ANALYSIS OF THE DYNAMIC BEHAVIOR OF CUTTING TOOLS WITH OPTIMAL FUNCTIONAL GEOMETRY IN THE PROCESSING OF ALLOY STEELS

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ABSTRACT: Vibrations, including the chatter phenomenon, result from the complex dynamic interaction between the cutting tool, the workpiece, and the machine tool. The geometry of the cutting tool plays a decisive role in this process, as the way in which the cutting edge engages with the material determines both the cutting forces and their transmission to the technological system. The main geometric parameters of the tool — rake angle, clearance angle, nose radius, inclination angle, and edge micro-geometry — have a significant influence on the dynamic behavior of the machining process. Even slight variations in these parameters can lead to major changes in system stability. Optimizing the cutting tool geometry contributes to reducing vibration amplitudes, increasing cutting stability, and improving surface quality through lower roughness. An appropriate functional geometry enables higher stable cutting depths, leading to greater productivity without compromising dimensional accuracy or surface integrity. In this study, alloy steel 42CrMo4 (EN 10083-3) samples of Ø50 mm were machined through longitudinal turning using two tool variants: a conventional tool (T01) and an improved one (T02). Vibrations were measured along Y and Z directions and analyzed using the Fast Fourier Transform (F.F.T.). The results were statistically processed through multiple regression to determine correlations between tool geometry, cutting parameters, and vibration levels.

Keywords: tools, transformation method fast Fourier (FFT), vibrations, multiple regression analysis, functional geometry.

INTRODUCTION

Machining processes are often affected by a series of technical problems generated by dynamic phenomena that occur during the machining process. These phenomena lead to reduced productivity, reduced surface quality and, implicitly, increased manufacturing costs [1] .

The modern development of the manufacturing industry is based on several essential principles: flexibility of the manufacturing process (especially the machine- tool -tool relationship), obtaining superior surface quality and keeping production costs as low as possible. In order to comply with these principles, the cutting tool plays a decisive role, which is why it is necessary to use tools with optimal geometry [2].

The geometry of cutting tools is initially designed as a constructive geometry, but during the cutting process it is transformed into a functional geometry [3]. The functional geometry directly influences the course of the machining process and, accordingly, the quality of the parts obtained. Currently, the emphasis is placed mainly on the constructive geometry, without always taking into account the fact that the functional geometry is also influenced by technological parameters, such as cutting speed, feed and dimensions of the machined part [9].

It is important to emphasize that the use of tools with inappropriate geometry favors the appearance of vibrations, dynamic manifestations with negative effects on the process and the result of the machining [11].

At the same time, the creation of high-performance products requires the use of materials with improved properties, which implies adjustments to the technological machining processes. Therefore, it is necessary to adopt technical solutions that allow the sustainable flexibility of the cutting technological processes, in order to ensure the efficiency and quality of production.

Machining of parts by cutting is currently the main method used in the machine building industry to generate functional surfaces.

Of all the machining processes, cutting operations have a share of approximately 70% in the manufacture of components in the machine building industry, which explains their importance in the development and competitiveness of the industrial sector.

Mechanical cutting processes are complex, however, because the technological system consisting of the machine tool, the fixture, the tool and the workpiece (the M.U.S.D.P. system) is predominantly elastic [1]. This elasticity determines the occurrence of inevitable dynamic phenomena during machining. The vibrations generated can negatively affect the quality of the surfaces obtained, reduce production capacity, lead to premature wear of the machine tool and tools, and increase manufacturing costs due to the need for corrective interventions and additional resource consumption.

The monitoring and evaluation of these dynamic phenomena is carried out through specialized measurement and analysis techniques, which track both the parameters formed in the cutting process and the rigidity of the technological assembly. Vibrations occur as a result of the interaction between the components of the M.U.S.D.P. system and the variable mechanical stresses to which it is subjected during machining.

The dynamics of the machine tool play an essential role in the stability of the cutting process.

In turning operations, three main types of vibrations can be identified:

- vibration free;
- vibration forced;
- vibration self-excitement(chatter)[10].

The first two categories can be reduced by identification and elimination sources of excitation . In exchange, vibrations self-excited are more difficult to control because of mechanisms complexes that generate them, being explained by may many theories, such as: hypothesis Taylor 's theory his Kashirin, theory his Sokolovsky, theory his Harness and Grig, respectively theory Tobias.

