www.czasopisma.pan.pl PAN www.journals.pan.pl

Metrol. Meas. Syst., Vol. 28 (2021) No. 4, pp. 735–749
DOI: 10.24425/mms.2021.137705

METROLOGY AND MEASUREMENT SYSTEMS
Index 330930, ISSN 0860-8229
www.metrology.wat.edu.pl

WAVINESS AT DRY HIGH-SPEED FACE MILLING OF SOME HARD STEELS

Irina Beşliu-Băncescu$^{1)}$, Laurenţiu Slătineanu$^{2)}$, Margareta Coteaţă$^{2)}$

1) *Ştefan cel Mare University of Suceava, Department of Mechanics and Technology, Universităţii Street, 13, 720229 Suceava, Romania,* (*irina.besliu@usm.ro*)
2) *Gheorghe Asachi Technical University of Iaşi, Department of Machine Manufacturing Technology, D. Mangeron Blvd, 59A, 700050 Iaşi, Romania,* (✉ *slati@tcm.tuiasi.ro*, +40 723 718 675, *mcoteata@tcm.tuiaso.ro*)

Abstract

Waviness is a parameter used to complete information on the machined surface state. There is little scientific and technical information on the influence exerted by the cutting conditions and the workpiece material hardness on the values of some parameters that define the waviness of milled surface. No works have been identified to present such information for dry high-speed face milling applied to hard steel workpieces. A factorial experiment with four independent variables at three variation levels was planned to model the influence of milling speed, feed, cutting depth, and steel hardness on the total heights of the profile and surface waviness for dry high-speed face milling. Mathematical processing of experimental results was used to identify the power type function and empirical mathematical models. These models highlight the direction of variation and the intensity of influence exerted by the considered input factors on the values of two waviness parameters in the case of dry high-speed face milling of samples made of four hard steels. It has been observed that the increase in steel hardness increases the total heights of the profile and surface waviness. In the case of two types of steel, a good correlation was identified between the values of the total profile waviness height and the total surface waviness height, respectively, using the Pearson correlation coefficient.

Keywords: waviness, dry high-speed face milling, hard steels, milling parameters, hardness, empirical mathematical models.

1. Introduction

Milling can be applied to obtain a large variety of surfaces. The most common use of milling is to obtain flat surfaces when the end milling tools usually ensure a good surface finish and a high material removal rate. If the cutting speeds are 5–10 times higher than the normal speeds, we can take into consideration the so-called **high-speed milling**. In the last three decades, the problem of high-speed cutting of hard materials has been investigated. It is accepted that high-speed cutting of hard materials is defined as cutting with speeds exceeding 5 m/min of materials that have

Article history: received May 3, 2021; revised June 13, 2021; accepted July 9, 2021; available online August 24, 2021.

a hardness of more than 48 *HRC*. It shows that, generally, high-speed cutting is achieved without using the cooling-lubricants, and, for this reason, it is considered a green technology.

If a milled flat surface is analyzed, its deviations refer to form deviations (deviations of first-order), waviness (deviations of second-order), and roughness (deviations of third and fourth order) [1]. This classification is based on the ratio of the asperities' wavelength and their heights. There is a common agreement to consider the asperities that have a ratio between the wavelength and height between 50 and 1000 as **waviness**. There is also a view to consider only the wavelength when classifying the geometrical deviations of the machined surfaces. In such case, asperities with a wavelength of 1–10 mm are considered waviness, and even the asperity height is expressed in micrometers.

There are many research works whose results have been published and regarding the roughness of the surfaces obtained when applying high-speed milling or other machining processes for obtaining planar surfaces. However, there are relatively few papers that particularly address the waviness of flat surfaces obtained with high-speed milling of hard materials. Thus, Raja *et al*. tried to clarify the separation of the concepts of roughness, waviness, and form when using adequate robust filters [2]. They appreciated the necessity to ensure the development of stable machining processes and provide functional correlation by the analysis of the bandwidth using digital filters. The problem of using adequate filters to separate the waviness from other geometrical deviations was also addressed by other researchers [3, 3–8].

Boryczko approached the problem of surface irregularities that define waviness and roughness in turned surfaces [9–11]. He proposed a method to simultaneously analyze the roughness and waviness components when considering the transverse profiles of the turned surfaces. One of his conclusions is that it is possible to evaluate the capabilities of machine tools better when monitoring the evolution of surface roughness and waviness in time. Wieczorowski *et al.* have shown that measurements of the parameters that characterize deviations of machined surface can provide different results and more in-depth research is needed to identify appropriate explanations for these differences [12]. Jiang *et al*. considered that in face milling, surface waviness is generated by unstable low-frequency milling chatter involving the tool and the workpiece [13]. The researchers highlighted the possibility of diminishing the milling chatter or improving the milling process stability affecting the milling parameters. Cai *et al.* took into consideration the visual aspect of the waviness generated by the cutting tool during peripheral milling of test pieces made of the Ti-6Al-4V alloy when different green environments are used [14]. They have come to the conclusion that the direction of the surface waviness corresponds to the tool axis in a plane perpendicular to the feed direction. Gusev and Fomin performed experimental research resulting in the elaboration of a polynomial of the first degree as a regression function to highlight the influence exerted by the depth of cut, feed, rotation speed, and the number of tool teeth on waviness in milling with a shaping cutter [15]. The research aimed to obtain the required waviness of milled contoured surface by establishing adequate milling characteristics. Nimel Sworna Ross and Manimaran mentioned that when milling the difficult-to-machine Ni-Cr alloy using a PVD-TiAlN coated WC tool, the 2D surface roughness profiles result in more stability in the case of cryogenic cooling [16]. At the same time, when using the milling process mentioned above, the waviness patterns are more oscillating in the case of dry milling, wet milling, and cooling environment based on the use of a minimum quantity. Chen et al. showed that the marks generated by cross grinding of spherical and aspheric surfaces are difficult to be removed in the subsequent polishing operation due to the elasticity of the flexible polishing pad, which takes the shape of the previously generated waviness [17]. The waviness generated by the grinding process was also approached by Yan *et al.* who considered that a disadvantage of the so-called parallel grinding method is the direct transfer of the grinding wheel profile waviness onto the grinded surface [18].

