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The Effect of Milling Parameters of Vanadis 4 Extra Steel on Cutting Force Values and Roughness of Machined Surface

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ABSTRACT

The article presents the results of experimental studies of the milling process of Vanadis 4 Extra – tool steel 1.2210 with a four-flute AlCrN-coated end mill. On the basis of the measured values of the total cutting force *F* and the roughness parameters *Ra* and *Rz* of machined surfaces, the relationships between specified cutting parameters and the analyzed roughness parameters were determined. Regression model of cutting force *F* was developed considering statistically significant cutting parameters. The developed model was validated using an additional set of recorded force values. Regression models were also created for the roughness parameters *Ra* and *Rz* of machined surfaces but they were found to be too inaccurate for the prediction of the aforementioned texture parameters. After analysis of the results obtained, it was found that the cutting speed v_c had no effect on the value of the total cutting force *F*, while its influence on the roughness parameters was noticeable. It was also shown that, of the technological parameters a_p, a_e and f_z within the assumed ranges of variation, the depth of cut a_p, has the greatest effect on the cutting force *F*, the width of cut a_e and the feed rate f_z have a smaller effect. It was also shown that in the case of low cutting speeds v_c the parameter *Ra* of the machined surface roughness strongly depends on the depth of cut a_p and width of cut a_e. At the same time it was noticed an increase in the *Rz* parameter with decreasing cutting speed v_c. The remaining technological parameters, however, also significantly affect the obtained values of the *Rz* roughness parameter measured on the machined surface.

Keywords: milling, Vanadis 4 Extra, tool steel 1.2210, cutting force, surface roughness.

INTRODUCTION

Tool steel 1.2210 (115CrV3) with a commercial name Vanadis 4 Extra structural material is a cold-working tool steel produced by powder metallurgy that offers an extremely good combination of wear resistance and toughness for tools for special applications. Manufacturing tools from high-alloy steels exhibit heat and mechanical processing problems compared to low-alloy steels, often leading to higher production costs. As a consequence of its thoroughly balanced alloying composition and powder metallurgy production, tool steel 1.2210 has better machinability compared to competing AISI D2 steel (1.2379 – X153CrMoV12). A very big advantage of tool steel 1.2210 is its high dimensional stability after quenching and tempering, higher than that of other high-alloy cold working tool steels. tool steel 1.2210 is a chromium-molybdenum-vanadium alloy steel characterized by: very good ductility, high adhesive-abrasive wear resistance and high compressive strength. It also features relatively good machinability, according to Uddeholm [1].

Tool steel 1.2210 is principally well suited for applications where adhesive wear or chipping is the main cause of tool (punch or die) defects. Examples of dies are shown in Figure 1.

The material is also suitable for punching and forming sheets of higher strength steel. It meets

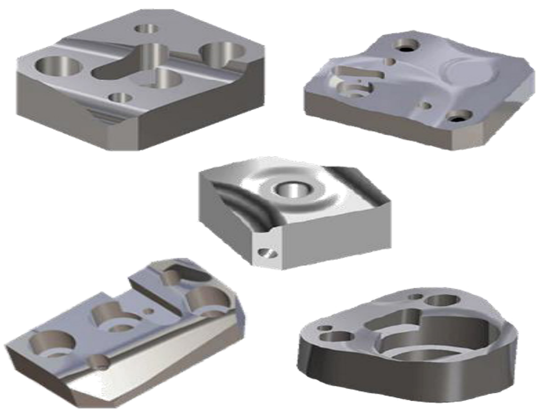

Figure 1. Sample die views

high requirements for tool steel which are closely related to its good abrasive wear resistance and ductility. Tool steel 1.2210 is classified as a hard-to-machine material due to its properties, which Uddeholm describes in [1].