The need for vibration control is increasing in the context of current industrial demands for increased productivity, precision and reliability, while reducing costs and scrap. Vibration reduction methods are divided into two categories:

❖ **Passive methods**, based on:

- use of tools or I carry a tool with Amortization integrated,
- gripping devices optimized ,
- increasing the rigidity of the technological system [7].

❖ **Active methods,** which use real time vibration monitoring and the application of compensation signals to achieve the anti-resonance phenomenon, being effective over a wider frequency range [5][8].

Analysis of technological processes has shown that the reduced rigidity of the technological system accentuates the negative effects of vibrations and affects the performance of turning processing. Therefore, increasing rigidity and effectively managing dynamic phenomena are essential conditions for optimizing the cutting process [12,13].

ANALYSIS OF THE EVOLUTION OF THE FUNCTIONAL GEOMETRY OF THE TOOL WHEN TURNING WITH LONGITUDINAL ADVANCE

The longitudinal feed turning process is carried out according to the kinematic scheme illustrated in Figure 1. In the case of this operation, the difference between the designed and actual geometric parameters results from the change in the direction of the effective cutting speed (Ve) relative to the main cutting speed (V), as a result of the introduction of the feed speed (V_f). Based on the scheme in Figure 1, the effective cutting speed V_e can be determined, which forms an angle η with the direction of the main speed V. The value of this angle η, called the angle of the main cutting direction, can be calculated using the velocity triangle, according to the relationship [2],[6]:

$$tg\eta = \frac{v_f}{v_e} = \frac{n \cdot f}{\pi \cdot D_M \cdot n} = \frac{f}{\pi \cdot D_M} \quad (1)$$

where: f is value work progress in mm/rev:
n - speed of the part ; D_M - diameter point cutting edge current in which the analysis is done .

In time conduct the processing process by splintering geometrically tool construction chipper will amend in a geometry functional.

The changes geometrically products refer to the seating angle (α) and the clearance angle (γ). Thus geometrically functional of the tool will be characterized by seating angle effective (α_{Fe}) respectively clearance angle effective (γ_{Fe}). In these terms angles What characterized geometrically the functional properties of the tool can be expressed with the relationships:

$$\gamma_{Fe} = \gamma + \eta$$
$$\alpha_{Fe} = \alpha - \eta \quad (2)$$

Also, by replacing the angle η in the corresponding expressions, the calculation relations for determining the functional geometry of the cutting tool are obtained:

$$\gamma_{Fe} = \gamma + arctg\frac{f}{\pi \cdot D_M}$$
$$\alpha_{Fe} = \alpha - arctg\frac{f}{\pi \cdot D_M} \quad (3)$$

Analyzing relations (2) and (3), it can be observed that differences appear between the constructive geometry and the functional geometry. Thus, the clearance angle tends to increase, which, in certain situations, can be advantageous. On the other hand, the seating angle decreases, with the risk that it may become very small or even negative, in which case the cutting process can no longer proceed under normal conditions, because the active edge would no longer allow adequate chip evacuation.

If the functional geometry of the cutting tool is analyzed in a longitudinal section, then the values of the angles corresponding to the functional geometry can be determined with the following relationships:

$$\gamma_{Fe} = \gamma + arctg\frac{f}{\pi \cdot D_M}\sin\chi_r$$
$$\alpha_{Fe} = \alpha - arctg\frac{f}{\pi \cdot D_M}\sin\chi_r \quad (4)$$

Relations (4) show that the functional geometry of
The tool in the longitudinal plane also depends on the analysis diameter of the part, denoted
D_M.

This dependence can lead to a variable roughness of the machined surface, depending on the diameter of the part. Under these conditions, it becomes necessary to identify technical solutions that allow obtaining a stable functional geometry that is favorable to the cutting process.

A modern direction in this regard is the use of intelligent cutting tools, capable of dynamically adapting their geometry, depending on the actual machining conditions.

