CHARACTERISTICS OF NANO PROFILES OBTAINED BY FACE MILLING PROCESSES

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Abstract: *The main contribution of this study consists in an attempt to develop a mathematical characterization of the micro profiles generated in face milling operations with round inserts tools and an analyze of the surface texture obtained by face milling of X210Cr12 and C45 probes in different hardness states. The novelty of the work presented in the paper is a combination of both in the theory and experimental techniques used. The paper does not have industrial applications, but the research can be helpful in some specific manufacturing situations, for instance if precise machining of hard parts is involved*

Keywords: *face milling, micro profiles,*

1. Introduction

Milling is considered to be the machining process is which the undesired material from the workpiece is detached by cutting with rotary cutters, called mills while a feed motion is enabled/realized by the workpiece or the tool. Due to its wide range of surfaces that can be generated, and its versatility milling is one of the most common forms of machining. The milling processes are usually applied in order to machine parts that do not have rotation axis, are not axially symmetric and present features, such as holes, slots, pockets, and even complex surface contours.

According to the geometry of the machined surfaces, the geometry of the milling tool, the orientation of the spindle axis and the cutting moved needed different types of milling processes can be defined. The major milling operations are considered to be: the peripheral milling face milling and end milling.

The peripheral milling operation, also known as cylindrical milling involves horizontal spindles parallel with the workpiece and mills with the cutting teethe located on its circumference periphery of the tool.

The end milling operations uses tools with diameters considerable smaller than the workpiece width and with helical cutting edges carried over onto the cylindrical cutter surface. Specific to these milling tools is the possibility of cutting both with the peripheral cylindrical surface and with the front face.

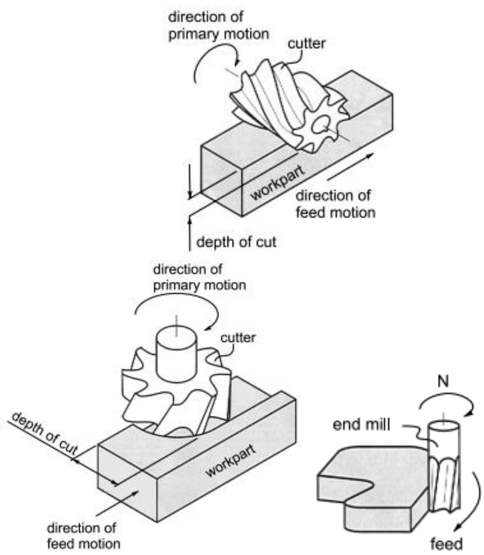


Figure 1: *The main conventional milling operations [5]*

In the case of face milling operations, the spindle (tool axis) is positioned perpendicular to the machined surface of the workpiece and carried out for machining flat surfaces with different orientations.

Following the recent trends in manufacturing technologies that require complex form surfaces machined with increases productivity and at low costs, the milling machines and operations now know a various range of types that involve special designed milling tools, advanced tool materials, cutting moves on more than 3 axes.

Between these new modern milling operations, a special place is occupied by hard milling technologies. These machining techniques are the cutting processes that correspond to the situations when cutting speed is slightly higher cutting than the ones specific to the conventional cutting processes and the material hardness is higher than 48 HRC [2]. The development of these machining technologies is strictly related with the achievements from the tool material and geometry field/area and the researches carried out in order to develop ……… and precise manufacturing equipment.

The advantages of hard machining reported by the scientific literature usually refers to: reduction of machining costs by diminishing process time and the reduction of tool variety, improved surface integrity, burr free components, lower cutting forces, elimination of part distortion caused by heat treatment, the elimination of the cutting lubricants, increased fatigue life of the workpiece, compressive residual stress and high removal rates (Beşliu, 2014). Hard milling proved to be beyond all an ultraprecision machining method and that is why their major industrial application is the die and mold manufacturing field. Specific to this industry sector is the requirements of generating extremely precise and qualitative surfaces on hard and extremely hard workpieces. The surface roughness that are usually reported to be obtained under some cutting parameters in hard milling operations is less than 0.25µm [4].

