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EFFECT OF CUTTING PARAMETERS ON CUTTING FORCES IN TURNING OF CPM 10V STEEL

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Abstract: *The objective of this paper is to investigate the effect of cutting parameters on cutting forces during turning of CPM 10V steel with coated cutting tool. Machining of CPM 10V steel and finding a suitable tool is very challenging due to its physical and mechanical properties, especially since the machining of this material has not been extensively researched. The experiments were carried out using an Index GU -600 CNC lathe and the cutting forces were measured in process. A three-factorial three-level experimental design was used for the experiments. Statistical method analysis of variance (ANOVA) is applied to study the effects of cutting speed, feed rate, and depth of cut on cutting forces. The results of this study show that depth of cut has the most significant effect on main force and radial force, while feed rate and cutting speed have the most significant effect on feed force. The developed model can be used in the machining industry to predict and analyze cutting parameters for optimal cutting forces.*

Key words: *CPM-10V steel, powder metallurgy, cutting parameters, ANOVA.*

Uticaj parametara rezanja na sile rezanja pri struganju CPM 10V čelika. *Cilj ovog rada je da se ispita uticaj parametara rezanja na sile rezanja pri struganju CPM 10V čelika sa presvučenim reznim alatom. Obrada CPM 10V čelika i pronalaženje odgovarajućeg alata je veoma izazovno zbog njegovih fizičko-mehaničkih svojstava, pogotovo što obrada ovog materijala nije opširno istražena. Eksperimenti su izvedeni na Index GU-600 CNC strugu i merene su sile rezanja u procesu. Za eksperimente je korišćen trofaktorski trostepeni eksperimentalni dizajn. Statistička metoda analize varijanse (ANOVA) se primenjuje za proučavanje efekata brzine rezanja, pomaka i dubine rezanja na sile rezanja. Rezultati ovog istraživanja pokazuju da dubina rezanja ima najznačajniji uticaj na glavnu silu i radijalnu silu, dok pomak i brzina rezanja imaju najznačajniji uticaj na silu pomoćnog kretanja. Razvijeni model se može koristiti u mašinskoj industriji za predviđanje i analizu parametara rezanja za optimalne sile rezanja.*

Ključne reči: *CPM-10V čelik, metalurgija praha, parametri rezanja, ANOVA.*

1. INTRODUCTION

In the recent past, considerable improvements have been made in turning, making it easier to machine materials that are difficult to cut and resulting in better machinability (better surface finish and lower cutting forces). The forces acting on the tool are an important aspect of machining. Knowledge of cutting forces is necessary for estimating power requirements and designing machine tool elements and fixtures that are sufficiently rigid and free from vibration. Most of the energy consumed in metal cutting is converted to heat near the cutting edge of the tool, and many of the economic and technical problems in machining are caused by this heating. Therefore, proper selection of cutting tools and process parameters to achieve high cutting performance in a turning operation is a critical task [1].

Steels with high vanadium content in the tooling industry are used, such as cutting blades, paper cutters, drilling tools, cold forming tools, etc. The main problem with this type of steel is reduced toughness, which is an undesirable consequence of increasing the vanadium content. Powder metallurgy is a technology developed to obtain a fine carbide structure, even when a high content of alloying additions is made. Soon, crucible metallurgists discovered that much higher alloy steels, especially high vanadium steels, were possible with powder metallurgy. In 1978, the "Powder Metallurgy" method was used to develop CPM 10V steel with a high vanadium content (about 10%), which has both good wear resistance and high toughness. Since then, CPM 10V has been widely used in tools that require high wear resistance and have a toughness problem [2].

Figure 2 shows the difference in the microstructure of steels produced by conventional methods and powder metallurgy. The difference in the homogeneity of the microstructure is visible.