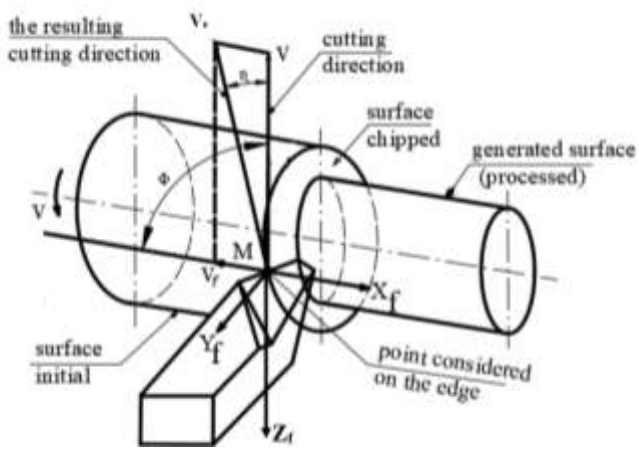

Figure 1. Kinematics of turning with longitudinal feed

MATERIALS USED IN EXPERIMENTAL RESEARCH

The machine building industry uses a wide range of materials to make components and structures, each material being 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 and 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 our research , with a diameter of Ø50 mm, according to table no. 1.

Table no. 1 - Composition CHEMICAL and property mechanical .

ID number	Materials used in conducting research	Diameter D [mm]	Speed splintering V [m/min]	The advance f [mm/re]	Depth of cut , a_p [mm]
LONGITUDINAL FEED TURNING					
1.	Steel alloy 42CrMo4 - EN 10083-3	Φ50	[90-140]	[0.2-0.36]	[0.9-3.6]

The cutting regime parameters used in the experimental research are according to Table 2.

Table no.2- Parameters cutting regime .

ID number	Materials used in conducting research	Diameter D [mm]	Speed splintering 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 and mechanical properties, because the functional geometry of the tool can change during machining, influencing the cutting conditions.

During the experiments, 2 options for fixing the plate were tested:

- **T01** – classic tool, Figure 2.a;
- **T02** – improved tool with a spring washer under the insert, Figure 2.b

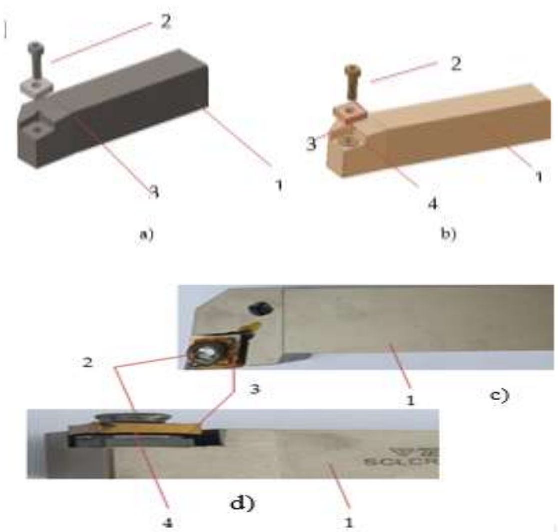

Figure 2. Turning cutting tools used in the research:
a, c - in the classic version (T01); b, d - with improved constructive form with an elastic washer (T02); 1 - knife body; 2 - fixing screw; 3 - removable insert; 4 - elastic washer d - special cutting tool used during research

As for the spring washer, it is a spring-disc washer, Figure 3, which corresponds to the DIN 2093 B standard, A2 1.4305 steel, and is produced by Vinsco. Spring Limited, Changzhou , China, this was further processed by machining, Figure 3 a, so as to ensure an optimal value of the elastic system created on the entire active part of the cutting tool.

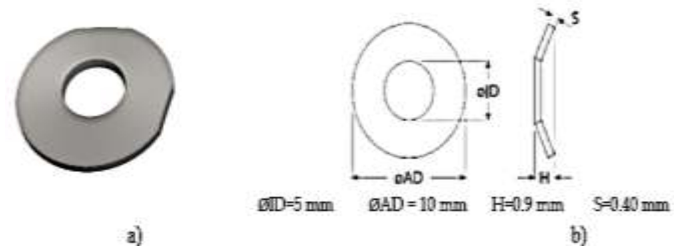

Figure 3. Spring-disc spring washer, DIN 2093 B:

VIBRATION MEASUREMENT IN TURNING MACHINING

Machining generates constant vibrations, classified into forced, self-excited and relaxation vibrations. The objective of the research was to reduce self-vibrations by using an improved cutting tool.

The phenomenon of self-vibrations is explained by several theories: variation of cutting forces (Taylor), improper geometry of the clearance face (Kaşirin), modification of the tool geometry during machining (Sokolcvsky) and variation of the cutting depth (Harnis and Grig). To limit self-vibrations , it is essential to maintain an optimal functional geometry of the tool. In the research, vibrations were measured in the Y and Z directions, using tools T01, T02 with the NI USB-9233 acquisition board (Figure 4).

