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Investigation and Modelling of Surface Roughness During Milling of GJL-250 Gray Cast Iron and S235JR Steel Using Mixed Ceramic Tools

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***Abstract*— Milling is one of the most common methods for processing flat surfaces, providing satisfactory accuracy and low surface roughness at high production rates. This paper presents the results of a study on the surface roughness of machined parts made of GJL-250 gray cast iron and S235JR carbon structural steel, obtained by milling with a single-tooth milling cutter with Al_2O_3/TiC mixed ceramic replaceable insert. Using the methods of the planned experiment and the multifactorial regression analysis, the combined influence of the cutting speed and the feed per tooth on the surface roughness has been evaluated, and corresponding adequate theoretical-experimental models have been constructed. Combinations of cutting speed and feed per tooth have been determined that result in minimum surface roughness on the machined surfaces for the two materials studied.**

Keywords —carbon structural steel, gray cast iron, milling, mixed ceramic tools, regression models, roughness

I. Introduction

Planing, slotting, grinding, broaching and milling are the main methods of processing flat surfaces in mechanical engineering. Milling is one of the most common among them, as it provides a combination of high productivity and satisfactory accuracy at low roughness. When milling, 7 ÷ 6 degrees of accuracy and roughness of up to R_a = 0.4 µm of the machined surfaces are achieved [1], [2].

The process of milling uses tools, made of high-speed tool steel, cermets and cutting mineral ceramics. The application of milling cutters with replaceable mineral ceramic inserts aims at processing difficult-to-machine materials (5 –15%), hardened steels (20 – 29%) and cast irons (65 – 70%) under dry cutting conditions, achieving cutting speeds of up to 1200 m/min, minute feed rates of up to 5000 mm/min and roughness of up to 0.63 µm [3]. These tools have a number of advantages compared to the ones, made of high-speed tool steels and cermets, due to their high hardness, wear and temperature resistance, as well as to the good chemical resistance of the mineral ceramic materials and the low coefficient of friction during cutting [4] – [7]. As a result, the mineral-ceramic tools are considered to be among the most suitable for CNC machine tools and various automatic machines [8] – [14]. However, their application is limited by their high brittleness and sensitivity to temperature changes, and their low transverse strength [15].

The application of cutting ceramics with an emphasis on the turning process has been studied by a number of authors. The productivity and wear mechanisms of ceramic tools in machining various materials under different operating conditions (cutting mode, lubricants and coolants, type of wear-resistant coatings) have been established [16].

Kumar et al. [17] studies two types of ceramic cutting tools – mixed ceramic and zirconium nitride-enhanced ones - and evaluates the machinability of hardened steel using the criteria of tool wear, surface roughness, and cutting forces. Hong [18] has proven that oxide and mixed ceramic tools are suitable for machining hardened steel due to their high wear resistance. Bhattacharyya et al. [19], in turn, finds that mixed ceramic tools provide higher

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productivity than those, made of oxide and nitride ceramics in machining cast iron. A study, conducted by Charles [20], when machining automotive hubs, made of ductile cast iron, shows that the use of tools, made of composite ceramic materials, leads to an increase in tool life of up to 2.5 times, as well as to a higher cutting speed, compared to machining with cermet tools with wear-resistant coatings.

Shnfir et al. [21] investigate the machinability of hardened steel AISI 1045 during face milling using SiAlON and whisker (SiCW) based ceramic inserts. The influence of the cutting conditions, of the hardness of the machined material and of tool geometry on the resultant cutting force, energy consumption and wear on the rear surface, has been established. The authors have proven that feed rate is the most influential factor, and the decrease in the feed rate leads to significantly lower resultant cutting forces (by approximately 74%). This creates conditions for a significant reduction in cutting power.

While studying the influence of the radius of curvature of the cutting tool edge in milling hardened AISI H13 steel (50 HRC), Li et al. [22] find that with increasing the radius, the cutting forces, plastic deformation and residual compressive stress also increase, while surface roughness decreases to a certain limit value.

When milling, it is a difficult task to perform interrupted cutting with ceramic tools both due to the impact load, undergone by the inserts during machining, and because of the tool brittleness. In addition, the recommended in the literature working conditions for milling with mineral ceramic tools concern particular tools and specific machined materials.

