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Machinability of Short Rotary Parts Made of Improveable Steels with Robotic Feeding

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***Abstract*— Heat-treated steels (hardened with subsequent high-temperature tempering) are widely used in the manufacture of critical parts subjected to elastic and impact loads. The publication examines their machinability when machining on CNC lathes with robotic feed. The average roughness of the machined surfaces – Ra – was used as a criterion for their machinability. Based on the experimental results, regression models were developed and optimization of the technological process was performed.**

***Keywords*— CNC turning; empirical models; genetic algorithm.**

I. INTRODUCTION

The development of industrial production in the 21st century is marked by the rapid introduction of new technologies [1] – [5], which fundamentally change the way of organization, management and efficiency of production processes. One of the main drivers of this transformation are the machines with numerical program control (CNC – Computer Numerical Control), which allow achieving high accuracy, repeatability and flexibility in the processing of parts [6] – [9].

Despite their advantages, CNC machines have one serious drawback – their high productivity is often not used effectively due to the need for manual operation. Loading and unloading of parts, changing pallets and handling of blanks are usually performed by operators, which leads to unpredictable downtime and limits production capacity. According to a number of studies, auxiliary operations account for 25÷40% of the total production cycle time [10]. This means that even the most modern CNC machine cannot reach its full potential without an integrated automated feeding system.

Here, the role of industrial robotics comes to the fore. Robots for servicing CNC machines provide reliable, fast and safe manipulation of blanks and finished parts, eliminating or significantly reducing downtime. The implementation of such systems creates conditions for "lights-out manufacturing" – production without operators, which is especially relevant in conditions of shortage of qualified labor [11] – [16].

All this clearly shows the relevance of the issue of optimizing technological processes in machining parts on CNC machines using robotic feeding. The topic is strategic for the development of the Bulgarian industry in the context of its integration into the European production network and the achievement of the goals of Industry 4.0 and Industry 5.0 [17] –[24].

II. MATERIALS AND METODS

The machined parts - Fig. 1, are made of 42CrMo4 steel. This is a medium-alloyed, hardenable structural steel for the production of machine elements.

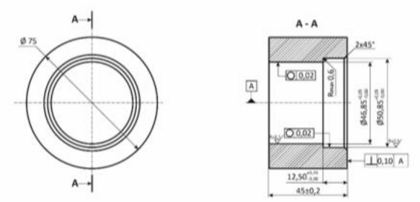

Fig.1. Machined parts.

After heat treatment (oil quenching and high-temperature tempering) – Fig. 2, the hardness of the parts is HRC 35, and the yield strength $R0.2 \geq 850$ MPa. The chemical composition of the steel according to DIN EN ISO 683-2 is presented in Table 1 [25].

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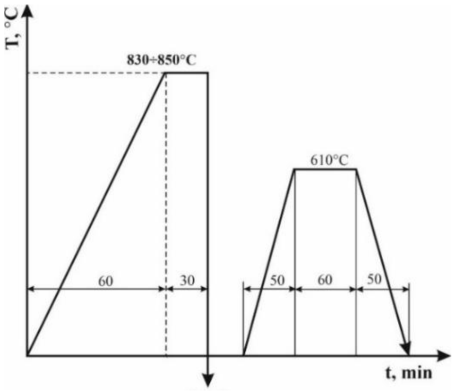


Fig.2. Time-temperature curve of the thermal treatment of the parts.

TABLE 1 CHEMICAL COMPOSITION OF THE STEEL

C	Si	Mn	Ni	Cr	Mo	P	Cu
0.405	0.239	0.652	0.110	0.894	0.180	0.012	0.227

The experiments were conducted in industrial conditions on a HARRIS C320KTT CNC lathe – Fig. 3, with an RV-8CRL robotic feeding station – Fig. 4.

Fig. 3. General view of the HARRIS C 320KTT CNC lathe.

Fig.4. Robotic station RV-8CRL.

The roughness of the machined surfaces was measured on the inner diameters of the parts Ø50.85 and Ø46.85 with a TESA Rugosurf 20 profilometer using the criterion "arithmetic mean deviation from the profile centerline" - Ra.

III. RESULTS AND DISCUSSION

In order to analyze the machinability of the details in the robotic feeding, mathematical models were compiled and a statistical analysis was conducted – AnoVA (Analysis of Variance). In it, the cutting speed (Vc, m/min) – X_1, and the feed (f, mm/rev) – X_2, were selected as input variables (controlled factors). The average roughness (Ra, µm) of the machined internal surfaces – Y_1 (Ø50.85) and Y_2 (Ø 46.85) were studied as objective functions.

The compilation of the mathematical models is based on the obtained experimental results at cutting speed - Vc 140÷180 mm/min and feed - f 0.045÷0.065 mm/tur.

