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Investigation of the Machinability of 42CrMo4+QT Steel in Tool Turning with Carbide Inserts on CNC Machines with Robotic Power Supply

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***Abstract*—The optimum machining conditions recommended in the literature for one of the most commonly used materials for responsible heavy-duty workpieces in mechanical engineering, 42CrMo4+QT steel, are valid only for certain cutting tools and machine tools. This paper presents the results of an investigation of the machinability of this type of steel on the criteria of cutting tool lifetime and roughness of machined surfaces in turning on CNC machines with robotic power supply. A planned experiment has been carried out as a result of which theoretical and experimental models have been obtained and graphical dependencies, reflecting the influence of cutting speed and feed when working with replaceable carbide inserts from different manufacturers have been constructed. The dependencies allow to predict with sufficient accuracy the tool lifetime of the studied inserts and the roughness of the machined surfaces using cutting conditions in a certain range. The analysis carried out shows that the machinability of 42CrMo4+QT steel depends on the elements of the cutting conditions, with the widest variation in the values of the cutting tool lifetime criterion. The cutting speed has a stronger influence on this criterion. The optimum cutting conditions that guarantee maximum tool lifetimes of the studied inserts and minimum roughness of the machined surfaces ware determined.**

***Keywords*— machinability, modeling tool lifetime, roughness..**

I. INTRODUCTION

Steel 42CrMo4+QT is a hardened version of steel 42CrMo4, in which the content of chromium and molybdenum as the main alloying elements contributes to its high strength, durability and wear resistance. This makes it particularly suitable for the manufacture of parts in mechanical engineering, operating in conditions requiring high strength and hardness, such as parts of compressors, turbines, working elements of heavy ground and underground equipment, parts for agricultural machinery, etc. [1], [2]. The optimal conditions for its processing specified and recommended in the literature are valid only for certain cutting tools and metal-cutting machines [3] - [4]. Till now, there is no information on the machinability of this type of steel, using cutting tools with carbide indexable inserts on CNC lathes with robotic power supply.

The aim of the present work is to investigate the influence of cutting speed and feed on the machinability of 42CrMo4+QT steel according to the criteria of cutting tool lifetime and roughness of the machined surfaces when machining with replaceable carbide inserts from different manufacturers on CNC turning machines with robotic power supply, to obtain relevant theoretical and experimental models and to determine the optimal cutting conditions.

II. MATERIALS AND METHODS

To investigate and model the effect of cutting condition elements on the tool lifetime of carbide inserts and the roughness of the machined surfaces when machining 42CrMoS4-QT steel on CNC lathes with a robotic power supply, a two-factor optimal design experiment was conducted, using an orthogonal central composition design. The number of trails is:

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

The feed f (mm/rev) and the cutting speed Vc (m/min) were selected as the control factors. The cutting depth was a_p = 1.5 mm.

The machined worpiece (Fig. 1), made of steel 42CrMo4+QT, have hardness HRC=33.8, yield strength point $f_y \geq$ 850 MPa and chemical composition presented in Table 1.

The experiments were conducted on a HARRIS C400 CNC lathe with a FANUC BOXI Raptor Auto Loader robotic feeding station (Fig. 2). Zet Chemie ZET-cut 6040 GTL was used as the coolant.

Replaceable carbide inserts from various manufacturers were used as cutting tools [11] - [13]. The carbide inserts have coatings (Table 2) ensuring high wear resistance.

The inserts were set in a quick-change type toolholder, providing the following geometrical parameters: tool major cutting edge angle $\kappa_r = 95°$, tool minor cutting edge angle $\kappa_r' = 5°$, tool orthogonal rake angle $\gamma_0 = -6°$, tool orthogonal clearance $\alpha_0 = 7°$, nose radius $r_\varepsilon = 0.4$ mm.

TABLE 1 CHEMICAL COMPOSITION OF 42CRMO4 +QT STEEL

Chemical composition (Wt%)							
C	*Si*	*Mn*	*Ni*	*Cr*	*Mo*	*P*	*Cu*
0.405	0.239	0.652	0.110	0.894	0.180	0.012	0.227

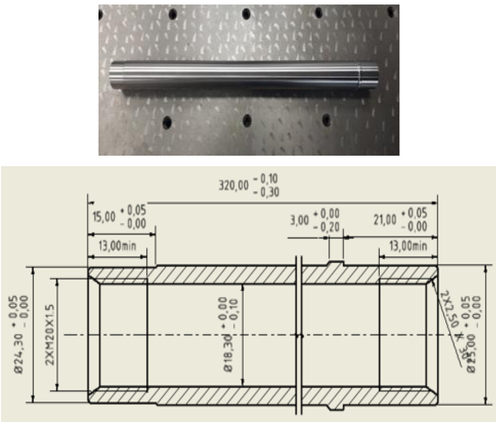


Fig. 1 Machined workpiece

In order to study the tool lifetime and roughness, single-factor experiments were conducted to determine the effect of the number of machined workpieces on roughness at given values of cutting speed and feed (Fig. 3) [14].

