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INFLUENCE OF SOME MACHINING CONDITIONS ON THE VALUE OF *Rz* SURFACE ROUGHNESS PARAMETER AT END MILLING OF CAST IRON

BY

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Abstract. The research presented in this paper aimed to determine some empirical mathematical models able to highlight the influence exerted by some end milling process input factors on the surface roughness parameter *Rz* in the case of test samples made of two distinct cast irons and to compare the experimental results with the results obtained by means of the theoretical models. The experimental tests were performed in accordance with the requirements of a full factorial experiment with three independent variables at two levels. Empirical mathematical models of power type function for the *Rz* roughness parameter were determined by mathematical processing of the experimental results of the end milling process. The differences found between theoretical and experimental model could be explained both by the distinct physical-mechanical properties of the two cast irons and by the peculiarities of the fragile chips generation in the milling process of cast iron.

Keywords: end milling; cast iron; surface roughness parameter *Rz*; theoretical model; empirical model.

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1. Introduction

In the field of machine building, the concept of processing refers to the successive change of the workpiece geometric shape and/or physical-mechanical properties of the workpiece material to obtain parts manufactured in accordance with the recommendations that exist in the mechanical drawings.

If the quantitative changes of the workpiece are considered, the so-called *cold processing methods* could be classified in the following categories:

a) *Processing methods with material removal from workpiece* as a consequence of processes that generate chips (turning, milling, planning, broaching, drilling, grinding etc.) or of erosion processes (electrical discharge machining, electrochemical and chemical machining, plasma and ion machining, ultrasonic machining, laser beam machining, electron beam machining, water jet machining etc.) (Nanu and Buzdugan, 1976);

b) *Additive processing methods*, when the deposition or superficial alloying processes develop on the workpiece surface or on an initial support (chemical deposition, electrochemical deposition, laser beam deposition, electron beam deposition, plasma beam deposition etc.);

c) *Processing methods that do not generate significant changes of the workpiece mass* (photoengraving, heat treatment etc.).

As one could notice, the milling is the machining method included in the larger group of machining methods by cutting. Within the end milling process, the cutting multi-edge tool achieves the main rotation motion; the feed motion is materialized by the cutting tool or by the workpiece in a plane that has a position perpendicular to the milling tool rotation axis. There are several main milling methods (such are the end milling of flat surfaces, milling of cylindrical surfaces, milling of profiled surfaces etc.). The end milling allows obtaining of flat surfaces in many practical situations, due to its high material removal rate, relatively low roughness and good accuracy of the machined surfaces.

The obtaining of a certain roughness of the part surfaces is of high importance due to the necessity of ensuring an acceptable lifetime of the manufactured parts. There are many factors that exert influence on the values of the surface roughness parameters and one could take into consideration the properties of the workpiece material, geometric parameters of the tool active zone, parameters of the milling process, presence and properties of the work fluid, stiffness of the machining system etc. (Bohosivici, 1991; Calea *et al*., 1968, Epureanu *et al*., 1983, Pruteanu, 2005, Vlase *et al*., 1993).

The roughness could be defined as the assembly of the irregularities of the machined surface for which certain values of the ratio between the wavelengths and the heights of the irregularities are conventionally established. Nowadays, one considers that this ratio must have values lower than 50 (Bohosievici, 1991).

Within the so-called evaluation system (a system in which certain characteristics such as the pitch of the irregularities, the basic length, the mean line of the profile etc. are defined), it was possible to consider some parameters that can be used to evaluate the surface roughness. In this paper, such a considered parameter was the maximum height *Rz* of the profile (previously assessed by ten-point determinations).

For the complete definition of the current profile, it is not sufficient to use only one roughness parameter, but it is necessary to set those parameters and coefficients that ensure consistency with the correct operating conditions of the investigated surface. For this purpose the following aspects must be taken into consideration: the significance of the parameter, which is chosen in relation to the functional role of the considered surface, the process used to obtain the considered surface, the compatibility of the available measuring means with the selected roughness parameter (Pruteanu, 2005).

In accordance with the recommendations included in the standard SR ISO 4287, there are several groups of parameters able to offer information concerning the assessed profile (*prominent and empty amplitude parameters*, such as the maximum peak profile height *Rp*, maximum profile valley depth *Rv*, maximum height of the profile *Rz*, mean height of the profile elements *Rc*, total height of profile *Rt* etc., *mean ordinates*, such as the mean arithmetic deviation of the assessed profile *Ra*, root mean square deviation of the assessed profile *Rq*, skewness of assessed profile *Rsk*, kurtosis of the assessed profile *Rku* etc.), *pitch parameters*, *hybrid parameters*, *curves and associated parameters*). In the research presented in this paper, one preferred to use the maximum height of the profile *Rz*, for which some theoretical relations were identified in the accessed literature.

