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The influence of cutting parameters and tool geometry on cutting force in turning hard materials

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Abstract. With the turning operation can obtain complex shape, impossible to do by other process and can process the symmetrical part around an axis. The new technology of turning machine helps to process complex workpiece, with the CNC code can programming each dimension or characteristic. The geometry of tool has a big influence for the shape of the chips, for the friction between the tool and the workpiece, for the cutting force and for durability of the tool. The making of chip and the cutting force of the tool depends on cutting parameters. Within this project is being determined the cutting force according to the parameters. (Feed and Cutting Speed) of the turning with two different tool and different geometry. For experimental procedure, the cutting parameters for the dependance of force on these parameters are varying. You can choose the optimal geometry and parameters depending on the necessary cutting force.
Keywords: turning, chip, CNC, cutting parameter, cutting force

Introduction

In the process of turning, an edge is so pressed into the material, that the material is deformed and begins to flow in the form of chips. The cutting force influences the power during the processing, high forces means a high necessary power of machine (available power being limited). It will appear temporary deformation of tool and stock, which make permanent vibrations and deformations, therefore the processing tolerances will be lost.[1] Technologic process is being characterized by: values of cutting parameters (specific for operations: turning, drilling, milling, grinding), stock material (alloy steel), dimensional characteristic of processing (length, diameter), the material and the geometry of cutting tools (carbide insert, the shape of the tool, the length of active edge, nose radius) and the conditions of processing (cooling and lubricating). The method of determining the cutting parameters have evolved with technical progress made in the construction of machines: CNC machines, multipurpose machine, handling robots, flexible manufacturing lines, high-performance cutting tools, intensive working regimes).[1]
In the modern industry, different methods are being searched to minimize the consumption of tools, materials and increase the precision of machining. [2], [3].
Selecting the optimal cutting parameters, such as Feed and Cutting Speed, is a very important problem for each processing process. In practice, the cutting parameters are selected from the databases offered by the tool manufacturers, but the range given by them are actually starting values and are not optimal values.[4]
Cutting forces influence surface quality, machining accuracy and tool wear [5]. Cutting forces are influenced by the material of the blank, the geometry of the tool and the existing machining conditions. The more the stock is tough, cutting forces will be high.[6] The modeling of the cutting forces through analytical models is performed starting from experimental data and allows the knowledge of the phenomena during the cutting process. [7]
In this work will be analyzed the influence of cutting parameters (speed and advance) on the cutting force when machining a hard material with 2 cutting tools with different geometries. The mathematical

model of this dependence will be established based on experimentally obtained data, knowing that dependence is expressed through an exponential equation.

Experimental procedure and measurements

Processing is carried out on a Speed 20-11 lathe. It has two sleds with tools for processing in the main spindle and another sled for processing in the sub-spindle after the cutting-off the workpiece, Figure 1.

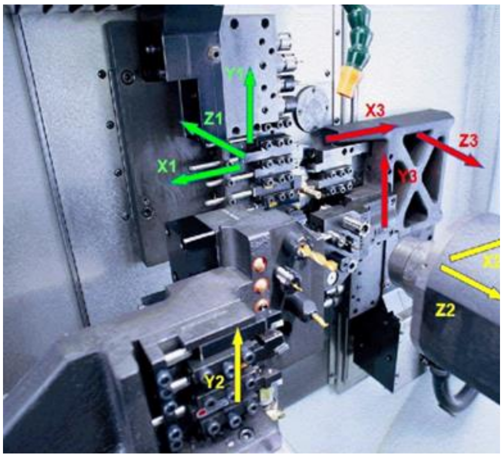
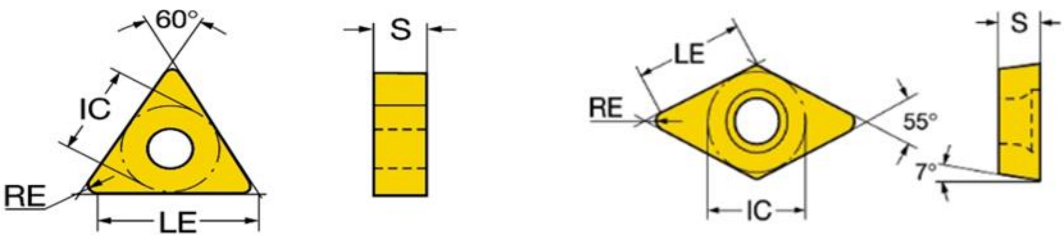