Some issues regarding the generation of waviness by the pull broaching process were addressed by Legutko *et al.* [19].

It should be noticed that in accessible literature, there is relatively little information concerning the influence exerted by milling parameters and material hardness on waviness characteristics and less information valid for high-speed milling. The research whose results are presented in this paper aimed at ample characterization of the high-speed face milling of certain hard steels. An objective of this study was to obtain additional information concerning influence exerted by milling input factors and steel hardness on two of the output parameters of technological interest that characterize the profile of surface waviness.

2. Initial considerations

In characterizing the geometrical aspects of the machined surface state, waviness is mentioned after the form deviations and before the surface roughness. Waviness refers to profile deviations of second-order that are repeated at equal intervals and for which the wavelength is much higher than the amplitude and their pitch is higher than their height (ISO 4287:1997).

The considered face milling scheme using a face milling tool is presented in Fig. 1. The milling tool achieves the rotation motion around its axis *Oz*, while the test piece placed on the machine tool table performs rectilinear feed motion f in a plane perpendicular to the milling tool rotation axis.

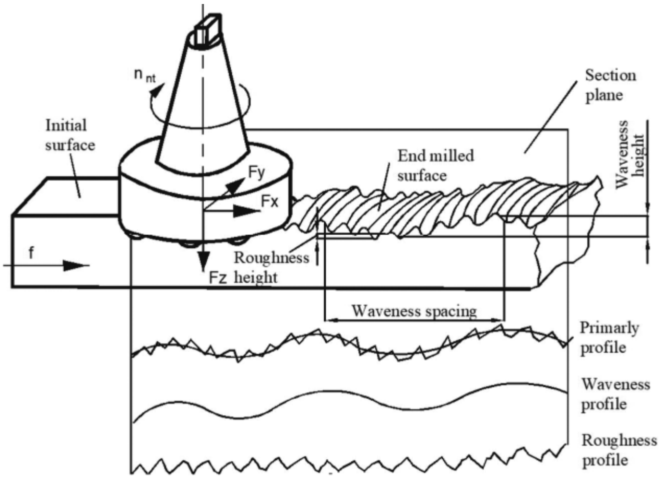


Fig. 1. Theoretical generation of waviness and roughness in face milling process.

The sectioning plane defined by the face mill rotation axis and the feed motion direction first highlights the primary surface profile. From this primary surface profile, the waviness profile and the roughness profile could be obtained using adequate filters.

The parameters that geometrically define the waviness profile were mentioned in the International Standard ISO 4287:1997 – Geometrical product specification (GPS) – Surface texture: Profile method – Terms, definitions, and surface texture parameters. The parameters calculated for the waviness profile are symbolized using the letter W. One such parameter is the total height W_t of the profile which is determined as the sum of the highest heights of the profile and the highest depths of the profile valleys for the so-called assessment length. Moreover, the waviness parameter W_t is considered as the peak to valley height of the waviness profile [20]. When the waviness refers to a surface, a parameter with a larger significance could be defined and the symbol used in this case includes the letter S (surface) effectively. Thus, the symbol of the parameter that corresponds to the total height of the surface waviness is SW_t.

The roughness profile can be generated by the recurring effect of the feed motion, by the number of the cutting inserts, and by high-frequency vibration. The profile waviness could be caused by the periodical or pseudo periodical movement of the face milling tool along its rotation axis, due to, for example, a low-frequency vibration component, to shape deviations of the guides used in the rectilinear translation motion of the table slide, to unevenness of mechanical properties of the test piece material, *etc*. Usually, the rotating tool axis is considered as having a direction perpendicular to the machine tool table, but always there is a small angle inclination to this direction and sometimes it could be necessary to analyze the influence exerted by the low-frequency vibration along such an inclined position of the rotating tool axis. There is also the opinion that waviness could be generated by clamping deviations, deviations in the tool or cutter geometry, tool or workpiece vibration, spindle tilt in face milling, the chatter of the tool and workpiece, *etc*. [14, 21]. All the factors mentioned above could exert influence on the sizes that define the profile waviness. Other factors capable of affecting the profile waviness could be the milling parameters (depth of cut a_p, feed rate f, peripheral speed v of the cutting tips).

For this reason, experimental research concerning the influence exerted by the parameters of the milling process and by the hardness of steel test pieces in high-speed face milling process should be considered [22].

3. Method

As test piece materials, two types of carbon steel with average carbon content were selected. One of these steels (C45U) is commonly used as standard material in experimental tests for evaluating the machinability of the materials. The other carbon steel was the non-alloy cold work tool steel type C80U. To further investigate the behavior of hard steels subjected to high-speed milling, two types of alloyed steel were selected, namely, the high carbon tool steel X210Cr12 and respectively the standard alloy bearing steel 100Cr6. Some characteristics of the steels used during the experimental research (chemical composition, hardness) were mentioned in Table 1. The hardness of the steel used in each of the experimental tests was also specified in Table 2. Heat treatments of quenching and annealing were applied to the test pieces made of each steel considered. Taking into consideration an investigation aimed at highlighting the influence exerted by the steel hardness on the waviness characteristics, different heat treatments were applied to the test pieces, ensuring the hardness variation from low to high obtained by quenching. Due to the

Table 1. Characteristics of the steel test pieces used in the experimental research.