In this regard, the present paper describes a study of the roughness of the machined surfaces of gray cast iron and structural steel parts during face milling with a mixed mineral ceramic tool and recommends appropriate values of cutting speed and tooth feed for the two studied materials.

II. Materials and Methods

The experimental studies were conducted on a universal milling machine TOS FD 40, without the use of a lubricant and coolant (Fig. 1).

A single-tooth milling cutter (Fig. 2), operating on the principle of "extensive final cleanup" was used to conduct the experiment. The milling cutter has a diameter D = 200 mm and geometric parameters as follows: tool back race angle γ_p=-6°; tool back clearance angle α_p=6°; tool major cutting edge angle κ_r=90°; tool minor cutting edge angle κ_r'=0°.

The studied mineral ceramic insert is made of mixed ceramics (60% Al_2O_3 + 40% TiC) with a hardness of HV 28000 N/mm^2 (HIP). The insert is set so that the auxiliary cutting edge is parallel to the surface under machining (Fig. 2).

Fig.1 Experimental setup. 1-workpiece, 2- tool, 3-machine TOS FD 40

The roughness of the machined surfaces was studied when milling parts, made of gray cast iron GJL-250 and carbon structural steel S235JR with chemical composition and physical-mechanical properties, presented in Table 1 [23]. The dimensions of the machined parts were:

- length 75 mm, width 65 mm and height 20 mm – for steel S235JR;
- length 50 mm, width 35 mm and height 30 mm – for gray cast iron GJL-250.

The workpieces of both materials were pre-machined with a ten-tooth end milling cutter (z=10), under the following cutting mode: rotational frequency 630 min^{-1}; cutting depth 0.5 mm; minute feed rate 80 mm/min.

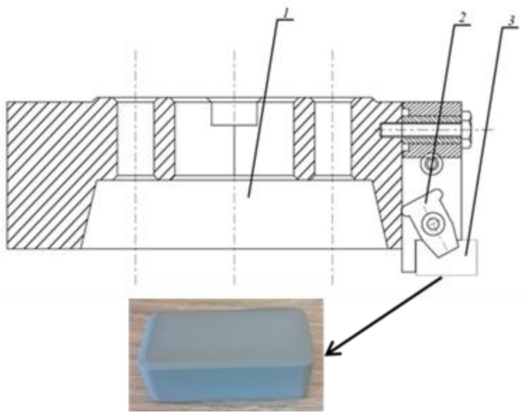


Fig. 2 Single-edged milling cutter. 1-body, 2-clamp, 3 mineral-ceramic insert

TABLE I. CHEMICAL COMPOSITION AND PHYSICAL- MECHANICAL PROPERTIES OF THE STUDIED MATERIALS

Machined Material	**Hardness HV**	**Tensile strength Rm, N/mm²**	**Yield strength $Rp_{0,2}$, N/mm²**	**Relative elongation A, %**	**Chemical composition, %**
GJL-250 (EN 1561: 1997)	245	250-350	450	0.6	C-3.15, P-0.22, Mn-0.6, S-0.1, Si-2.1, Fe
S235JR (EN 10250-2:2000)	130	390-490	235	26	C-0.17, P-0.035, Mn-1.4, S-0.035, N-0.12, Cu-0.55

The experimental studies, aimed at determining the roughness, were carried out under the following cutting mode: cutting speed Vc=400÷700 m/min; tooth feed fz = 0.89÷1.79 mm/z; depth of cut ap =0.05mm = const. The mode is determined depending on the types of materials under machining and the recommended values by various manufacturers [24], [25], and it is consistent with the rotation frequencies and minute feeds of the TOS FD 40 milling machine.

The roughness of the machined surfaces was evaluated according to the criterion Ra (μm) - arithmetical mean deviation of the roughness profile. It was measured with a digital roughness meter "Mitutoyo SJ201 P/M" (Fig. 3) [26].

Fig.3 General view of the roughness meter Mitutoyo SJ201 P/M

III. RESULTS AND DISCUSSION

A planned multifactorial experiment of the type, given below, was conducted according to an optimal central compositional plan to study and model the influence of the individual elements of the cutting mode on the surface roughness Ra, obtained when machining gray cast iron GJL-250 and carbon structural steel S235JR:

$$N=2^2+2.2+1 \quad (1)$$

The general form of the model is:

$$Y_i=b_0+b_1X_1+b_2X_2+b_{11}X_{12}+b_{22}X_{22}+b_{12}X_1X_2 \quad (2)$$

where: $Y_1=Ra_1$ is the roughness of the machined surfaces of gray cast iron GJL-250; $Y_2= Ra_2$ – roughness of the machined surfaces of structural steel S235JR; b_0, b_1, b_2, b_{11}, b_{22} and b_{12} – regression coefficients; $X_1= V_c$ (m/min); $X_2= f_z$ (mm/z) – controlling factors, the variation levels of which can be seen in Table 2.