The manufacturer of tool steel 1.2210 declares good machinability of this material, but there is a lack of publications describing machinability tests of this material. From the analysis of the literature, however, it appears that there is a wide range of research relating to topics associated with the study of changes in the properties of the material, especially mechanical properties, as a result of the addition of various types of alloying additives. They are presented and discussed, e.g., in the paper by Chang S.-H. et al. [2]. The studies of corrosion properties and resistance to mechanical wear are described by Üstünyagiz et al. [3] and Yan et al. [4]. Authors of publications also present topics related to the study of structural modifications of the material as described by Arslan et al. [5] and Yan et al. [6]. The study of the behavior of the structure of the material as a result of applying of heat treatment is described by Yan et al. [7], and the analysis of the material treatment process by EDM and WEDM methods applied to workpieces made of tool steel 1.2210 is given by Sudhakara et al. [8].

Chemical and physical properties of tool steel 1.2210 are shown in Table 1 and Table 2. The data presented in both tables refer to the material in the delivery condition corresponding to its hardness of about 230 HB [1].

This material is used in technological processes for the manufacture of innovative punches and dies, which are applied in precision punching, due to its functional properties. It is a material with enhanced mechanical properties which guarantee increased durability of punches and dies. It should be mentioned that the innovativeness of tools made from this material lies primarily in the fact that punches and dies are characterized by their high precision, very low surface roughness and complex shape.

Surface quality is one of the most important indicators of engineering materials. It also plays an important role in determining the quality of manufactured parts. Adequate surface roughness provides a significant improvement in the tribological properties of the material, fatigue resistance and aesthetic appearance of the product as presented by Kivak [9] and Chen et al. [10].

An important issue from the point of view of machining is tool wear. The degree of tool wear significantly affects the quality of the surface obtained after machining. Surface roughness and tool wear are influenced by many parameters, such as: the tool material, micro and macro geometry of the tool, type of anti-wear coating, technological parameters and type of machined material [11]. Ensuring close to the minimum machined surface roughness and tool wear while optimizing these parameters is very important

Table 2. Physical properties [1]

Temperature	20 °C	200 °C	400 °C
Density			
kg/m^3	7700	-	-
Elasticity coefficient			
MPa	20 600	200 000	185 000
Thermal expansion coefficient			
°C from 20	-	10.9×10^{-6}	11.7×10^{-6}
Thermal conductivity			
W/m °C	-	30	30
Specific heat			
J/kg °C	460	-	-

Table 1. Chemical properties and delivery condition [1]

Vanadis 4 Extra	C	Si	Mn	Cr	Mo	V
Chemical composition, %	1.4	0.4	0.4	4.7	3.5	3.7
Delivery condition	app. 230 HB					

for reducing machining costs as mentioned by Chen et al. [10]. Suitable heat treatment and plastic deformation processes concerning the material of workpiece – powder steel which was additionally infiltrated by bronze with MoS2, in order to increase metal mechanical properties, can also noticeably influence the cutting forces and machined surface texture parameters Sa and Sq as presented by Leksycki et al. [12]. Baig et al. [13] showed that in case of micro-milling of Monel 400 super alloy specimen, applying up-milling or down-milling processes, the most important factor influencing surface roughness of machined surface and top burr width is feed rate. On the other hand, as far as tool wear is concerned the leading role play the depth of cut and tool coatings [13].

Numerous studies have shown that cutting edge geometry has a great influence on the surface quality of machined parts [14]. It has also been observed, e.g. by Gara et al. [15], that tool geometry plays a significant role in surface roughness and tool wear. Studies on machining processes show that cutting tools and process parameters are important elements of process planning. Proper selection of cutting tools and technological parameters can seriously reduce energy intensity and machining time as described by Fetecau et al. [16] and Chen et al. [10], among others.

Due to the high dimensional stability after quenching and tempering of produced by powder metallurgy tool steel 1.2210, its very good ductility and high adhesion-abrasion resistance as well as its good machinability, and therefore – high suitability of tool steel 1.2210 for making tools out of it, it is justified to perform research dedicated to this steel. The goal is to better understand the properties of tool steel 1.2210 under different machining conditions and make better use of it in the production of tools, e.g. dies and punches, from that steel.