Tool lifetime was defined as the number of workpieces machined in a specific cutting conditions, with the roughness of the machined surface Ra=3,0 μm as the wear criterion.

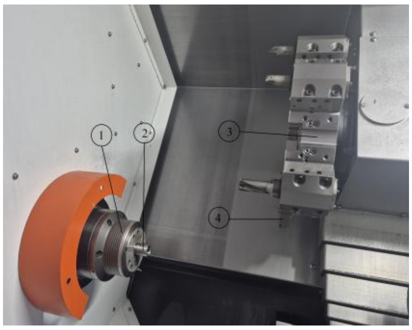


Fig. 2 Workspace of a HARRIS C400 CNC lathe with robotic power supply (1 – chuck; 2 - workpiece; 3 – turret head; 4 – cutting tool)

TABLE 2 CARBIDE REPLACEABLE INSERTS

Insert (ISO 13399)	Manufacturer	Coated
CCMT09T304-F1 TP2501	SECO	CVD: $TiN + Al_2O_3$
CCMT09T304-MP	PALBIT	CVD $TiN+Al_2O_3+TiCN$
CCMT09T304-F3M IC807	ISCAR	PVD: TiAlN+TiN

The roughness was determined for a number of machined workpieces n=50 and a specific cutting conditions and was measured with a TESA Rugosurf 20 profilometer.

Based on preliminary information, a type of model has been adopted:

$$Y_{hp} = B_0 + \sum B_i X_i + \sum B_{ii} X_i^2 + B_{12} X_1 X_2 \qquad (2)$$

where: $Y_{1p} = T_p$ – tool lifetime; $Y_{2p} = Ra_p$ - roughness of the machined surfaces; $p = 1, 2, 3$ - number corresponding to the type of insert (Table 2); X_1= f (mm/rev); X_2= V_c (m/min).

The levels of variation of the control factors are presented in Table 3.

III. RESULTS AND DISCUSSION

The experimental design and experimental data are shown in Table 4.

The processing of the experimental results was carried out in accordance with the methodology set out in [15], in the sequence:

- determining the coefficients of the model;

- significance check of the regression coefficients by Student's t- test at significance level α=0.05;

- calculation of the determination coefficient $\hat{R}^2$;

- significance testing of the multiple coefficient by Fisher's criterion at the significance level α=0.05.

The research results were processed with the software product QstatLab [16], and the resulting models are shown in Table 5.

TABLE 3 LEVELS OF CONTROL FACTORS

Control factors		Factor levels		
Coded	***Natural***	***-1***	***0***	***+1***
x_1	f (mm/rev)	0.12	0.15	0.18
x_2	Vc (m/min)	130	150	170

The models describe with sufficient accuracy the relationship between tool lifetime and roughness and the cutting conditions elements Vc and f. The values of the coefficient of determination $\widehat{R}^2$ and the tabulated F^T and calculated $\widehat{F}$ value of the Fisher criterion are presented in Table 5. Table 4 presents the determined values of the tool lifetime $\hat{T}_p$ and roughness $\hat{Ra}_p$ of the machined surface in accordance with the constructed theoretical and experimental models (Table 5).

The graphical interpretation of the determined models is shown in Fig. 4.