The experimental design with the experimentally measured roughness values for the two machined materials are presented in Table 3.

The experimental results were processed in accordance with the methodology, presented in [27], in the following sequence: determination of the model coefficients; checking for significance of the regression coefficients using the Student's t-test; determination of the multiple correlation coefficient; checking for significance of the multiple coefficient, using the Fisher's test.

TABLE II. LEVELS OF CHANGE IN THE CONTROLLING FACTORS

Controlling factors		**Factor levels**		
Coded	***Natural***	***-1***	***0***	***+1***
X_1	V_c, m/min	446	575	703
X_2	f_z, mm/z	0.89	1.34	1.79

TABLE III. PLAN MATRIX AND EXPERIMENTAL DESIGN PLAN WITH EXPERIMENTAL DATA AND THEORETICAL VALUES

№	**X_1**	**X_2**	**Vc, m/min**	**fz, mm/z**	**GJL-250**		**S235JR**	
					R_{e1}	$\widehat{R_{e1}}$	R_{e2}	$\widehat{R_{e2}}$
1	-1	-1	446	0.89	0.3405	0.3418	0.1316	0.1375
2	+1	-1	703	0.89	0.4302	0.4305	0.1387	0.1401
3	-1	+1	446	1.79	0.4699	0.4697	0.1341	0.1310
4	+1	+1	703	1.79	0.4385	0.4372	0.4150	0.4073
5	0	-1	575	0.89	0.3901	0.3885	0.1359	0.1286
6	0	+1	575	1.79	0.4540	0.4556	0.2486	0.2594
7	-1	0	446	1.34	0.4112	0.4101	0.1330	0.1302
8	+1	0	703	1.34	0.4372	0.4382	0.2635	0.2697
9	0	0	575	1.34	0.4264	0.4264	0.1935	0.1900

The results of the research were processed using the QstatLab software [28] and regression models were obtained, presented in Table 4.

The roughness values, determined by the models for milling steel and cast iron, are presented in Table 3.

The created models describe with sufficient accuracy the relationship between the roughness R_a and the cutting mode elements V_c and f_z, which is proven by checking the significance of the multiple correlation coefficient R^2. The presented models are adequate, since the condition $F_R > F_{\alpha,\nu1,\nu2}$ is fulfilled with a 95% confidence probability. The empirical F_R and the tabular values $F_{\alpha,\nu1,\nu2} = F_{0,05,5,3}$ of the Fisher test criterion (α = 0.05 – significance level; ν_1 = n-1 and ν_2 = N-n – degrees of freedom) for each of the regression models are presented in Table 4.

To assess the ability of the constructed regression models to predict responses to new, unperformed observations, the predicted values of R^2_{pred} were determined for each of the models (Table 4). The high values of R^2_{pred} (0.989 and 0.947) show a good ability of the obtained models to predict new, untested quantities.

TABLE IV. REGRESSION MODELS AND STATISTICAL ANALYSIS

Regression models	F_R	$F^{0.050}_{\alpha,5,3}$	$\hat{R}^2_{adj}$	R^2_{pred}
Ra₁=-0,22259825+0,00096375 Vc +0,43380305 fz-1,3E-7 Vc2 - 0,0217284 fz2-0,00052362 Vc fz	653.49	9.013	0.998	0.989
Ra₂=0,83520863-0,00175659Vc-0,58780043fz+6,2E-7Vc2+0,01967078fz2+0,0011834 4Vcfz	131.86	9.013	0.988	0.947

Graphical interpretation of the constructed models for roughness change depending on the cutting speed V_c and the feed f_z is shown in Fig. 4.

To determine the influence of the controlling factors on the roughness, an analysis of variance (ANOVA) was performed. The influence is graphically interpreted in Fig. 5.