Literature analysis shows that there is a lack of research on milling, optimization of cutting parameters as well as the influence of cutting parameters on surface roughness and tool wear for tool steel 1.2210 powder steel. Therefore, in this paper, the authors present the results of an experimental study of milling tool steel 1.2210 with the cylindrical part of an end mill and describe the effect of selected milling process parameters on the cutting force *F* and selected surface roughness parameters of machined samples made of tool steel 1.2210.

MATERIALS AND METHODS

The applied experimental plan included 4 input variables: cutting speed v_c, feed per tooth f_z, depth of cut a_p and width of cut a_e. The input variables assumed 3 levels of variation each. The experiment plan was created in statistical software JMP 12.0.1 [17] using the Custom Design function. The initial model involved calculating main effects and all two-factor interaction effects as well as performing 15 trials. The designated plan was the D-optimal plan. The results from those trials were used to develop regression models. To develop the models a backward regression with mean-centering of predictors was used [18, 19].

The developed models were then verified using another 5 trials. Parameter sets for the models' validation trials were obtained using the Augment Design function. The parameters for the training and validation trials are shown in Table 3 and Table 4. The values given in Table 3 and Tab. 4 are sorted in order to better illustrate changes in subsequent parameters, while the actual executed experiment plans involved randomizing the trials.

The output variables were the total cutting force *F* and the surface roughness parameters *Ra* (arithmetic mean height) as well as *Rz* (average maximum height).

The milling tests were performed on a five-axis DMU 100 MonoBlock milling center. A specimen made of tool steel 1.2210 with dimensions of 100 mm × 50 mm × 50 mm was clamped in

Table 3. Sets of milling parameters used in training trials

Trial No.	v_c, m/min	a_p, mm	a_e, mm	f_z, mm/t
1	100	5	2	0.02
2	100	5	4	0.04
3	100	10	2	0.04
4	100	10	4	0.02
5	100	20	2	0.02
6	100	20	4	0.03
7	125	10	3	0.03
8	125	20	3	0.04
9	125	20	4	0.02
10	150	5	2	0.04
11	150	5	4	0.02
12	150	10	2	0.02
13	150	10	4	0.04
14	150	20	2	0.03
15	150	20	3	0.02

Table 4. Milling parameter sets used in validation tests

Trial No.	v_c, m/min	a_p, mm	a_e, mm	f_z, mm/t
1	100	5	2	0.04
2	100	5	4	0.02
3	100	20	2	0.04
4	150	5	2	0.02
5	150	20	4	0.04

a custom-designed holder, bolted to a Kistler 9257b piezoelectric force gauge. With the help of that piezoelectric force gauge the components of the total cutting force *F* generated in the milling processes with specified technological parameters were recorded. The test stand is presented in Fig. 2 and Fig. 3. The measurement system also included an NI USB-6218 DAQ measurement card with the sampling rate set to 20 kHz, a Kistler 5070 multi-channel charge amplifier, and a computer with LabVIEW SignalExpress software for recording the values of the cutting force components and subsequent analysis of the obtained results. Roughness measurements of the machined surface were always made immediately after the machining pass using a Mitutoyo Surftest SJ-210 device.

As a machining tool, end mill with a working part diameter of 12 mm and was selected. A sketch of the tool is shown in Figure 4. It is a 4-blade tool, helix angle 35 degrees, corner chamfer 0,3 x 45 degrees, coated with AlCrN.

