ANALYSIS OF THE INFLUENCE OF IMPROVED CUTTING TOOLS (WITH OPTIMAL FUNCTIONAL GEOMETRY) ON CUTTING FORCES IN THE PROCESSING OF ALLOY STEELS

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ABSTRACT: The cutting forces generated during machining result from the complex interaction between the cutting tool, the workpiece, and the machine tool. The magnitude and direction of these forces are strongly influenced by the geometry of the cutting tool, as the way in which the cutting edge penetrates the material determines the stress distribution, the thickness of the plastically deformed layer, and the transmission of loads within the technological system. The geometric parameters of the tool — rake angle, clearance angle, nose radius, inclination angle, and edge micro-geometry — have a major influence on the mechanical behavior of the cutting process. Even minor variations in these parameters can significantly alter the main components of the cutting force (tangential, radial, and feed forces). Optimizing the functional geometry of the tool leads to a reduction in cutting forces, improved process stability, decreased tool wear, and enhanced surface quality of the machined part. The experimental study was carried out through longitudinal turning of 42CrMo4 alloy steel (EN 10083-3, Ø50 mm), using two tool variants: a conventional tool (T01) and an improved tool (T02). The experiments, designed according to the factorial plan methodology, enabled a comparative analysis of cutting force components and the establishment of dependency relationships between tool geometry, cutting parameters, and the resulting cutting forces.

Keywords: conventional cutting tool, improved cutting tool, multiple regression analysis, functional tool geometry, cutting force components

INTRODUCTION

The machining process is characterized by a high complexity, given by the simultaneous interaction of mechanical, thermal and tribological phenomena that manifest themselves in the tool-chip-part contact zone. Modeling these phenomena requires a thorough understanding of the mechanisms of severe plastic deformation, heat generation and heat transfer during the cutting process [2]. In the machine building industry, where most components are made through high-precision mechanical machining processes, optimizing cutting regimes becomes essential for reducing manufacturing costs and increasing the functional durability of finished products. This context leads to the need to design and develop new types of cutting tools capable of providing superior performance in terms of wear resistance, thermal stability and tribological behavior in the contact zone [1]. The costs related to cutting tools represent a significant contributor to the total production cost structure. In parallel, the progressive increase in energy consumption and costs associated with cutting processes amplifies the economic impact on industrial processes [3]. From the perspective of optimizing the cutting process, the analysis of cutting forces is of major importance, as they represent essential parameters for the correct sizing of tools and machine tools, for estimating energy consumption and for controlling the quality of the surfaces generated [4].

The machine building industry, characterized by significant economic growth dynamics, imposes high requirements regarding technological efficiency, surface integrity and competitiveness of production costs. In this sense, the creation of optimized functional geometries of tools, in correlation with the selection of adaptive cutting regimes, becomes a determining vector for increasing process performance. Machine tools dedicated to the processing of advanced alloys use large amounts of energy, which makes it necessary to identify technological solutions with a direct impact on energy efficiency.

Numerical modeling and simulation of cutting processes are indispensable tools for analyzing tool–material behavior under variable loading conditions. By modeling the tool–chip interface, it is possible to predict the values of tangential and normal forces, the temperatures generated in the secondary deformation zone, and their effects on tool wear and energy consumption. Numerous studies have been published in the specialized literature on the evaluation of machine tool energy consumption in relation to the processed materials and the tool configurations used [5], [6]. The results of these studies indicate that an optimal selection of cutting parameters (speed, feed, depth of cut) corroborated with an optimized functional tool geometry can reduce the total energy consumption by up to 6–40% [7], [8].

Therefore, further research into the relationship between tool geometry, cutting regime and energy consumption is essential. Minimizing energy consumption can be achieved by implementing advanced tool configurations, adapted to materials with low machinability and high-efficiency cutting regimes.