Surface texture feature has an important influence on the use of mechanical parts performance. In cutting operations, the rough surface texture is a result of the traces left by the sharp cutting edges of the tool on the workpiece. Different types of cutting tools and different cutting moves will leave different surface micro topographies and levels of roughness

Scientific literature reveals a large number of factors that affect the surface micro topography besides the cutting tool geometry and tool path. In order to highlight the main factors that influence the surface texture obtained in cutting processes in general a Cause-Effect Diagram was considered, figure 2. The factors affecting surface texture in general and surface roughness were grouped according to the element that generates them in 4 categories: workpiece characteristics, tool characteristics, machine tool and machining process.

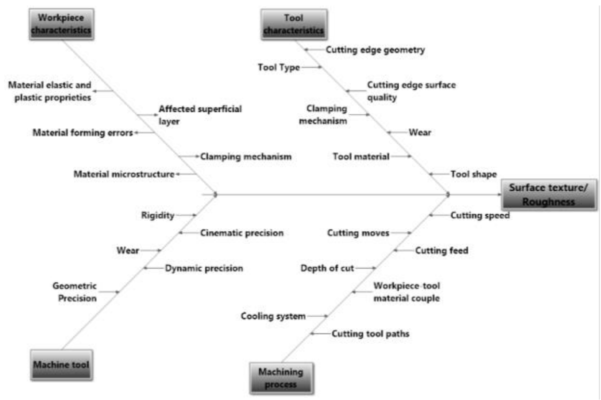


Figure 2: *Fishbone diagram with factors affecting surface texture and roughness*

Also, when analyzing machined surface textures resulting from milling operations of phenomena such as, tool deflections, tool run-outs and vibrations etc. must be considered. The vibrations that appear in cutting processes can have different internal and external sources. In milling operations, the important sources of vibration are the self-excited vibration. The cause of this kind of vibrations are the internal sources that provide energy for the system. There are situations when, the energy will exceed damping, thus vibrations sustain or even grow in amplitude. The vibrations will determine the phenomena known as ***regeneration of waviness***, which affects the chip thickness [3].

In order to quantitatively describe the machined surface texture, most of the time mathematical descriptions are required. In this work surface texture of surfaces generated by hard face milling processes is studied from scallop height and equations are proposed to characterize the micro topography.

The surface texture resulting from face milling operations is the result of the subsequent cutting actions of face mill cutting edges. Theoretically, the points on the cutting edge have trochoidal paths, which leave feed marks on the surface. The theoretical study made in order to characterize the surface texture obtained in hard face milling operations was realize by considering a face milling tool with only one round insert. For industrial applications of these results they can be extended for more realistic situations for milling tools with more than one cutting edge.

Due to the wide-spread use of round insert for hard face milling operations, it was considered important to investigate the surface texture resulting from these processes. The main advantages of these type of cutting inserts is reflected on the smoother surface finish, high flexibility allowing different type of interpolations, economicity due to the possibility of using more edges than other geometries, the universality as being suitable for machining in all types of materials with high material removal rates. Also, round insert is considered very strong geometries and therefore suitable in difficult operations and materials.

2. Theoretical considerations

Ideally, cutting edges, due to the composition between the cutting movements involved- rotation of the tool and linear translation with a certain feed of the workpiece, will have trochoidal paths that will leave feed marks on the surface as it can be seen in figure 3.

If we consider the point of the cutting-edge M, that is position on the circumference of a circle with diameter D that is actually equal to the circle at which the cutting edges of the face milling tool are disposed and is usually equal to the tool diameter. The above-mentioned circle is rolling along an imaginary line (Δ).

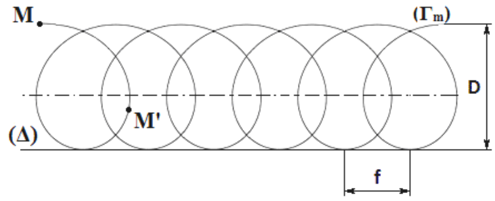


Figure 3: *The trochoidal trajectory of the cutting inserts [1]*

The distance that is reached by the center of the circle after a full rotation is equal to the cutting feed f. The trochoidal curve (Γm) described by the point M is the actual face milling trajectory of a cutting edge of the tool. According to the rules of free rolling the equation of the trochoidal trajectory can be determine as being:

$$\begin{cases} x_M = f \cdot \dfrac{\theta}{2\pi} + R \cdot sin\theta \\ y_M = R \cdot cos\theta\,. \end{cases} \quad (1)$$