Steel (ISO symbol)	**Chemical composition (percent by weight)**	**Hardness, *HB* (annealed state)**	**Hardness, *HRC* (after heat treatment)**
C45U	0.45% C	210	21–46
X210Cr12	2.05% C, 12% Cr	248	22–59
C80U	0.80% C, 0.2% Mn	192	50–62
100Cr6	0.99% C, 1.5% Cr, 0.35% Mn	223	26–62

different chemical compositions of the considered steels, it was not possible to obtain the same hardness through the applied heat treatments. In this way, as can be seen from Table 2, *HRC* hardness values of 21 to 46 were obtained for steel 1 C45, 22–59 for steel X210Cr12, 50 up to 62 for steel C80U, and 26 up to 62 for steel 100Cr6.

Table 2. Experimental conditions and results.

Exp. no.	Process input factors							Process output parameter							
	Milling conditions			Hardness, *HRC* (average values)				Profile waviness height W_t (DIN EN ISO 4288)				Area (surface) waviness height SW_t (ASME B46.1)			
	Milling speed, v, m/min	Milling feed, f, mm/rev	Depth of cut, a_p, mm	C45U	X210Cr12	C80U	100Cr6	C45U	X210Cr12	C80U	100Cr6	C45U	X210Cr12	C80U	100Cr6
1	408.40	0.16	0.2	21	22	50	26	0.315	1.003	0.729	0.715	0.950	1.248	0.534	0.505
2	571.70	0.25	0.5	21	22	50	26	1.364	0.856	0.690	2.423	0.529	1.033	0.436	1.215
3	817.00	0.63	0.8	21	22	50	26	1.454	1.143	1.846	0.920	0.664	1.093	1.133	1.178
4	408.40	0.25	0.8	28	53	55	55	0.442	0.638	0.724	1.414	1.021	0.726	1.251	1.278
5	571.70	0.63	0.2	28	53	55	55	2.180	1.261	0.750	0.847	1.412	1.272	0.456	1.257
6	817.00	0.16	0.5	28	53	55	55	1.265	1.661	0.252	0.640	0.431	0.777	0.171	0.745
7	408.40	0.63	0.5	46	59	62	62	1.722	1.680	2.096	1.337	0.877	1.009	1.367	0.765
8	571.70	0.16	0.8	46	59	62	62	0.999	0.639	1.490	3.449	1.254	0.825	1.634	1.576
9	817.00	0.25	0.2	46	59	62	62	1.096	0.998	0.813	3.134	0.477	0.707	0.477	1.539

The experimental tests were performed on a universal milling machine tool intended mainly for tool-making workshops, using the subassembly with a vertical main shaft. Since this milling machine did not allow high rotation speed specific to the high-speed milling process, a special device for obtaining such high rotation speeds was assembled instead of the initial subassembly corresponding to the main shaft. The main shaft of the device was driven in rotational motion by an electric motor through a belt drive. By changing the belt wheels, it was possible to change the rotation speed of the main shaft easily. In this way, it was possible to attain rotation speeds of the main shaft of up to 8000 rev/min.

As a cutting tool, a face milling tool of the assembled construction was preferred. It was possible to place and mechanically clamp the round carbide tool inserts on the tool body. The material of the round carbide tool inserts was PVD TiAlN 9603A KC1 IC12, commercialized by Franken and recommended for machining workpieces made of materials with a hardness up to 62-64 *HRC*. To widen the available range of cutting speeds, the body of the face milling tool was provided with some radial channels, in which it was possible to position and clamp the insert support at different radial distances to the rotation axis of the face milling tool. Mechanical fastening of the round carbide tool inserts in its support was used. The milling tool had a single round insert to avoid the possible influence of the insert positioning in the milling tool body on the roughness and waviness of flat milled surfaces. The values of the main parameters corresponding to the insert used were: clearance angle $\alpha = 0$, rake angle $\gamma = 10$.

To investigate a possible correlation between the measurable values of waviness characteristics and the size of the main component F_z of the cutting force, a type 9257B Kistler dynamometer with its measuring platform was used. The dynamometer was placed and clamped on the longitudinal slide table of the milling machine (Fig. 2).

Fig. 2. Image of the milling zone during the experimental research.

The experimental research aimed at obtaining a global image concerning the influence of certain input factors of the milling process on some process output parameters of technological interest in the case of the high-speed face milling of hard steels [22]. One of such process outputs parameters was the waviness of the face milled surfaces. The experimental tests had to allow identifying empirical mathematical models capable of highlighting the influence of the variation of the process input factors (as independent variables) on the values of some characteristics of the waviness (as output parameters of the process or the dependent variables).

In the face milling process, as input factors whose values were modified during the experimental tests, the milling parameters (peripheral speed v of the milling tool, the feed f, the depth of cut a_p), and the hardness HRC of the steels machined were selected. A new carbide insert for each experimental test was also used in order to avoid the influence of the cutting tool wear on the followed output parameters. On the other hand, upon examining the active surfaces of the carbide inserts, it was found that they did not show visible traces of wear after each experimental test.

A planned fractional factorial experiment of type $L9$ was used to reduce the number of experimental tests. A non-monotonic variation of the process output parameter (of the waviness characteristic) with the values of process input factors considered as variables was the adopted hypothesis. This meant that it is possible to have one or more maximum or minimum peak values for the process output parameters. For this reason, three levels of variation have been established for the values of all three parameters of the face milling process. In the case of the milling speed, high values were considered, trying to answer the question of how the increase in milling speed v could affect the values of the considered process output parameters (waviness characteristics).

Total height W_t of the waviness profile (determined according to the regulations included in the standard (DIN EN ISO 4288), and, respectively, total height SW_t of the surface waviness (determined according to the standard ASME B46.1) were taken into account as the characteristics of waviness. There are, of course, several parameters for characterizing the deviations of the real surface from the desired one [23], but it was assumed that the two parameters of the waviness (*Wt* and *SWt*) provide the most significant information on the researched aspects and also allow a comparison of the results. For measuring and recording the values of the waviness characteristics, a *µscan* noncontact optical profilometer *by Nano focus* was used. As results of measurements and recordings can also be affected by temperature variation generated by various heat sources found near the profilometer [24, 25], the measurement and recording of some waviness parameters were performed under normal laboratory conditions, taking into account the hypothesis that the results will not be significantly influenced by temperature variation.

