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INFLUENCE OF INCLINED SURFACE MACHINING ON SURFACE TOPOGRAPHY IN 3-AXES BALL NOSE END MILLING

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Abstract: *The objective of this experimental study is to give emphasis about influence of different inclinations of workpiece surface in complex curved surfaces metal cutting in 3-axes milling, using ball nose end mills. A ball nose end mill has a semi-sphere at the end tool and the result of milling, roughness of surface, is an uncut strip created between the two cylindrical cutting passes, called cusp height and it's the most important aspect. In 3-axes ball nose end milling, a possibility to avoid cutting at tool tip, that is moving in a linear motion and the cutting speed is zero, is to assure for workpiece surface a minimal inclination angle, between tool axis and surface normal. When machining an inclined surface with ball nose end mill, different tool path strategies are possible and the cutting conditions and surface topography are seriously influenced. The experimental results, demonstrate that employing different inclination angle in accord with some tool path orientations can improve surface quality with better machine and tool utilization, with considerably shorter manual polishing time.*

Key words: *milling, ball nose end mill, surface topography, roughness.*

1. INTRODUCTION

Complex curved surfaces (sculptured surfaces) are encountered in many objects such as small batch components, automotive parts, aircraft components, turbine blades, injection moulds and dies, electrodes for electrical discharge machining etc. A ball nose end mill, also known as spherical end mill or ball end mill has a semi-sphere at the tool end. Ball nose end mills are used extensively in the complex surfaces machining and has very complex machining mechanism, as the cutting edge is determined on spherical surface. When a cutter with a non-flat end, such as a ball nose end mill, is used to cut a desired surface, uncut strip (cusp, scallops) are created between the tool edges cutting passes [1] (Fig.1).

This modern milling is a very universal machining method and during the past few years, hand-in-hand machine tool developments, milling has evolved into a method that machines a very broad range of configurations. Tooling developments have also contributed to the new possibilities along with the gains in productivity, reliability and quality and recently, according to coating technology, direct milling for hardened steel has become possible and importance of ball nose end mill is increasing.

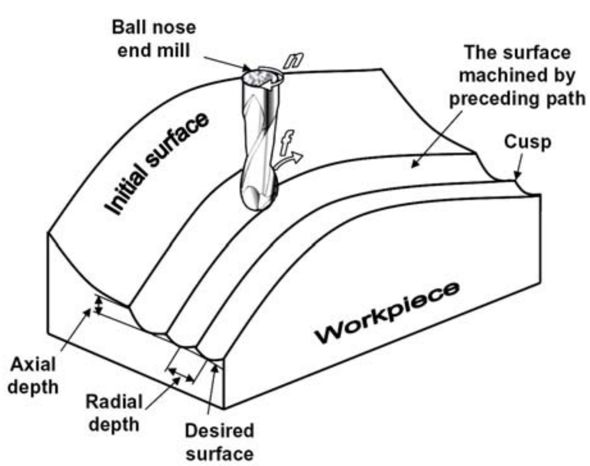

Fig. 1. Ball nose end milling process.

But, the machining process with a ball nose end mill is very complex, because of an intermittent cutting and a changing of chip thickness during cutting and operation results in a surface with a large number of scallops and for remove these scallops, if surface roughness require, is necessary benchwork, that consist in manual grinding and hand polishing (super-finishing) which give a satisfying surface accuracy. Human skills, based on experience and judgment, can not be complete and different persons use different pressures when doing grinding and polishing, with negative impact on the dimensional and geometrical accuracy and too many hours benchwork spent for this.

In spite of the difficult cutting mechanism with a ball nose end mill, many papers reported as [2], where investigates and evaluates the different cutter path orientations when high-speed finish milling inclined hardened steel, at a workpiece inclination angle of 75^0, which demonstrate that employing a vertical downward orientation achieved the longest tool life but in terms of workpiece surface roughness, vertical upward orientation is generally preferred. Other paper [3] deals with the analysis of the surface generating mechanism and the machined surface shape with ball nose end mill base on deflections. On the other hand, the undeformed chip volume and cutting area (cross-section) is obtained by geometric analysis [1] and the geometric relationship of the cutting edge and workpiece inclination in 3-axes ball nose end milling in 3D-CAD are reported in [4, 5].