Over the years, the researchers investigated the influence of the cutting conditions on the roughness parameters for distinct machining methods. Experimental researches were designed and developed on test samples made of various metallic and non-metallic materials.

Thus, Abbas *et al.* have investigated the possibilities of optimizing the values of the cutting parameters to diminish the roughness of the surfaces obtained by end milling on parts made of high alloy steels (Abbas *et al*., 2016). The experimental results showed that the milling feed rate exerts a high influence on the minimum value of the roughness parameters *Ra* and *Rt* of the machined surface.

Tomadi *et al*. have studied the effect exerted by the cutting conditions on the surface roughness parameters in the case of the flat milling of the composite materials alloys (Tomadi *et al*., 2017). Five parameters that characterize the cutting conditions were considered: type of the cutting tool, cutting speed, milling feed, depth of cut, and the volume of the removed material. One concluded that the cutting tool affects the value of the surface roughness parameters in a proportion of 45.5%, when it is necessary to obtain a good final surface. Other main influence factors are the amount of chips obtained after processing (weight of 20.2%), and the depth of cut (13.2%).

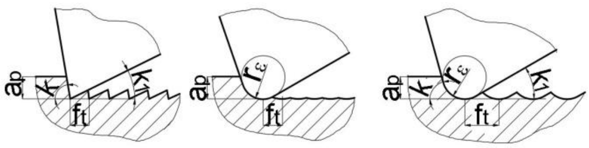


Fig. 1 – Asperities generation that involve a distinct participation of the milling tool active zones.

Rawangwong *et al*. developed investigations concerning the optimal cutting conditions in the case of flat milling of nodular cast iron, using metal carbide cutters and studied the effect of the main factors of the milling conditions on the surface roughness (Rawangwong *et al*., 2013). They have aimed to determine mathematical empirical models and proposed a linear function that shows that the cutting speed has a significant effect on the roughness parameters of the machined surface.

In the present paper, a comparison of the theoretical values of the *Rz* surface roughness parameter with the values experimentally obtained was considered. Experimental researches were performed using a full factorial experiment with three independent variables (feed per tooth *f*, cutting speed *v* and depth of cut a_p) and two experimental levels on two different type of cast irons.

2. Generation of the Surface Asperities at End Milling

The processed surface profile is materialized especially by the active zone shape of the cutting tool edge. Thus, in Fig. 1 three situations were taken into consideration. The situation presented in Fig.1*a* appears when there is not a tool corner radius and the tool active zone includes only the main edge and the secondary one, respectively. Fig. 1*b* shows the way of surface generation when the tool that participates to the generation of surface profile has a corner radius. In Fig. 1*c*, the surface profile is the result of the action exerted both by the rounded zone of the cutting edge and by the rectilinear zones of the cutting edges that correspond to the main and secondary edges.

If only the rounded zone of the cutting tool edge is involved in the surface asperities generation, then the relation used to estimate the size of the surface roughness parameter *Rz* (Epureanu *et al*., 1983) is the following:

$$Rz = r_\varepsilon - \sqrt{{r_\varepsilon}^2 - \frac{f^2}{4}} \cong \frac{f^2}{8 \cdot r_\varepsilon}, \tag{1}$$

where f is the feed rate, and r_ε – the tool corner radius. The relation could be applied when the following conditions are met:

$$k > arc\sin(\frac{f}{2r_\varepsilon}), \tag{2}$$

and

$$k_1 > arc\sin(\frac{f}{2r_\varepsilon}), \tag{3}$$

where k is the main cutting edge angle, and k_1 is the end cutting edge angle.