Where f is the cutting feed, R the radius of the circle at which the cutting edges of the tool are disposed, Θ is the rotation angle that can be determined between the initial position of point M and the position of the same point at the time of the measurement. If considering a coordinate system with the center in the center of the circle with the diameter D and Oy axis parallel with imaginary line (Δ) the rotation angle *Θ* can be written as:

If replacing equation (2) in equation (1) the trochoidal curve (Γm) becomes:

$$y - R \cdot cos\left[2\pi\left(x - R \cdot sin(arcos\frac{y}{R}\right)/f\right] = 0\,. \quad (3)$$

In most cases of practical situations of face milling the cutting feed f (measured in mm / rev) is much smaller than the tool diameters. That is why the tool trajectories can be approximated as circle arcs. In face milling operations with round inserts the cutting edges will describe in their movements sections of torus as it can be seen in figure 4.

3D surface topographies after milling are affected by the cutter’s edge projection into the workpiece. In order to quantitatively describe the machined surface texture, a analyze of scallop height is required. Theoretically the profile from the axial plan will be compound of circular arcs that form cusps heights that can be calculated with the following equation:

$$a=r-\sqrt{r^2-(f/2)^2} \tag{4}$$

where r is the radius of the circle describe by the sharped edge of the inserts and f is the cutting feed.

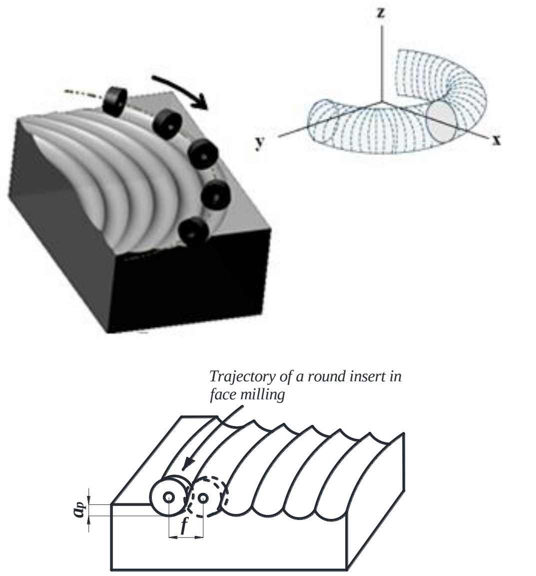


Figure 4: *Surface texture generation in face milling operation with round insert tools*

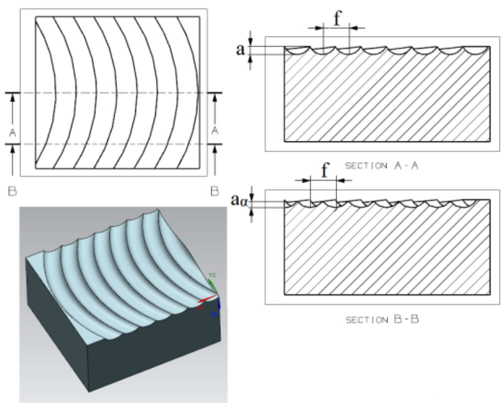


Figure 5: *Cusp height variation along the transversal plans [1]*

Transversal micro profiles of the machined surfaces will vary along the transversal plans situated at different distances from the plan containing the tool axis. The cusp height is decreasing with the increase of the distance between the measuring plan and the so called axial plan that contains the tool axis and cutting feed direction as it can be seen in figure 5. The arcs that compose the cusps height in the profiles from the transversals plans distanced from the axial plan result from the intersections of the two spiric sections. A spiric section is defined as the curve of intersection of a torus and a plane parallel to its rotational symmetry axis. The cusps height can be determined considering that in the section C-C created by a plane containing the center of the tool and situated at an angle α_r from the directions of the cutting feed the cusp height is generated by the intersection of two imaginary circles with the diameter equal to the one of the round insert like it can be seen in figure 6. The distance between the centers of the two circles mentioned before f_α that can be determined as:

$$f_\alpha=\sqrt{R^2+f^2+2\cdot R\cdot f\cdot \cos\alpha_r}-R \tag{5}$$

Where R is the radius of the circle described by the centers of the round inserts, f is the cutting feed (the distance between two consecutive positions of the tool after one rotation of the tool), α_r the angle that determines the position of the measurement plan B-B.