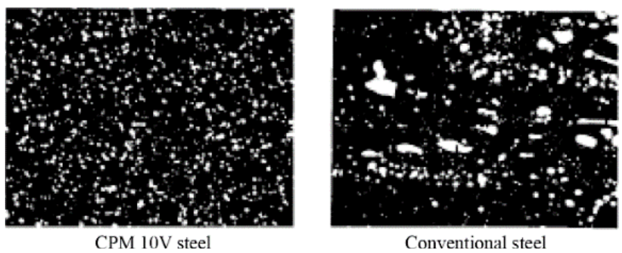

Fig. 1. Microstructure of CPM 10V steel and conventional steel [2]

This paper aims to analyze the parameters of the processing mode (cutting depth, feed rate, and cutting speed) on the cutting forces (The main cutting force - $\mathbf{F_v}$, radial force - $\mathbf{F_p}$, and feed force $\mathbf{F_f}$), as well as to develop a mathematical model. Minitab 17 software was used to analyze the results.

Note: The manuscript was presented at the 14. International Scientific Conference MMA held in Novi Sad, Serbia, 23.-25. September, 2021.

2. MATERIALS AND METHODS

2.1 Experimental setup

Experimental work was carried out at the Faculty of Technical Sciences, in the Laboratory for Conventional Machining.

The conditions for experimental testing are given in this chapter. Conditions apply to: The workpiece material, machine tool, cutting tool and, cutting conditions, measuring technique.

The workpiece material: Experimental tests were performed on CPM 10V steel produced by powder metallurgy. Powder metallurgy is a technology developed to obtain a fine carbide structure even when a large amount of alloying additions are used. 10V is the evolution of the earlier 4÷5% vanadium steel. Its combination of toughness, wear resistance, and cutting edge stability predestines it to replace tool steels that are prone to chipping at the tool cutting edge during cold working [3]. The chemical structure is shown in Table 1. The workpiece had a length of 80 mm (cutting length) and a diameter of 40 mm.

Steel	C	Mn	Si	Cr	V	Mo	S
10V	2,45	0,5	0,9	5,25	9,75	1,30	0,07

Table 1. Chemical s tructure of CPM 10V steel [4]

Machine tool: The experimental work was carried out at the Department of Production Engineering, the Faculty of Technical Sciences in Novi Sad. The machining was conducted on a Index GU-600 CNC lathe in dry condition.

Cutting tool: A turning cutter SVLBL2525M16, with cemented carbide inserts („SECO“ type VBMT160408-M5, TP1501) with coated Ti(C,N) + Al2O3+ Cr (Used edgde detection) [5]. Table 2 illustrates the geometrical characteristics of the ccutting tool positioned on its tool holder.

Geometrical Characteristics of VBMT160408-M5 insert	Value
Clearance angle major	5°
Insert included angle	35°
Theoretical cutting edge length	16,61 mm
Corner radius	0,80 mm
Insert thickness	4,76 mm

Table 2. Geometrical specifications of VBMT160408-M5 insert [5]

Catting conditions:

- Cutting speed *v*,
- Feed rate ***f***,
- Depth of cut *a*.

Table 3 is shown machining parameters and their levels based on the material of the workpiece and the recommendations of the tool manufacturer.

Levels	Depth of cut *a [mm]*	Feed rate *f [mm/rev]*	Cutting speed *v [m/min]*
Max. **+1**	1,6	0,26	600
Midium **0**	1,13	0,22	424
Min. **-1**	0,8	0,18	300

Table 3. Machining parameters and their levels

Measuring technique: For the cutting force measurements a Kistler® three-axis piezoelectric type 9257A is used (Figure 2a). The dynamometer is mounted on the machine via a specially designed holder, as shown in Figure 2b.

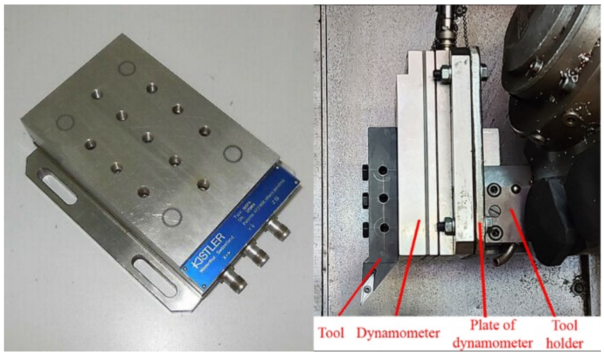

Fig. 2. a) The 3-axis Kistler 9257A dynamometer, b) specially designed holder of dynamometer

The piezoelectric dynamometer is connected to a charge amplifier through 3 coaxial cables shielded, grounded, and waterproof. Further on, the amplifier communicates with a PC across an A/D card, which converts the analogy signal to digital. The signal processing is performed by the LabView program. Figure 3 illustrates the layout diagram for the data processing.