ANALYSIS AND MEASUREMENT OF FORCES WHEN TURNING PARTS

Cutting forces are the result of the mechanical interaction between the cutting tool and the machined material during the chip removal process. These forces are essential for initiating and sustaining the chip formation mechanism, as they ensure the elastic and plastic deformation of the material in the cutting zone, the generation and propagation of the shear plane, and the chip detachment and evacuation from the active machining zone. Cutting forces must also compensate for the effects of frictional forces that occur both at the interface between the chip and the tool clearance face, and at the interface between the tool seating face and the generated surface of the part [5].

In the analysis of the longitudinal turning process, the force system is decomposed into three main components, related to the orthogonal reference system used in cutting - Figure 1:

- **Tangential force (Main force cutting force), (F_c)** – the dominant component, responsible for the effective cutting and directly correlated with the energy consumption of the process.
- **Axial force (Feed force), (F_f)** – the component associated with the tool movement in the feed direction, influencing the machining stability and surface roughness.
- **Radial force (Pressure force), (F_p)** – the component that acts perpendicular to the machined surface, having an impact on the rigidity of the part-tool-machine system and on the vibration tendency [6].

The mode of action and interdependence of these components of the cutting force, in the case of the longitudinal turning operation, are schematically presented in Figure 1.

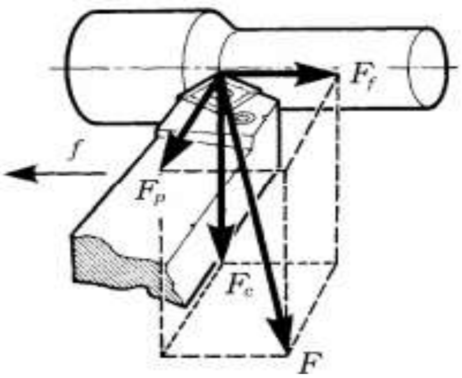

Figure 1. Cutting force components in longitudinal turning [6]

Cutting forces are an essential factor in assessing the machinability of materials, directly influencing the energy consumption during the machining process. High values of these forces can lead to significant elastic deformations of the tool and the part, as well as to the appearance of vibrations or even plastic deformations of the semi-finished product, which can lead to non-compliance with the imposed tolerances [8]. [9], [10].

The studies conducted aimed to analyze the variation of cutting forces depending on the modification of the functional geometric parameters of the tool used in the turning operation.

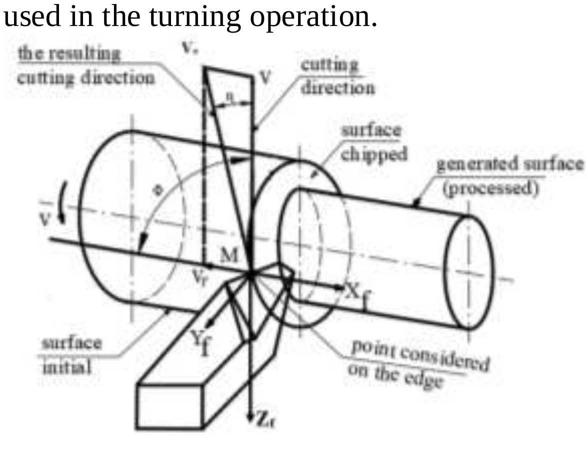

Figure 2. Kinematics of turning with longitudinal feed

To develop a mathematical model regarding the evolution of cutting force values in relation to tool geometry, the starting point was the relationship:

$$F_i = K_{i11} \cdot a_p \cdot f^{i-c} \left(\sin \chi_r\right) \quad (1)$$

where: K_{c11} is the specific cutting force;

χ_r - cutting edge angle; ic – exponent that is determined experimentally, i =c, f, p.