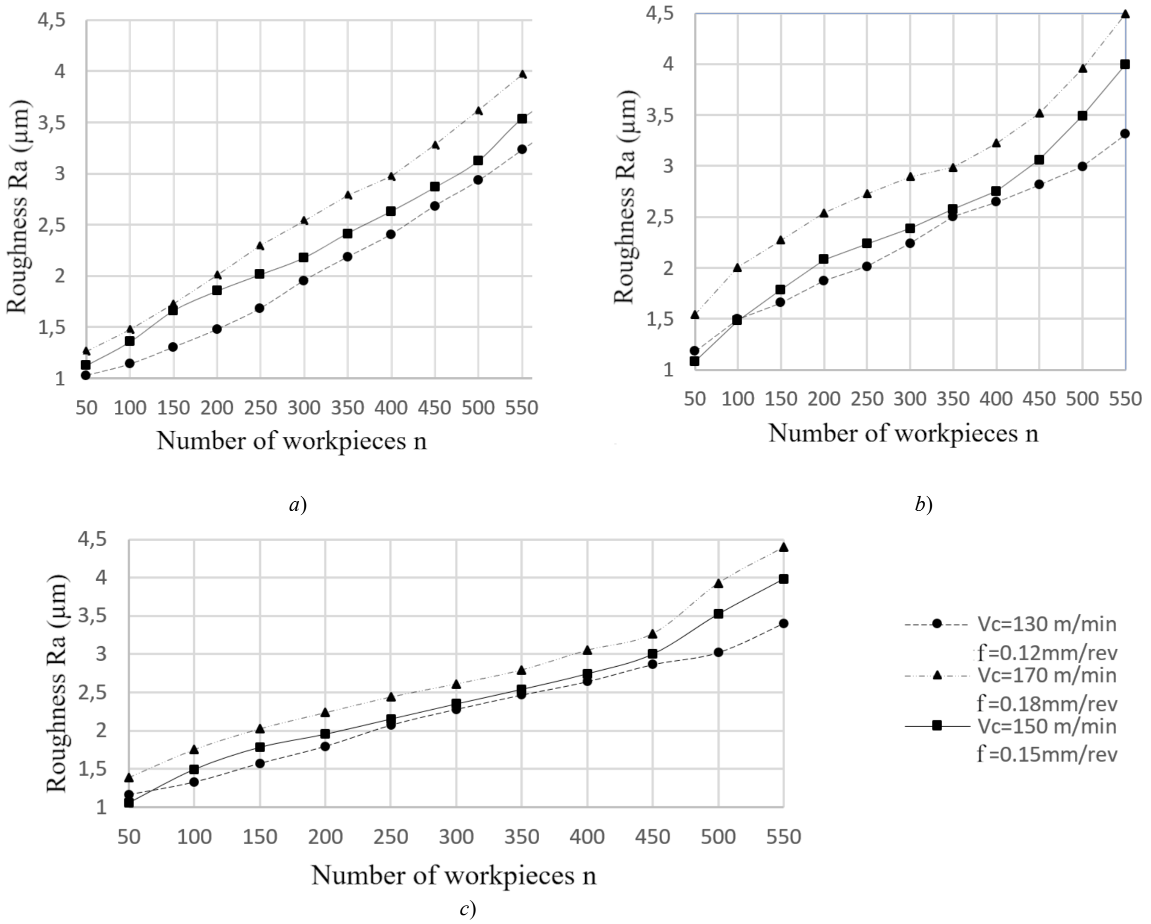


Fig. 3 Variation of roughness depending on the number of machined workpieces in turning with replaceable carbide inserts: *a* - CCMT09T304-F1 TP2501 of a company SECO; *b* - CCMT09T304-MP of a company PALBIT; *c* - CCMT09T304-F3M IC807 of a company ISCAR.

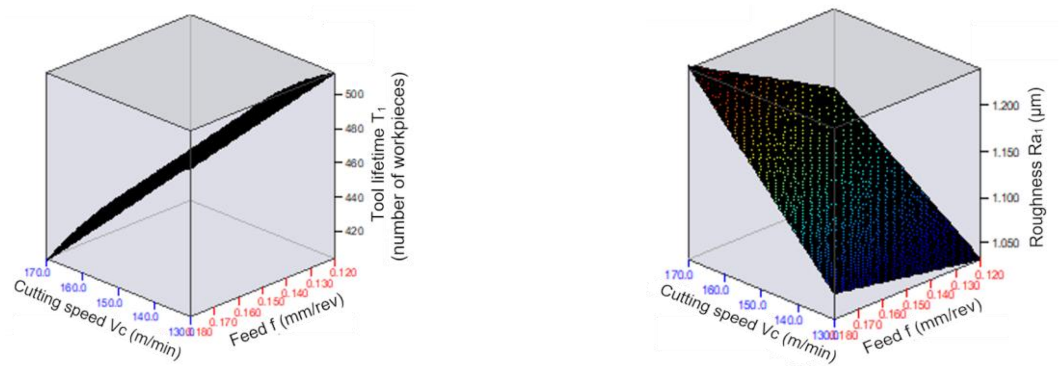
TABLE 4. EXPERIMENTAL DESIGN AND EXPERIMENTAL DATA

No	Cutting conditions		Tool lifetime (number of workpieces)						Roughness, µm					
	f (mm/rev)	V_c (m/min)	T_1	$\hat{T}_1$	T_2	$\hat{T}_2$	T_3	$\hat{T}_3$	Ra_1	$\hat{Ra}_1$	Ra_2	$\hat{Ra}_2$	Ra_3	$\hat{Ra}_3$
1	0.12	130	510	512	500	501	490	490	1.028	1.032	1.179	1.166	1.168	1.159
2	0.18	130	490	491	475	476	475	474	1.039	1.059	1.254	1.268	1.235	1.230
3	0.12	170	425	426	400	401	420	420	1.176	1.153	1.183	1.174	1.189	1.184
4	0.18	170	405	404	355	356	390	390	1.264	1.241	1.543	1.561	1.389	1.388
5	0.12	150	480	479	455	456	465	463	1.057	1.092	1.087	1.109	1.109	1.122