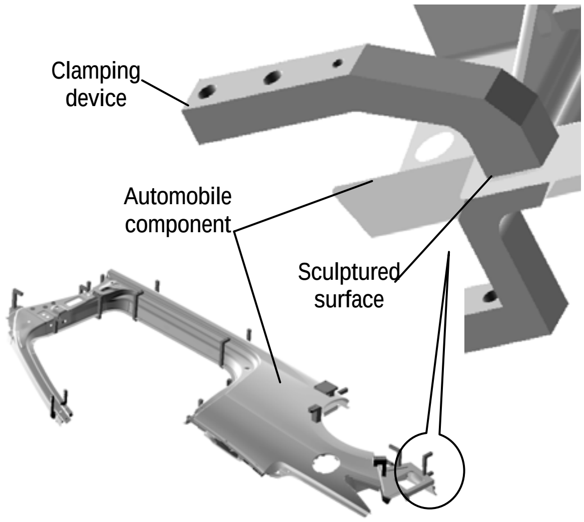

Fig. 2. Automobile component and clamping devices.

Ball nose end mills are useful cutters for machining a three dimensional shape in generally very complex like mould and die but exist many small pieces (clamping devices, gripers etc.), used in automotive industry, which have a generally simple geometry but at least one small surface which is sculptured and mast be in correlation with automobile component part design (Fig. 2).

For manufacturing these parts, most used are 3-axes CNC milling centre and sculptured surfaces can have different orientations in relationship with tool axis. The influence of surface orientations (inclination), however was not considered in machined strategy, starting with tool path program in CAM software which can allows management of various modes of tool paths generation (parallel plan, contour, zig-zag, iso-planar etc.) but can not decide which is the best. Nevertheless the choice of a machining strategy remains an expert field and the objective of this experimental research is to verify theoretical study made by authors [4, 5] and develop a methodology of machining directions according to the surface inclination.

2. EXPERIMENTAL PROCEDURE

2.1. Tooling and workpiece

A new indexable solid carbide ball nose end head was used in this experiment, type SECO TOOLS Minimaster B120P with coating code F30M, with 2-flute, 4 mm radius, helix angle and radial rake angle of 0^0. Workpiece made from general use steel OL 37 type, STAS 500/1;2-80, with a nominal composition of 0.20% C, 0.80% Mn, 0.07% Si, 0.06% P, 0.06% S and Fe balance was used in the experimental work. The cutting experiments were carried out in down milling on a workpiece with four little surfaces for different tool path orientations (Fig. 3), for each angle inclination θ on values 15^0, 30^0, 45^0 and 60^0. The cutter path orientation is crucial in achieving desired machined surface [4, 5] and without considering the impact of cutting edge with undeformed chip in different path strategy with adequate consideration of the chip area variation, cutting forces, temperature and vibration analysis, the result can lead to cutter failure and therefore lead to unnecessary waste of time, cost and poor surface quality.

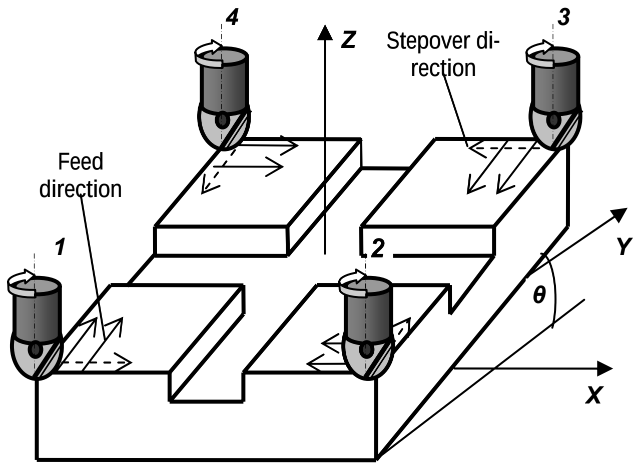

Fig. 3. Workpiece and tool path orientations.