The study of obtained experimental results was based on backward regression assuming a significance level of $\alpha = 0.05$. The same α value was used in all statistical tests. The normality of the distribution of the residuals and their heteroscedasticity

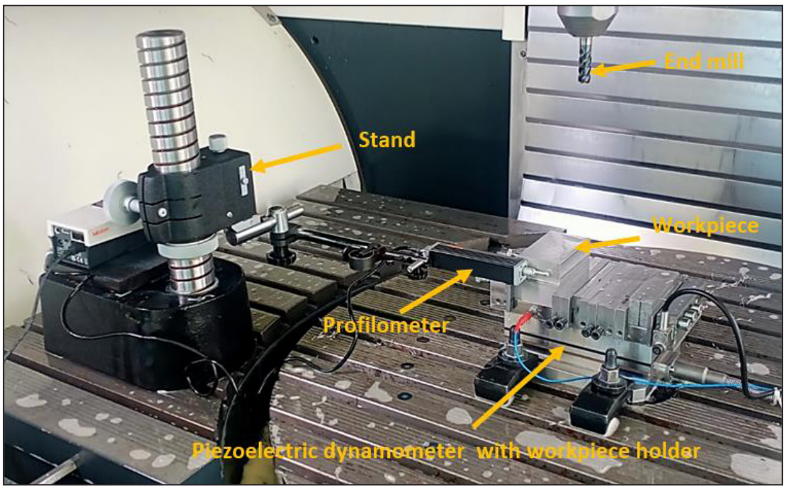

Figure 2. View of the test and measurement stand

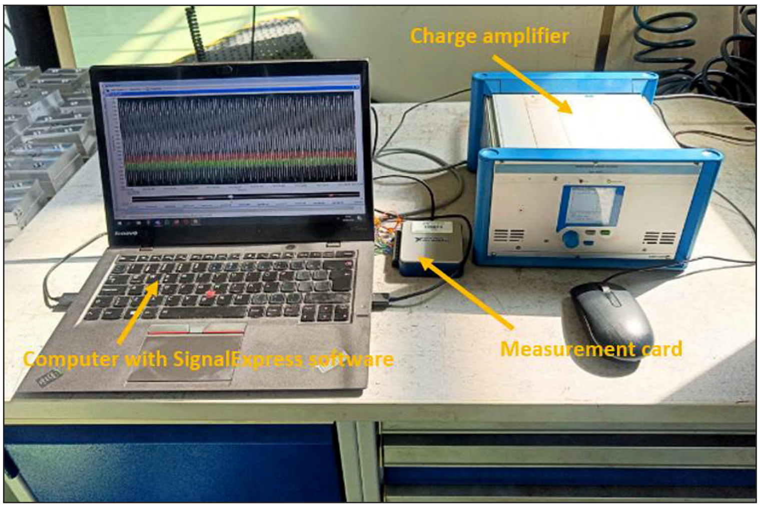

Figure 3. View of the stand for recording the components of the measured total cutting force *F*

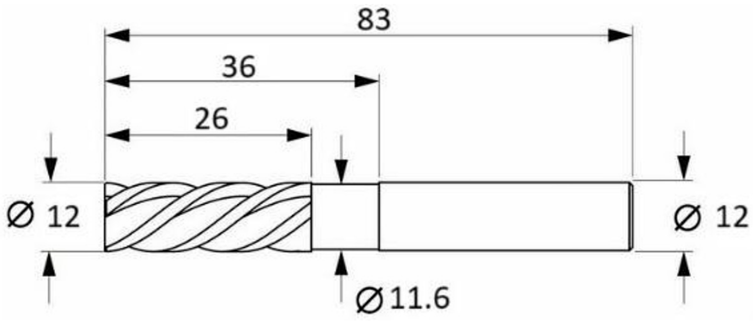

Figure 4. View and main dimensions of the applied end mill

were checked using a residuals by predicted values plot. The normality of the distribution of the residuals was additionally checked with the Shapiro-Wilk test [20]. To validate the model, the mean absolute percentage error (*MAPE*) index was used, expressed by the formula:

$$MAPE = \frac{100\%}{n}\sum_{i=1}^{n}\left|\frac{y_i-\hat{y}_i}{y_i}\right| \quad (1)$$

where: y_i – actual values observed in validation trials, $\hat{y}_i$ – values predicted from the regression equation, n – the number of observations.