Table 2 presents the levels of variation of the controlling factors, and Table 3 presents the average values of the studied parameters used to compile the mathematical model.

Based on the values in Table 3, the experimental plan was completed – Table 4.

TABLE 2 LEVEL OF VARIATION

Areas of variation	X_1, (V_c, m/min)	X_2, (f, mm/tur)	Coded values
$X_{i0} + \Delta X_i$	180	0,65	+1
X_{i0}	160	0,55	0
$X_{i0} - \Delta X_i$	140	0,45	-1

TABLE 3 AVERAGE EXPERIMENTAL RESULTS

X_1, (V_c, m/min)	изследвани параметри	X_2, (f, mm/tur)		
		0,45	0,55	0,65
140	Y_1, (Ra, µm)	0,248	0,346	0,445
	Y_2, (Ra, µm)	0,268	0,359	0,470
160	Y_1, (Ra, µm)	0,186	0,244	0,311
	Y_2, (Ra, µm)	0,248	0,291	0,347
180	Y_1, (Ra, µm)	0,158	0,188	0,240
	Y_2, (Ra, µm)	0,208	0,602	0,309

TABLE 4 EXPERIMENTAL PLAN

№	X_0	X_1	X_2	$X_1 X_2$	X_1^2	X_2^2	Y_1 (Ra, µm)	Y_2 (Ra, µm)
1	+1	+1	+1	+1	+1	+1	0,240	0,309
2	+1	-1	+1	-1	+1	+1	0,445	0,470
3	+1	+1	-1	-1	+1	+1	0,158	0,208
4	+1	-1	-1	+1	+1	+1	0,248	0,268
5	+1	+1	0	0	+1	0	0,188	0,602
6	+1	-1	0	0	+1	0	0,346	0,359
7	+1	0	+1	0	0	+1	0,311	0,347
8	+1	0	-1	0	0	+1	0,186	0,248
9	+1	0	0	0	0	0	0,244	0,291

The processing of the obtained results for the studied objective functions – Y_1 and Y_2, leads to the determination of linear regression equations of the type:

$$Y_{1,2} = b_0 - b_1x_1 + b_2x_2 - b_{11}x_{11} + b_{22}x_{22} - b_{12}x_{12} \quad (1)$$

The calculated model coefficients for Y1 and Y2 according to [26] – [34] are presented in Table 5.

TABLE 5 COEFFICIENTS OF REGRESSION EQUATIONS

	b_0	b_1	b_2	b_{11}	b_{22}	b_{12}
Y_1	0,2423	-0,0772	0,069	-0,0255	0,007	-0,0313
Y_2	1,2032	-0,3068	0,2217	-0,0448	0,0057	-0,041

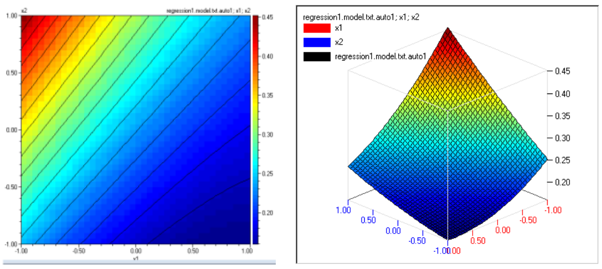
The obtained regression models for determining the average roughness Y_1 and Y_2 (Ra, μm) are represented by equations 3 and 4.

$$Y_1 = 0,2423-0,0772X_1+0,069X_2-0,0255X_{11}+0,007X_{22}-0,0313X_{12} \quad (3)$$

$$Y_2=1,203-0,3068X_1+0,2217X_2-0,0448X_{11}+0,0057X_{22}-0,041X_{12} \quad (4)$$

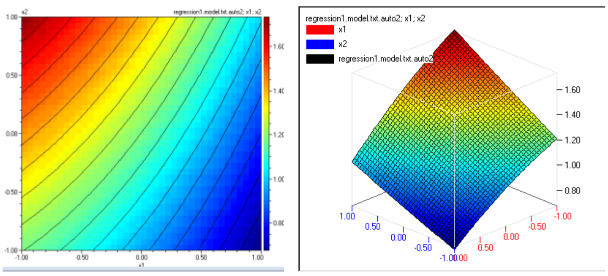
The adequacy check of the models according to the Fisher criterion [35] – [37] shows that they are adequate.

The graphical dependencies for 3 and 4 are presented in Fig. 4 and 6, respectively.



a. b.

Fig.3. Visualization of the solutions of the regression model for Y1(Ra, μm) when machining a hole Ø50.85 in two- and three-coordinate systems (a and b).



a. b.

Fig.4. Visualization of the solutions of the regression model for Y1(Ra, μm) when machining a hole Ø46.85 in two- and three-coordinate systems (a and b).

