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

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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 the milled surface. No works have been identified to present such information in the case of 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 in the case of dry high-speed face milling. Mathematical processing of the experimental results was used to identify power type function, empirical mathematical models. These models highlight the direction of variation and the intensity of the influence exerted by the considered input factors on the values of the 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 the steel hardness increases to 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

The milling can be applied to obtain a large variety of surfaces. The most common use of milling refers to obtaining 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 a hardness of more than 48 *HRC*. It can show that, generally, high-speed cutting is achieved without using the cooling-lubricating environments, and, for this reason, it is considered a green technology.

If a milled flat surface is analyzed, its deviations refer to the 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 asperities heights. There is the agreement to consider the asperities that have a ratio between the wavelength and height between 50 and 1000 as a **waviness**. There is also the opinion to consider only the wavelength when classifying the geometrical deviations of the machined

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surfaces. In such a case, the 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 whose subjects regard the roughness of the flat surfaces obtained when applying high-speed milling or other machining processes for obtaining planar surfaces. However, there are relatively few papers that partially address the waviness of the flat surfaces obtained by 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 that it is necessary to ensure the development of stable machining processes and provide functional correlation by the analysis of the bandwidth using the digital filters. The problem of using adequate filters to separate the waviness from other geometrical deviations was also addressed by other researchers [3-8].

Boryczko approached the problem of surface irregularities that define the waviness and roughness in the cases of 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 was that when monitoring the evolution in time of the surface roughness and waviness, it is possible to evaluate the machine tools' capabilities better. Wieczorowski *et al.* have shown that measurements of the parameters that characterize deviations of the machined surface can provide different results and that more in-depth research is needed to identify appropriate explanations for these differences [12]. Jiang et al. considered that in the case of face milling, the surface waviness is generated by the 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 acting on the milling parameters. Cai *et al.* took into consideration the visual aspect of the waviness generated by the cutting tool during the peripheral milling of test pieces made of Ti-6Al-4V alloy when different green environments are used [14]. They considered that the direction of the surface waviness corresponds to the tool axis in a plane perpendicular to the feed direction. Gusev and Fomin developed experimental research finalized with 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 the waviness, in the case of milling with shaping cutter [15]. The research aimed to obtain the required waviness of the 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 PVD-TiAlN coated WC tool, the 2D surface roughness profiles result in more stability in the case of the cryogenic cooling [16]. At the same time, when using the milling process mentioned above, the waviness patterns are more oscillating if the dry milling, wet milling, and cooling environment based on the use of a minimum quantity of lubrication are applied. 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 waviness by pull broaching process were addressed by Legutko *et al.* [19].

It can notice that in the accessible literature, there is relatively little information concerning the influence exerted by the milling parameters and the material hardness on the waviness characteristics and less information valid for the high-speed milling. The research whose results are presented in this paper aimed at an ample characterization of the high-speed face milling of certain hard steels. An objective of this study was to obtain additional information concerning the influence exerted by the 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, the waviness is mentioned after the form deviations and before the surface roughness. The waviness refers to the 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 materializes a rectilinear feed motion f in a plane perpendicular to the milling tool rotation axis.

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 sizes 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 on 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.

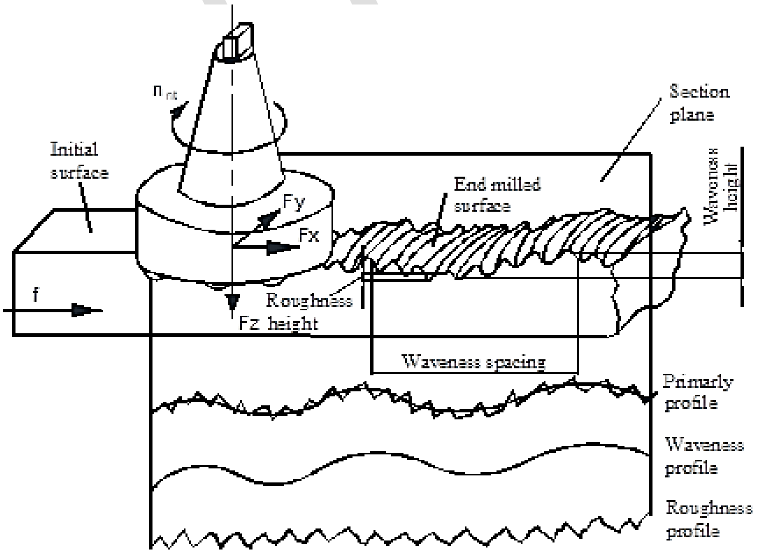


Fig. 1. Theoretical generation of the waviness and roughness in the case of the face milling process.

