] stated that wear causes the edges of straight tools to become rounded and their diameter to become smaller than the nominal figure. This effect is highly significant when hard materials are machined, such as tempered steels with more than 50 HRC. It can be minimized by using successive new tools and by implementing a CAM program in several stages of rough machining and finishing. In general, attempts are made to perform the whole finishing process with the same tool removing the smallest possible volume of the material.

## 5. Burr formation and surface quality

Burrs in machined workpieces are a big drawback to productivity. Burrs require additional finishing operations (deburring) and complicate assembly, and these operations can damage the part, especially in the micro scale. As the demand for component tolerances and surface quality becomes more stringent and cost pressure increases, the burr issue needs to be addressed at the point of prevention rather than rectification [12]. It is best to avoid or, at least, minimize burrs by careful choice of tool, machining parameters and tool path or workpiece material and part design. In fact, most burrs can be prevented or minimized with process control.

The most important parameters that affect burr formation can be associated with several categories: tool geometries (rake angle, lip relief angle, and cutting edge radius), workpiece material properties (strength, ductility, strain-hardening coefficient, and temperature dependence of properties), and process conditions (feed, cutting speed, and the use of coolant) and others (tool diameter, tool wear, tool material, machine stiffness, etc). Burr formation affects the workpiece accuracy and quality in several ways: dimensional distortion of part edge, challenges to assembly and handling caused by burrs in sensitive locations on the workpiece and damage done to the workpiece subsurface from the deformation associated with the exit of the cutting edge. This is especially true for precision-machined components, for which the fundamentals of machining are often not well understood. To effectively address burr prevention, the entire process chain (from design to manufacturing) must be considered to integrate all the elements affecting burrs, from the part design, including material selection, to the machining process [13].

Ng *et al.* [14] carried out an experimental study on the micro and the nano-scale cutting of aluminium 7075-T6 and stated that the surface roughness increases at undeformed chip thicknesses greater than the edge radius of the tool. However, when cutting at undeformed chip thicknesses smaller than the edge radius of the tool, the generated surface is much rougher. This can be attributed to the dominant effect of the ploughing process when cutting at undeformed chip thicknesses smaller than the edge radius of the tool. A ploughing process typically displaces material sideways and ahead of the cutting tool. This generates a surface that is typically rougher when compared to a surface generated mostly by the shearing of the work material. This observation is in agreement with observations in macroscale cutting operations, where the generated surface roughness commonly increases with undeformed chip thickness.

### 5.1. Case study

In order to do a comprehensive study on surface roughness and burr formation of the machined surfaces, cutting parameters such as feed rate as well as machining strategies were varied to optimize micro milling [15]. Machining was performed using the CNC machining centre MIKRON, model VCE 500. It is a conventional full size, 11kW, 3-axis CNC machining centre with a maximum of spindle speed of 7500 rpm. In this research, aluminium alloy (Al2011) was machined. The tool used for machining the workpiece was a cemented carbide K10 end mill with 0.8 mm in diameter. The feed rate of 2μm/tooth and the spindle speed of 6500 rpm were considered in this experimentation. Three machining strategies were used: constant overlap spiral, parallel spiral, and parallel zigzag. Table 1 shows the values of the surface roughness parameter (RzI) as a function of machining strategies. Figure 2 shows a comparison between the three different strategies. The burrs produced with the second strategy (parallel spiral) are much more pronounced. The constant overlap spiral strategy was the one that produced the best result. Surface roughness profiles and the value of RzI (Ten-point eight - ISO 4287/1) comparison are shown in Figure 3. Also, the constant overlap spiral strategy was the one that produced the best result with respect to RzI (Figure 3a).