6	0.18	150	455	457	420	421	440	440	1.132	1.150	1.387	1.354	1.253	1.259
7	0.15	130	505	502	490	488	480	482	1.095	1.046	1.085	1.083	1.032	1.046
8	0.15	170	415	415	380	378	405	405	1.172	1.197	1.243	1.234	1.131	1.137
9	0.15	150	470	468	440	438	450	452	1.127	1.121	1.087	1.098	1.062	1.042

TABLE 5. THEORETICAL AND EXPERIMENTAL MODELS AND STATISTICAL ANALYSIS

Insert	**Theoretical and experimental models**	**Fisher criterion**		$\widehat{R}^2$
		$\widehat{F}$	F^T	
CCMT09T304-F1 TP2501	$T_1 = 285 - 361.111.f + 5.333.V_c - 0.025.V_c^2$	695.476	5.409	0.99617
	$Ra_1 = 0.976 - 2.8109.f + 0{,}02518.f.V_c$	19.553	5.143	0.82264
CCMT09T304-MP	$T_2 = 469.583 + 666.667.f + 2{,}25.V_c - 0.0125.V_c^2 - 8.333.f.V_c$	1611.0	6.388	0.99876
	$Ra_2 = 9{,}3611 - 58{,}340f - 0{,}0597V_c + 148{,}704f^2 + 0{,}00015.V_c^2 + 0{,}119f.V_c$	43.696	9.013	0.96388
CCMT09T304-F3M IC807	$T_3 = 188.125 + 548.611.f + 5.271.V_c - 0.0208.V_c^2 - 6.25.f.V_c$	943.533	6.388	0.99788
	$Ra_3 = 8.099 - 55.64.f - 0.043.V_c + 165.37.f^2 + 0.00012.V_c^2 + 0.0554.f.V_c$	58.253	9.013	0.97281



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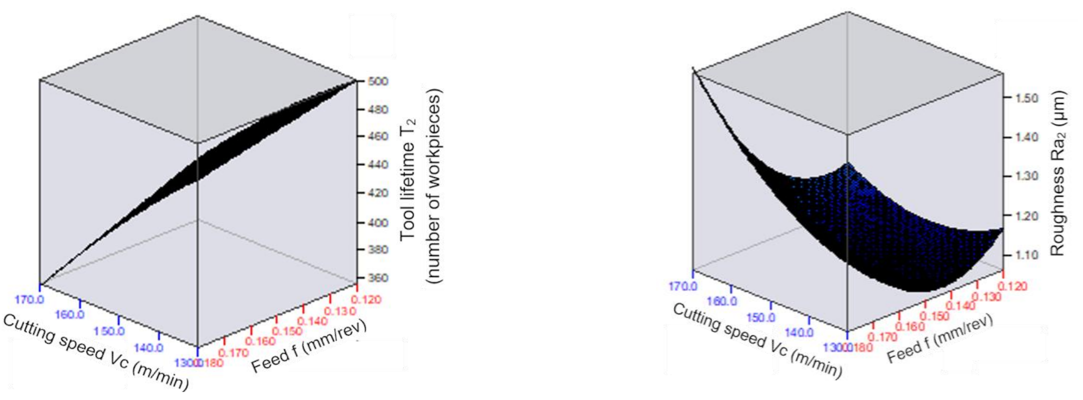