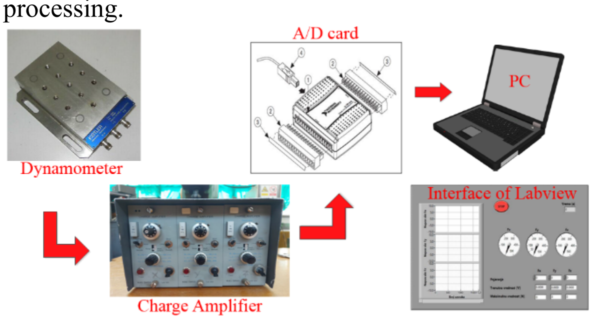

Fig. 3. Layout diagram for signal processing

3. RESULTS AND DESCUSSION

In table 4 is shown the setup of experiments and results of cutting forces. All of the experiments were conducted with one insert without coolant.

S. No.	Cutting parameters *a* [mm]	*f* [mm/rev]	*v* [m/min]	F_v	F_p	F_f
1	0,8	0,18	300	880,53	84,02	379,74
2	1,6	0,18	300	1594,42	177,13	339,89
3	0,8	0,26	300	1140,57	86,24	420,45
4	1,6	0,26	300	2154,48	187,84	421,54
5	0,8	0,18	600	784,58	69,42	397,23
6	1,6	0,18	600	1495,42	176,43	419,22
7	0,8	0,26	600	990,89	68,88	422,01
8	1,6	0,26	600	1971,29	175,00	455,99
9	1,13	0,22	424	1250,11	115,37	413,66
10	1,13	0,22	424	1260,04	112,31	397,19
11	1,13	0,22	424	1284,36	115,46	395,42
12	1,13	0,22	424	1287,87	115,28	396,24

Table 4. The setup of experiments and results of cutting forces

3.1 Response surface regresion: F_v

For regression analysis, analysis of variance (ANOVA), as well as the response surfaces commercially available statistical analysis software, was used. The analysis determined the significance of the model and the flow of the processing parameters on the cutting forces. Based on Table 4, an analysis of variance was performed. The results of the analysis are shown in Table 5.

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	7	1851178	264454	932,06	0,000
Linear	3	1778159	592720	2089,03	0,000
a	1	1461229	1461229	5150,07	0,000
f	1	282106	282106	994,27	0,000
v	1	34824	34824	122,74	0,000
Square	1	4705	4705	16,58	0,015
a*a	1	4705	4705	16,58	0,015
2-Way Interaction	3	43097	14366	50,63	0,001
a*f	1	40553	40553	142,93	0,000
a*v	1	167	167	0,59	0,486
f*v	1	2378	2378	8,38	0,044
Error	4	1135	284		
Lack-of-Fit	1	116	116	0,34	0,600
Pure Error	3	1019	340		
Total	11	1852313			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
16,8443	99,94%	99,83%	99,50%

Table 5. Response Surface Regression: $\boldsymbol{F_v}$ versus $\boldsymbol{a, f, v}$

Based on the value of P, a decision is made on the significance of the parameters. If the value of $\boldsymbol{P} <$ 0,05, the parameter is significant [6]. By reviewing Table 5, it can be concluded that all parameters are significant, except for $\boldsymbol{a * v}$.

The adequacy of the model is reflected in the value of "Lack-of-fit" the value of **P** is 0,600, which means that the model is adequate (the value of **P** must be higher than 0,05). After analyzing the mathematical model (R-sq and R-sq(adj)), it is concluded that the model is adequate. Since the value of the reduced model is greater than 90% (R-sq (adj) = 99,83%), it is adopted (Equation 1).

$$\boldsymbol{F_v = 335 - 300 * a + 648 * f + 0,284 * v + 176,6 * a^2 + 4450 * a * f - 2,873 * f * v} \quad (1)$$

The significance of parameters can be determined based on ANOVA analysis. Figure 4 shows the strength of the processing parameters for the force $\boldsymbol{F_v}$, where it can be seen that the greatest influence on the force $\boldsymbol{F_v}$ has the depth of cut, followed by a feed rate, and the least important is the cutting speed.