RESULTS

The influence of milling parameters on cutting forces

In the study, the only factors that did not affect the total cutting force F were the cutting speed and its interaction with the other milling parameters. The regression model developed, was a very good fit to the empirical data (coefficient of determination $R^2 > 0.99$) and was statistically significant ($p < 0.0001$). The coefficients of the model for the raw data and for the standardized data are shown in Table 5. The interaction representation shown in the graphs (with subtraction of mean values) is the result of centering the predictors. In the given form, the given coefficient means the "average" effect of a variable assuming other variables are held constant at their mean. Figure 5 graphically shows the impact of cutting parameters on cutting force. The blue dashed lines indicate the limits of the 95% confidence interval. The red vertical lines indicate the values of the predictors for which the output variable takes the value indicated by the horizontal red line. For a given input variable (parameter a_p, a_e or f_z), there is visible the prediction line determined at the values of the other parameters indicated by the vertical red lines. For example: the visible prediction line for f_z was determined at the values of the a_p = 12.5 mm i a_e = 3 mm. Figure 6 shows in graphical form the result of interaction effects. In each cell formed at the intersection of two milling parameters, the effect of their interaction is visible. The values of one of the parameters can be read from the scale. The other parameter takes only the extreme values. The red line indicates the prediction line for the smallest value of the second parameter under consideration. The blue line, on the other hand, denotes the prediction line for the largest value of the second parameter.

Table 5. Regression model coefficients for cutting force of machined surface roughness for raw data (estimate) and for standardized data (Std Beta)

Term	Estimate	Std Beta	Prob > |t|
Intercept	-735.2	0	<.0001
a_p	46.3	0.898	<.0001
a_e	158.4	0.436	<.0001
f_z	11101.8	0.302	<.0001
$(a_p-12.67)*(a_e-3)$	12.1	0.210	0.0002
$(a_p-12.67)*(f_z-0.029)$	745.4	0.125	0.0049
$(a_e-3)*(f_z-0.029)$	3262.4	0.081	0.0387

The greatest influence on the cutting force F was the depth of cut a_p, followed by a_e, and f_z. Increasing the values of these parameters resulted in an increase in the cutting force F. The authors of the paper Tang et al. [21] came to similar conclusions in their study. The obtained correlation is reasonable, since more cutting force is needed to remove a larger volume of material. In the interaction diagram (Figure 6) it can be seen that the studied interactions have a greater effect on F at higher than at moderate values of cutting parameters. This means that at a large value of any of the cutting parameters analyzed in the described

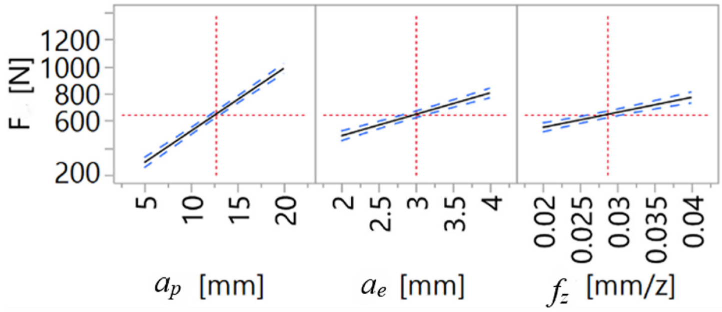

Figure 5. The influence of cutting parameters a_p, a_e, and f_z on the total cutting force F; the unit mm/z, associated with feed per tooth f_z, represents mm per tooth, i.e. mm/t

studies, i.e. a_e, a_p and f_z, changing values of the other parameters will affect the total cutting force F to a greater extent than at small values of the analyzed cutting parameters.

The mean absolute percentage error (*MAPE*) calculated according to the Eq. (1) from the model validation results was 7.15%. A *MAPE* value of less than 10% indicates that the developed model is very well capable of predicting values in the studied state space as shown in the book by Lewis [22].