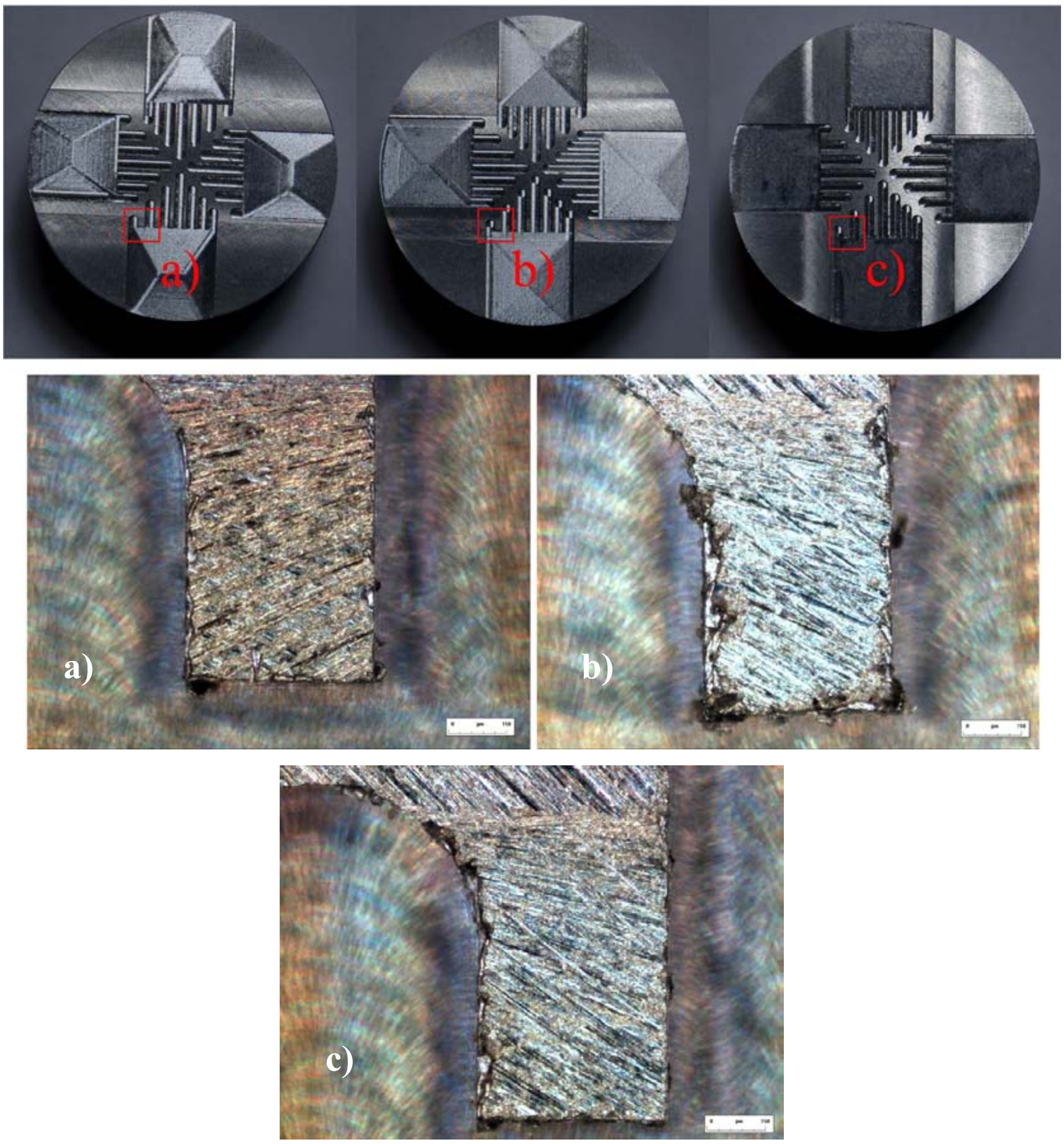


**Fig. 2** Comparison of strategies for the same 2μm/tooth feed rate:
(a) constant overlap spiral, (b) parallel spiral and (c) parallel zigzag

**Table 1** Surface roughness parameter (RzI) function as a machining strategy

| **Machining strategy** | **Surface Roughness (RzI-μm)** |
|---|---|
| constant overlap spiral | 0.67 |
| parallel spiral | 0.93 |
| parallel zigzag | 0.69 |