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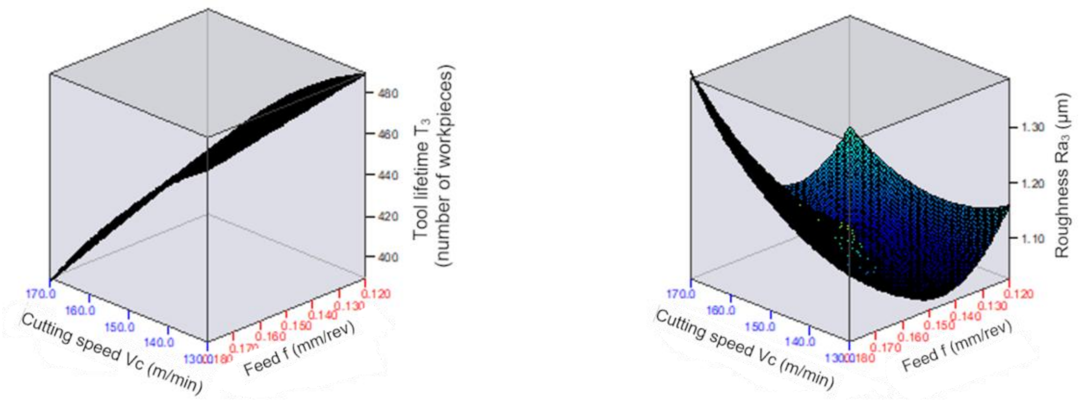
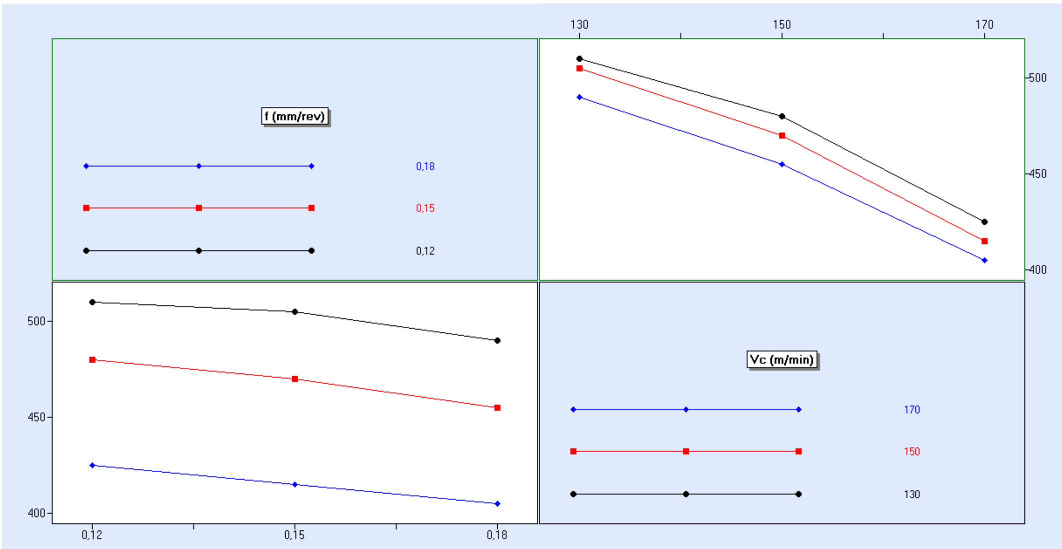


c)

Fig. 4 Graphical dependences of the tool lifetime of the inserts and the roughness of the machined surfaces depending on the feed f (mm/rev) and cutting speed Vc (m/min) (*a* - CCMT09T304-F1 TP2501 of a company SECO; *b* - CCMT09T304-MP of a company PALBIT; *c* - CCMT09T304-F3M IC807 of a company ISCAR)



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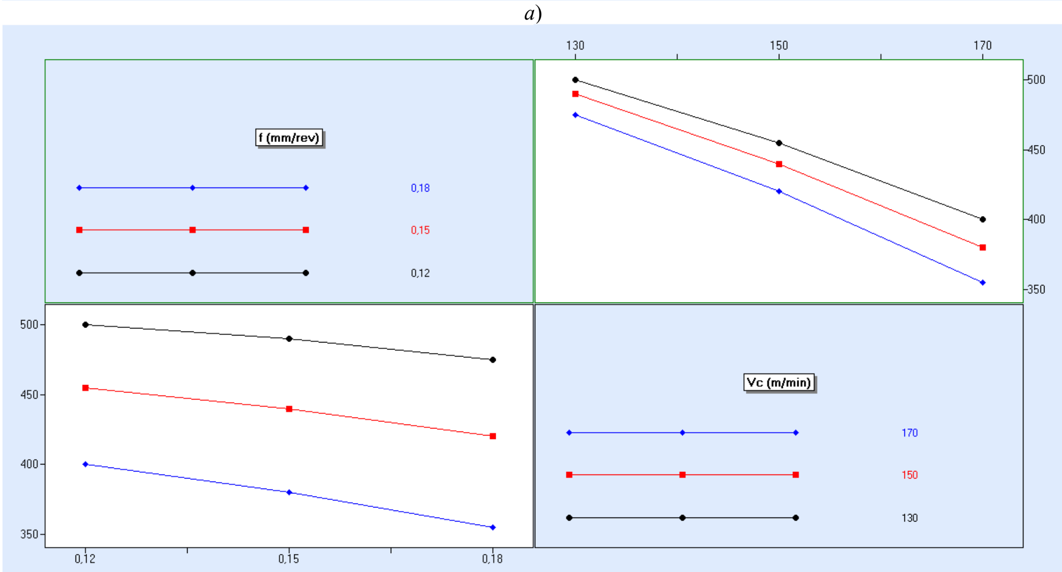