The processing of the digital data obtained using the laser profilometer was developed using the µscan analysis software and a free trial version of the Mountain map software.

Also, to analyze the surface topography of the machined parts, a 3D optical noncontact measuring system produced by *MahrFederal* was used. This system is composed of a confocal microscope and a white light interferometer and has a sub-nanometer resolution.

Both values of the input factors in the high-speed face milling process of hard steels, as well as the results obtained for the two waviness characteristics considered, were recorded in Table 2. Taking into account the variation in a specific range of the hardness values and the values of the waviness parameters, respectively, as well as the requirements for the reproducibility of the measurement results [12], in Table 2, the average values of the hardness and parameters of the waviness obtained as a result of the performing three measurements were entered. During the experimental tests, no cooling-lubricating liquids were used, trying to establish conditions for the ecological machining process.

4. Results

An example of the result obtained using the experimental data analysis software can be seen in Fig. 3. In (a) on the left, the profile corresponding to the sectioning plane could be observed, while in (b) on the right, the aspect of the machined surface and the position of the sectioning plane are highlighted. As expected, there can be seen the profile waviness along which the aspects of the roughness are also present. Both the waviness and roughness amplitude are affected by the preselected parameters of the high-speed face milling process and by the mechanical properties of the machined material (in this case, hardness of certain hard steels).

The experimental results included in Table 2 were mathematically processed using the *CurveExpert* software. Power type functions were preferred since such functions, with the values of the exponents attached to independent variables, offer a direct image concerning the intensity of influence exerted by each considered process input factor on the value of the process output parameter. In fact, in the field of machining processes, there are many other situations when power type functions were preferred to model the influence exerted by the process input factors. These are the cases of sizes that correspond to the cutting force components, cutting speed following the older Taylor relation or with other subsequent more complex relations, to the surface roughness parameters, *etc*. The following empirical mathematical models were established using the *CurveExpert* software:

- In the case of the total height of profile waviness W_t, evaluated for the considered steels as materials for test pieces:

$$W_{t\,C45U} = 0.118v^{0.343}f^{0.595}a_p^{-0.147}HRC^{0.197}\,, \tag{1}$$

$$W_{t\,X210Cr12} = 0.249s^{0.176}f^{0.232}a_p^{-0.062}HRC^{0.158}\,, \tag{2}$$

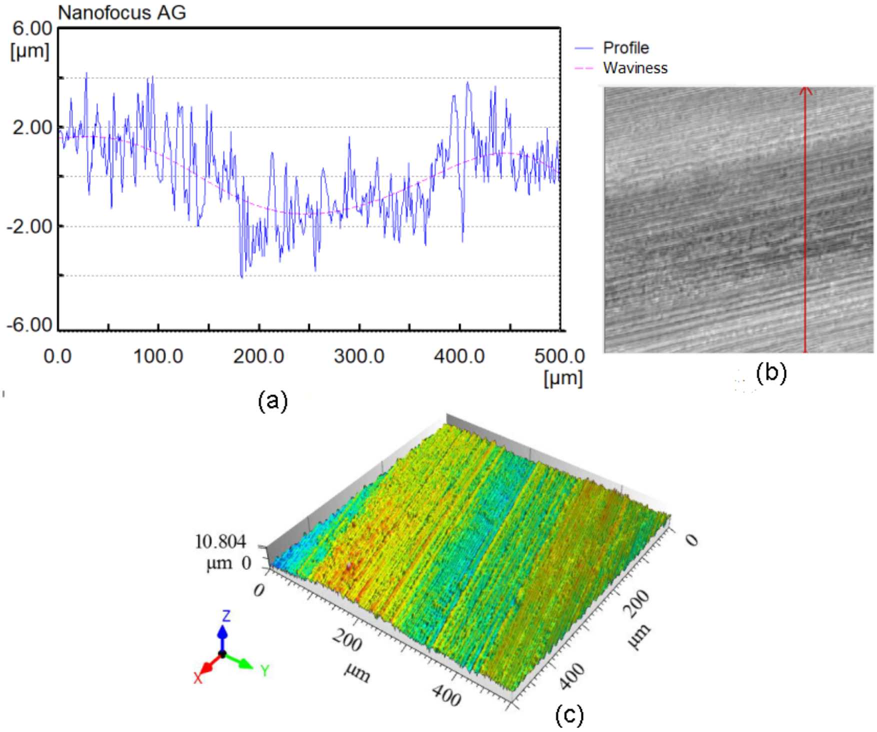


Fig. 3. Example of profile waviness and roughness for the test piece made of steel 100Cr6: (a) $a_p = 0.2$ mm, $f = 0.25$ mm/rev, $v = 817$ mm/min, 62 HRC, $SW_t = 3.067$ μm, $Ra = 0.937$ μm; cut-off $\lambda_c = 0.8$ mm;), recorded with the μscan laser profilometer by Nano focus and the Nanofocus AG software; (b) – position of the sectioning plan for obtaining the image in figure (c); (c) – profile analyzed with the optical 3D measuring system for the same test piece, elaborated by means of the 3D optical noncontact measuring system produced by MahrFederal.

$$W_{t\,C80U} = 0.000002 s^{0.106} f^{0.666} a_p^{0.599} HRC^{3.412}, \tag{3}$$

$$W_{t\,100Cr6} = 0.0203 s^{0.237} f^{-0.280} a_p^{-0.0699} HRC^{0.642}. \tag{4}$$