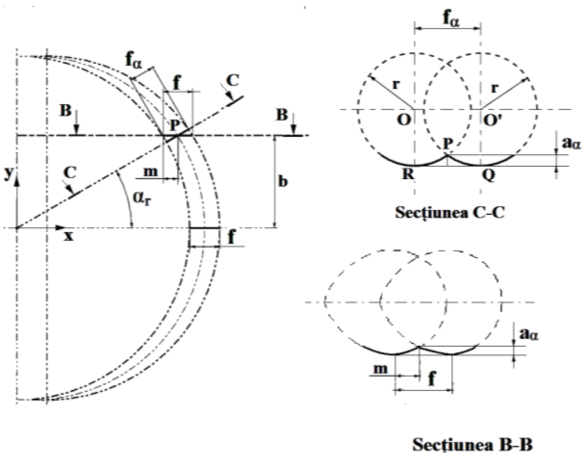


Figure 6: *The determination of cusps height for the transversal plans parallel to the axial plan [1]*

According to the assumptions made above the cusps distance a_α can be calculated with the following equation:

$$a_\alpha=r-\sqrt{r^2-[(2R^2+f^2+2R\cdot f\cdot \cos\alpha_r-2R\cdot\sqrt{R^2+f^2+2\cdot R\cdot f\cdot \cos\alpha_r})/4]} \tag{6}$$

In order to quantitative describe the profiles resulting from different machining operations surface roughness parameters are used. Roughness is typically considered to be the high-frequency, short-wavelength component of a measured surface. The most known surface roughness parameter is the arithmetic average of the roughness profile Ra. The theoretical value of the roughness parameter Ra can be determined considering the equation:

$$Ra=\int_{0}^{f} y(x)\cdot dx \qquad (7)$$

Where y is the equation of the curve that determines the surface 2D profile and f is the cutting feed.

Considering the above considerations for the axial plan the values for the arithmetic average of the roughness profile Ra can be calculated with the equation:

$$Ra=\int_{0}^{f} y(x)\cdot dx=\int_{0}^{f} \sqrt{r^2-x^2}+\frac{r^2}{f}\cdot arccos\frac{\sqrt{r^2-(f/2)^2}}{r}dx \qquad (8)$$

After completing the arithmetical calculus, the equation of Ra roughness parameter results:

$$Ra=2r^2 arccos\frac{\sqrt{r^2-(f/2)^2}}{r}+\frac{r^2}{2}arcsin\frac{f}{r}+f\sqrt{\left(1-\left(\frac{f}{r}\right)^2\right)}++\frac{f}{2}\sqrt{r^2-\left(\frac{f}{2}\right)^2} \qquad (9)$$

For the different transversal plan profiles parallel to the axial plan and situated at different distances from it the determination of an equation for the Ra roughness parameter involves establishing the equation of the arcs resulting from the intersections of the spiric sections (fig. 7). The equation of the spiric section in a xOz 2D plan with the center situated in the center of the imaginary torus according to the technical literature is:

$$(x^2+z^2+R^2-r^2+b^2)^2-4R^2(x^2+b^2)=0 \qquad (10)$$

If we translate the center of the coordinate system mentioned before in the point corresponding to the cusps height (figure 5), the spiric section equation will result in:

$$z_N=r\pm\sqrt{r^2-R^2-r^2-b^2-\left(\sqrt{R^2-b^2}+x_N\right)^2 \pm 2R\sqrt{\left(\sqrt{R^2-b^2}+x_N\right)^2+b^2}} \qquad (11)$$

After analyzing the two possible equations it resulted that the proper one is the one with the ”-” sign. If we consider that the mean line is situated at a distance d the equation of the Ra parameter will be equal to:

$$Ra=\int_{-f/2}^{+f/2} |z_N-d|\cdot dx_N \qquad (12)$$

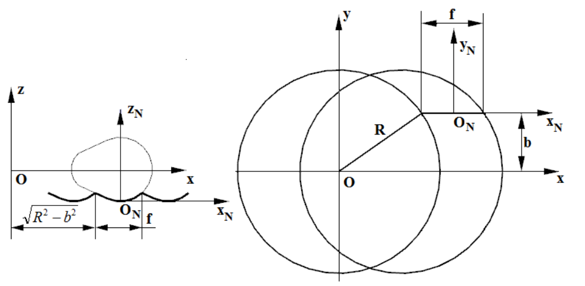


Figure 7: *The determination of the spiric section arc equations [1]*

Because of the enormous amount of work needed in order to calculate the complex integral an easier method that involved mathematical processing in order to determine the position of the mean line.

