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STUDY OF THE TOOL INCLINATION IN MULTI-AXES MILLING

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Abstract: *Sculptured surface milling is an important process commonly used in various industries such as aerospace, automobile, shipbuilding, and turbine and die/mould industries. Competitiveness in the market is imposing the need for decreasing production time and cost without sacrificing part quality. This study presented in this paper describes an experimental analysis of the influence of cutting tool axis inclination and effective cutting speed on the polishing time and tool life in multi-axis milling. It is applied to milling operations of pre-treated steel for plastic injection moulds. It is shown that using an appropriate strategy in milling improves machined surface texture, reduces manual polishing times and improves tool life.*

Key words: *multi-axis milling, tool orientation, effective cutting speed, polishing time, tool life.*

1. INTRODUCTION

Complex shaped parts such as dies, moulds, prostheses, turbine blades and aerospace parts can efficiently be machined by five-axis milling.

Computer aided design (CAD) software systems give us the potential to model very complex shapes. The growing complexity of products has been pushing the development of new manufacturing technologies. Complex or organic geometries introduce different and more complex manufacturing problems when lower surface roughness and minimum machining costs are objectives to be pursued.

At the same time, in order to reduce costs, high speed machining (HSM), which utilises high cutting speeds and consequently significant federates, has become popular. Therefore, machine tools have evolved in this direction. Generally, 5-axis machines have a structure based on a 3-axis Cartesian structure with the addition of two rotary axes. Concerning these rotation movements, three configurations are possible: the two rotation axes are installed on the top of the table or they can be added on the spindle axis (Z axis) or first axe on the table and the second axe on the spindle.

In milling surfaces of dies and moulds the machining and polishing operations represent sometimes approximately two thirds of the total manufacturing costs [1–2]. A suitable machining strategy can lower significantly manual labour as well as time and cost. Frequently, polishing operations are necessary due to the inappropriateness of machining strategies. To reduce the polishing cost of dies and moulds, appropriate machining strategy and appropriate cutting conditions should be selected to improve the dimensional accuracy, the surface texture and roughness while fine milling. Machining strategy includes the tool path pattern and the tool orientation. The cutting conditions include the cutting edge geometry, the feed rates, and the cutting speeds.

This work aimed at studying and analyzing different finishing strategies with different cutting conditions to assess their influence on polishing time and tool life. In this paper, firstly, the effective cutting speed variation in milling with a ball end tool is studied. Then an experimental study of the effect of finishing strategies on polishing time and tool wear is described.

2. MUTI-AXIS MILLING AND CUTTING SPEED VARIATION

2.1. Multi-axis milling

Multi-axis machining is a technology which underwent important innovation; it allows the realization of complex shape pieces for aeronautical and automotive industries, and for dies and moulds. Milling surfaces dies and moulds often requires the utilization of two supplementary rotary axes, (fourth and fifth axes) of the machine-tool (Fig. 1), to improve the precision of machining, with respect to geometry of the workpiece and surface quality, to increase tool life and avoid collision between cutter and the part.

Fig. 1 shows the five-axis machine tool. The machine have a 3 axis Cartesian structure (*X*, *Y*, *Z*) with the addition of tow rotatory axis of the table (C) and the second rotation axe of the spindle (B).

The study aim is to improve of process in the case of a plane surface milled with ball-end tool. The required objective is to control the produced surface quality. The objective is to optimize the trajectory and the inclination of the cutting tool in five axes milling, (in one-way and zigzag) in relation to the quality of milled surface, polishing time and tool life.

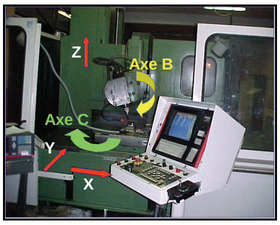


Fig. 1. Five axis milling machine.

2.2. End milling without inclination

The majority of the workshops of machining use 3-axis machine tools for milling operations. Under these conditions, the axis of the cutting tool is fixed and generally normal on the machined surface (Fig. 2).

The tool path in milling is the trajectory of the cutter centre, witch is also known as the Cutter location (CL) path, and is given by the NC part program. The cutter contact (CC) path is the tangential trajectory between the ball-end cutter and the part surface, and is shifted from the tool path by a distance equal to the cutter radius *R*. When the cutter moves in parallel trajectories, scallops are created on the finished surface. The distance between the parallel trajectories is the CC path interval or radial engagement a_e, which depends on the local curvature of the surface, the size of the cutter, and the allowable scallop height *H* remaining on the surface after the operations machining.