On inclined surface, the tool path orientations are determined by feed and according as stepover direction, the ball nose end milling can be (Fig.3):

1 - vertical upward -V.U.;
2 - horizontal upward - H.U.;
3 - vertical downward - V.D.;
4 - horizontal downward - H.D.

2.2. Experimental equipment and setup

The cutting tests were performed on a vertical CNC 3-axes milling machine Microcut Challenger 2412 with a continuous variable speed up to 10 000 rpm and a maximum spindle power of 25 kW (Fig. 4). To avoid tool holder collision with the workpiece fixture, a tool overhang of 120 mm was employed throughout the tests and the cutter were checked prior to machining, to ensure run out up to 0.01 mm. Surface images were performed on a microscope with magnification up to 20× equipped with high resolution digital camera and surface roughness measurement with Multi-parameter Surface Roughness Measuring Instrument LINKS Model 2222.

2.3. Cutting conditions employed

The effect of using different workpiece inclination and cutter path orientations was investigated in relation with chip formation, surface topography and roughness. The workpiece was fixed in an inclinable machine vice and all surface machining were conducted in dry cutting, with addition high pressure air blast delivered through a

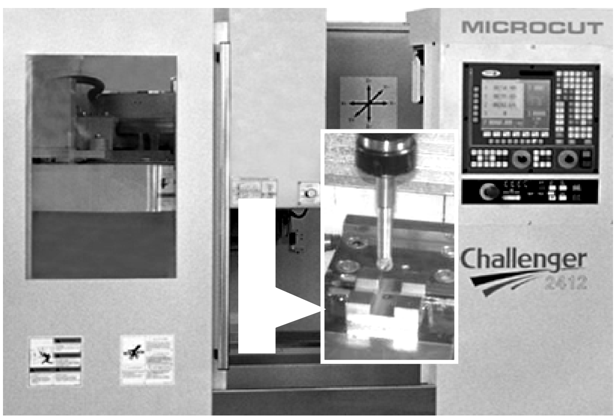

Fig. 4. CNC 3-axes milling centre, tool and workpiece.

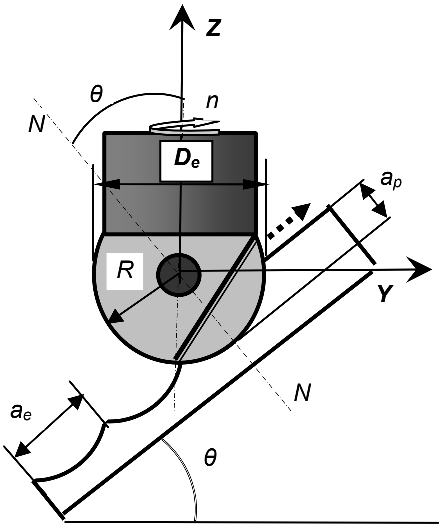

Fig. 5. Horizontal upward milling.

Table 1

Cutting parameters

Angle [DEG]	Effective diameter [mm]	Tool rotation [rpm]	Speed feed [mm/min]
15	6.30	3032	606
30	7.36	2595	519
45	7.92	2411	482
60	7.99	2400	480

nozzle, directed at the cutting area. The axial depth a_p and radial depth a_e of cut used were 0.8 mm and they were ensured that it was aligned on normal *N-N*, respectively along the workpiece surface, illustrated in figure 5, for horizontal upward milling. The feed per tooth used was 0.1 mm/tooth, cutting speed used was constant for all experiments 60 m/min and in accord with effective diameter D_e the tool rotation was calculated and summarized in Table 1:

3. EXPERIMENTAL RESULTS AND DISCUTION

Milling tests were conducted at a range of surfaces which were presented in Fig. 6, 7, 8, and 9.