Figure 1 Lathe axes

When the processing is in the main spindle, the sledge 1 is fixed and the axial movement is made by the stock. It has the possibility of moving the sledge on the X and Y axis. The sleigh 3 has the possibility of moving the tools on all three axes: X, Y, Z and the sledge 2 (on the sub-spindle) has the moving only in the direction of Y and the other movement (on X and Z) is made by the sub-spindle.

It will be used a three-axis lathe with several sleds for the analysis of the cutting process. The machining phase used in this experiment is the roughing phase, it is turned from a bar type stock with two cutting tools in the same time.

The cutting parameters will be varied and the cutting forces for two geometries will be measured. Two types of inserts will be tested: the first with null relief angle and the second with positive relief angle. The first insert tested is TNMG 160404, figure 2.a. The shape of this insert is triangular with null relief angle. This type of geometry gives a high rigidity, but also a better durability. Another advantage is that this insert has six cutting edges with which it can process. These tools are used for big depth of cut, for roughing, where there are large cutting forces. The second insert is DCMT 11 T302, is an insert with a positive relief angle (7°), figure 2.b. This is used for smaller depth of cut, where no large cutting forces are required and the Feed are relatively low compared to the TNMG insert. In both cases, the same nose radius R0.4 was used. The insert is made of metal carbide and covered by PVD with TiAIN+Al_2O_3.



a b

Figure 2 Insert geometry

Material to be processed is 42CrMo4 or 1.7225, is a European standard alloy steel, the delivery condition of this steel is mostly tempered and quenched, it has high strength, high toughness, good hardenability, temper brittleness, high fatigue limit, good impact resistance after quenching and tempering, and good low temperature impact toughness. This steel is suitable for the manufacture of large and medium-sized plastic molds requiring a certain degree of strength and toughness, transmission gears, rear axles, load-carrying connecting rods, spring clips and oil depth well drill pipe joints. [8] This turbo shaft has to meet several conditions, because this shaft is subjected to high revs, which means high temperatures and stress. The area where the bearings will be mounted, will be treated by electrical induction and then by tempering to meet the requirements of the material norm.

Table 1 Chemical composition of 1.7225

%	C	Si	Mn	P	S	Cr	Mo	Cu	Ni
Min.	0.38	-	0.60	-	-	0.90	0.15	-	-
Max.	0.45	0.40	0.90	0.025	0.023	1.20	0.30	0.25	0.5

This material has a low sulfur content. This lack of the sulfur leads to the difficulty of the cutting process. An advantage for high sulfur content is that it increases the machinability by cutting steel through the chip breaking (FeS) and lubrication (MnS) effect and increases the wear resistance of steels.
Depending on the functional role of each part, the manufacturer classifies each characteristic in more intervals required for the assembly where the part is used.

Table 2 Mechanical characteristics

Traction stress	Flow stress Rp0.2 [MPa]	Elongation A [%]
1100-1400	>1000	>10

Design of experiments, results and discussion

Following the experimental research on the dependence of the variables X1, X2, it was established that Y can be expressed by an expression bellow [4]:

$F = a \cdot v^b \cdot f^c$ where :

- a, b, c, d are constants;
- v – cutting speed, m/min
- f- feed, mm/r;

This dependency can be linearized by logarithm:

$\lg Fz = \lg a + b \cdot \lg v + c \cdot \lg f$

Making substitutions: $\lg F_z = Y$; $\lg a = A_0$; $b = A_1$; $\lg v = X_1$; $c = A_2$; $\lg f = X_2$; obtain the linear equation. To determine the equation, the coefficients A_0, A_1 and A_2 must be determined.

The input parameters used to perform this experiment are Feed f [mm/r] and cutting speed v[m/min], and output parameter is the cutting Force F[daN] necessary to determine the equation. The cutting force is calculated according to the electric intensity. The cutting force is determined indirectly, measuring the percentage of using the electrical intensity for each motor of the lathe (on each X, Z, Y axis). When performing this experiment, a complete factorial plan with repetition on each point is used (design of experiment, DOE), in this case m=4 (number of experiences) and $n = 5$ (number of repetitions) ➔ $N = 4 \cdot 5 = 20$.