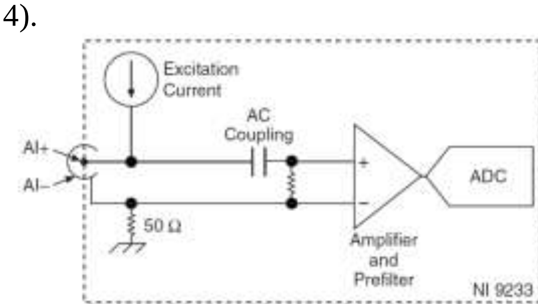

Figure 4. Schematic of a channel of the NI USB-9233 acquisition board

NI USB-9233 acquisition board offers four CHANNELS 24- bit analog with conditioning integrity and support for IEPE sensors . The signals are analog and digital filtered, AC coupled and buffered, for minimize noise, and sampled by a 24 - bit Delta-Sigma ADC. Operation correct require grounding connection and Supply permanent IEPE excitation current.

Vibration measurements were performed in the Z and Y directions, with two accelerometers mounted 25 mm from the tool tip (Figure 5). The data were processed in LabVIEW, saved in ASCII format and subsequently analyzed in Matlab using F.F.T.

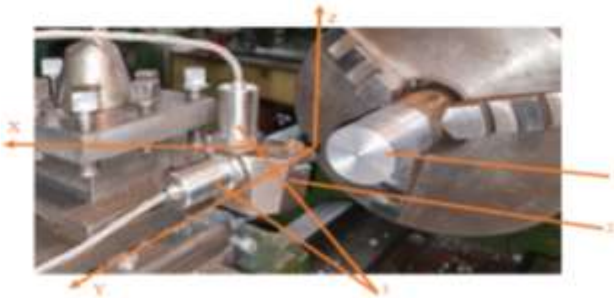

Figure 5. Scheme of the vibration measurement system: 1 - workpiece; 2 - tool; 3 – accelerometers for measuring vibrations in the Y and Z directions

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 would use the factorial experiment method, the design of which is presented in the following Table 3.

Table 3. The design experiences factorial used for achievement Research

Exp. no.	Input variable values (independent) Cutting parameters						measured output variable [m/s ^{2}],	
	Cutting depth a_p [mm]		advance [mm/ rev]		Cutting speed [m/min]		output variable), Vibration amplitude	
	-1	+1	-1	+1	-1	+1	Tool T01	Tool T02
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 the recommendations in the specialized literature [13], two levels were established for each parameter (corresponding to the limits of the allowed interval), which, within a complete 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 Table 2.8.

The experimental data were statistically processed using the software **STATISTICA**, 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

Following the processing of the 8 specimens by longitudinal feed turning, according to the factorial plan, using tools T01 and T02 respectively, the vibration amplitude values were determined. In Figure 6 the maximum amplitude values for specimen no. 5 are presented. The complete amplitude values for all 8 experiments are centralized in Table 4 and graphically represented in Figure 7, for each type of tool used.

The procedure used for vibration analysis involved the use of the Fast Fourier Transform (FFT) method, which is an analysis method that can provide information about the vibration waveform. The Fast Fourier Transform (FFT) analysis technique is an analysis method based on the vibration waveform. Since, in general, waveforms are complicated and difficult to analyze, by applying the FFT, the waveforms can be decomposed into a series of discrete sine waves.

Thus, the F.F.T method analysis took into account vibrations in the two directions Z and Y for both the cutting operations performed with the classic cutting tool T01 and those performed using the improved cutting tool variant T02, thus, the FFT analysis was performed for the cutting operations that involved the use of the two types of cutting tools (T01, T02)

Vibrations were analyzed in the two directions (Y, Z). In the case of the technological system consisting of tool, part, device, processing machine, it is advisable to perform vibration analysis in the frequency range 10 - 1000 Hz