The influence of milling parameters on surface roughness parameter *Ra*

In the conducted tests, the feed rate and its interactions had no effect on the *Ra* parameter of machined surface roughness. For the developed regression model, the coefficient of determination was $R^2 = 0.64$ and was statistically significant ($p < 0.0001$). The coefficients of the model for the raw data and for the standardized data are shown in Table 6. Figure 7 graphically presents the influence of cutting parameters on the roughness parameter *Ra*. Figure 8 graphically shows the influence of the interaction effect.

According to the developed model, as the depth of cut a_p and the width of cut a_e increase, the roughness expressed by the *Ra* parameter increases. Growing v_c causes a reduction in *Ra*. At large values of v_c or a_p, the effect of the latter parameter, i.e. the depth of cut a_p, on *Ra* becomes very small. Similar observations were presented

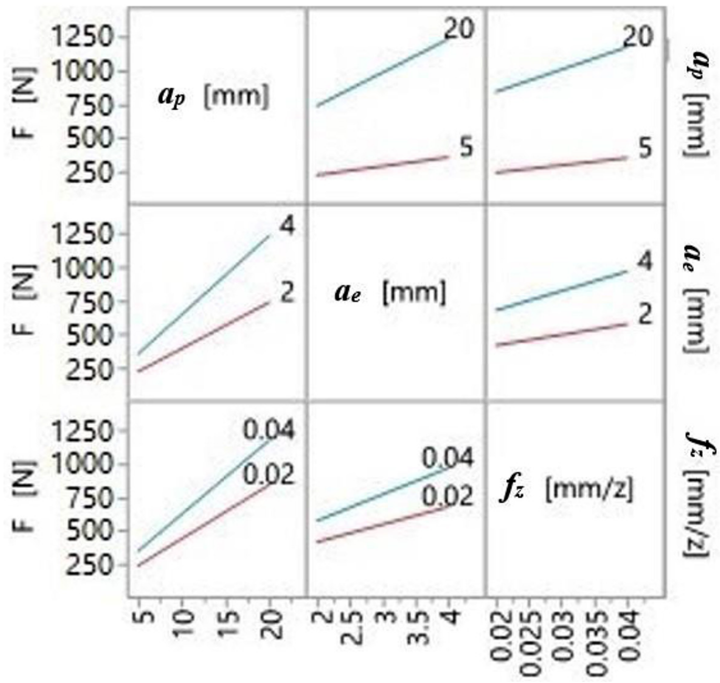

Figure 6. The influence of interaction effect of cutting parameters a_p, a_e, and f_z on the total cutting force F

Table 6. Regression model coefficients for *Ra* parameter of machined surface roughness for raw data (estimate) and for standardized data (Std Beta)

Term	Estimate	Std Beta	Prob > |t|
Intercept	0.3651	0	0.0022
v_c	-0.0032	-0.450	<.0001
a_p	0.0116	0.453	<.0001
a_e	0.0599	0.332	0.0013
$(v_c$ -150)*(a_p-12.67)	-0.0004	-0.347	0.0009

Due to the relatively low value of the coefficient of determination R^2, the developed model was not considered good enough for predicting *Ra* values. For this reason, the *MAPE* parameter (Eq. 1) was not calculated.

Both *Ra* and *Rz* parameters of the machined surface roughness decrease with growing cutting speed v_c (Fig. 7 and Fig. 9). This can be related to both the kinematics of the milling process with a multi-blade tool and different vibrations generated in studies described in paper by Wang et al. [23]. The authors noted that an increase in cutting force caused an increase in surface roughness parameters. It should be taken into account that the depth cut a_p and width of cut a_p influence the value of the cutting force *F* to the greatest extent.

Due to the relatively small value of the coefficient of determination R^2, the developed model was not considered good enough for predicting *Ra* values. For this reason, the *MAPE* parameter was not calculated.