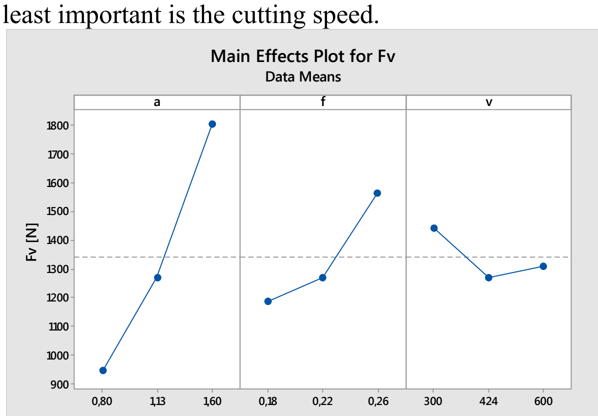

Fig. 4. Effect of cutting parameters on cutting force $\boldsymbol{F_v}$

3.2 Response surface regresion: F_p

In the same way, as for the force $\boldsymbol{F_v}$, an analysis of the force $\boldsymbol{F_p}$ was performed. The results of the analysis are shown in Table 6.

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	7	21629,9	3090,0	685,26	0,000
Linear	3	21065,5	7021,8	1557,21	0,000
a	1	20791,7	20791,7	4610,91	0,000
f	1	15,0	15,0	3,33	0,142
v	1	258,8	258,8	57,39	0,002
Square	1	83,4	83,4	18,49	0,013
a*a	1	83,4	83,4	18,49	0,013
2-Way Interaction	3	77,4	25,8	5,72	0,063
a*f	1	7,2	7,2	1,60	0,274
a*v	1	42,4	42,4	9,41	0,037
f*v	1	27,8	27,8	6,15	0,068
Error	4	18,0	4,5		
Lack-of-Fit	1	11,0	11,0	4,69	0,119
Pure Error	3	7,0	2,3		
Total	11	21648,0			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
2,12350	99,92%	99,77%	96,69%

Table 6. Response Surface Regression: $\boldsymbol{F_p}$ versus $\boldsymbol{a, f, v}$

The value of p for the "Lack of fit" function is 0.119, which means that the model is adequate (Equation 2). The feed rate is not significant for the penetration force $\boldsymbol{F_p}$, as well as all iterations with it ($\boldsymbol{a * f}$, and $\boldsymbol{f * v}$). The reduced mathematical model is shown by Equation 2.

$$\boldsymbol{F_p = 37 + 9,7 * a - 0,0157 * v + 36,42 * a^2 + 0,0384 * a * v} \quad (2)$$

Figure 5 shows the strength of the processing parameters for the force $\boldsymbol{F_p}$, where it can be seen that the largest and only influence on the force $\boldsymbol{F_p}$ has the depth of cut, while the feed rate and cutting speed have almost no effect.

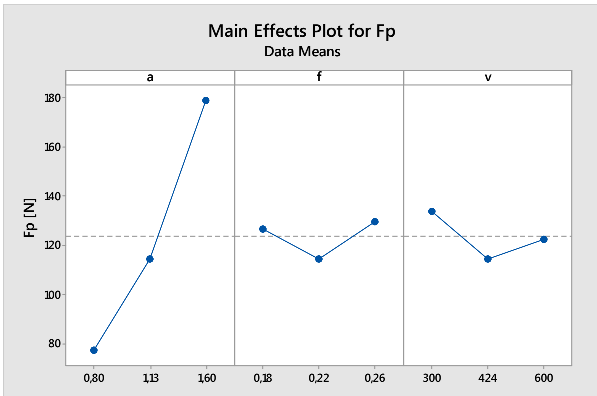

Fig. 5. Effect of cutting parameters on cutting force $\boldsymbol{F_p}$

3.3 Response surface regresion: F_f

As in previous times, an analysis for the force $\boldsymbol{F_f}$ was performed. The results of the analysis are shown in Table 7.