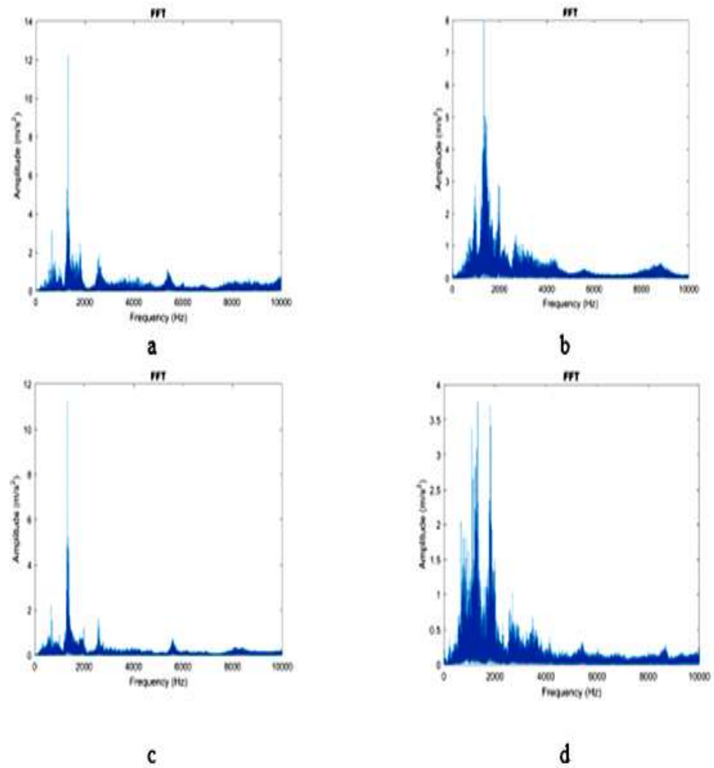

Figure 6. Vibration analysis by applying the FFT method:
a – in the Z direction in the case of machining with cutting tool T01;
b – in the Y direction in the case of machining with cutting tool T01;
c – in the Z direction in the case of machining with cutting tool T02;
d – in the Y direction in the case of machining with cutting tool T02;

Table 4. important amplitude vibration obtained from processing by longitudinal feed turning of material 42CrMo4 -EN 10083-3 - 50 mm , in follow review vibration by practice FFT method , (m/s^2)

No. Exp	Material: 42CrMo4 -EN 10083-3- Ø 50 mm ;									
	Parameters cutting regime						Value vibration measured [m/s2 [1]].			
	Cutting depth a_p[mm]		advance [mm/rev]		Cutting speed [m/min]		Z direction		Y- direction	
							SHARPENING TOOL			
							T 01	T 02	T 01	T 02
	0.9	3.6	0.2	0.36	90	140				
	-1	+1	-1	+1	-1	+1				
1	x		x		x		7.8	8	5.6	2.4
2	x		x			x	8.8	8.4	6.3	2.9
3	x			x	x		8.5	8.5	6.5	2.9
4	x			x		x	8.5	8.2	6.5	2.8
5		x		x		x	11.75	9.3	8.1	3.7
6		x		x	x		10.8	9.1 5	7.6	3.5
7		x	x			x	11.3	9.1	7.9	3.5
8		x	x		x		9.3	9.1	7.7	3.2
Value average of amplitude vibration							9.59	8.7	7.02	3.1

The experimental results obtained from the research on machining by turning with longitudinal feed for the material 42CrMo4 - EN 10083-3 - Ω 50 mm were processed using STATISTICA software, and Table 5 presents the results obtained from the processing using the multiple regression analysis method.

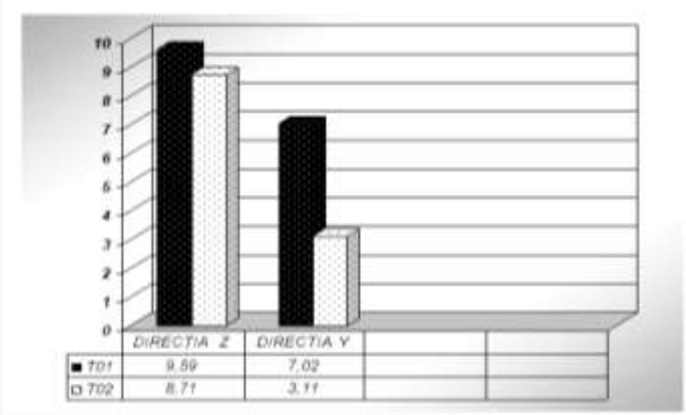

Figure 7. -Graphical representation of the performances obtained by the 2 tools T01 and T02 respectively