The calculation of the radial engagement a_e for milling flat planes machined by a ball end cutter is relatively simple. When the milling operation is completed, scallops remain on the finished surface a shown in Fig. 2. For a given allowable scallop height *H*, the radial engagement a_e can be obtained by following relation (1).

$$a_e = 2\sqrt{R^2 - (R-H)^2}, \tag{1}$$

where a_e denotes the radial engagement, *R* denotes the radius of a ball-end cutter, and *H* denotes the allowable scallop height.

The scallop height, *H* is the residual thickness on the part after finish machining which is generally eliminated by polishing. It depends only, when the cutting conditions are appropriate (weak feed per tooth f_z), on the nominal radius *R* of the ball-end mill and of the step of radial engagement a_e. It is clear that, for same radial engagement, the scallop height increases when the diameter or radius of the cutter decreases.

$$H = R\left(1 - \sqrt{1 - \left(\frac{a_e}{2R}\right)^2}\right). \tag{2}$$

Generally, in the case of the complex shapes machining, the effective cutting speed $V_{c\text{-}eff}$ varies, following the inclination of the ball-end cutter in relation to the manufactured elementary surface. However, in 3 axis milling, tool axis is normal to the machined surface (Fig. 2), the effective cutting speed $V_{c\text{-}eff}$ is given by the relation (3):

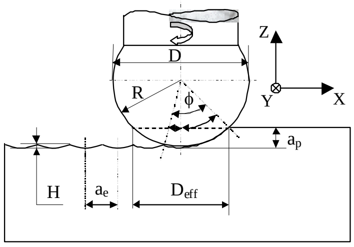


Fig. 2. Normal tool axis to the machined surface.

$$V_{c\text{-}eff} = \frac{\pi n \left(2\sqrt{Da_p - a_p^2}\right)}{1\,000}, \tag{3}$$

where *D* denotes the nominal diameter of a ball-end cutter, a_p denotes the axial engagement or axial depth of cut and *n* denotes spindle speed.

2.3. Machining with slopes of the tool

Schulz *et al.* [3], Bouzakis *et al.* [4] showed that machining with a slope of the hemispherical tool modifies the shapes and dimensions of the chips.

In this survey, one is going to determine the best combination of the inclination angle and the sense of feed rate V_f of the tool on the surface, polishing time quality state according to the machining conditions, as well as the minimal values of the inclination angle of the ball-end cutter and the effective cutting speeds correspondents in every configuration.

In order to avoid working with a slight effective cutting speed $V_{c\text{-}eff}$ or neighbouring of 0 m/min (normal tool axis to the machined surface), the tool axis must be inclined to an angle θ superior to a minimal value that depends on the machining configuration.

Tool inclination angle θ_n according to the negative rotation sense –*B*, the feed rate direction V_f according to the *Y* axis and the radial engagement a_e according to the sense + *X* (Fig. 3); condition to satisfy :

$$\theta_n > \arccos\left(\frac{R - a_p}{R}\right). \tag{4}$$

The effective cutting speed $V_{c\text{-}eff}$ is given by eq. (5):

$$V_{c\text{-}eff} = \frac{\pi n D \sin\left[\theta_n + \arcsin\left(\frac{a_e}{2R}\right)\right]}{1000}, \tag{5}$$

with the condition,

$$\arccos\left(\frac{R - a_p}{R}\right) < \theta_n \leq 90. \tag{6}$$

Tool inclination angle θ_n according to the positive rotation sense +*B*, the feed rate direction V_f according to the *Y* axis and the radial engagement a_e according to the sense +*X* (Fig. 4); condition to satisfy :

$$\theta_n \rangle \arcsin\left(\frac{a_e}{2R}\right). \tag{7}$$

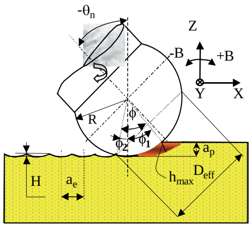


Fig. 3. Tilted tool position angle θ_n according to the negative rotation sense –*B* to the machined surface.

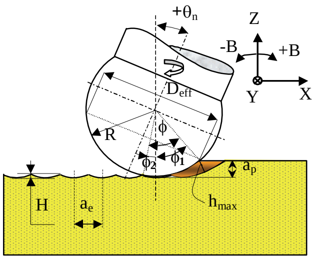


Fig. 4. Tilted tool position θ_n according to the positive rotation sense *+B* to the machined surface.