To simplify equation 1 and considering the significance of the coefficients and exponents, the following notation was created:

$$K_{i11} \cdot a_p \cdot f^{i-c} = k \quad (2)$$

Thus, equation 2 becomes:

$$F_i = k \cdot \sin \chi_r \quad (3)$$

The angle of the main cutting direction η can be expressed with a correlation of the form:

$$\eta = arctg(\frac{f}{\pi D_M} \cdot \sin \chi_r) \quad (4)$$

where: D_M is the diameter of a point M on the surface of the workpiece

Considering equations 3 and 4, equation 5 was obtained, which shows the dependence of the cutting force on the angle of the main cutting direction η and the diameter of a point on the workpiece D_M .

$$F_i = k \cdot \frac{tg\eta \cdot \pi \cdot D_M}{f} \quad (5)$$

Cutting force modeling plays an essential role in predicting the behavior of machining processes, as well as in determining the final characteristics of the parts obtained. At the application level, cutting force values can be used for sizing fixture systems, as well as for ensuring geometric accuracy and surface quality of the machined part.

Although direct measurement of forces and subsequent adjustment of machining parameters in the numerical control (NC) program are possible solutions, they are often limited by the high cost of monitoring equipment and the difficulty of operationally modifying control data.

In this context, it becomes necessary to develop alternative methods for controlling cutting forces, which can be effectively applied in different machining processes.

Based on equation 5, an optimal range of variation of the functional geometric parameters of the tool can be determined, so that the cutting force is minimized, implicitly contributing to reducing energy consumption in the cutting process.

MATERIALS USED IN EXPERIMENTAL RESEARCH

The machine building industry uses a wide range of materials to make components and structures, each selected according to the required mechanical and thermal properties.

These materials must combine strength and durability with the ability to meet the specific requirements of each type of machine or component.

With the rapid development of the industry, the materials used in machine construction have experienced significant progress, especially in terms of properties that allow increasing the performance of parts in operation. In this context, metallic materials remain dominant due to their superior mechanical-physical properties, which ensure strength, rigidity and durability under various operating conditions.

With the advent of modern materials with high mechanical and physical properties, the development of new manufacturing and processing technologies was required, capable of exploiting these properties under optimal conditions, both for the development of the material and for the precise processing of the component parts.

Based on these considerations, we decided to use 42CrMo4 steel semi-finished products (according to EN 10083-3 standard) in the research, with a diameter of Ø50 mm, according to Table 1.

Table 1. Chemical composition and mechanical properties.

No Ex	Materials used in conducting research	Diameter D [mm]	Cutting speed V [m/min]	The advance, f [mm/rev]	Depth of cut, a_p[mm]
LONGITUDINAL FEED TURNING					
1.	Alloy steel 42CrMo4 - EN 10083-3	Φ50	[90-140]	[0.2-0.36]	[0.9-3.6]

The cutting regime parameters are according to Table 2.

Table 2. Cutting mode parameters.

No Ex	Materials used in conducting research	Diameter D [mm]	Cutting speed V [m/min]	advance f [mm/rev]	Depth of cut, a_p[mm]
LONGITUDINAL FEED TURNING					
1.	42CrMo4 - EN 10083-3	Φ50	[90-140]	[0.2-0.36]	[0.9-3.6]

PRESENTATION OF TOOLS USED FOR APPLIED RESEARCH

For the experimental research, a numerically controlled SN 400 lathe was used, equipped with a SCLCL 2525 M12 turning tool and a DCMT11T308EN-SM CTC 2135 carbide insert.

The tool-insert assembly has the following constructive geometry: clearance angle γ = 8°, seating angle α = 6°, main attack angle
χr = 95° and cutting edge inclination angle λ = 8°.

The turning process is complex, especially for materials with high physical-mechanical properties, because the functional geometry of the tool can change during machining, influencing the cutting conditions.