– In the case of *the total height of the surface waviness parameter* SW_t, determined for the same considered steels:

$$SW_{t\,C45U} = 34.885 s^{-0.631} f^{0.108} a_p^{-0.075} HRC^{0.101}, \tag{5}$$

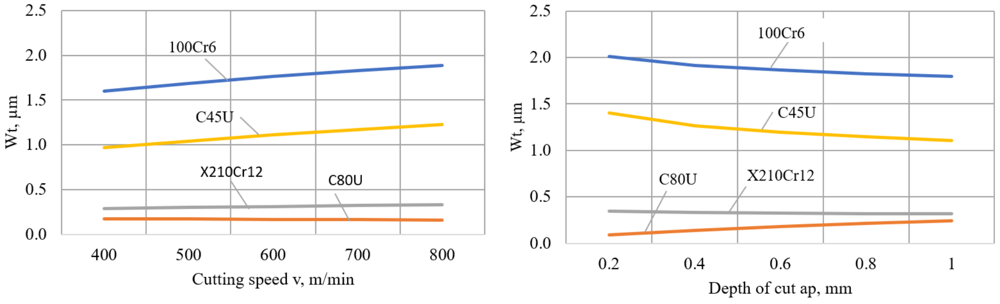
$$SW_{t\,X210Cr12} = 9.9115 s^{-0.196} f^{0.193} a_p^{-0.177} HRC^{-0.272}, \tag{6}$$

$$SW_{t\,C80U} = 0.000117 s^{-0.261} f^{0.266} a_p^{1.036} HRC^{2.859}, \tag{7}$$

$$SW_{t\,100Cr6} = 0.0482 s^{0.345} f^{0.042} a_p^{0.099} HRC^{0.283}. \tag{8}$$

On the base of the mathematical, empirical models represented by the equations (1)–(8), the graphical representations from Figs. 4, 5, and 6 were developed.

The analysis of the experimental results included in Table 2, the mathematical, empirical models, and the graphical representations from Figs. 4, 5, and 6 concluded with some general remarks.



(a) (b)

Fig. 4. The influence exerted by cutting speed v and depth of cut a_p on the height of the profile waviness W_t, following the established empirical mathematical models: (a) $f = 0.25$ mm/rev, $a_p = 0.5$ mm $HCR = 50$; (b) $v = 800$ m/min, $f = 0.25$ mm/rev, $HCR = 50$).

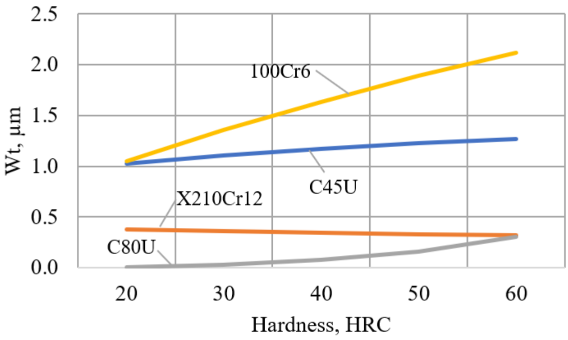
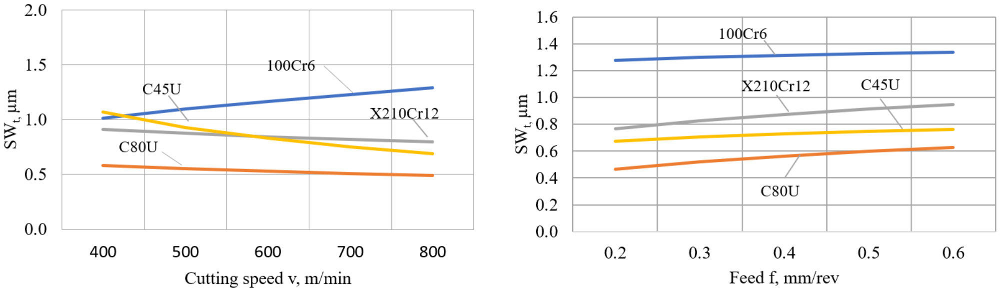


Fig. 5. Influence exerted by hardness HRC on the height of profile waviness W_t, following the established empirical mathematical models ($v = 800$ m/min, $f = 0.25$ mm/rev, $a_p = 0.5$ mm).



(a) (b)

Fig. 6. Influence exerted by cutting speed v and feed f on the height of surface waviness SW_t, following the established empirical mathematical models: (a) $f = 0.25$ mm/rev, $a_p = 0.5$ mm, $HCR = 50$; (b) $v = 800$ m/min, $a_p = 0.5$ mm, $HCR = 50$).

Thus, the first observation regards a certain diversity of the direction and intensity of the influences exerted by the process input factors on the sizes of the total height of the profile and surface waviness. To a certain extent, this diversity could be explained by the different behavior of the materials tested and, sometimes, by a possible large dispersion of the experimental results.

In the case of the waviness profile evaluated using parameter W_t, in all the situations, the increase in steel cutting speed v causes a low increase in waviness profile total height W_t, (Fig. 4a) since in all the empirical mathematical models, the exponents attached to size *HRC* have positive subunit values. The strongest influence appears in the case of steel 100Cr6, for which the exponent has the maximum absolute value when compared with the values of the other exponents attached to process input factor v. It is known that in the case of steels, the size of the components of main cutting force F_z could have one or more maximums [26, 27] when cutting speed v increases and it is possible that the increase in speed v corresponds to the ascendant zone of such a curve. The increase in the cutting force could generate a higher value of elastic deformation of the machining system, and this could be reflected by an increase in total height W_t of the profile waviness. On the other hand, an influence of the position of the sectioning plane through the test piece (see Fig. 3) could appear.

In all the examined situations there can also be noticed, an increase in the total height of waviness profile W_t when there is an increase in hardness *HRC* of the test piece steel (Fig. 5). The fact could also be explained by the increase in the main component F_z of the main cutting force and, in association with this increase, an increase in the low-frequency vibrations amplitude specific to the face milling process.

With a single exception (in the case of steel 100Cr6), increase in the feed f led to an increase in total height W_t of the waviness profile. It is known that the increase of the main component F_z of the cutting force when the feed value also increases and arguments similar to those mentioned above could explain the influence exerted by the size of feed f on total height W_t of the waviness profile.