The roughness profile can be generated by the recurring character 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, for example to a low-frequency vibration component, by the shape deviations of the guides used in the rectilinear translation motion of the table slide, by the 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 with such an inclined position of the rotating tool axis. There is also the opinion that the waviness could be generated by the 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 the conditions of the high-speed face milling process could 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 a standard material in experimental tests of 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 as a result of using 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 considered steel. Taking into consideration an investigation aiming 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 values obtained by quenching. Due to the 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 the steel 1 C45, 22-59 for the steel X210Cr12, 50 up to 62 for the steel C80U, and 26 up to 62 for the steel 100Cr6.

Table 1. Characteristics of the test pieces' steels 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

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 the achieving of 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 the 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 use rotation speeds of the main shaft up to 8000 rev/min.

As a cutting tool, a face milling tool of assembled construction was preferred. On the tool body, it was possible to place and mechanically clamp the round carbide tool inserts. 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 inserts 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 inserts positioning in the milling tool body on the roughness and waviness of the flat milled surfaces. The values of the main parameters corresponding to the insert used were: clearance angle α=0 °, rake angle γ=10 °.

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, ap, 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

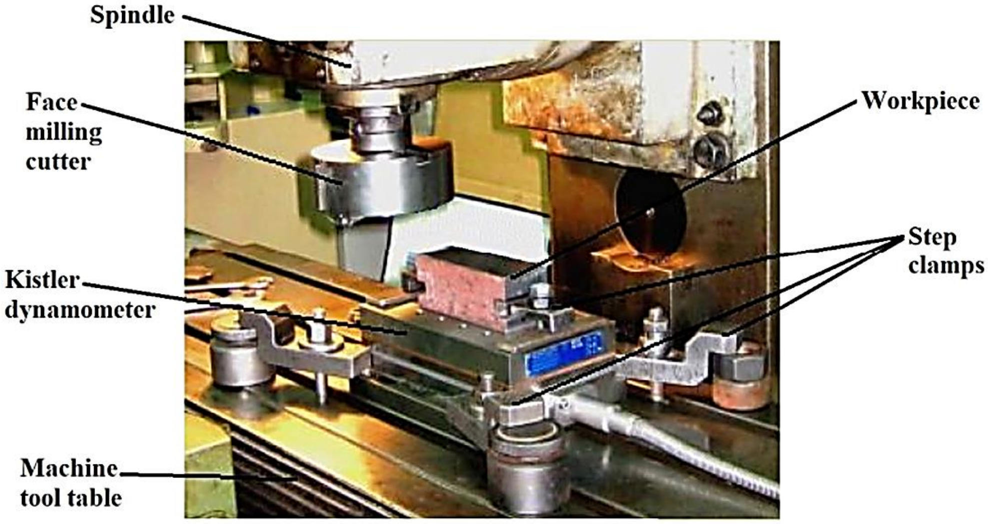


Fig. 2. Image from the milling zone during the experimental research.

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

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 the 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 used were selected. Avoiding the influence of the cutting tool wear on the followed output parameters was also achieved using a new carbide insert for each experimental test. On the other hand, 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 *L*9 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 would mean 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 of the milling speed v could affect the values of the considered process output parameters (waviness characteristics).

As the characteristics of the waviness, there were taken into account the total height W_t of the waviness profile (determined according to the regulations included in the standard (DIN EN ISO 4288), and, respectively, the total height SW_t of the surface waviness (determined according to the standard ASME B46.1). There are, of course, several parameters for characterizing the deviations of the real surface to the desired one [23], but it was appreciated that the two parameters of the waviness (Wt and SWt) provide significant information on the researched aspects and also allow a comparison of the results. For measuring and recording the values of the waviness characteristics, the noncontact optical profilometer *μscan by Nano focus* was used. The results of measurements and recordings can be affected by the 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 a laser profilometer was developed using the μscan analysis software and a free trial version of 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 white light interferometer and has a sub-nanometer resolution.