During the experiments, 2 variants of cutting insert fixation were tested:

- **T01** – classic tool, Figure 3.a;
- **T02** – improved tool with a spring washer under the insert, Figure 3.b

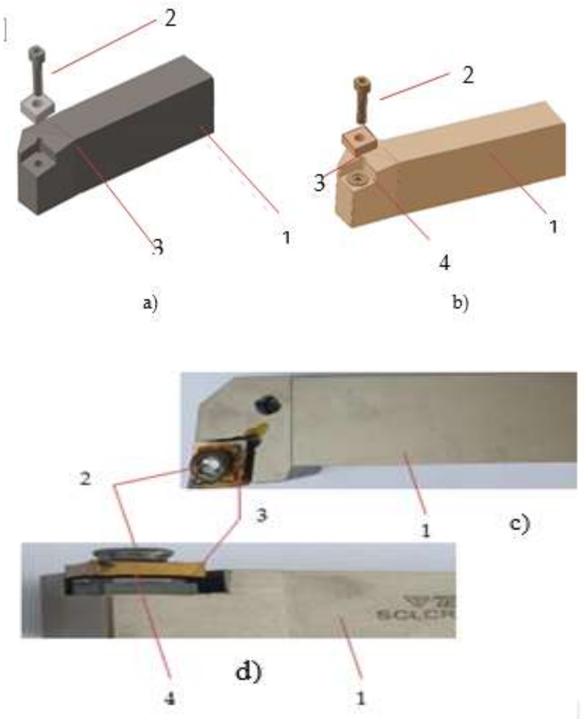

Figure 3. Turning cutting tools used in the research: a, c - in the classic version (T01); b, d - with improved constructive form with an elastic washer (T02); 1-knife body; 2-fixing screw; 3-removable insert; 4 - elastic washer; d - improved cutting tool used during research

As for the spring washer, it is a spring-disc washer, Figure 4, which corresponds to the DIN 2093 B standard, A2 1.4305 steel, and is produced by Vinsco Spring Limited, Changzhou, China, it has been additionally processed by machining, Figure 4 a, so as to ensure an optimal value of the elastic system created on the entire active part of the cutting tool.

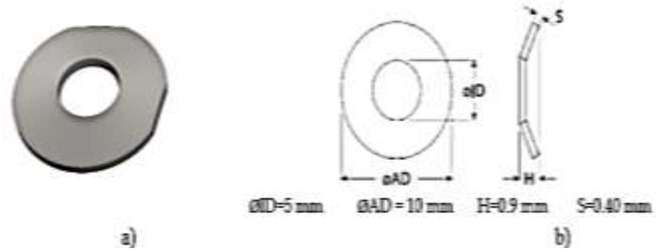

Figure 4. Spring-disc spring washer, DIN 2093 B:

FORCE MEASUREMENT IN TURNING MACHINING

In order to monitor the forces developed during the cutting process, the experimental setup shown in Figure 5 was used, which allows the determination of the force components on the three orthogonal axes. A piezocapacitive force sensor, model PCB 261A13 (PCB), capable of recording both dynamic and quasi-static loads was used for the measurements. The sensor has an electrical capacitance of 70 pF and has a maximum measurement limit of 44.48 kN in the Z direction, and 19.57 kN in the X and Y directions, respectively.

Before performing the measurements in the turning process, the sensor was subjected to a calibration operation, consisting of applying static forces in the range of values corresponding to the working range. The calibration was performed using an Instron 5587 tensile-compression testing machine, to ensure the accuracy and reproducibility of the recorded values.

The electrical signal generated by the force sensor is transmitted via a low-noise cable to the CMD 600 digital load amplifier (HBM). The amplified signal is subsequently processed and recorded by the Quantum X MX840B data acquisition system (HBM). For the acquisition, processing and analysis of the force values during the technological process, the Catman software package was used, integrated into the acquisition system.