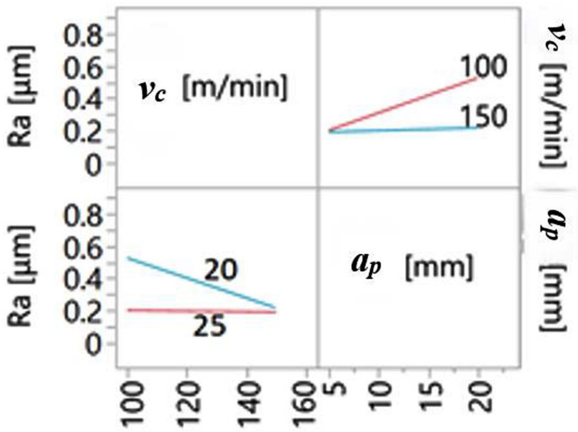

Figure 8. The influence of interaction effect of cutting parameters v_c and a_p on the *Ra* parameter of machined surface roughness

The influence of milling parameters on surface roughness parameter *Rz*

In the conducted study, all cutting parameters influenced the *Rz* parameter of machined surface roughness. For the developed regression model, the computed coefficient of determination was $R^2 = 0.62$ and was statistically significant ($p < 0.0001$).

The coefficients of the model for the raw data and for the standardized data are shown in Table 7. Figure 9 graphically shows the influence of cutting parameters on the R_z roughness parameter. Figure 10 graphically presents the result of the interaction effect. According to the developed model, if a_s, a_p, a_e and f_z increase the roughness of machined surface expressed by the *Rz* parameter increases as well. Similar relationships were presented by the authors of the paper [24].

Table 7. Regression model coefficients for *Rz* parameter of machined surface roughness for raw data (estimate) and for standardized data (Std Beta)

Term	Estimate	Std Beta	Prob > |t|
Intercept	0.6604	0	0.3394
v_c	-0.0142	-0.375	0.0006
a_p	0.0693	0.515	<.0001
a_e	0.3117	0.329	0.0021
f_z	31.8843	0.333	0.0020
$(v_c$ -150)*(a_p-12.67)	-0.0013	-0.205	0.0497

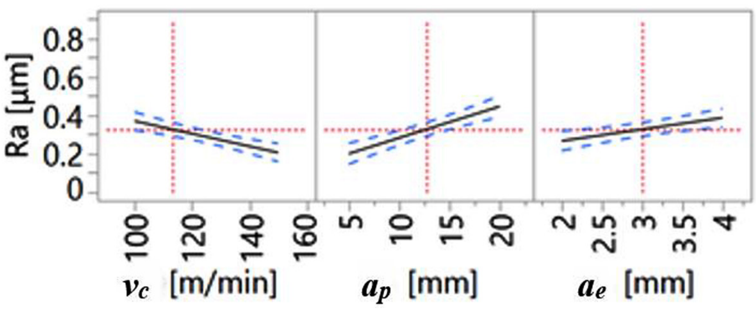

Figure 7. The influence of cutting parameters v_c, a_p and f_z on the *Ra* parameter of machined surface roughness

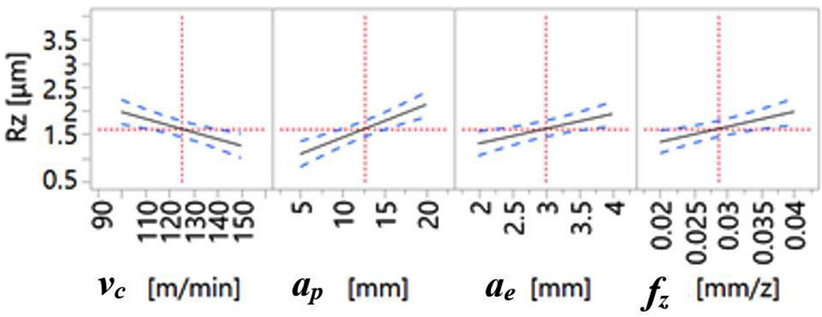

Figure 9. The influence of cutting parameters on the *Rz* parameter of machined surface roughness