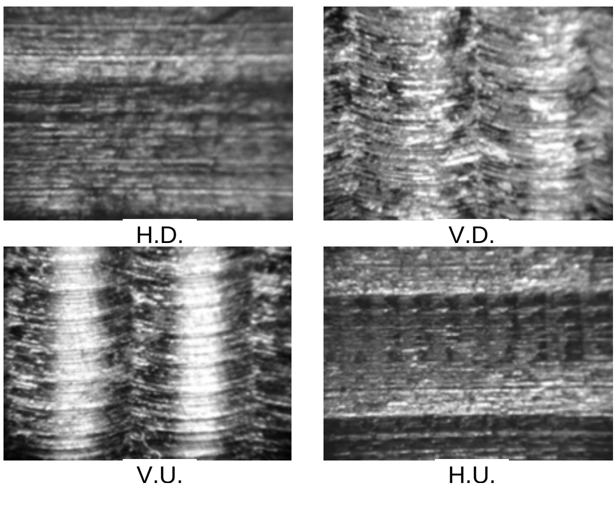

Fig. 6. Surfaces topography for 15^0.

Photographs positions, tool paths orientations and their abbreviations are in accord with Fig. 3. These results show the differences aspects of surfaces topography (20× magnification) for different inclinations and tool path orientations, approving that different cutting conditions, although using the same cutting parameters. In generally is a big difference between vertical upward, (V.U.) and vertical downward (V.D.).

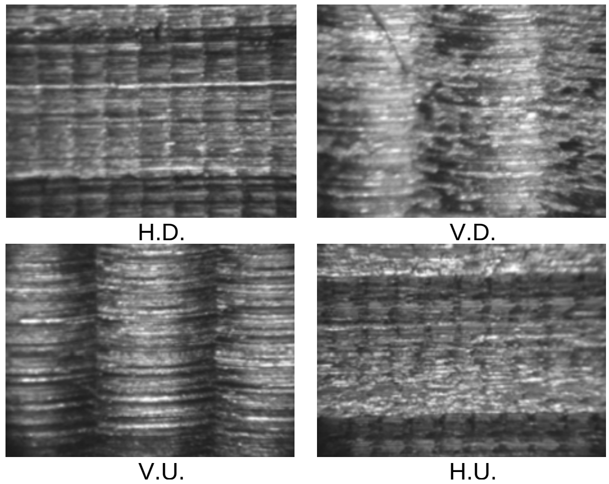

Fig. 7. Surfaces topography for 30^0.

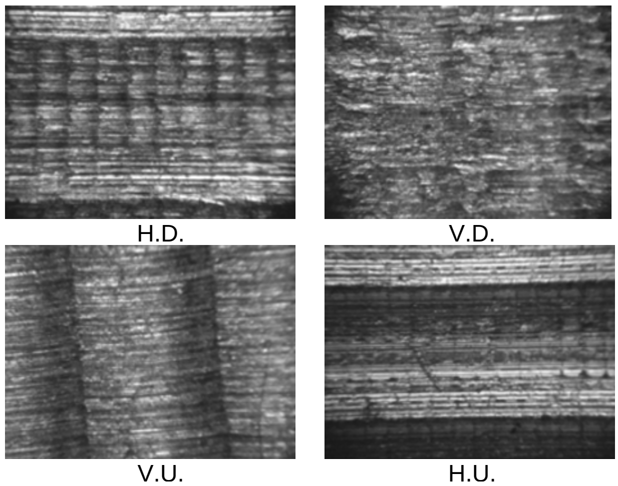

Fig. 8. Surfaces topography for 45^0.