In order to determine the Ra parameter values, a program that was able to calculate the values of the values of the $\sum(z_N-d_V)^2$, starting from a small value of the d_V and continuously increasing it with very small Δd_V and by considering also pre-establish small l increase variations for x_N. Typically, these amounts will be constituted of a series of values that will record an accurate minimum accepted value for dV established before the situation when the values of the sums $\sum(z_N-d_V)^2$ start to increase. The above-mentioned value will be considered to be the distance d that characterizes the position of the mean line.

Once the value for the mean line position d it is determinate, a computing program for determining the roughness parameter Ra, can be made for a sets of known values of the independent variables b, R, r and f, were b is the distance of the measurement plan from the axial plan as can be seen in figure 6, R is the radius of the circle described by the center of the inserts of the milling tool, r is the diameter of the cutting insert and f is the value of the cutting feed.

The values will establish considering a factorial experimental plan with 2^4 runs.

By taking into consideration the values obtained by simulation, considering the theoretical equation of a profile function determined by an imaginary torus sections with a plan parallel and situated at a distance b from the axial plan than contains the tool axis and the cutting feed direction, and considering a factorial experimental plan the values obtained for the Ra parameter were afterwards processed in order to determine an equation for the roughness parameter Ra containing the independent variables *b, R, r și f* .

With the use of a computer program that is based on the Method of Least Square method a function type equation could be determined for the Ra parameter with the value of Gauss criteria of SG=0,1618842:

$$Ra=2{,}850717\cdot R^{0{,}6575271}\cdot f^{1{,}953524}\cdot r^{-0{,}999101}\cdot b^{-0{,}2647281} \quad (13)$$

By analyzing the above Ra parameter equation, we can observe that the exponents of the cutting feed and insert radius independent variables are compatibles with those that the scientific literature offers in order to theoretically calculate the value of Ra parameter of the surfaces obtained by milling operations:

$$Ra=\frac{f^2}{8r}\,[\mu m] \quad (14)$$

Where f is the cutting feed and r is the radius of the cutting tool insert.

According to the theoretical equation (14) of the Ra surface roughness parameter micro profiles can be obtained in face milling if feed rates of 0.3 mm/rev are adopted.

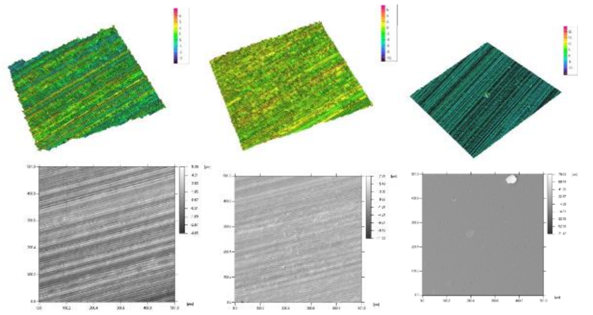
In actual face milling operations, the 2D profiles are different from the theoretical one due to the shape aberrations and the roughness of the cutting edges, the wear of the tool, the appearance of vibration, the low rigidity of the machine tool, the elastic recovery and other factors. Most of these factors mentioned before are in strong correlation with the machining conditions chosen.

2. Experimental results

In the following, some results that reflect the surface texture and micro profiles obtained after performing ultra-precision hard face milling operations by using milling tools with a single round insert are presented. The inserts used for the experimental work were 9603A KC1 IC12 type commercialized by Franken as destined for hard machining operations conditions. The geometry of the cutting inserts used consists in a cutting-edge diameter of ϕIC=12mm, thickness of b=4,5mm and the angle of clearance of 15^0.

The 3D surface topographies images obtained with the µScan laser profilometer after hard face milling operation reflect the cutter's edge projection into the workpiece. Surface profiles consist of wavelengths related to the cutting feed value f which is related to the kinematic-geometric projection of cutter into the workpiece.

Under high magnification surface texture have different aspects when they are cut under different cutting conditions. For instance in figure 8 are presented the surface textures generated by hard face milling of X210Cr12 cold tool steel with different machining conditions: a. material hardness 22HRC, cutting speed v=817m/min, cutting feed f=0.63mm/rev, depth of cut ap=0,8mm b. material hardness 53HRC, cutting speed v=408.4m/min, cutting feed f=0.25mm/rev, depth off cut ap=0,8mm, c. material hardness 59 HRC, cutting speed v=817m/min, cutting feed f=0.25mm/rev, depth of cut ap=0.2mm. The images were obtained with the µScan laser profilometer and processed with the specialized µScan software and present measurements made on 501x501µm areas. The Ra surface parameter corresponding to these textures are of: a. Ra=0.9µm, b. Ra=0.849µm, c. Ra=0.654µm.