Table 3 Factors and levels used in the experiments and results for TNMG insert

Nr. exp.	v[m/min]	f[mm/r]	mx		mx	mx	mx	mx	
1	93.258	0.2	204.784		289.848	211.085	214.235	207.934	
2	110.528	0.2	236.584		183.419	186.078	183.419	180.761	
3	93.258	0.25	214.235		207.934	217.386	214.235	217.386	
4	110.528	0.25	186.078		191.394	188.736	188.736	186.078	
mz	mz	mz	mz	Mz	my	my	my	my	my
136.184	132.119	137.200	134.151	138.216	100.613	94.516	99.597	100.613	101.630
108.045	116.620	116.620	111.475	110.618	78.890	84.035	84.035	82.320	84.035
153.461	146.347	143.298	145.330	147.363	111.793	110.776	112.809	110.776	111.793
117.478	120.908	117.478	124.338	114.048	92.610	94.325	94.325	94.325	94.325
Input parameters		Forces on X axis			Forces on Z axis		Forces on Y axis		

The range of variation of the input parameters used to perform this experiment is: for the Feed f from 0.2 to 0.25 [mm/r] and for the Cutting Speed v[m/min] from 93.258 to 110.528.

For the first roughing tool, which remove a less material than the second roughing tool, depth of cut is between 1.45-2.05mm. The second tool has another depth of cut: 1.9-3.25mm.
In the case of TNMG insert, the design of experiment will be carried out and the values obtained for the measurements are presented in Table 4.

Table 4 Factors and levels used in the experiments and results for DCMT insert

Nr. exp.	v[m/min]	f[mm/r]	Mx		mx	mx	mx		mx
1	93.258	0.2	31.505		25.204	37.806	25.204		25.204
2	110.528	0.2	18.608		21.266	23.924	18.608		26.583
3	93.258	0.25	25.204		25.204	25.204	25.204		40.957
4	110.528	0.25	26.583		18.608	26.583	26.583		31.899
mz	mz	mz	mz	mz	my	my	my	my	my
85.369	87.402	86.385	81.304	82.320	84.353	86.385	87.402	86.385	85.369
86.608	67.743	66.028	66.885	72.030	73.745	69.458	70.315	72.030	71.173
90.450	91.467	88.418	92.483	94.516	88.418	89.434	89.434	90.450	90.450
78.033	70.315	91.753	85.750	86.608	74.603	75.460	75.460	77.175	75.460
Input parameters		Forces on X axis			Forces on Z axis		Forces on Y axis		

After processing the data using regression analysis, the coefficients for the normed variable equation are obtained, then the coefficients in the natural variable, which are replaced in the initial exponential equation.

Table 5 Coefficients obtained for the equation

Coefficient	Fx	Fz	Fy	Fx	Fz	Fy
	TNMG insert			DCMT insert		
a	3.843501	4.886624	4.442687	3.745367	3.941178	4.156870
b	-0.813445	-1.174688	-1.047717	-1.058204	-0.809008	-1.049594
c	-0.151912	0.650193	0.548177	0.324633	0.620464	0.224565

The equations obtained for the null relief angles are:

$$\begin{aligned} F_x &= 10^{3,843501539} \cdot s^{-0,813445318} \cdot f^{-0,151912847} \\ F_z &= 10^{4,88662433} \cdot s^{-1,174688507} \cdot f^{0,650193088} \\ F_y &= 10^{4,442687245} \cdot s^{-1,047717552} \cdot f^{0,548177762} \end{aligned} \quad (1)$$

The equations obtained for the positive relief angles are:

$$\begin{aligned} F_x &= 10^{3,745367035} \cdot s^{-1,05820416} \cdot f^{0,32463395} \\ F_z &= 10^{3,94117869} \cdot s^{-0,809008094} \cdot f^{0,620464247} \\ F_y &= 10^{4,156870821} \cdot s^{-1,049594375} \cdot f^{0,224565037} \end{aligned} \quad (2)$$

The suitability of the equation to represent the experimental data is verified using the Fisher test (F-test). Through the adequacy test (Model Adequacy Checking) it shall be determined whether the equation chosen to represent the experimental data is appropriate. The suitability of the equation can be tested to represent experimental data using the F (Fisher) test. To apply this test is calculated [9]:

$$F = \frac{s_A^2}{s_D^2} \quad (3)$$

where: s_D^2, standard residual;
s_A^2 adequacy residual.