Both the values of the input factors in the high-speed face milling process of hard steels, as well as those of the results obtained in terms of 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 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 the left zones of the figure, the profile corresponding to the sectioning plane could be observed, while in the right zones, the aspect of the machined surface and the position of the sectioning plane are highlighted. As expected, it can be seen the existence of the profile waviness along which aspects of the roughness are also present. Both the waviness and roughness amplitude are affected by the 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, by the values of the exponents attached to the independent variables, offer a direct image concerning the intensity of the 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 to model the influence exerted by the process input factors, power type

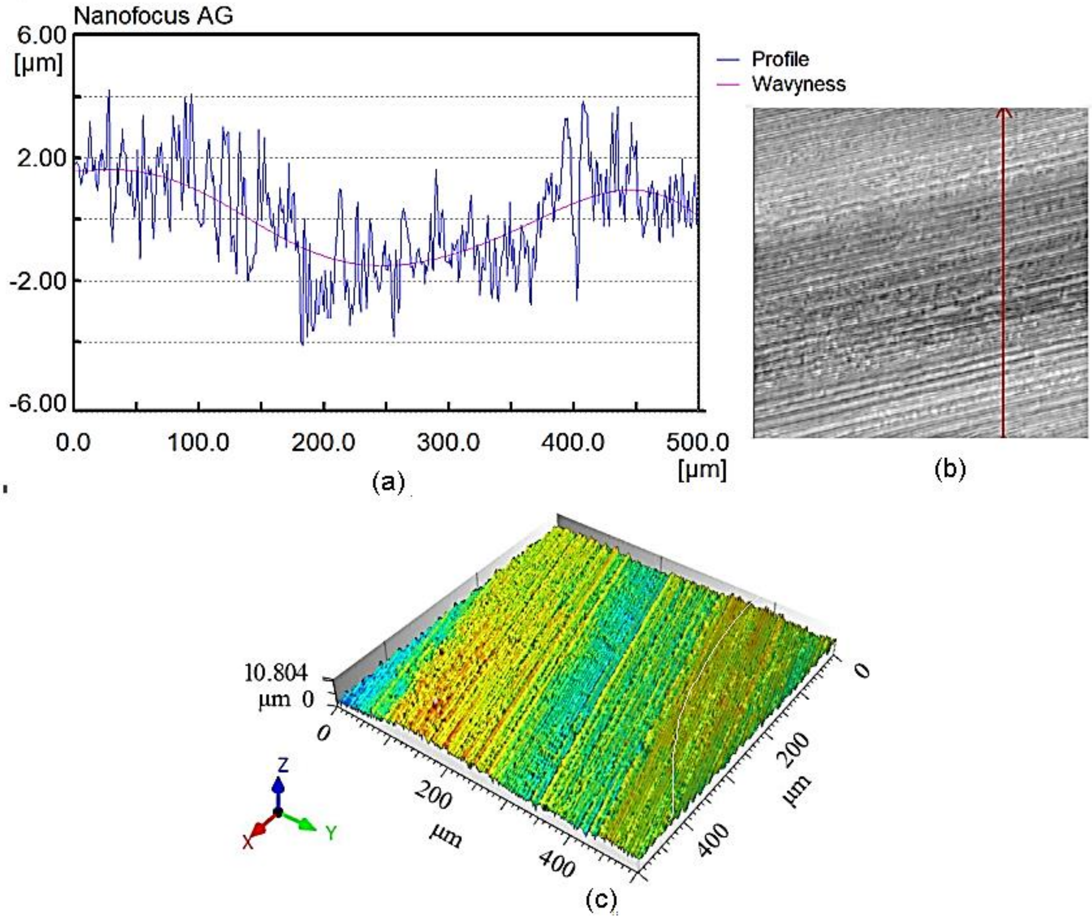


Fig. 3. Example of profile waviness and roughness for the test piece made of steel 100Cr6: (a) a_p=0.2 mm, f=0.25 mm/rev, v=817 mm/min, 62 *HRC*, SW_t= 3.067 µm, Ra= 0.937 µm; cut-off λ_c=0.8 mm;), recorded with the laser profilometer µscan by Nano focus and the Nanofocus AG software; (b) - the position 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.

functions were preferred. These are the cases of the 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 mathematical, empirical models were established using the *CurveExpert* software:

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

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

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

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

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

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

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

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

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

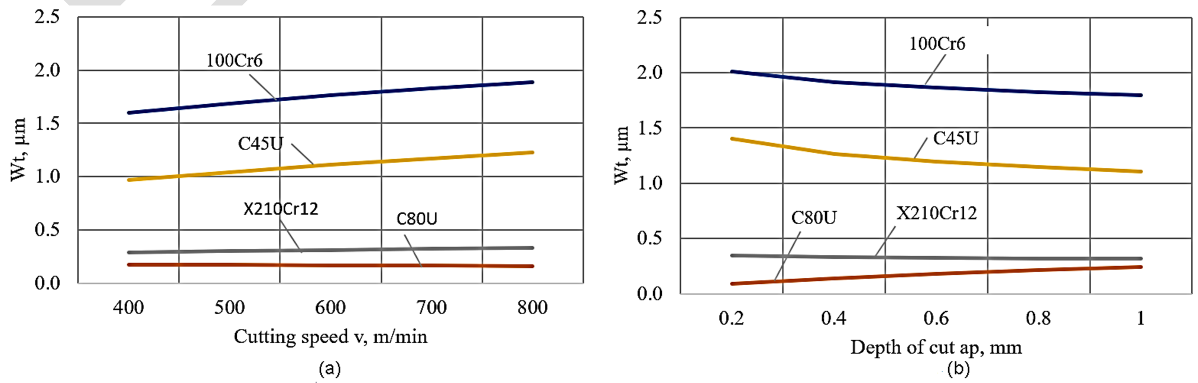
$$SW_{t\,100Cr6} = 0.0482s^{0.345} f^{0.042} a_p^{0.099} HRC^{0.283} \tag{8}$$

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.

Thus, a 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 tested materials and sometimes by a possible large dispersion of the experimental results.

In the case of the waviness profile evaluated using the parameter W_t, in all the situations, the increase in the steel cutting speed v determines a low increase in the waviness profile total height W_t, (Fig. 4, *a*) since in all the empirical mathematical models, the exponents attached to the 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 the process input factor v. It is known that in the case of steels, the size of the components of the main cutting force F_z could have one or more maximums [26, 27] when the cutting speed v increases and it is possible that the increase of the speed v corresponds to the ascendant zone of such a curve. The increase in the cutting force could generate a higher value of the elastic deformation of the machining system, and this could



(a) (b)

Fig. 4. The influence exerted by the cutting speed v and the 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 *HRC*=50; (b) v=800 m/min, f=0.25 mm/rev, *HRC*=50).

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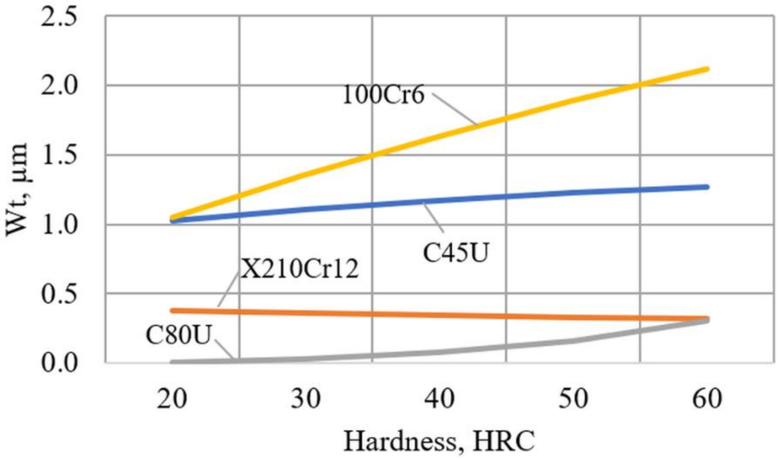

Fig. 5. The influence exerted by the hardness *HRC* on the height of the profile waviness W_t, following the established empirical mathematical models (v=800 m/min, f=0.25 mm/rev, a_p=0.5 mm).

be reflected by an increase of the 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.

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

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

Also, as a result, with a single exception (valid, in this case for the steel C80U), it can notice that the increase in the depth of cut a_p determines a decrease in the total height W_t of the waviness profile (Fig. 4, *b*). 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 of 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 noticed situation. An increase in the depth of cut a_p determined a diminishing in the total height SW_t of the surface waviness, as seen in (7) and (8).