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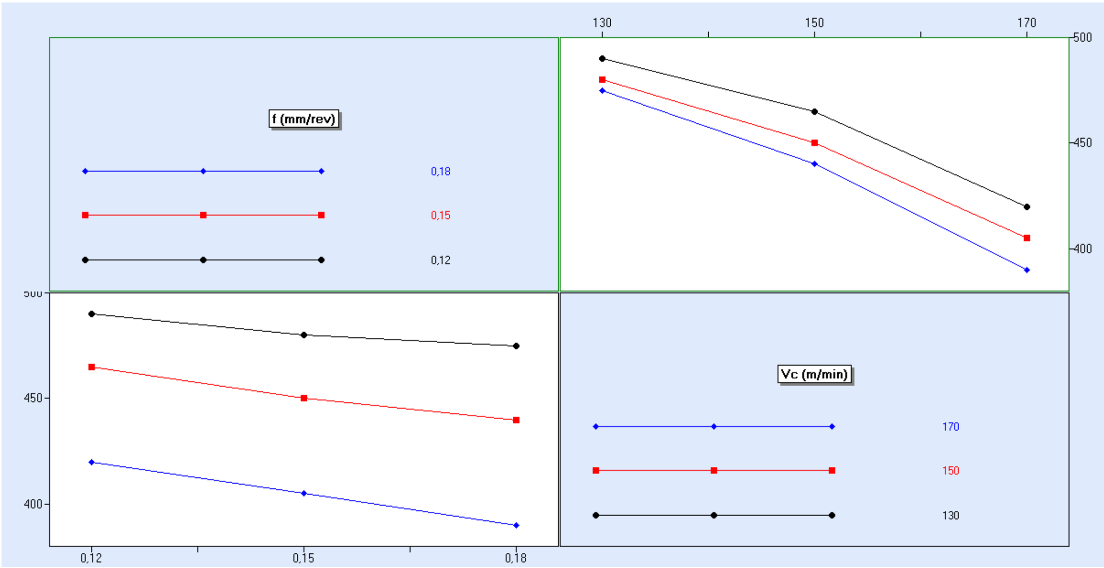

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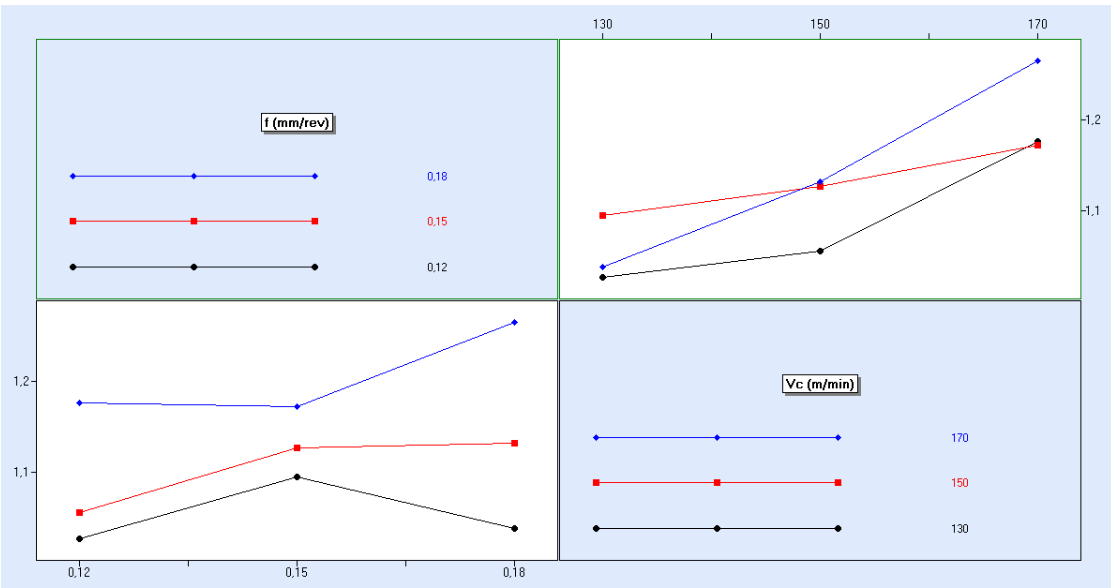
Fig. 5 Visualisation of the influence of the feed f and cutting speed Vc on the tool lifetime of machining with carbide inserts: *a* - CCMT09T304-F1 TP2501 of a company SECO; *b* - CCMT09T304-MP of a company PALBIT; *c* - CCMT09T304-F3M IC807 of a company ISCAR