Also, as a result, with a single exception (valid, in this case for the steel C80U), one can notice that the increase in the depth of cut a_p determines a decrease in total height W_t of the waviness profile (Fig. 4b). Usually, the increase in depth of cut a_p generates an increase in the size of the main component F_z of the cutting force. However, there are situations when such an increase in a_p could determine a decrease in the size of the cutting forces due to a certain specific behavior of the steel at the increase in the depth of cut a_p. Such an effect could explain the observed situation. An increase in the depth of cut a_p determined a diminishing in total height SW_t of the surface waviness, as seen in (7) and (8).

In the case of total height SW_t of the surface profile, it can be noticed that a stable influence is exerted by the size of feed f whose increase causes an increase in total height SW_t of the surface waviness (Fig. 6b). This fact could be explained by the increase in elastic deformation of the machining system when the cutting forces increase, and so does the amplitude of the low-frequency vibration increases.

As a result, in the case of three types of steel (except steel 100Cr6), the increase in milling speed v led to a decrease in total height SW_t of the surface waviness (Fig. 6a).

An increase in cutting speed v could determine an improved plastic behavior of the steel, due essentially to the increase in the temperature in the cutting zone and, finally, a decrease in the cutting forces and the amplitude of the low-frequency vibration of the machining system.

With a single exception (valid in the case of steel X210C12), the increase in steel hardness *HRC* led to an increase in total height SW_t of the surface waviness. This fact could relate to the increase in the sizes of the main component F_z of the cutting force, as in the case of total height W_t of the profile waviness.

As mentioned above, within the experimental research, to obtain a general image concerning the machinability of some hardened steels when using high-speed milling, not only the values of the machined surface waviness were measured. The values of the components of the cutting forces and the values of surface roughness parameter *Ra* were also measured. In all these cases,

Metrol. Meas. Syst., Vol. 28 (2021), No. 4, pp. 735–749
DOI: 10.24425/mms.2021.137705

power type empirical mathematical functions were used to model the influence exerted by the considered input factors of the face milling process (cutting speed v, feed f, depth of cut a_p, test piece material hardness HRC). To answer the question if there are any similarities or even common aspects among the considered process output parameters (waviness, roughness, and size of main component F_z of the milling force), all the empirical mathematical models were included in Table 3.

Table 3. Power type empirical mathematical models for the other considered output parameters (surface roughness parameter Ra and the main component F_z of the cutting force) in the face milling process.

Steel	**Empirical mathematical models**
C45U	$Ra = 7.116v^{-0.226}f^{0.111}a_p^{0.163}HRC^{-0.354}$ $F_z = 169.28v^{-0.256}f^{0.258}a_p^{0.583}HRC^{0.557}$
X210Cr12	$Ra = 0.799v^{-0.059}f^{0.077}a_p^{0.115}HRC^{-0.089}$ $F_z = 44.4v^{0.082}f^{0.217}a_p^{0.0516}HRC^{0.174}$
C80U	$Ra = 2.65v^{-0.162}f^{0.187}a_p^{0.034}HRC^{-0.140}$ $F_z = 0.000004v^{0.323}f^{0.493}a_p^{0.926}HRC^{4.047}$
100Cr6	$Ra = 0.275v^{0.030}f^{0.101}a_p^{0.108}HRC^{0.061}$ $F_z = 14.44v^{-0.260}f^{0.523}a_p^{0.716}HRC^{1.460}$
C80U	$Ra = 2.65v^{-0.162}f^{0.187}a_p^{0.034}HRC^{-0.140}$ $F_z = 0.000004v^{0.323}f^{0.493}a_p^{0.926}HRC^{4.047}$
100Cr6	$Ra = 0.275v^{0.030}f^{0.101}a_p^{0.108}HRC^{0.061}$ $F_z = 14.44v^{-0.260}f^{0.523}a_p^{0.716}HRC^{1.460}$

On the other hand, it should be noted that the power type functions (preferred to be used here since they are accepted as empirical models when investigated other output parameters in the cutting processes) are not able to take into consideration the possible existence of one or more maximum or minimum peaks of the experimental results. They are more convenient in the case of monotone variation of the process output parameter, and this is not the case when studying, for example, the influence exerted by the cutting speed on the values of the main component F_z of the cutting force or surface roughness parameter Ra. This means that in the future, it will still be necessary to use other empirical mathematical functions (which do not assume a monotone variation of the dependent variable at the change of values corresponding to the dependent variable) to obtain an adequate model when taking into consideration the experimental results. Such non-monotonic functions can be, for example, a polynomial of two or higher degrees, a hyperbolic function, *etc.*

5. Correlation between the two investigated waviness characteristics

Since the two characteristics of the waviness (total height W_t of the surface profile and the height SW_t of the surface waviness) were determined in the same experimental conditions, the question if there is a correlation between them could be formulated. Information in this regard could be provided by the value of the so-called correlation coefficient (Pearson r_{xy}'s correlation coefficient):

$$r_{xy} = \frac{n\sum x_i y_i - \sum x_i \sum y_i}{\sqrt{n\sum x_i^2 - \left(\sum x_i\right)^2}\sqrt{n\sum y_i^2 - \left(\sum y_i\right)^2}}, \tag{9}$$

where n is the number of measurements included in each of the two-comparison series of measured values x_i and y_i, and $i = 1, 2, \ldots, n$. it is conventional to assume a strong correlation between the two series of considered sizes when the Pearson's coefficient is close to 1.00 or −1.00, and a low correlation when the Pearson's coefficient has a value close to zero. It is also assumed that if the value of calculated Pearson's coefficient r_{xy} is closer to the value −1 (in the case of *negative* or *inverse* correlation) or +1 (for the *direct* or *positive* correlation), there can exist a better correlation between the two series of values subject to comparison.