In the case of the total height SW_t of the surface profile, it can notice that a stable influence is exerted by the size of feed f, whose increase determines an increase in the total height SW_t of

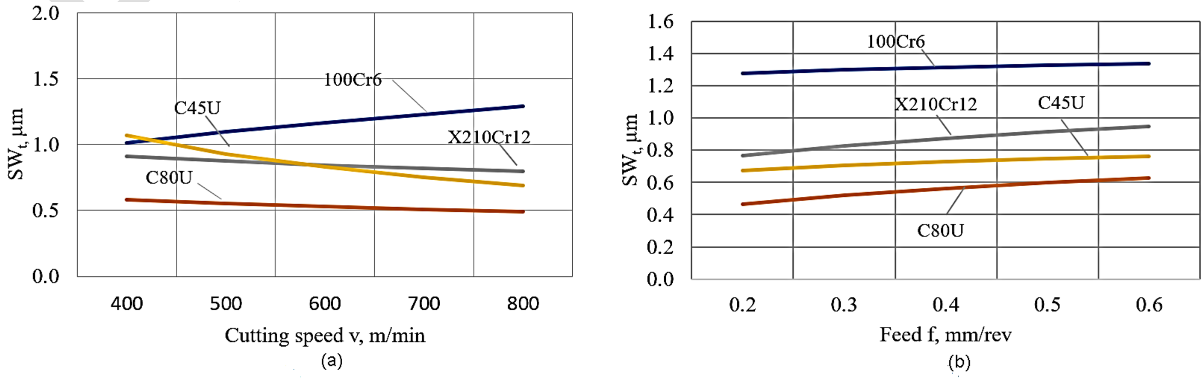

Fig. 6. The influence exerted by the cutting speed v and feed f on the height of the surface waviness SW_t, following the established empirical mathematical models: (a) f=0.25 mm/rev, a_p=0.5 mm, *HRC*=50; (b) v=800 m/min, a_p=0.5 mm, *HRC*=50).

the surface waviness (Fig. 6, *b*). The fact could be explained by the increase in the elastic deformation of the machining system when the cutting forces increase, and the amplitude of the low-frequency vibration increases also.

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

An increase in the 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 the steel hardness *HRC* led to an increase in the 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 the 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 the surface roughness parameter *Ra* were also measured. In all these cases, 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 a question if there are certain similarities or even common aspects among the considered process output parameters (waviness, roughness, and size of the 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 main component F_z of the cutting force) in the case of 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 can remark 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 the surface roughness parameter *Ra*. This means that in the future, it is necessary to use still other empirical mathematical functions (which do not suppose a monotone variation of the dependent variable at the change of the 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 (the total height W_t of the surface profile and the total 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, …, n. There is the convention to consider 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 considered that if the value of the 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), it could exist a better correlation between the two series of values subject to comparison.

In this way, the values of r_{xy}=0.108 for the steel C45U, r_{xy}=0.198 for the steel X210Cr12, r_{xy}=0.774 for the steel C80U, and r_{xy}=0.754 for the steel 100Cr6 have been determined. Following the existing conventions, it is considered that there is a low positive correlation for the 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 the 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 supplementary 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.

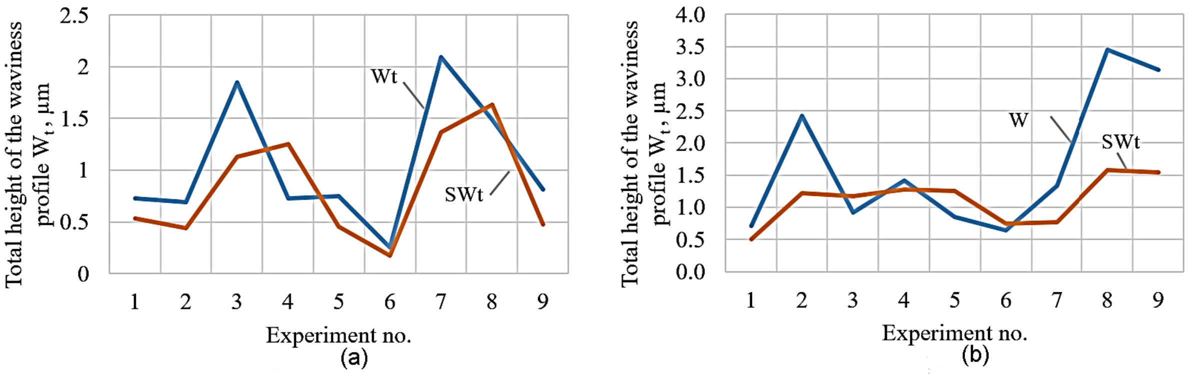

Fig. 7. Correlation between the total height of the waviness profile W_t and the total height of the surface waviness SW_t parameters in the cases of steels C80U (*a*) and 100Cr6 (*b*).

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 materialized 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 a 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 the steel hardness, whose increase increases the total height of profile and surface waviness total height. An increase in the total height of the 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 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.

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