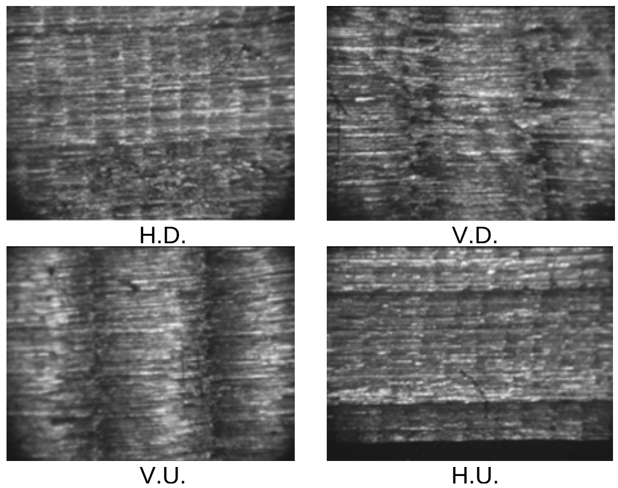

Fig. 9. Surfaces topography for 60^0.

Comparison in terms of the surface aspects vertical upward orientation achieved the best cutting conditions, which are in accord with edge cut entrance and chip area transition to the high chip thickness and small area [5].

In opposite situation, vertical downward orientation achieved the worst surface topography, with irregular scallops and many scratches because the edge cut entrance in undeformed chip is to the small chip thickness and very large contact between cutting edge and machined surface. In the same, horizontal upward (H.U.) is more favourable that horizontal downward (H.D.) in especially for 45^0 inclined workpiece (Fig. 8).

Surface quality as a result of ball nose end milling is determined by topography and can be evaluated using different parameters. Theoretically, it is the best to calculate ten points for the height of irregularities *Rz*, but this parameter is not usually mentioned in a technical drawing. This function fulfils the arithmetical mean deviation of the profile *Ra,* which is used in this experiment, measured in longitudinal direction (feed direction). The average mean surface roughness parameter *Ra* (Table 2), was determined in the feed directions and was measured for a sampling length of 4.0 mm and cut-off length of 0.8 mm, and represented in Fig. 10.

The result clearly illustrate in graphics that are good cutting conditions around of 15^0 inclination less for using a horizontal upward tool path orientation (H.U.) explicable by edge cut entrance to the high chip thickness and big area [4].

For 30^0 inclination, *Ra* value increase and worst conditions are for horizontal downward (H.D) when the tool tip is still in cutting [4]. Workpiece inclination of 45^0 determines decrease *Ra* parameter exception, for vertical upward tool path. Increasing of workpiece inclinations over the 45^0 determines in increasing *Ra* parameter

Table 2

Ra parameter values

Angle [DEG]	**V.U.**	**H.U.**	**V.D.**	**H.D.**
	Ra [µm]			
15	0.377	1.154	0.601	0.689
30	1.079	0.891	1.071	1.698
45	0.715	0.413	1.203	0.645
60	1.151	0.846	0.863	0.833

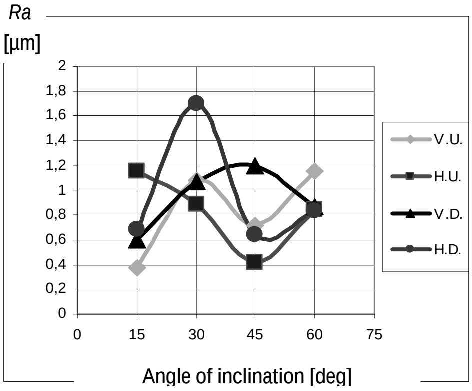

Fig. 10. Influence of surface inclination on *Ra* parameter.

values too, explicable by increasing of radial cutting force component which produce tool deflection [3].

4. CONCLUSIONS

The following conclusions have been derived from this experimental research:

- Geometric model presented in [1] for ball nose end milling is confirmed and influence of inclined surface and tool path orientations on cutting process [4, 5], can be evaluated for different cutting parameters.
- The best cutting conditions are around the 15^0 and 45^0 surface inclinations for the most tool path strategy.
- Use always vertical upward tool path orientations for inclined surface around 15^0 and horizontal upward, for 45^0.
- Avoid using horizontal upward in case to have surface inclinations around the 15^0 angle, horizontal downward for 30^0 and vertical downward for 45^0.
- If is possible, avoid to milling surface over the 45^0-50^0 surface inclinations because, the tool deflection increase and resulted a low surface quality.

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