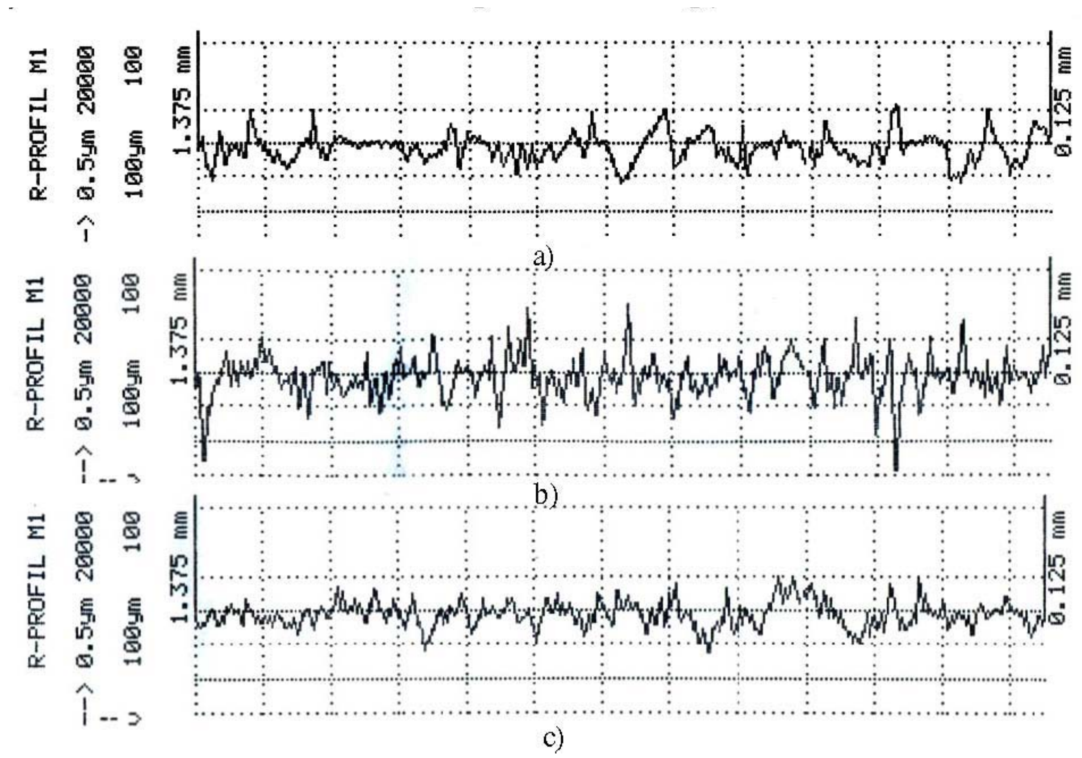


**Fig. 3** Surface profile comparison between strategies for the same feed rate of 2 μm /tooth:
a) constant overlap spiral-RzI=0.67 μm, b) parallel spiral-RzI=0.93 μm and c) parallel zigzag-RzI=0.69 *μm*

## 6. Conclusions

The current article reviewed some important aspects of effects and conditions in the micro milling of metallic materials, namely, chip thickness, size effect, cutting forces, cutting temperature, tool wear and tool failure, burr formation and surface quality. Based on the analysis of the case study, the following conclusions can be drawn from the micro milling of an aluminium alloy (Al 2011):

- the strategy with which the best results for a constant feed rate of 2mm/toothwere achieved was the strategy of " constant overlap spiral" with small, unnoticeable burrs and a surface roughness parameter (RzI) of 0.67 μm.
- it is possible to machine micro surfaces almost without burrs;
- machining strategy influences the surface finish and the presence of burrs.

In future it would be interesting to perform tests at a higher cutting speed in order to study the influence of the cutting speed on the surface finish and the presence of burrs. It would also be interesting to test the machining of more complex surfaces with three-dimensional profiles and others materials, such as steel, polymers, and composites.

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