In this way, the values of $r_{xy} = 0.108$ for steel C45U, $r_{xy} = 0.198$ for steel X210Cr12, $r_{xy} = 0.774$ for steel C80U, and $r_{xy} = 0.754$ for steel 100Cr6 have been determined. Following the existing conventions, it is considered that there is a low positive correlation for steels C45U and X210Cr12 (since the values of the Pearson's coefficient is in the interval [0.1–0.3]), and, respectively, a strong positive correlation for steels C80U and 100Cr6 (since the values of the Pearson's coefficient are between 0.5 to1.0). This strong correlation valid for the last two types of hard steel is highlighted additionally by the graphical representations from Fig. 7, where the values of the total height of the profile and surface waviness were illustrated for each of the tests made in certain experimental conditions.

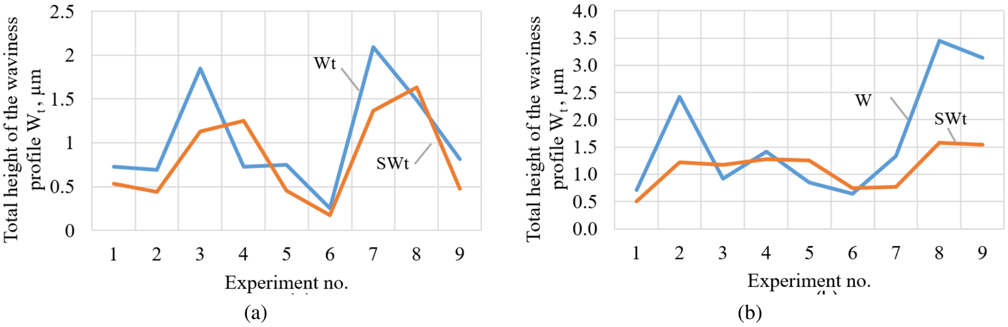


Fig. 7. Correlation between the total height of the waviness profile W_t and the total height of the surface waviness SW_t parameters in the cases of steels C80U (a) and 100Cr6 (b).

6. Conclusions

The waviness is one of the parameters used to characterize the machined surface state. An experiment with three levels of the process input factors was designed and performed to obtain additional information concerning how different process input factors affect the total height of the profile and surface waviness generated by the high-speed face milling process of hard steels. The test pieces were made of four types of steel found in different structural phases and having different hardness because of the applied heat treatments. As output parameters, the total heights of the profile and surface waviness were used. By mathematical processing of the experimental results, power type functions were determined as empirical mathematical models. The exponents attached to each of the process input factors highlighted the intensity of the influence exerted by the cutting speed, feed, depth of cut, and steel hardness on the total height of the surface and profile waviness. A constant effect was noticed in the case of influence exerted by steel hardness whose increase increases the total height of profile and surface waviness total height. An increase in the total height of surface waviness was generated as the feed size increased. As the hardness of steel increases, an increase in total heights of profile and surface waviness is expected. In

*Metrol. Meas. Syst.,*Vol. 28 (2021), No. 4, pp. 735–749
DOI: 10.24425/mms.2021.137705

workshop practice, a decrease in these values can be achieved by reducing the size of the feed and, possibly, by increasing the number of passes used to remove a certain machining allowance. In the case of two types of steel, a good correlation was found between the total height of the profile waviness and the total height of the surface waviness.

References

[1] Vakondios, D., Kyratsis, P., Yaldiz, S., & Antoniadis, A. (2012). Influence of milling strategy on the surface roughness in ball end milling of the aluminum alloy Al7075-T6. *Measurement*, *45*(6), 1480–1488. https://doi.org/10.1016/j.measurement.2012.03.001

[2] Raja, J., Muralikrishnan, B., Fu, S., & Liu, X., (2002). Recent advances in separation of roughness, waviness and form. *Precision Engineering, 26*(2), 222–235. https://doi.org/10.1016/S0141-6359(02)00103-4

[3] Clarysse, F., & Vermeulen, M. (2004). Characterizing the surface waviness of steel sheet: reducing the assessment length by robust filtering. *Wear*, *257*(12), 1219–1225. https://doi.org/10.1016/j.wear.2004.04.006

[4] Mezghani, S., & Zahouani, H. (2004). Characterization of the 3D waviness and roughness motifs. *Wear*, *257*(12), 1250–1256. https://doi.org/10.1016/j.wear.2004.04.006

[5] Lingadurai, K., & Shunmugam, M. S. (2006). Metrological characteristics of wavelet filter used for engineering surfaces. *Measurement*, *39*(7) 575–584. https://doi.org/10.1016/j.measurement.2006.02.003

[6] Gogolewski, D., & Makiela, W. (2018). Application of wavelet transform to determine surface texture constituents. In Durakbasa, N. M., Gencyilmaz, M. G. (Eds.). *Proceedings of the International Symposium for Production Research 2018*, (pp. 224–231). Springer. https://doi.org/10.1007/978-3-319-92267-6_19

[7] Gogolewski, D. (2020). Influence of the edge effect on the wavelet analysis process. *Measurement*, *152*, 107314. https://doi.org/10.1016/j.measurement.2019.107314

[8] Toteva, P., & Koleva, K. (2019). Application of new generation geometrical product specifications in the practice in small and medium sized enterprises. *MTeM 2019. MATEC Web of Conferences, 299*, 04006. https://doi.org/10.1051/matecconf/201929904006

[9] Boryczko, A. (2010). Distribution of roughness and waviness components of turned surface profiles. *Metrology and Measurement Systems*, *17*(4), 611–620. https://doi.org/10.2478/v10178-010-0050-4

[10] Boryczko, A. (2011). Profile irregularities of turned surfaces as a result of machine tool interactions. *Metrology and Measurement Systems*, *18*(4) 691–700. https://doi.org/10.2478/v10178-011-0065-5

[11] Boryczko, A. (2013). Effect of waviness and roughness components on transverse profiles of turned surfaces. *Measurement*, *46*(1), 688–696. https://doi.org/10.1016/j.measurement.2012.09.007