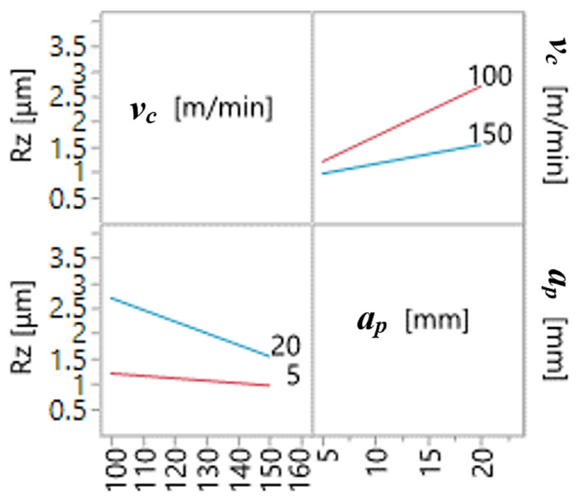

Figure 10. The influence of interaction effect of cutting parameters v_c and a_p on the *Rz* parameter of machined surface roughness

in the body system of the tool and specimen at different cutting speeds. The energy released in the milling process, which depends on the cutting parameters, also influences the heat released and the contact conditions between the cutting edge and the workpiece. These factors, acting simultaneously, affect the surface formed with particular tool and its roughness. These are issues for further experimental and theoretical research.

CONCLUSIONS

Summarizing the obtained experimental results and the developed models, the successive conclusions can be reached:

1. The change in cutting speed v_c and its interaction with the other cutting parameters in the range tested does not have a statistically significant influence on the change in the value of the total cutting force *F*. The greatest effect on the increase in cutting force *F* was shown by the depth of cut a_p, to a lesser extent by the width of cut a_e and to the least extent by the feed rate f_z.
2. The greatest effect on the increase in total cutting force *F* was shown by the depth of cut a_p, to a lesser extent by the width of cut a_e and to the least extent by the feed rate f_z. This conclusion follows the results of performed experiments and requires considering the ranges of variation of technological parameters applied. In particular, the depth of cut a_p varied in range <5 mm, 20 mm>, the width of cut a_e was in range <2 mm, 4 mm> and the feed rate f_z was in range <0.02 mm/t, 0.04 mm/t>. The results of experiments combined with their statistical analysis indicated that for the parameters evolving within those ranges the greatest effect on the increase in cutting force *F* was shown by the depth of cut a_p. The impact of both the width of cut a_e and the feed rate f_z on the cutting force *F* was clearly noticeable but less significant than the depth of cut a_p.
3. According to the developed model and the analysis of obtained results, it can be deduced that the value of the feed rate f_z does not significantly affect the value of the parameter *Ra* of the machined surface roughness, while it strongly depends on the depth of cut a_p and width of cut a_e in the case of low cutting speeds v_c. The influence of the described parameters f_z, a_p and a_e decreases as the cutting speed v_c increases.
4. Analyzing the *Rz* parameter of the machined surface roughness, an increase in the *Rz* parameter was perceived with decreasing cutting speed v_c. The remaining technological parameters also significantly affect the obtained values of the *Rz* roughness parameter measured on the machined surface. Analyzing the *Rz* parameter of the machined surface roughness, an increase in the *Rz* parameter was perceived

with decreasing cutting speed v_c. Similar relationship is also observed between the *Ra* parameter and the cutting speed v_c. It might be caused by different vibrations generated in the body system of the tool and specimen at different cutting speeds. However, such result requires further theoretical and experimental studies with the consideration that the remaining technological parameters also significantly affect the obtained values of the *Rz* roughness parameter measured on the machined surface.

5. Considering small number of available studies on the milling of produced by powder metallurgy tool steel 1.2210 as well as the range and results of investigations presented in the paper it is reasonable to conduct further research towards a greater understanding of the phenomena occurring during the cutting process of this steel, as well as to extend the scope of research to include issues concerning: tool wear, the shape accuracy and dimensional accuracy of the workpiece, and the condition of the surface layer after milling.

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