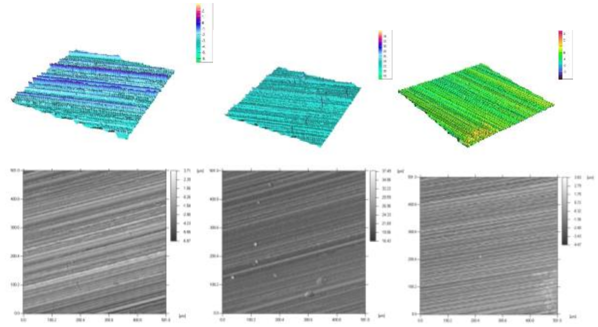
a. b. c.

Figure 8 *The surface textures generated by hard face milling of X210Cr12 cold tool steel with the following machining conditions: a. material hardness 22HRC, cutting speed v=817m/min, cutting feed f=0.63mm/rev, depth of cut ap=0,8mm b. material hardness 53HRC, cutting speed v=408.4m/min, cutting feed f=0.25mm/rev, depth off cut ap=0,8mm, c. material hardness 59 HRC, cutting speed v=817m/min, cutting feed f=0.25mm/rev, depth of cut ap=0.2mm.*

Also, the texture obtained by machining with shaped edges will be different from a material to another. Figure 9 presents the surface 3D topographies generated with the same machining conditions with the ones from figure 10 on an C45 material. The corresponding Ra roughness parameters values for this surface texture are: a. Ra=0.878µm, b. Ra=0.898µm, c. Ra=0.724µm.

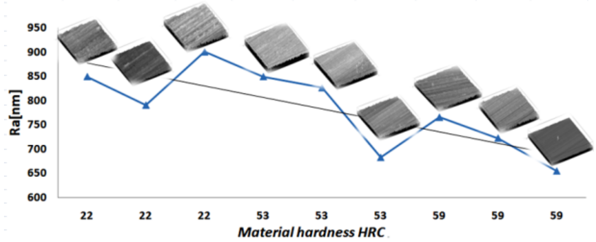
Most of the surface textures presented before reveal clearly regularly spaced and running parallel cutting grooves that may confirms the absence of chatter vibration. For instance, in figure 9 that presents the surface texture obtained by hard face milling of a C45 steel grade of 46 HRC with the following cutting conditions: v=817m/min, cutting feed f=0.25mm/rev, depth of cut ap=0.2mm show wavy grave that may be a result of internal vibrations. The differences in the depth of the resulting cutting groove are an result of the roughness of the cutting insert edge.

The surface texture in the case of C45 steel present more pronounced micro asperities than those generated on the *X210Cr12* tool steel: This may be a result of the elastic recovery that is more pronounced within the materials with larger elastic modules that conduct to a decrease of the surfaces cusps heights. Also, it is known that in the case of materials with higher tensile straight the plastic deformations and the friction coefficient between the chip and the front face of the cutting tooth are lower generating smaller values for the roughness parameters.



a. b. c.

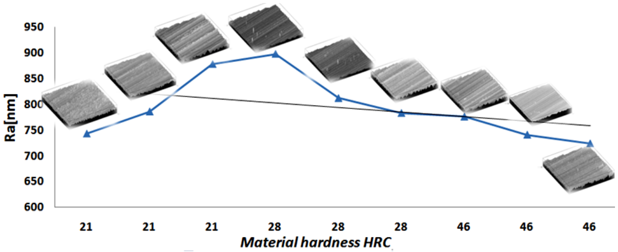
Figure 9: *The surface textures generated by hard face milling of C45 grade steel with the following machining conditions: a. material hardness 21HRC, cutting speed v=817m/min, cutting feed f=0.63mm/rev, depth of cut ap=0,8mm b. material hardness 28 HRC, cutting speed v=408.4m/min, cutting feed f=0.25mm/rev, depth off cut ap=0,8mm, c. material hardness 46 HRC, cutting speed v=817m/min, cutting feed f=0.25mm/rev, depth of cut ap=0.2mm.*



v , m/min	408,4	571,7	817	408,4	571,7	817	408,4	571,7	817
f, mm/rev	0,16	0,25	0,63	0,25	0,63	0,16	0,63	0,16	0,25
ap, mm	0,2	0,5	0,8	0,8	0,2	0,5	0,5	0,8	0,2