The analysis of the constructed models (Table 4 and Fig. 4) and of the results of the conducted variance analysis (Fig. 5) show that:

- The roughness R_a of the machined surfaces when milling S235JR steel is less than that when machining gray cast iron GJL-25. The influence of the cutting speed V_c and feed f_z on R_a is different for the two machined materials and is more pronounced when milling S235JR steel.

- When milling gray cast iron GJL-250, the roughness of the machined surfaces R_a depends on the feed f_z to a greater extent than on the cutting speed V_c. With increasing the feed in the studied range, the roughness R_a increases from 1.9% to 27.5%, with the influence being more pronounced at lower cutting speeds. The roughness R_a changes depending on the cutting speed V_c in the range from 6.7% to 21%, and the change is greater at lower feed (f_z =0.89 mm/z).

- When machining structural steel S235JR, the influence of the feed f_z and of the cutting speed V_c is commensurate. When the speed increases in the studied range (from 446 to 703 m/min), the roughness increases from 1.8% to 67%. An increase in the feed from 0.89 to 1.79 mm/z leads to an increase in roughness (R_a) from 5.1% to 68%, respectively.

Appropriate combinations of the cutting speed Vc and tooth feed fz were determined, at which minimum roughness Ra was obtained for the two studied materials (Table 5). The QstatLab software product was used, and the random search method with increasing density was applied. A visualization of the process is presented in Fig. 6a – for gray cast iron GJL-250 and in Fig. 6b – for structural steel S235JR.

Confirmatory experiments were conducted, and the difference between the theoretical ($\widehat{R_a}$)ˆ and the experimental roughness value R_a was within 0.58% for gray cast iron GJL-250 and 4.8% for structural steel S235JR (Table 5).

TABLE V. OPTIMAL VALUES FOR MACHINING GRAY CAST IRON GJL-250 AND STEEL S235JR

Machined material	Controlling factor		$\widehat{R_a}$, µm	R_a, µm
	V_c, m/min	f_z, mm/z		
GJL-250	446	0.89	0.342	0.340
S235JR	575	0.89	0.128	0.136