The effective cutting speed $V_{c\text{-}eff}$ is given by eq. (8):

$$V_{c\text{-}eff} = \frac{\pi n D \sin\left[\theta_n + \arccos\left(\frac{R-a_p}{R}\right)\right]}{1000}, \qquad (8)$$

with the condition :

$$\arcsin\left(\frac{a_e}{2R}\right) < \theta_n \le 90 - \arccos\left(\frac{R-a_p}{R}\right). \qquad (9)$$

3. EXPERIMENTATION AND RESULTS

3.1. Experimental procedure

The cutting experiments were carried out on a 5-axis vertical milling machine ‘Gambin 120 CR’ equipped with the numerical control unit ‘Num 1060’ (Fig. 1). They were performed under dry cutting conditions. The material of the work-piece is a hardened steel type SP 300 widely used for plastic injection moulds. The hardness of this material is 300 HB. Its chemical composition is presented in Table 1.

The ball-end tool of diameter is 16 mm from, “Widia” is composed of two teeth and is a carbide base (94% WC + 6% Co) coated with TiCN, the flank angle is 15° and the rake angle is 0°. The study aimed to compare machined surfaces based on six different finishing strategies. The radial depth of cut or radial engagement a_e is 0.5 mm, the axial depth of cut a_p is 0.4 mm, and the feedrate V_f is 377 mm/min are kept unchangeable. The spindle speed *n*, directions and the angles of inclination of the tool used for each finishing configuration strategy are presented at Table 2 and Fig. 5.

3.2. Polishing time

Manual polishing of machined surfaces is necessary to achieve required roughness recommended in the dies and moulds industry. To assess the gain on polishing time in minutes for these six different machining configurations, the different samples has been polished manually using abrasive papers of grade 320–1 200, and diamond paste.

Table 1

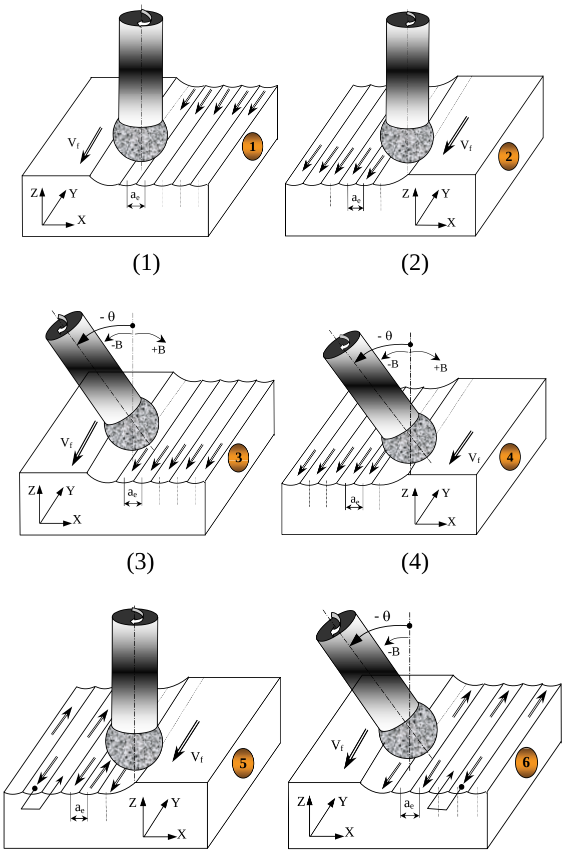
Chemical composition of the SP300 steel

Chemical composition	C	Mn	Cr	Mo	S	Specific additives
Weight (%)	0.25	1.3	1.3	0.4	0.02	Ca, V, B

Table 2

Machining configuration (from (1) to (6))

Conf.	θ (°)	*n* [rot/min]	Feel slope of the tool
(1)	0	3695	Without inclination, a_e towards –*X*, V_f direction is according to –*Y*
(2)	0	3695	Without inclination, a_e towards +*X*, V_f direction is according to –*Y*
(3)	–17	1886	Inclination according to –*B*, a_e towards –*X*, V_f direction is according to –*Y*
(4)	–17	1886	Inclination according to –*B*, a_e towards +*X*, V_f direction is according to –*Y*
(5)	0	3695	Without inclination, a_e towards +*X*, V_f direction is in zigzag
(6)	–17	1886	Inclination according to –*B*, a_e towards –*X*, V_f direction is in zigzag



(1) (2)

(3) (4)

(5) (6)

Fig. 5. Machining configuration (from (1) to (6)).