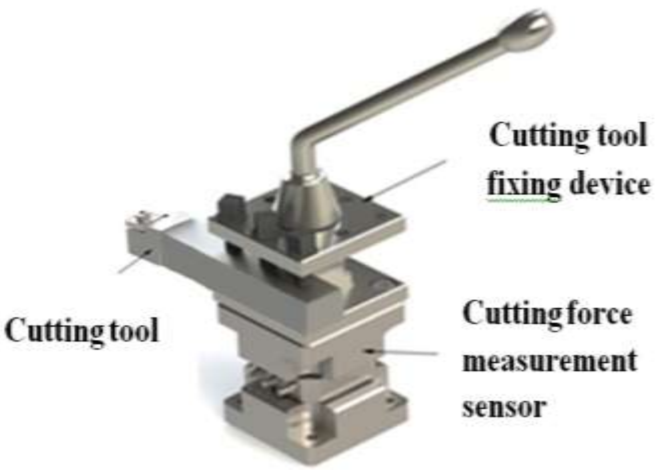

Figure 5. The system used to measure cutting forces.

RESEARCH METHODOLOGY USED

Experimental research was the main method used, which involves the controlled modification of independent variables to observe the effect on the dependent variable, under well-defined conditions. The experiment included a control group and an experimental group, to allow for the highlighting of causal relationships.

To ensure the validity of the results, procedures for controlling confounding variables, randomization, and statistical analysis of the obtained data were applied.

This method allows for the precise assessment of the influence of technological factors and the formulation of scientifically substantiated conclusions.

In order to conduct the experimental research, we used the factorial experiment method, the design of which is presented in the following table.

Table 3. Factorial experimental design used to conduct the research

Exp. no.	Input variable values (independent) Cutting parameters						The value of the measured output variable [daN],	
	Cutting depth a_p [mm]		advance [mm/rev]		Cutting speed [m/min]		The result (output variable), Cutting force	
							Tool T01	Tool T02
	-1	+1	-1	+1	-1	+1		
1	x		x		x			
2	x		x			x		
3	x			x	x			
4	x			x		x		
5		x		x		x		
6		x		x	x			
7		x	x			x		
8		x	x		x			
Average value of the output variable								

Steel blanks were used in the research, and the cutting regime parameters were selected according to Table 2. The input variables (controlled factors) considered in the experiment were: cutting depth, feed and cutting speed.

Based on recommendations from the specialized literature [7], two levels were established for each parameter (corresponding to the limits of the allowed range), which, within a full factorial design with 3 factors, led to the realization of 8 experiments, presented in Table 3.

The minimum recommended level for each cutting parameter (depth of cut, feed, cutting speed) was assigned the value "–1", and the maximum level was assigned the value "+1". The output variables analyzed were: vibration amplitude, according to STATISTICA software, by performing multiple regression analysis for each output variable. The regression analysis allowed establishing the relationships between the dependent variables and the input factors, respectively quantifying the influence of the cutting regime parameters on the system behavior and obtaining the mathematical models necessary for interpreting and predicting the results.

EXPERIMENTAL RESULTS OBTAINED

The values of the forces F_c, F_f and F_p (daN) presented in Table 4, Table 5, Table 6 obtained from the longitudinal feed turning of the material 42CrMo4 - EN 10083-3 - Ø 50 mm, using the cutting tools T01 and T02, respectively, were statistically analyzed with the help of the specialized software STATISTICA, using the multiple regression method. The results of this multiple regression analysis for each type of cutting tool are presented in Table 7.

Table 4. Values of the F_c component for the 2 cutting tool variants, daN

No. Exp.	Material: 42CrMo4 -EN 10083-3 - Ø 50 mm ;							
	Cutting parameters						Measured force value [daN].	
	Cutting depth a_p [mm]		advance [mm/rev]		Cutting speed [m/min]`		The value of the F component $_c$	
	0.9	3.6	0.2	0.36	90	140	Cutting tool T01	Cutting tool T02
	-1	+1	-1	+1	-1	+1		
1	x		x		x		122.5	118.7
2	x		x			x	124.8	121.2
3	x			x	x		185.7	174.8
4	x			x		x	194.7	186.9
5		x		x		x	625.8	612.4
6		x		x	x		618.78	608.7
7		x	x			x	447.89	427.9
8		x	x		x		435.9	422.5
Average cutting force value							344.50	334.13

Table 5. Values of the component F_f for the 2 cutting tool variants, daN.