In case of repetition of experiments at each point, the dispersions are calculated with the relations:

$$s_D^2 = \frac{SR_D}{\nu_D} = \frac{\sum_{k=1}^{m}\sum_{i=1}^{n}\left(Y_{ik} - \overline{Y_k}\right)^2}{m \cdot (n-1)} \quad (4)$$

$$s_A^2 = \frac{SR_A}{\nu_A} = \frac{n\sum_{k=1}^{m-1}\left(Y_k - \hat{Y}_k\right)^2}{m \cdot n - P} \tag{5}$$

where: $\overline{Y}_k - \hat{Y}_k$ represents the differences from the values on the line to the average values calculated for each experimental value for X. The calculated F value is compared to a standard F value. [9]

Table 6 Residuals

Type of insert	s_{Dx}^2	s_{Dz}^2	s_{Dy}^2	s_{Ax}^2	s_{Az}^2	s_{Ay}^2
TNMG	0.001646033	0.000151491	8.06543E-05	4.22898E-06	1.12583E-05	2.1886E-06
DCMT	0.006794192	0.001185581	4.50701E-05	0.000566565	5.03525E-05	3.9149E-06

Table 7 Fisher test

Type of insert	F_x	F_z	F_Y	Fstandard
TNMG	0.00164	0.00015	0.00008	
DCMT	0.00679	0.00118	0.00004	2.54
Conclusion	Adequate	Adequate	Adequate	

To validate the determined models (equations 1 and 2), calculate the values of the forces using the developed model and percentage error. In Table 8, the measured and calculated forces with equations 1 and 2 are presented, then the error, and in figure 3 the graphs of these values are shown to see the proximity between the two methods of determination. The errors obtained from the analytical and experimental calculation for the TNMG test will be analyzed below:

Table 8 Comparison of experimental and predicted cutting force values

v [m/min]	f [mm/r]	F_X meas	F_X model	Eror Fx %	F_Z meas	F_Z model	Eror Fz %	F_Y meas	F_Y model	Eror Fy %
TNMG										
93.258	0.2	225.57	222.56	1.33	135.57	131.33	3.12	99.39	99.05	0.34
110.528	0.2	194.05	193.83	0.11	112.67	107.57	4.52	82.66	82.89	0.28
93.258	0.25	214.23	215.14	0.42	147.15	151.84	3.18	111.58	111.93	0.31
110.528	0.25	188.20	187.37	0.44	118.84	124.37	4.64	93.98	93.68	0.31
DCMT										
93.258	0.2	28.98	27.17	6.25	84.55	82.04	2.98	85.98	85.61	0.42
110.528	0.2	21.79	22.70	4.14	71.85	71.50	0.49	71.34	71.63	0.39
93.258	0.25	28.35	29.21	3.02	91.46	94.22	3.01	89.64	90.01	0.41
110.528	0.25	26.05	24.40	6.31	82.49	82.12	0.45	75.63	75.31	0.42