Table 5. Parameters obtained after performing the multiple regression analysis applied for vibration amplitude values obtained by longitudinal feed turning of the material 42CrMo4 - EN 10083-3 - 50 mm

rise used	Material: 42CrMo4-EN 10083-3 - 50mm ;						
	important regression parameters obtained in follow completion regression analysis multiple						
	Z direction						
	R^2	F	df	p	$a_p b^*$	$f b^*$	$V b^*$
T01	0.915	14.38	3.4	0.013	0.949	0.423	0.212
T02	0.926	16.78	3.4	0.009	0.862	0.357	0.171
Y- direction							
	R^2	F	df	p	$a_p b^*$	$f b^*$	$V b^*$
T01	0.953	27.38	3.4	0.0039	0.938	0.315	0.274
T02	0.929	17.59	3.4	0.009	0.883	0.274	0.205

The analysis of the results in Table 5, obtained by multiple regression, highlights the fact that the influence of cutting parameters (a_p, f, V) on the vibration amplitude differs depending on the type of tool used. For the machining of 42CrMo4–EN 10083-3 steel, Ø50 mm, the best performances were obtained with the improved cutting tool T02.

The results obtained for cutting tools T01 and T02 have high values of the coefficient of determination R^2 (0.91 – 0.96) , which means that: the models describe the variation of vibration amplitude very well .
Large F values and $p < 0.05$ show that the regressions are: statistically significant , so the results are credible.

These observations are confirmed by the values presented in Table 4, as well as by the FFT analysis performed on the Z and Y directions, which indicate minimal vibration levels for tool T02. The average vibration amplitude values for the 2 tools are summarized in Table 4 and graphically represented in Figure 7.

The analysis of the multiple regression results indicates that the obtained statistical model describes very well the variation of the vibration amplitude, having high values of the coefficient of determination (R^2) for both tools and in both measurement directions (Z and Y).

This confirms the strong correlation between the cutting regime parameters (depth of cut (a_p), feed (f) and cutting speed (V) and the level of vibrations generated during machining.

The analysis of experimental data shows that the T01 (classic) tool exhibits higher vibration amplitudes in both directions (Y and Z), which indicates a higher sensitivity to vibrations compared to the T02 tool. The T02 tool, with improved geometry and construction features, ensures a more stable behavior in the cutting process, generating lower amplitudes for the same values of technological parameters.

- The model obtained for the Z direction

highlights, in turn, a strong dependence of the amplitude on the cutting depth: the exponents ≈ 0.95 (T01) and ≈ 0.87 (T02). Thus, variations in the cutting depth produce marked changes in the amplitude in the Z direction.

- The advance f influences theamplitude

in the Z direction to a more moderate extent (≈ 0.42 for T01 and $\beta \approx 0.36$ for T02), which indicates that reducing the feed can improve both the surface roughness and the vibrations

- Cutting speed VVare the lowest

exponent in the model for Z ($\gamma \approx 0.21$ for T01 and ≈ 0.17 for T02), a sign of a smaller direct influence on the amplitude in the Z direction; however, changes in V can modify thermal conditions and edge wear, also having indirect effects on vibrations

- Multiple regression analysis indicates

the fact that the amplitude of the vibrations in the Y direction depends predominantly on the depth of cut of $_p$, the associated exponent being significant (≈0.94 for T01, ≈0.88 for T02). This confirms the critical role of the depth of cut in the occurrence of lateral instabilities and chatter phenomena.

- Comparatively, the advance f presentsa

moderate influence on the amplitude in the Y direction (exponents ≈0.32 for T01 and ≈0.28 for T02), which shows that decreasing the feed can contribute to reducing lateral vibrations, but the effect is smaller than that of the cutting depth.

CONCLUSIONS

Based on the statistical analysis by multiple regression, it is found that the amplitude of vibrations in the turning process is determined mainly by the cutting depth, while the feed exerts a secondary influence, and the cutting speed has a reduced impact on the dynamic behavior of the cutting system.

The experimental results highlight the fact that the classic tool (T01) generates higher vibration amplitudes in both the axial (Z) and lateral (Y) directions, indicating a heightened sensitivity to dynamic excitations and, implicitly, a lower vibrational stability. In contrast, the improved tool (T02) presents lower amplitude values for the same technological conditions, an aspect that can be attributed to the optimization of the cutting edge geometry and the increase in the rigidity of the tool-toolholder assembly.

Thus, from the perspective of ensuring process stability and obtaining superior quality of the machined surface, it is recommended to use the T02 tool or appropriately adapt the working regime when using the T01 tool, especially by limiting the cutting depth and by maintaining the rigidity of the technological system at the highest possible level.

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