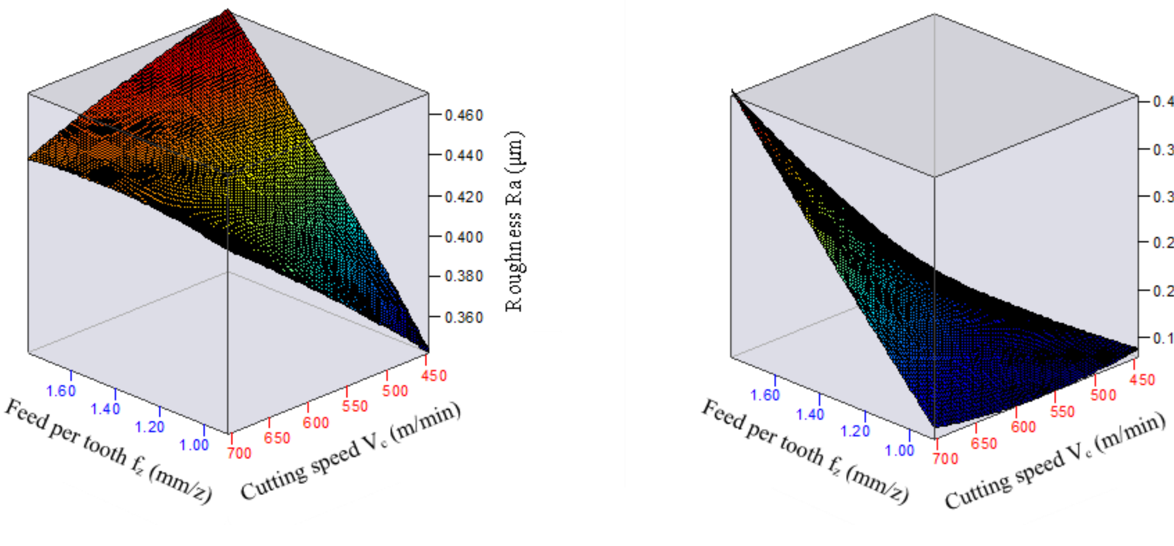
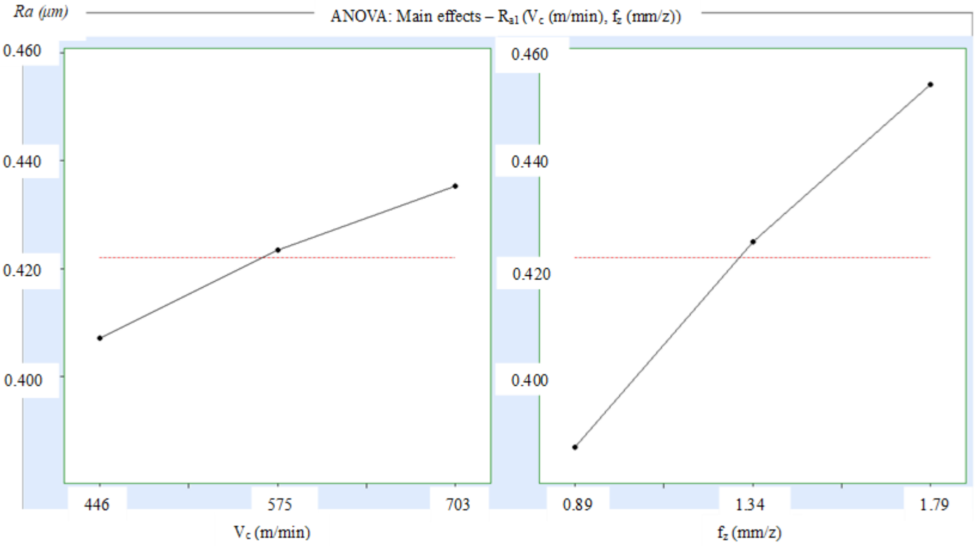
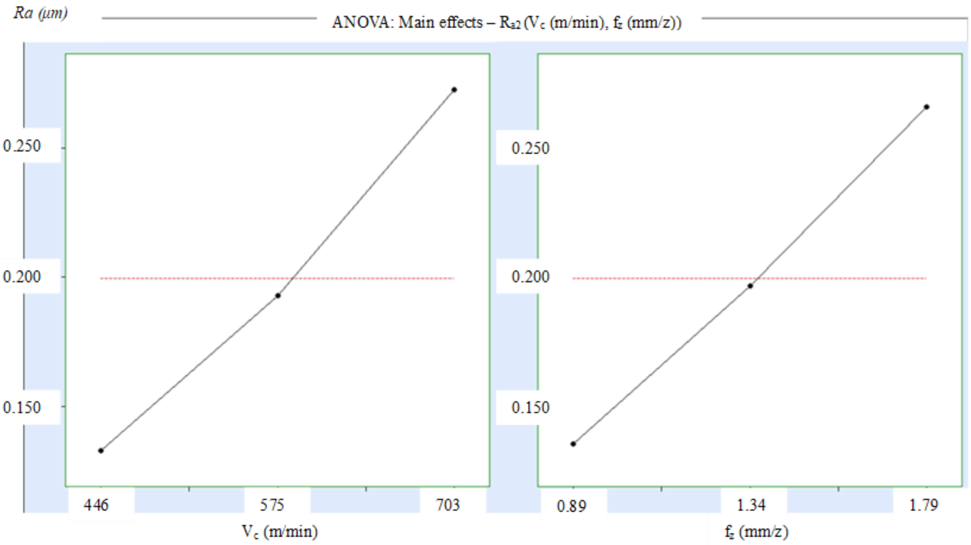


Fig. 4. Influence of the cutting speed V_C and feed f_z on the roughness R_a when machining: a) gray cast iron GJL-250; b) carbon structural steel S235JR



a)



b)

Fig. 5. Visualization of the effects of the cutting speed V_C and feed f_z when machining: a) gray cast iron GJL-250; b) carbon structural steel S235JR