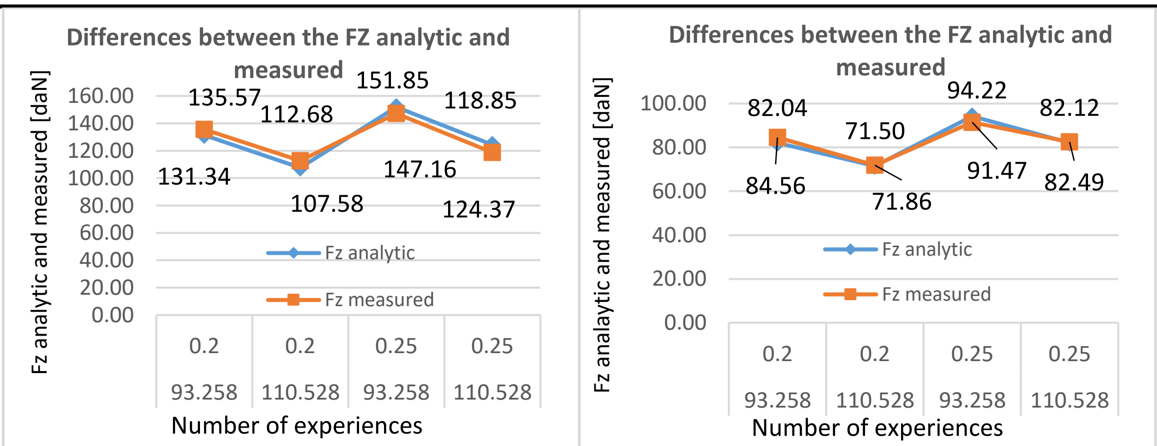


Figure 3. Experimental and predicted cutting force values TNMG/ DCMT

It is noticed that the error obtained is less than 7%, it follows that the model is validated. From the graphical representation of the measured and calculated force results a good concordance of their evolution.

For the two cases, different values for cutting speed and feed will be replaced in each equation to see the dependence of the force on these parameters. At the first replacement, the feed is kept constant and the speed varies, then vice versa. The total cutting force was calculated with the relationship: $F_t = \sqrt{F_x^2 + F_y^2 + F_Z^2}$.

Values for speed and feed will be replaced in the equations obtained. In the first table, the cutting speed varies and the feed is constantly maintained. The values obtained are completed in Table 9.

Table 9. Evolution of the cutting force calculated with equations (1) and (2) according to the cutting speed (v=variable; f= constant)

v	f	Fx	Fz	Fy	Ftotal	Fx	Fz	Fy	Ftotal
[m/min]	[mm/r]	TNMG160404				DCMT11T304			
100	0.1	233.627	77.099	62.961	253.949	20.152	50.431	68.095	87.099
200	0.1	132.938	34.153	30.456	140.594	9.677	28.784	32.897	44.771
300	0.1	95.589	21.212	19.915	99.919	6.301	20.734	21.494	30.523
400	0.1	75.645	15.129	14.732	78.537	4.647	16.429	15.892	23.326

Increasing the cutting speed decreases the cutting forces, but due to the large friction between the cutting edge and the material to be removed, thermal influences will appear. The influence of force in this case is shown in Figure 4.