If the sintered metal carbide tip does not have a rounded edge and it consists of only two rectilinear edges, then the relation that corresponds to the surface roughness parameter *Rz* (Epureanu *et al*., 1983) is as follows:

$$Rz = \frac{f}{ctg\ (k) + ctg\ (k_1)}. \tag{4}$$

If the asperity profile includes both a rounded edge and rectilinear zones (obtained as a consequence of the action exerted both by the tool corner radius and by the rectilinear zones of the cutting tool edge), the relation for the surface roughness parameter *Rz* becomes (Epureanu *et al*., 1983):

$$Rz = \frac{1}{ctg\ (k) + ctg\ (k_1)} \cdot \left[f - r_\varepsilon \cdot \left(tg\left(\frac{k}{2}\right) + tg\ \left(\frac{k_1}{2}\right)\right)\right]. \tag{5}$$

In the above-mentioned case, it is necessary to meet the conditions:

$$k < arc\sin(\frac{f}{2r_\varepsilon}) \tag{6}$$

and

$$k_1 < arc\sin(\frac{f}{2r_\varepsilon}). \tag{7}$$

If the following inequalities are valid:

$$k < arc\sin(\frac{f}{2r_\varepsilon}), \tag{8}$$

$$k_1 > arc\sin(\frac{f}{2r_\varepsilon}), \tag{9}$$

then the surface roughness parameter *Rz* could be evaluated by means of the relation:

$$Rz = r_\varepsilon(1 - \cos k) + f \sin k \cos k - \sin k \sqrt{f \sin k\ (2r_\varepsilon - f \sin k)} \tag{10}$$

In the research presented in this paper, only the mathematical model (1) was used to theoretically determine the value of the surface roughness parameter

Rz: in this case, the feed rate f must have a value lower than 0.8 mm/rev. This value was established to meet the inequalities:

$$2r_\varepsilon \sin[min(k,k_1)] < f > 2r_\varepsilon \sin[max(k,k_1)]. \qquad (11)$$

3. Experimental Conditions

The experimental conditions were designed to ensure the establishing of some empirical mathematical models for the *Rz* roughness parameter in the case of end milling applied to test samples made of two distinct cast irons, and thus to illustrate the influence exerted by certain milling process input factors on the size of the surface roughness parameter *Rz*. Secondly, such empirical mathematical models could facilitate the verification of the extent to which the experimental values approximate the values that can be determined by using the theoretical models.

The milling of flat surfaces was developed on the base of the machining scheme presented in Fig. 2.

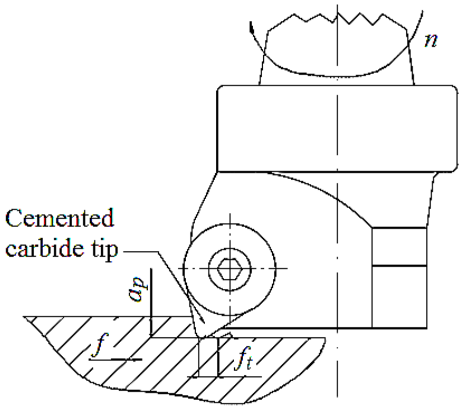


Fig. 2 – Scheme of the end milling process.

The test samples were made of two cast irons of distinct chemical compositions, as can be seen in Table 1.

Metallic carbide tips were used as material of the milling tool active zones. One preferred a tool with a single carbide tip to avoid thus the effect exerted by the possible errors of placing all the cutting tips in the same plane perpendicular on the tool rotation axis. The diameter that corresponds to the cutting tip position had a value d_t = 50 mm.

To measure the values of the *Rz* roughness parameter and to obtain the asperity profile, a Taylor Hobson type roughness meter was used.

The cutting conditions were determined by considering the recommendations included in the practical handbooks. The two values established for the two levels of the milling process input factors were f_{min} = 0.15 mm/rev, f_{max} = 0.5 mm/rev, v_{min} = 40 m/min, v_{max} = 100 m/min, $a_{p\,min}$ = 0.5 mm, and $a_{p\,max}$ = 1.5 mm.

Table 1
Chemical Composition of the Two Cast Iron Samples

Chemical composition [%]	Cast iron no. 1	Cast iron no. 2
Fe	91.0	92.2
C	> 4.5	> 4.5
Si	2.09	1.96
Mn	0.901	0.399
P	0.224	0.147
S	>0.150	> 0.150
Cr	0.141	0.0240
Ni	0.132	0.0694
Ti	0.105	0.0377
W	0.382	0.336
Pb	0.102	0.0570

The proper values of the process input factors and the experimental results obtained in experimental test were mentioned in Table 2.