The value of p for the "Lack of fit" function is 0,325, which means that the model is adequate (Equation 3). The depth of cut is not significant for the force $\boldsymbol{F_f}$, as well iterations $\boldsymbol{a * a, a * f}$, and $\boldsymbol{f * v}$. In this case, a reduced mathematical model will not be used, because the value of R-sq(adj) is <90%, so the original mathematical model was used, whose accuracy is R-sq = 96,24%.

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	7	8513,10	1216,16	14,62	0,010
Linear	3	6470,36	2156,79	25,92	0,004
a	1	37,02	37,02	0,44	0,541
f	1	4227,86	4227,86	50,82	0,002
v	1	2205,48	2205,48	26,51	0,007
Square	1	31,75	31,75	0,38	0,570
a*a	1	31,75	31,75	0,38	0,570
2-Way Interaction	3	1934,15	644,72	7,75	0,038
a*f	1	350,20	350,20	4,21	0,109
a*v	1	1121,72	1121,72	13,48	0,021
f*v	1	462,23	462,23	5,56	0,078
Error	4	332,79	83,20		
Lack-of-Fit	1	104,76	104,76	1,38	0,325
Pure Error	3	228,03	76,01		
Total	11	8845,89			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
9,12131	96,24%	89,65%	19,62%

Table 7. Response Surface Regression: $\boldsymbol{F_f}$ versus $\boldsymbol{a, f, v}$

$$F_f = 343{,}4 - 228 * a + 649 * f + 0{,}153 * v + 22{,}5 * a^2 + 414 * a * f + 0{,}1974\, a * v - 1{,}267\, f * v \qquad (3)$$

Figure 6 shows the strength of the processing parameters for the force $\boldsymbol{F_f}$, where it can be seen that the largest influence on the force $\boldsymbol{F_f}$ has the feed rate and cutting speed, while the depth of cut has no effect.

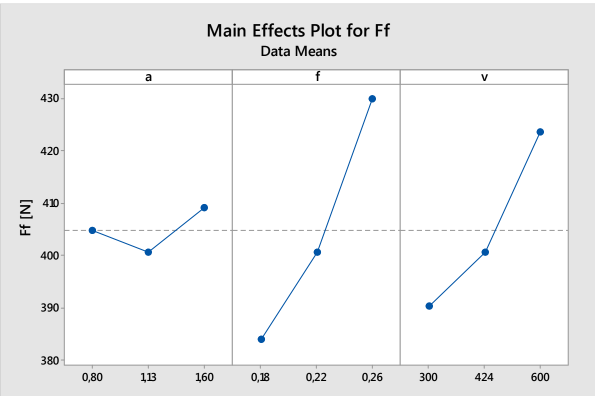

Fig. 6. Effect of cutting parameters on cutting force $\boldsymbol{F_f}$

4. CONCLUSION

Based on the theoretical and experimental studies carried out and the analyzes performed, the following conclusions can be drawn:

- Collecting data on forces in the cutting zone is a complicated process and depends on a variety of factors as well as on the accuracy of the measurement and acquisition system. A properly tuned measurement and acquisition system is a prerequisite for a good experiment.
- Design of experiments and analysis of variance contributes greatly to accurately represent the adequacy and significance of models and parameters, thus facilitating the work of researchers.
- The machinability of CPM 10V tool steel in terms of cutting forces is better with increasing cutting speed (as cutting speed values increase, forces decrease).
- The major influence on the main cutting force is the depth of cut followed by feed rate and the least important is cutting speed.
- Radial cutting force: depth of cut has the greatest influence, while feed rate and cutting speed have no influence.
- Feed rate and cutting speed have a similar influence on feed force while the depth of cut has no influence.

Continuing research in the field of machining CPM 10V tool steel with carbide inserts can go in the direction of expanding the factors influencing the cutting forces in turning. Optimization of the process is also the way to be followed in further research.

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