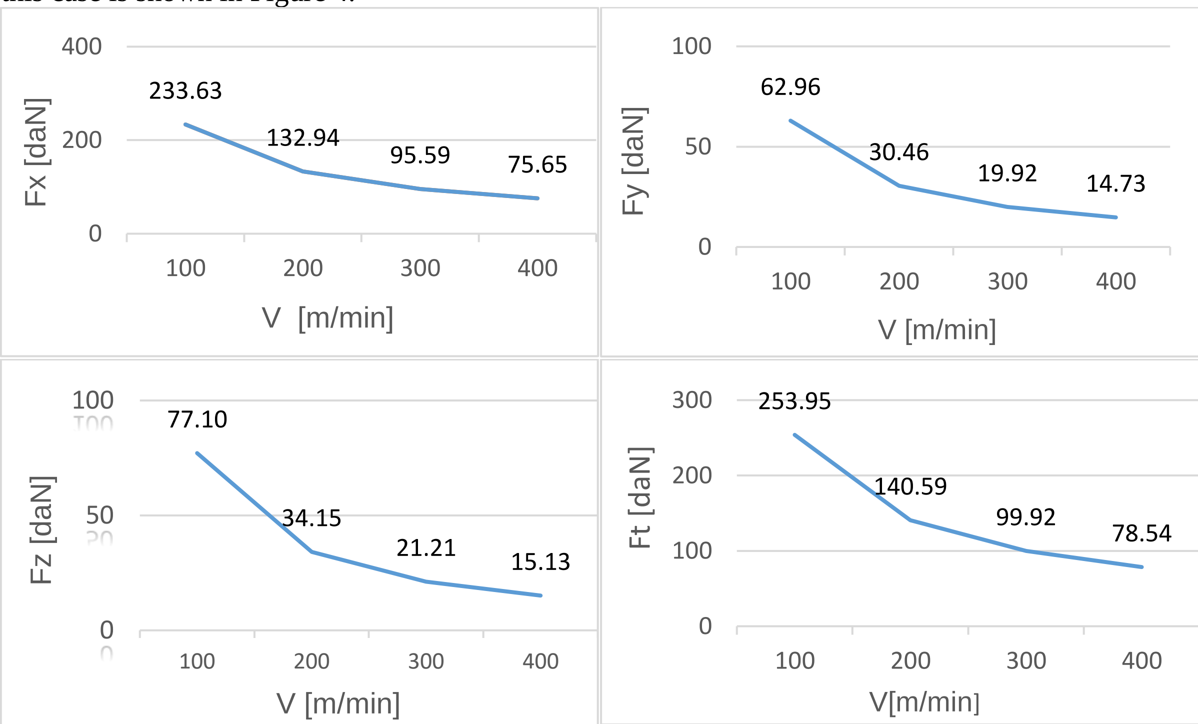


Figure 4. TNMG160404 (v=variable; f=constant)

When varying the cutting speed in the case of processing with an insert with a positive relief angle, we have the same dependence of the cutting force as in the previous case. Differs only the values of forces, which are lower in this case. The friction force with the material is less, but at the same time the insert does not have the same rigidity. The trend of force in this case is shown in Figure 5.

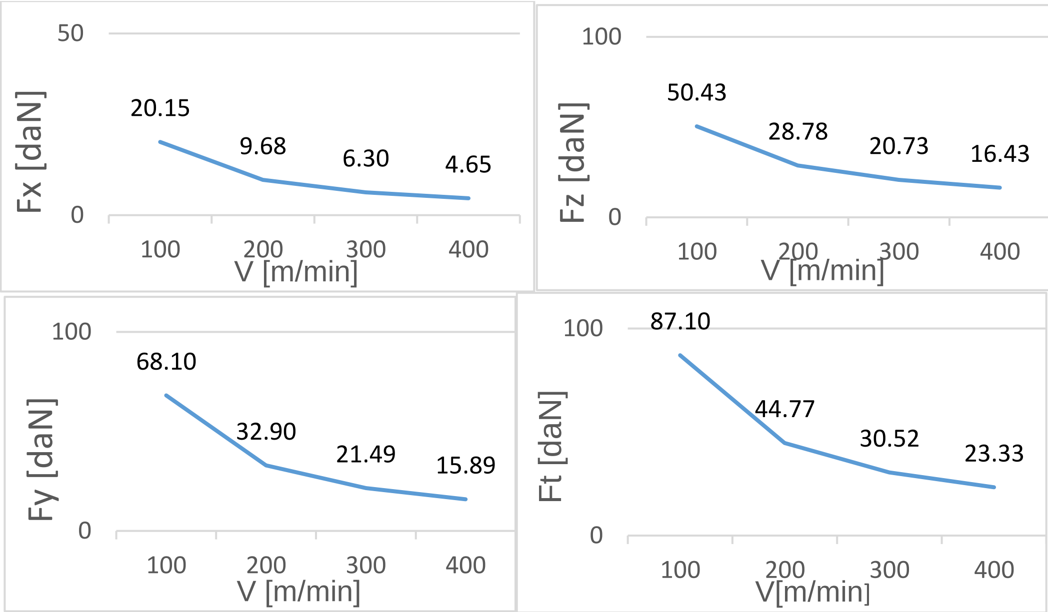


Figure 5. DCMT11T304 (v=variable; f=constant)

Table 10 Evolution of the cutting force calculated with equations (1) and (2) according to the cutting speed (v=constant; f= variable)

s [m/min]	f [mm/r]	Fx	Fz	Fy	Ftotal	Fx	Fz	Fy	Ftotal
		TNMG160404				DCMT11T304			
100	0.1	233.627	77.099	62.961	253.949	20.152	50.431	68.095	87.099
100	0.2	210.277	120.999	92.064	259.486	25.237	77.531	79.564	113.923
100	0.3	197.716	157.498	114.979	277.701	28.788	99.709	87.148	135.519
100	0.4	189.261	189.893	134.620	300.003	31.606	119.194	92.964	154.430

When increasing the feed, the total cutting force increases in both cases. Only one difference is observed on the X axis, where in the case of processing with neutral geometry, the force has a small downward tendency. This happens, because the relief surface is straight over its entire height and has a much greater rigidity. In this case, the force changing is shown in Figure 6.