Table 2
Experimental Conditions and Results

Exp. no.	Values of the process input factors			Values of the surface roughness parameter *Rz* [µm]	
	a_p [mm]	f [mm/tooth]	v [m/min]	Cast iron no. 1	Cast iron no. 2
1	0.5	0.126	39.25	18.8	23.1
2	1.5	0.126	39.25	11.7	19.1
3	0.5	0.198	39.25	32.3	34.9
5	1.5	0.198	39.25	44	37.8
5	0.5	0.126	98.91	14.9	10.1
6	1.5	0.126	98.91	14.2	16.1
7	0.5	0.198	98.91	16.4	13.4
8	1.5	0.198	98.91	9.78	19.7

4. Processing of the Experimental Results

The processing of the experimental results aimed to determine the mathematical empirical models by means of a software based on the method of least squares (Crețu, 1992). The software facilitates the selection of the adequate empirical mathematical models among some distinct possible functions, but in the research presented in this paper, it was preferred to choose a power type mathematical function, because this type of mathematical relationship is most used in the field of machine building.

The empirical mathematical models obtained correspond to the relation (12) for the cast iron number 1 and the relation (13) for the cast iron number 2:

$$R_z = 1051.683 \cdot a_p^{-0.157} \cdot f^{0.899} \cdot v^{-0.590} \qquad (12)$$

$$R_z = 1888.271 \cdot a_p^{0.168} \cdot f^{0.873} \cdot v^{-0.705} \qquad (13)$$

The graphical representations from Figs. 3-5 were elaborated taking into consideration the empirical mathematical models (12) and (13).

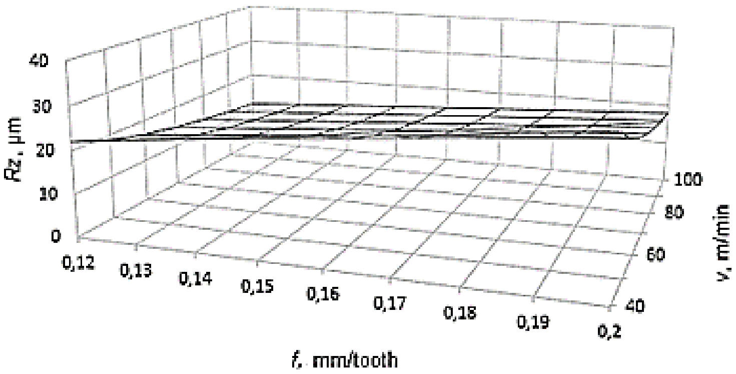


Fig. 3 – Influence exerted by the feed per tooth *f* and by the milling speed *v* on the value of the surface roughness parameter *Rz* in the case of the cast iron no. 1 (a_p = 1 mm).

The examination of the empirical mathematical models and of graphical representations highlights that in the case of the end milling of the test samples made of two distinct cast irons the highest influence on the value of the surface roughness parameter *Rz* is exerted by the size of the feed rate *f* in the case of the both cast irons, because the values of the exponents attached to this process input factor has the maximum absolute value in the both mathematical models. As expected, an increase in the feed rate results in an increase in the value of the roughness parameter *Rz*, as an increase in the cutting speed *v* determines a decrease in the value of the roughness parameter *Rz*. However, the increase in the *Rz* roughness parameter at the increase of the feed rate *f* is less than that corresponding to the theoretical model valid in this case (relation (1)), and the fact can be explained also by the particular processes of fragile chips generation during the milling. These processes do not provide conditions for the generation of the asperities profiles according to theoretical expectations, as can also be seen from the profiles shown in Fig. 6. In these graphical representations of the real asperities profiles, one can notice a certain difference of the real shape of the asperities profiles from the shape of an ellipse arc, which would occur theoretically instead of the circle arc, due to distinct magnification along the ordinate and abscissa axes, when the graphical representations that correspond to the asperities real profiles were elaborated.

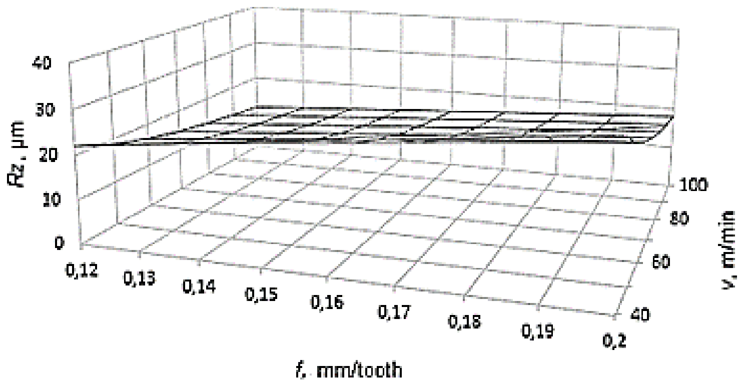


Fig. 4 – Influence exerted by the feed per tooth *f* and by the milling speed *v* on the value of the surface roughness parameter *Rz* in the case of cast iron no. 2 (a_p = 1 mm).