No. Exp.	Material: 42CrMo4 -EN 10083-3 - Ø 50 mm ;							
	Cutting parameters						Measured force value [daN].	
	Cutting depth a_p [mm]		advance [mm/rev]		Cutting speed [m/min]		The value of the F component $_f$	
	0.9	3.6	0.2	0.36	90	140	Cutting tool T01	Cutting tool T02
	-1	+1	-1	+1	-1	+1		
1	x		x		x		24.78	21.54
2	x		x			x	25.47	22.09
3	x			x	x		29.87	25.78
4	x			x		x	31.25	27.89
5		x		x		x	99.78	94.78
6		x		x	x		96.58	92.58
7		x	x			x	82.54	78.58
8		x	x		x		80.36	75.89
Average cutting force value							58.82	54.89

Table 6. Values of the F_p component for the 2 cutting tool variants, daN

No. Exp.	Material: : 42CrMo4 -EN 10083-3 - Ø 50 mm ;							
	Cutting parameters						Measured force value [daN].	
	Cutting depth a_p [mm]		advance [mm/rev]		Cutting speed [m/min]		The value of the F component $_p$	
	0.9	3.6	0.2	0.36	90	140	Cutting tool T01	Cutting tool T02
	-1	+1	-1	+1	-1	+1		
1	x		x		x		17.54	14.58
2	x		x			x	18.65	16.01
3	x			x	x		21.85	18.75
4	x			x		x	23.58	19.68
5		x		x		x	72.58	68.78
6		x		x	x		69.87	65.89
7		x	x			x	54.78	50.14
8		x	x		x		51.98	48.36
Average cutting force value							41.35	37.77

Table 7. Parameters obtained after performing the multiple regression analysis applied for the force values F_c, F_f, F_p,

(daN), obtained during longitudinal feed turning of the material 42CrMo4 -EN 10083-3 - Φ 50 mm

Cutting tool use yourself	**Material: 42CrMo4 -EN 10083-3 - Ø 50 mm ;**						
	The values of the regression parameters obtained after performing the multiple regression analysis						
	Cutting force component $F_{c,}$						
	R^2	F	df	p	$a_p b^*$	$f b^*$	$V b^*$
T01	0.979	63.97	3.4	0.0007	0.940	0.309	0.019
T02	0.974	51.55	3.4	0.0011	0.939	0.314	0.015
Cutting force component $F_{f,}$							
T01	0.991	161.41	3.4	0.0001	0.983	0.175	0.029
T02	0.991	154.49	3.4	0.0001	0.980	0.172	0.030
Cutting force component $F_{p,}$							
T01	0.977	56.86	3.4	0.0009	0.984	0.256	0.048
T02	0.972	47.57	3.4	0.001	0.978	0.255	0.041

In the machining process of the 42CrMo4 - EN 10083-3 material, with a diameter of Φ 50 mm, the T02 cutting tool stood out for its significantly superior performance compared to the classic T01 cutting tool. It recorded the best results, demonstrating high efficiency in reducing cutting forces.

The advanced efficiency of the T02 tool is documented in Tables 4, 5, and 6. Thus, for the machining of 42CrMo4 - EN 10083-3 material with a diameter of Φ 50 mm, the smart tool T02 represents the optimal solution. The average values of the cutting force components (Fc, Ff, Fp), determined for each tool type and material, have been centralized and are presented in Figure 6, providing a clear comparative picture of the tool performances under various machining conditions.