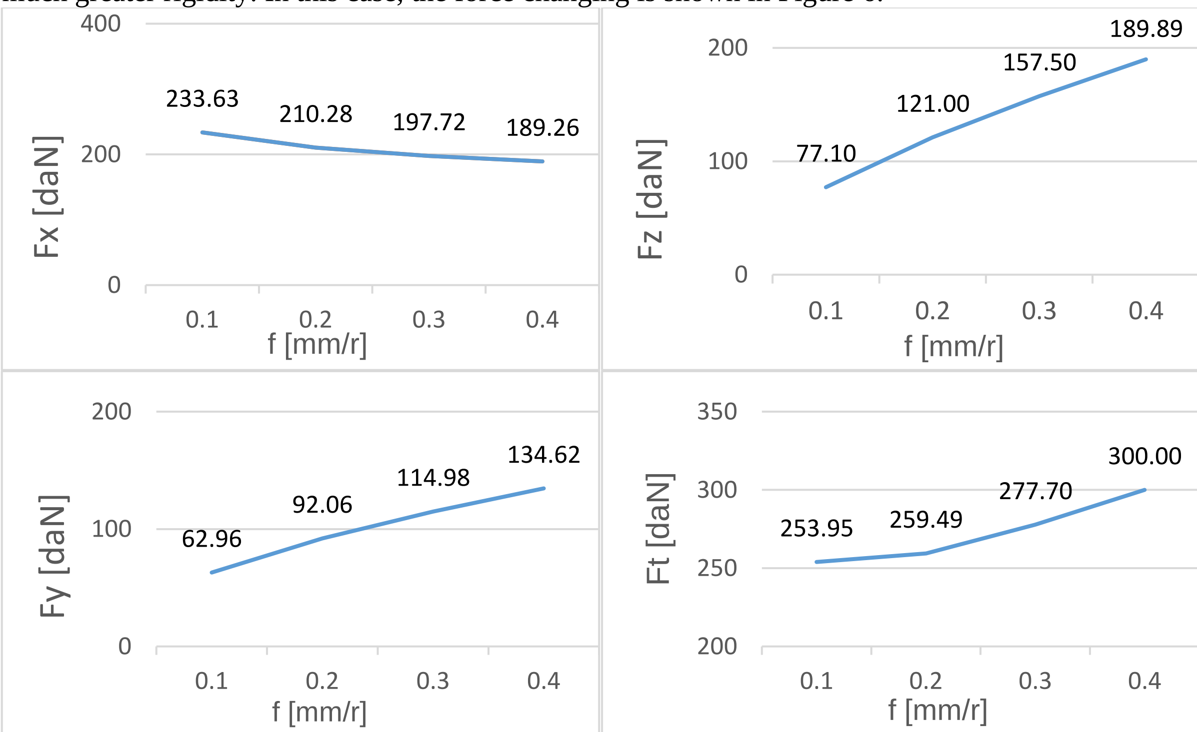


Figure 6. TNMG160404 (v=constant; f= variable)

In the case of positive geometry, the nose tool is more brittle, it can break faster. Because of this it is used more in the finishing phases. Figure 7 shows the dependence of the force for the insert with a positive relief angle when the speed is constant and the feed variable.