[12] Wieczorowski, M., Cellary, A., & Majchrowski, R. (2010). The analysis of credibility and reproducibility of surface roughness measurement results. *Wear*, *269*(5-6), 480–484. https://doi.org/10.1016/j.wear.2010.05.003

[13] Jiang, L., Yahya, E., Ding, G., Hu, M., & Qin, S. (2013). The research of surface waviness control method for 5-axis flank milling. *International Journal of Advanced Manufacturing Technology*, *69*, 835–847. https://doi.org/10.1007/s00170-013-5041-7

[14] Cai, C., Liang, X., An, Q., Tao, Z., Ming, W., & Ming Chen, M. (2021). Cooling/lubrication performance of dry and supercritical CO_2-based minimum quantity lubrication in peripheral milling Ti-6Al-4V. *International Journal of Precision Engineering and Manufacturing – Green Technology*, *8*(5), 405–421. https://doi.org/10.1007/s40684-020-00194-7

[15] Gusev, V. G., & Fomin, A. A. (2017). Multidimensional model of surface waviness treated by shaping cutter. *Procedia Engineering*, *206*, 286–292. https://doi.org/10.1016/j.proeng.2017.10.475

[16] Nimel Sworna Ross, K., & Manimaran, G. (2019). Effect of cryogenic coolant on machinability of difficult to machine Ni-Cr alloy using PVD TiAlN coated WC tool. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, *41*, 44. https://doi.org/10.1007/s40430-018-1552-3

[17] Chen, B., Li, S., Deng, Z., Guo, B., & Zhao, Q. (2017). Grinding marks on ultra-precision grinding spherical and aspheric surfaces. *International Journal of Precision Engineering and Manufacturing – Green Technology*, *4*, 419–429. https://doi.org/10.1007/s40684-017-0047-5

[18] Yan, G., You, K., & Fang, F. (2020). Three-linear-axis grinding of small aperture aspheric surfaces. *International Journal of Precision Engineering and Manufacturing – Green Technology*, *7*, 997–1008. https://doi.org/10.1007/s40684-019-00103-7

[19] Legutko, S., Kluk, P., & Stoić, A. (2011). Research of the surface roughness created during pull broaching process. *Metalurgija-Sisak then Zagreb, 50*(4), 245–248.

[20] International Organization for Standardization. (1996). *Geometrical Product Specifications (GPS) – Surface texture: Profile method – Motif parameters* (ISO 12085:1996(en)). https://www.iso.org/obp/ui/#iso:std:iso:12085:ed-1:v1:en

[21] Stephenson, D. A, & Agapiou, J. S. (2016). *Metal Cutting Theory and Practice. Third edition.* CRC Press. https://doi.org/10.1201/978131537311

[22] Beşliu, I. (2013). *Contributions to the study of the high-speed milling process of some hard materials* [Doctoral dissertation, Gheorghe Asachi Technical University]. (in Romanian)

[23] Pawlus, P., Reizer, R., Wieczorowski, M., & Krolczyk, G. (2020). Material ratio curve as information on the state of surface topography – A review. *Precision Engineering*, *65*, 240-258. https://doi.org/10.1016/j.precisioneng.2020.05.008

[24] Miller, T., Adamczak, S., Świderski, J., Wieczorowski, M., Łętocha, A., & Gapiński, B. (2017). Influence of temperature gradient on surface texture measurements with the use of profilometry. *Bulletin of the Polish Academy of Sciences. Technical Sciences, 65*(1), 53–61. https://doi.org/10.1515/bpasts-2017-0007

[25] Grochalski, K., Wieczorowski, M., Pawlus, P., & H'Roura, J. (2020). Thermal sources of errors in surface texture imaging. *Materials, 13*(10), 2337. https://doi.org/10.3390/ma13102337

[26] Klocke, F. (2011). *Manufacturing processes 1. Cutting.* Springer-Verlag. https://www.springer.com/gp/book/9783642119781

[27] Petruhi, P. G. (1974). *Cutting the construction materials, cutting tools and machine tools*. Mashinostroenie. (in Russian) https://www.studmed.ru/petruha-pg-rezanie-konstrukcionnyh-materialov-rezhuschie-instrumenty-i-stanki_f97044450c66.html

Irina Beşliu-Băncescu graduated in machine manufacturing technology from the Gheorghe Asachi Technical University in Iaşi, Romania in 2009. She received her PhD in 2013. In her thesis she addressed issues related to the high-speed milling process. She is currently a lecturer at the Department of Mechanics and Technologies at Ştefan cel Mare University of Suceava, Romania. She is a co-author of 3 books and of more than 70 papers published in journals or conference proceedings. Her current field of research includes advanced manufacturing technologies, CAM and CNC machining technologies, advanced measurement technology.

Margareta Coteaţă graduated from Gheorghe Asachi Technical University of Iaşi, Romania in 2001 and obtained her master's degree in science in 2002. She received her PhD in 2009. Currently, she is a lecturer in the Department of Machine Manufacturing Technology, Gheorghe Asachi Technical University. She is a co-author of 10 books, first author, or co-author of over 130 papers published in journal or conference publications. Her current field of interest includes non-traditional manufacturing processes, mainly electrochemical machining, electric discharge machining, laser beam machining, composite materials.

Metrol. Meas. Syst., Vol. 28 (2021), No. 4, pp. 735–749
DOI: 10.24425/mms.2021.137705

Laurenţiu Slătineanu graduated from the Polytechnic Institute in Iaşi, Romania (specializing in machine manufacturing technology), in 1971. He received his PhD from the Polytechnic Institute of Iaşi in 1980. He is professor emeritus of Gheorghe Asachi Technical University in Iaşi, Romania. He has contributed to publication of more than 30 books as the first author or co-author, of over 300 papers published in journals or in conference proceedings, and of more than 50 Romanian patents. His current field of interest includes machine manufacturing technology, non-traditional machining processes, and technological innovation.