When conducting the analysis of variance of the model, Qv Stat Lab AnoVA was used. The graphical interpretation of the results for the three coded values for Y_1 and Y_2 (Ra, μm) are presented in Fig. 5 and 6, respectively.

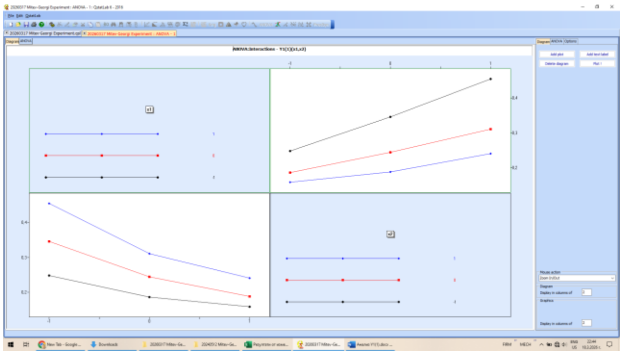


Fig. 5. Analysis of variance of the dependence $Y_1 = f(X_1, X_2)$ at X_{-1}; X_0 and X_{+1}.

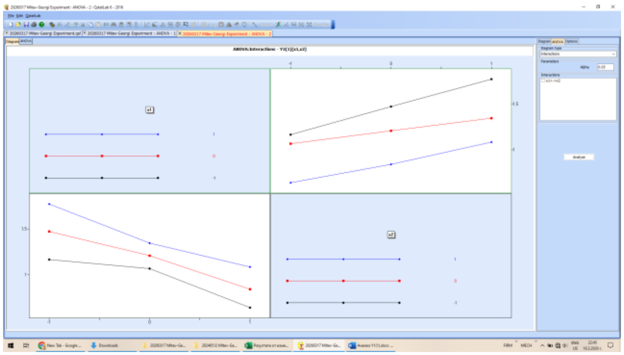


Fig. 6. Analysis of variance of the dependence $Y_2 = f(X_1, X_2)$ at X_{-1}; X_0 and X_{+1}.

The optimization of the technological process for the machinability of short rotary parts from improveable steels with robotic feeding was made based on set values Y_1 min and Y_2min. It was carried out by random search with increasing density (genetic algorithm) [31] – [33]. The graphical interpretation is shown in Fig. 7 and 8. for machined holes Ø50.85 and Ø46.85, respectively.

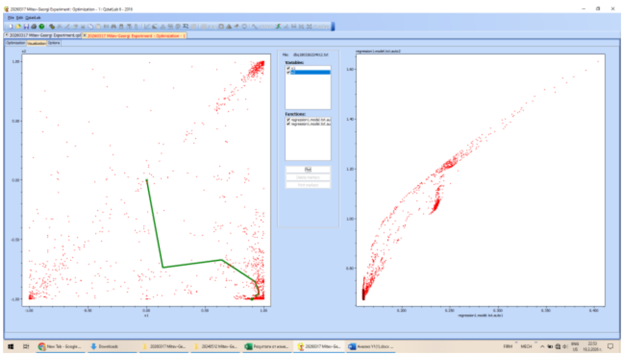


Fig.7. Optimization of the technological process for machining holes Ø50.85 at Y_1min.

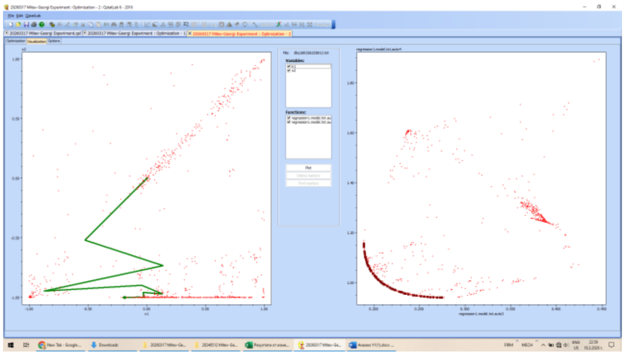


Fig.7. Optimization of the technological process for machining holes Ø46.85 at Y_2min.

IV. Conclusions

The following more important conclusions can be formulated from the conducted research and the results obtained:

- The machinability of improved medium-alloy structural steels was studied when machining short rotary parts on CNC lathes with robotic feeding according to the criterion of average roughness deviation on the machined surfaces - Ra.
- Empirical models of the studied functions were compiled and their adequacy was checked using the Fisher criterion.
- The dispersion analysis performed has shown that optimal working conditions for the given material, speed and feed are achieved at Vc = 180 m/min and f = 0.45 mm/tur.
- The optimization of the technological process was done based on the given values Y1 min and Y2 min. It was carried out by random search with increasing density (genetic algorithm).

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