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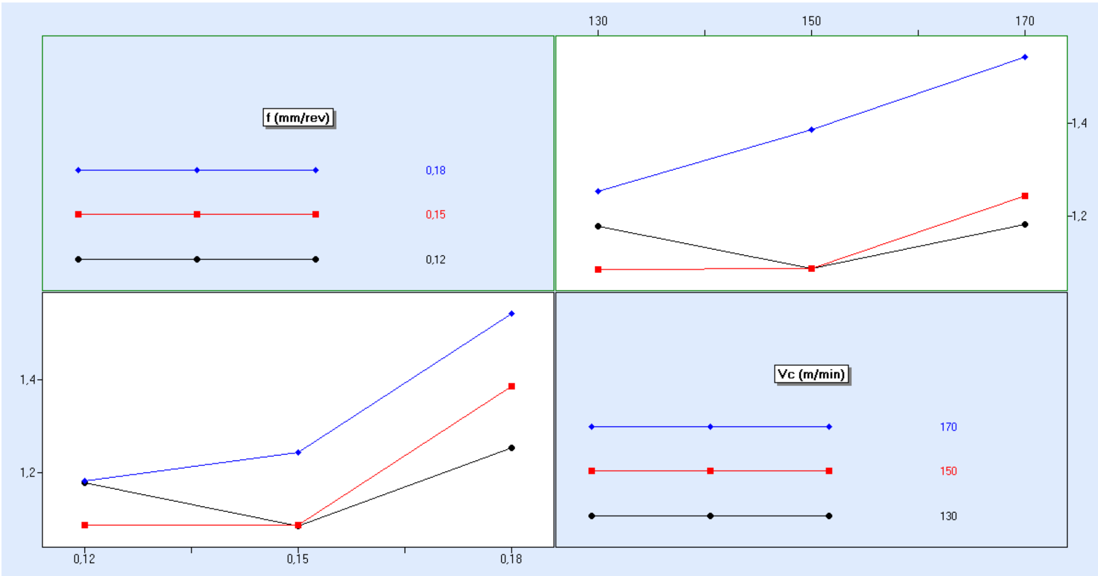

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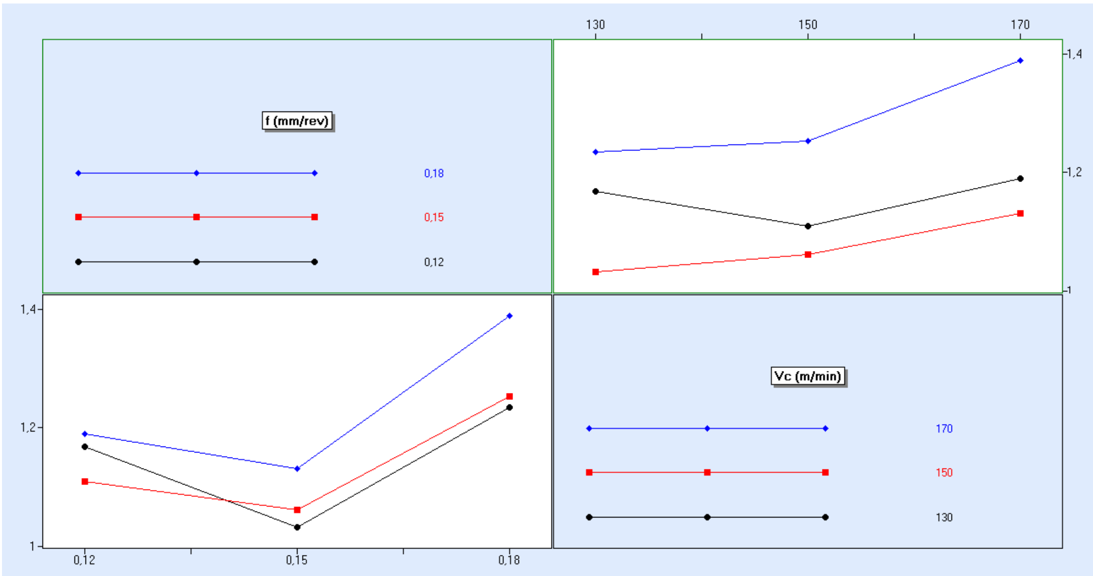

c)

Fig. 6 Visualisation of the influence of the feed f and cutting speed Vc on the roughness of machining with carbide inserts: *a* - CCMT09T304-F1 TP2501 of a company SECO; *b* - CCMT09T304-MP of a company PALBIT; *c* - CCMT09T304-F3M IC807 of a company ISCAR.

Analysis of variance (ANOVA) was performed to determine the influence of the control factors on tool lifetime and roughness. The graphical interpretation of this influence is shown in Fig. 5 and Fig. 6.