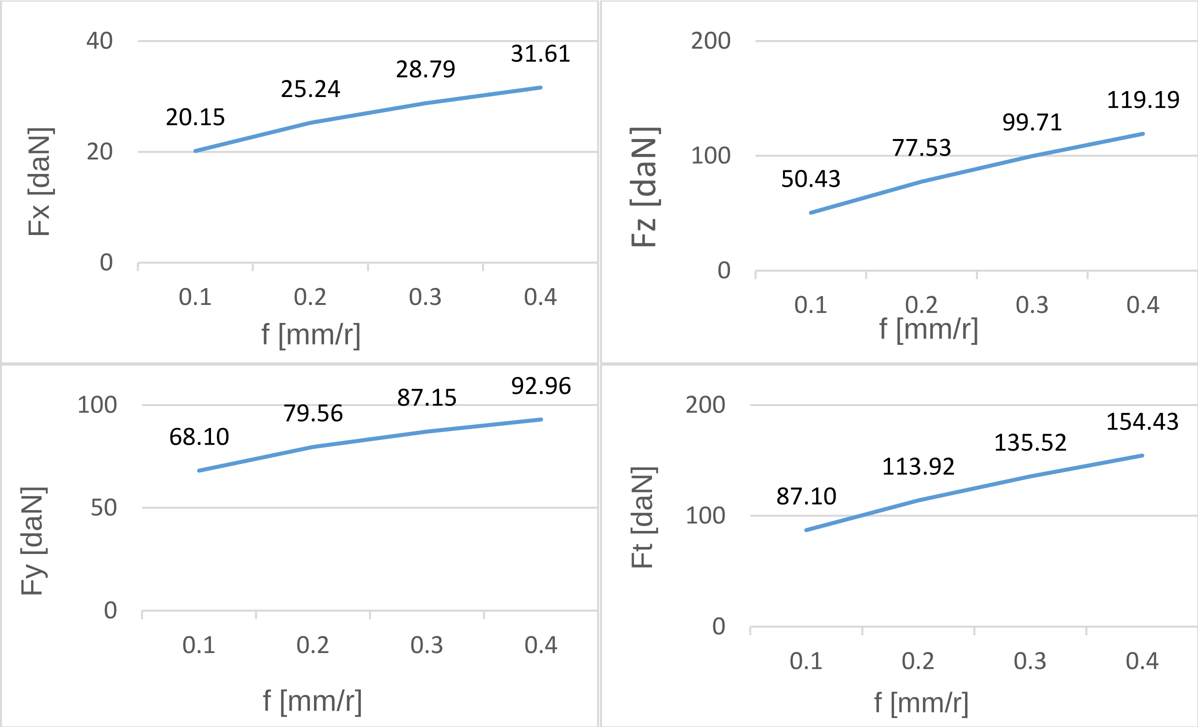


Figure 7 DCMT11T304 (v=constant; f= variable)

When increasing the feed and maintaining the constant cutting speed, the Total Cutting Force tends to high values. The cutting inserts are made in such a way that it can be used with high depth of cut specified by the manufacturer, so that the insert is not necessarily affected by the high cutting forces. Machine tool must provide these forces necessary for processing and the working conditions must not affect the requested characteristics on the part.

Conclusion

This work shows the machinability of a steel 1.7225, depending on the cutting parameters. An experimental study has been presented that compares cutting forces when using two cutting tool geometries. The cutting forces were evaluated in case of increasing the cutting speed, then increasing the cutting advance. [10]

Changing the cutting parameters, we can get small forces, but the size of the chip will be different. In the case of high speeds and small feeds, long chips will form, which will be in the work area, which will lead to repeated stops during turning processes. So, a compromise must be chosen between the cutting force, the type of chip and optimal durability. The tools will be chosen in terms of durability-price ratio and type of chip breaker. When gradually increasing the feed, an increase in the cutting force is observed. A minimum feed must be established, which will be optimal for chip fragmentation. If the durability/price ratio is followed, the cutting parameters must be at a low values, so that the release of the chips is not a problem. If CNC lathes provide cooling with high-pressure pumps, more high parameters can be used, since the cutting edge of the tools would not be subjected to high temperatures.

In conclusion, when processing the roughing of the material 42CrMo2 (1.7225) the following cutting parameters are recommended: f = 0.25 mm /r; v=103.6 m/min, and in terms of insert geometry, the null relief angle is recommended, because this insert is rigid, it has 6 edges, compared to the tool with a positive relief angle that has only 2 cutting edges. The cutting force does not affect, since the machine tool provides the necessary force for processing with these tools. The durability for the first roughing tool, TNMG160404 tool, is 500 workpieces/edge per edge, and 1100 workpieces/edge for the second roughing tool, while the durability in the case of the DCMT11T304 tool is a maximum of 300 workpieces/edge.

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