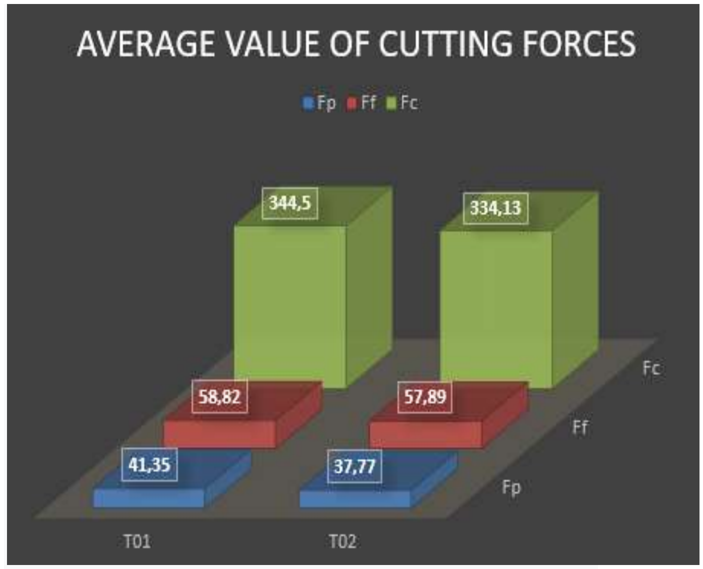

Figure 6. -Graphical representation of the performances obtained by the 2 tools T01 and T02 respectively

After performing multiple regression analysis on the measured values of the cutting force components for the 42CrMo4 material, machined with tools T01 and T02, the following conclusions can be drawn:

- **Quality of mathematical models**

The high values of the coefficient of determination (R^2 between 0.97 and 0.99) indicate that the developed regression models describe very well the evolution of the cutting forces as a function of the machining parameters. This means that the variations in the forces are almost entirely explained by the variations in the technological parameters considered (depth of cut, feed and cutting speed).

Also, the very low values of the probability $p < 0.05$ confirm the statistical significance of the models, which demonstrates that the results are conclusive and reproducible.

- **Influence of technological parameters**

The analysis of the regression coefficients shows that the cutting depth (a_p) has the greatest influence on all the components of the forces (F_c, F_f, F_p). This result is logical, because increasing the depth leads to the removal of a larger volume of material, which determines a considerable increase in the mechanical effort exerted by the tool.

The feed (f) has an average influence on the forces. Increasing the feed causes a thicker chip, which additionally demands the tool, but the effect remains smaller compared to that of the depth.

The cutting speed (V) has **the least influence**

Thi.s is explained by the fact that the speed primarily affects the thermal regime in the cutting zone, and not the amount of material removed. Therefore, the influence of the speed on the value of the forces is minimal.

- **Behavior of tools T01 and T02**

The differences observed between the models obtained for tools T01 and T02 are relatively small, but may indicate **differences in cutting efficiency** . Thus, the tool that shows slightly lower values of the measured forces for the same parameters can be considered **more efficient.**

CONCLUSIONS

The study highlights that optimization of the cutting process should be achieved primarily by controlling **the depth of cut** , as this determines the most significant increase in cutting forces. Feed adjustments can be used for fine-tuning the process, while cutting speed can be selected mainly based on thermal, tool life and surface quality criteria, with little impact on the level of forces.

- **Classic tool performance (T01) compared to the improved tool (T02)**

Comparing the results for the two tools highlights differences in the level of cutting forces and process efficiency. Tool T01 (classic tool) shows slightly higher force values, which indicates higher mechanical stress, lower energy efficiency and a possible tendency towards faster wear under identical working conditions. In contrast, tool **T02**, designed to improve the cutting process, generates lower force values, which confirms a **more stable and efficient operation** . This can be attributed to an optimized geometry.

➢ **Technological advantages of the T02 tool**

Using the improved tool has the following direct benefits:

- decrease in energy consumption in cutting time;
- reducing the stress on the main shaft and of the mechanical elements of the machine;
- **slower tool wear** → tool life increased life;
- the possibility of adopting regimes more aggressive cutting without affecting process stability;
- improving surface quality obtained thanks to a more uniform process.

The comparative analysis shows that **the improved cutting tool T02 offers superior performance** compared to the classic tool T01, due to lower cutting forces and increased process stability.

Consequently, for machining 42CrMo4 material in conditions of efficiency, precision and durability, **T02 represents the optimal solution**,allowing both increased productivity and reduced operating and maintenance costs.

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