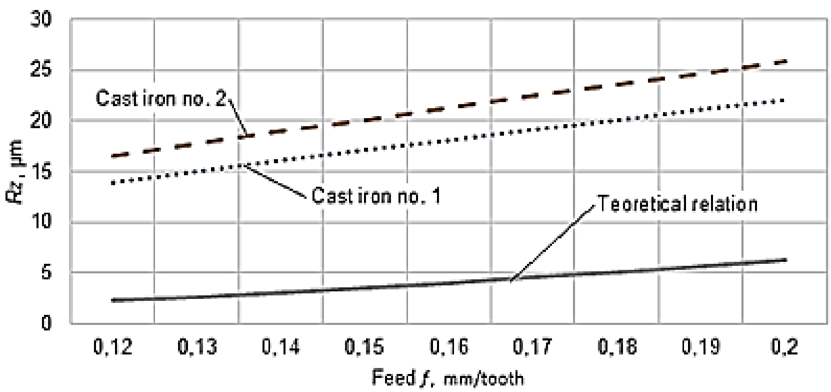
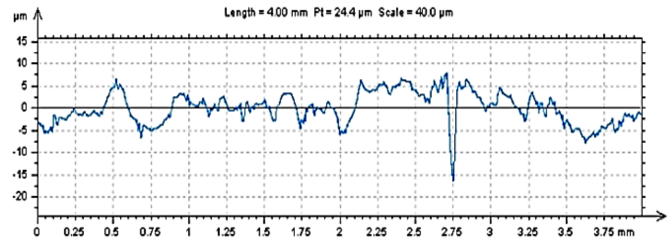


Fig. 5 – Influence exerted by the feed per tooth *f* on the *Rz* surface roughness parameter according to the theoretical model and the empirical mathematical models established for the test samples made of two distinct cast irons).



a

b

Fig. 6 – Asperities profiles for surfaces obtained by end milling on test samples made of two distinct cast irons: *a* – cast iron no. 1, *b* – cast iron no. 2 (a_p = 0.5mm, f = 0.126 mm/rot, v = 98.91m/min, profilograms obtained using the Taylor Hobson Roughness Tester).

5. Conclusions

The evaluation of the validity of some theoretical relations for assessing the roughness of a surface obtained by end milling was possible by comparing the theoretical mathematical model presented in the specialty literature with the obtained mathematical empirical models determined for two distinct cast irons. By the method of experiments design, it was possible to ensure a minimum number of experimental tests, using three independent variables (cutting speed, feed per tooth, depth of cut) at two experimental levels. An end mill type cutting tool with only one sintered metal carbide tip was used, because it was necessary to diminish the influence possible to be exerted by the error of positioning all the cutting tips in the same plane perpendicular on the milling tool rotation axis. By mathematical processing of the experimental results, empirical mathematical models of power type functions were determined. The empirical mathematical models and graphical representations based on them have revealed the influence of the values of the milling conditions parameters on the values of the roughness parameter *Rz* of the milled surface. Due to the physical-mechanical properties and chemical composition of the test samples made of two distinct cast irons, the graphical representations showed that the theoretical values are lower than those obtained by the experimental way.

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INFLUENȚA UNOR CONDIȚII DE PRELUCRARE ASUPRA VALORII PARAMETRULUI DE RUGOZITATE *Rz* LA FREZAREA FRONTALĂ A UNOR FONTE

(Rezumat)

Lucrarea urmărește determinarea modelelor matematice empirice pentru evidențierea influenței valorilor unora dintre factorii de intrare în procesul de frezare frontală asupra parametrului de rugozitate a suprafeței *Rz* în cazul frezării unor epruvete realizate din două fonte având compoziții chimice distincte și respectiv compararea rezultatelor experimentale cu rezultatele obținute prin intermediul modelelor teoretice. Testele experimentale au fost efectuate în conformitate cu cerințele unui experiment factorial complet cu trei variabile independente la două niveluri. Modelele matematice empirice de tip funcție de putere pentru parametrul de rugozitate *Rz* au fost determinate

prin prelucrarea matematică a rezultatelor experimentale obținute în cazul frezării frontale. Diferenţele constatate între modelul teoretic și cel experimental ar putea fi explicate atât prin proprietățile fizico-mecanice diferite ale celor două fonte, cât și prin particularitățile generării unor aşchii fragile în procesul de frezare a fontei.