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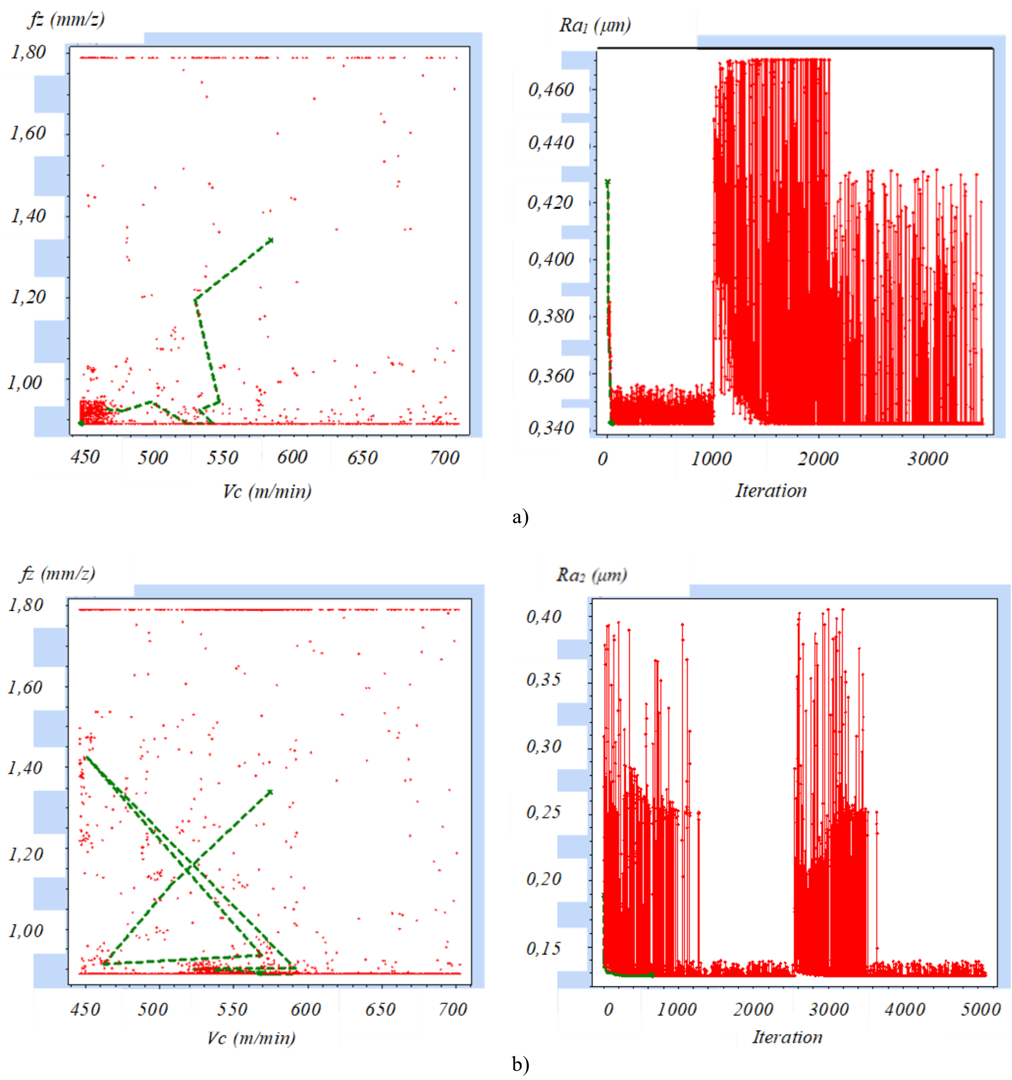

Fig. 6. Determination of optimal cutting conditions for obtaining minimum roughness when machining: a) gray cast iron GJL-250; b) structural steel S235JR

IV. Conclusions

The paper presents the results of a study of the roughness of the machined surfaces of gray cast iron GJL-250 and carbon structural steel S235JR parts, obtained during face milling on a single-tooth end milling cutter with a replaceable insert, made of mixed ceramics - Al_2O_3/TiC.

The complex influence of the cutting speed V_c and tooth feed f_z on the roughness R_a of the machined surface has been evaluated, and the corresponding adequate regression models have been constructed.

The created models make it possible to predict with sufficient accuracy the roughness of the machined surfaces of parts made of the two studied materials, which is proven by the prognostic value R^2_{pred} (0.989 and 0.947).

For both studied materials it has been found that the tooth feed has a greater influence on the roughness of the machined surfaces, with the increase in f_z leading to an increase in R_a of up to 67% when machining S235JR steel, and up to 27.5% when machining GJL-250 gray cast iron.

Combinations of cutting speed V_c and tooth feed f_z have been determined, at which the roughness of the surfaces, machined according to the R_a criterion is minimal for the studied materials (Table 5).

The conducted studies confirm the working capacity of the single-tooth milling cutter with a replaceable mineral ceramic cutting insert by the roughness criterion of the machined surface R_a when processing S235JR steel and GJL-250 gray cast iron.

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