The polishing criterion is to obtain a luster finish characterized by an arithmetical mean deviation of the surface Sa equal to 0.05 µm. Fig. 6 shows clearly the difference of the polishing time value of the six machining configuration.

Configuration (1) is used as a reference to evaluate the time saving. It is clear that by machining configuration (3) tool inclination (–17°) provides the best time gain (37%). The reduction of the manual polishing time does not depend solely on the increase cutting speed effective, but also strategy of machining and consequently the surface quality.

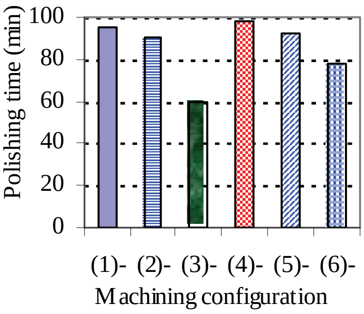


Fig. 6. Polishing time of six configurations.

3.3. Tool life

Cutting-tool life is one of the most important economic considerations in metal cutting. In finishing and roughing operations, the various tool angles, tool geometry, cutting speeds, and feed rate are usually chosen to give an economical tool life. Clearly, any tool or work material improvements that increase tool life will be beneficial. To form a basis for such improvements much effort has been made to understand the nature of tool wear and other forms of tool failure.

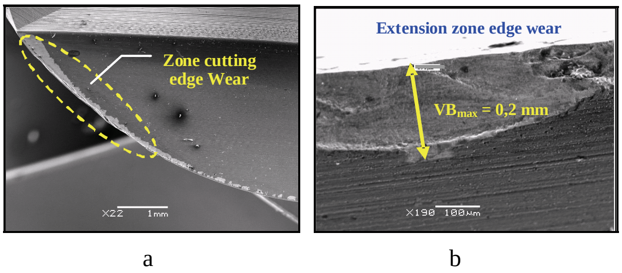
As tool damage, by wear or fracture, increases, the surface roughness and accuracy of the machined surface deteriorates. Eventually the tool must be changed. Some criteria must be developed to decide when to do this. In factories there is a tendency to adopt flexible criteria according to the needs of a particular operation, while in laboratories inflexible criteria are adopted to evaluate tool and work material machining capabilities [5].

In factories, tool life criteria where the concern is acceptable accuracy or surface roughness, the most suitable way to judge life is by measuring the size or roughness of machined parts. Life is determined when the measured levels exceed a limit.

In laboratories, tool wear is almost always used as a life criterion because it is easy to determine quantitatively. The amount of flank wear is often used as the criterion because it is flank wear that influences work material surface roughness and accuracy. When abrasion is the main cause of flank wear, the wear pattern is relatively uniform and easy to measure.

In the study, a measure of tool life is the time to develop a flank wear land VB = 0.2 mm (Fig. 7).

Tool life investigation (Fig. 8) confirmed the benefits in choosing strategy machining configuration (3) as compared to the other configuration. The milling with the appropriate tool axis inclination is more important as compared to the machining with not tool orientation, normal tool axis on the machined surface (configuration (1)).



a b

Fig. 7. Flank wear of a carbide tool; a – zone cutting edge wear; b – extension zone edge wear.

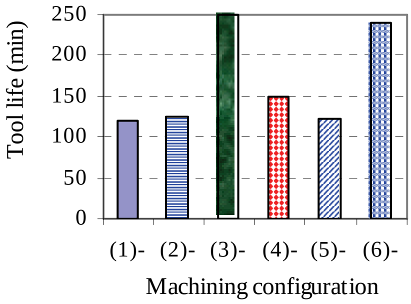


Fig. 8. Tool life to six configurations.

The improvement tool life increases more 110%. The increase in the tool life depends considerably on the increase of the cutting speed effective $V_{c\text{-}eff}$, of the strategy machining and as well as phenomenon of the cut.

4. CONCLUSIONS

This paper has investigated the effect of the tool orientation on the variation effective cutting speed, on the tool life and polishing time saving while multi-axis milling of dies and moulds for plastic injection.

Experimental results described in previous paragraphs have shown that disadvantages of three axes machining results from the existence of very low cutting speeds, even null when the tool axis is normal to the machined surface. This mode of machining generates a bad surface quality, maximum the polishing time and the very limited tool life.

A suitable slope of the cutting tool by the means of the fifth machine tool axis, improves considerably work piece machined surface quality:

- Lower polishing time, if the luster finish criterion is applied, appropriate tool inclination provides more than 37% of polishing time saving compared to the tool with no orientation.
- Improvement tool life is 110% compared to the 3 axis milling.

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