The analysis of the obtained theoretical and experimental models and of the graphical dependencies constructed on their basis shows that:

- The machinability of 42CrMo4+QT steel under the criterion cutting tool lifetime depends on the cutting conditions, and with increasing values of Vc and f there is a decrease in tool lifetime, i.e. deterioration in machinability (Table 6). The influence of the cutting speed is stronger, and its variation in the investigated range leads to a variation of the tool lifetime from 19% to 29% for individual inserts. The increase of the feed leads to decrease of the tool lifetime with 5 to 8.4% (Table 7). The highest tool lifetime, respectively the best machinability of 42CrMo4+QT steel according to this criterion was obtained when machining with the inserts CCMT09T304-F1 TP2501 of the company SECO (T = 512 workpieces at feed f_{min} = 0.12 mm/rev and Vc_{min} = 130m/min; T = 404 workpieces at f_{max} = 0.18 mm/rev and Vc_{max} = 170 m/min) (Table 6).

- The evaluation of the machinability by the roughness criterion of the machined surfaces shows that with increasing f and Vc, there is an increase in roughness i.e. a deterioration in machinability (Table 6). According to this criterion the best machinability, i.e. the lowest roughness is obtained when machining with the inserts CCMT09T304-F1 TP2501 of the company SECO (Ra = 1032 μm at f_{min}= 0.12 mm/rev and Vc_{min} = 130 m/min; Ra = 1.241 μm at f_{max} = 0.18 mm/rev and Vc_{max} =

170 m/min) (Table 6). For the CCMT09T304-F1 TP2501 inserts, there is a stronger influence of the cutting speed on the roughness, and for the CCMT09T304-MP and CCMT09T304-F3M IC807 inserts - of the feed on the roughness (Table 7).

The optimization of the cutting conditions elements was carried out by determining the combination of feed rate f (mm/rev) and cutting speed Vc (m/min) at which maximum tool lifetime of the cutting inserts and minimum roughness of the machined surfaces is achieved (Table 8).

TABLE 6 LIMITS OF VARIATION OF THE CRITERIA OVER THE RANGE OF CUTTING CONDITIONS INVESTIGATED

Insert	f_{min} = 0.12 mm/rev Vc_{min} = 130 m/min		f_{max} = 0.18 mm/rev Vc_{max} = 170 m/min	
	T (number of workpieces)	*Ra (µm)*	*T (number of workpieces)*	*Ra (µm)*
CCMT09T304-F1 TP2501	512	1.032	404	1.241
CCMT09T304-MP	501	1.166	356	1.561
CCMT09T304-F3M IC807	490	1.159	390	1.388

TABLE 7 INFLUENCE OF CUTTING CONDITIONS ELEMENTS ON MACHINABILITY CRITERIA, %

Insert	f_{min} = 0.12 mm/rev f_{max} = 0.18 mm/rev		Vc_{min} = 130 m/min Vc_{max} = 170 m/min	
	ΔT	*ΔRa*	*ΔT*	*ΔRa*
CCMT09T304-F1 TP2501	4.9	5.3	20.9	14.4
CCMT09T304-MP	8.4	21.2	29.1	12.9
CCMT09T304-F3M IC807	5.3	11.9	19.0	7.9

TABLE 8 CUTTING CONDITIONS PROVIDING MAXIMUM TOOL LIFETIME AND MINIMUM ROUGHNESS

Insert	Cutting conditions			T (number of work-pieces)	Ra (µm)
	f (mm/rev)	*Vc (m/min)*	*a_p mm*		
CCMT09 T304-F1 TP2501	0,12	130	1,5	512	1,032
CCMT09 T304-MP	0,12	130	1,5	501	1,166
CCMT09 T304-F3M IC807	0,12	130	1,5	490	1,159

IV. CONCLUSIONS

The machinability of 42CrMo4+QT steel was investigated on the cutting tool lifetime with replaceable carbide inserts and roughness of machined surfaces when machined on CNC lathes with robotic power supply. As a result of the investigation, the following conclusion can be drawn.

1) Theoretical and experimental models for the tool lifetime of the inserts and the roughness of the machined surfaces as 42CrMo4+QT steel machinability criteria have been built, reflecting the influence of the feed f and the cutting speed Vc.

2) Graphical dependencies have been constructed, with the help of which the tool lifetime of the examined inserts and the roughness of the machined surfaces can be predicted with sufficient accuracy in the cutting conditions in the range f = 0.12 - 0.18 mm/rev and Vc = 130 - 170 m/min.

3) The obtained models and relationships show that the machinability of 42CrMo4+QT steel depends on the elements of the cutting conditions, with the widest variation in the values of the cutting tool lifetime criterion. The cutting speed has a stronger influence on this criterion.

4) With the increase of cutting speed and feed, there is a decrease in tool lifetime and an increase in roughness i.e. deterioration in machinability of 42CrMo4+QT steel. The best machinability is obtained when machining with SECO's CCMT09T304-F1 TP2501 inserts.

5) The optimal cutting conditions were determined which guarantee maximum tool lifetime of the examined inserts and minimum roughness of the machined surfaces (Table 8).

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