Figure 10: *The influence of workpiece hardness and different cutting conditions on the surface texture and surface roughness parameter Ra when hard face milling of an X210Cr12 steel grade*

Figure 10 presents the variation of the roughness parameter Ra and the surface textures with the material hardness obtained after hard milling of a X210Cr12 grade cold work tool steel in different machining conditions. Below of the material hardness values the other cutting parameters values are given- the cutting speed v in m/min, the cutting feed f in mm/rev and the depth of cut a_p in mm. As it can be seen the workpiece material hardness plays an important role on the aspect of the surface textures and on the profiles surface roughness. The lowest value of the Ra parameter for the machining conditions mentioned in figure 10 corresponded to the higher material hardness, the higher cutting speed value (817m/min), the medium value of the cutting feed (0.25mm/rev) and the lowest value of the cutting depth (0.2mm). This result confirms in a way the general recommendation from the scientific literature regarding the optimal conditions for obtaining optimal surface quality that stipulate the usage of higher cutting speeds and small depth of cuts. Also, an important aspect is the general tendency, that shows a decrease of the surface roughness with the increase of the workpiece material hardness.



v , m/min	408,4	571,7	817	408,4	571,7	817	408,4	571,7	817
f, mm/rev	0,16	0,25	0,63	0,25	0,63	0,16	0,63	0,16	0,25
ap, mm	0,2	0,5	0,8	0,8	0,2	0,5	0,5	0,8	0,2

Figure 11: *The influence of workpiece hardness and different cutting conditions on the surface texture and surface roughness parameter Ra when hard face milling of a C45 steel grade*

Figure 11 shows the surface textures obtained with the laser profilometer on the hard face milling tests carried out on C45 steel grade probes with different material hardness and different machining parameters. Similar to the case of the variation of the roughness parameter Ra with the material hardness obtained after hard milling of a X210Cr12 grade cold work tool steel (figure 10) the general tendency for the results presented shows a decrease of the surface roughness with the increase of the material hardness even if at first it seems the contrary. The maximum surface roughness was obtained for the situation of machining a probe with a material hardness of 28 HRC which was considered the medium value, with the minimum cutting speed, the medium cutting feed and the highest depth of cut from the machining conditions selected for the experiments. The best surface quality from the experiments carried out on the C45 steel grade corresponded to the probe of a hardness of 46HRC that was face milled with the highest cutting speed (817m/min), the mean feed rate value (0.25 mm/rev) and the smallest depth of cut (0.2mm). In general, for the results presented in figure 11 the smallest value of the cutting feed conducted to improves surface roughness.

4. Conclusions

In conclusion micro profiles surface textures can be obtained by hard milling cutting processes if the proper machining conditions are adopted. The experimental work developed shows that material roughness plays an important role on the hard-milling performances from the surface quality point of view. As regarding the other machining conditions, higher values of cutting speeds in correlation with small depth of cut can conduct to improved surface roughness.

References

[1] Beşliu I., *Contributions to the study of high-speed milling process of some hard materials.* Phd. thesis (in Romanian), Iaşi: “Gheorghe Asachi” Technical University of Iaşi, 2013.

[2] Beşliu I., Slătineanu L., Coteaţă M., *Machinability Aspects Investigations in Hard Milling of AISI W1 Hardened Tool Steel*, Applied Mechanics and Materials, Vol. 657, pp. 83-87,2013

[3] Imani B.M. , Layegh E., *Comprehensive Simulation of Surface Texture for an End-Milling Process*, Scientia Iranica, Vol. 15, No. 3, pp 340-347, 2008

[4] Ding T., Zhang S., Wang Y., Zhu X., *Empirical models and optimal cutting parameters for cutting forces and surface roughness in hard milling of AISI H13 steel*, International Journal of Advanced Manufacturing Technology ; 51(1), pp.45-55, 2010

[5] Marinov V., *Manufacturing Technology*, Lecture notes on WEB, Available from http://me.emu.edu.tr/majid/classes.htm