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Cutting Forces in the Milling of Difficult-to-Machine Material used in the Aero Space Industry Using a Monolithic Ceramic Milling Cutter

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The constantly developing aerospace industry places demands on increasing productivity and production efficiency. At present, new construction materials are being produced that have better physical and mechanical properties than conventional materials. In addition to new materials, new cutting materials and new machining technologies are being developed. The combination of suitable machining technology, material and tool will achieve excellent product surface quality, long tool life and thus production efficiency. Due to its mechanical and physical properties, technical ceramics can be used in the machining of difficult-to-machine materials, in which there is mechanical stress on blows, impacts, abrasions and other damage. Thanks to these properties, ceramics as a material is very suitable for the production of machine tools. The presented article deals with the applicability of ceramic milling cutters in high-speed machining of nickel alloy, which is used mainly in the aerospace industry. The evaluation of the experiment took place by means of DoE - analysis of cutting forces, the result of which is the creation of the dependence of cutting forces on cutting conditions. Based on the data obtained, it is possible to continue to further intensify the cutting conditions in the area of high-speed machining.

Keywords: Trochoidal Milling, Surface Quality, Monolithic Ceramic Cutter

1 Introduction

Research into productivity issues is important especially in industries where it is necessary to take large amounts of material in a short time. In connection with the use of difficult-to-machine materials, productive machining methods have been developed. The research of these methods focuses on the adjustment of cutting parameters, or on the optimization of the tool path [1]; [2], [3]

Moreover, chip formation [4] and some surface integrity parameters [5]; [6] are investigated. Other important studies in this area are focused on tool wear and machining of nickel and titanium alloys [7]; [8]. One of the productive methods of machining difficult-to-machine materials is high-speed milling. High-speed machining (HSM) makes it possible to increase the volume of material removed, improve the quality of the machined surface and tool life while significantly increasing the cutting speed, while the cross-section of the removed chip is minimal [9]. In terms of cutting speeds, machining above 600 $m.min^{-1}$ is considered high-speed machining [10]; [11]; [12]. In experiments, it was found out that each material has a so-called high cutting speed limit [13]; [14]. This limit depends on the type of cutting material, the geometry of the cutting edge, the design of the tool, etc. [15]; [16], [17].

1.1 Milling cutting forces

The total machining force F is the force by which the tool acts on the workpiece and is pressed into the material to be machined. The machined material exerts an equally large and oppositely oriented resistive reaction force on the tool. The total machining force is the resultant one of the two components, namely the active component F_a and the passive component F_p, but in principle it does not act in a simplified way in 2D space; it acts in the general direction and in 3D space it can be divided into three mutually perpendicular directions. The displacement component F_f acts in the x-axis; the normal component F_{fn} acts in the y-axis as normal to the displacement component. The passive component F_p acts in the z-axis. The active force component F_a can be considered as the result of the cutting component F_c and its normal F_{cn} and at the same time as the result of the feed component F_f and its normal F_{fn}. The components of the machining force can be measured indirectly, for example from the output power of the machine's electric motor or the power torque with respect to the axis of rotation [11], [18].

The passive force component F_p is the smallest component of the machining force; in the case of non-linear milling has several times smaller magnitude than F_x and F_y, the active force component is often more important than the passive component, but the passive component has a higher information value from a technological point of view. [9]; [19]. The different indication of the cutting forces is due to the fact that when measuring the cutting forces using a dynamometer, its coordinate system is used, in other cases the designation according to the direction of action of the cutting forces was appropriate. During non-linear milling, the direction of the applied forces changes due to the rotation of the tool and the movement along the non-linear path.

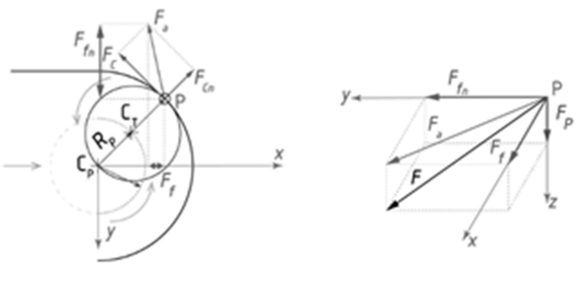

Fig. 1 *Scheme of cutting forces in 2D and in 3D view*

The presented decomposition is based on a general description of the components of the total cutting force according to the relevant standards. However, it was approached a simplified notation (x, y, z) in the article, which is based on the use of a three-component dynamometer with Cartesian coordinate system and also with respect to a complex kinematic structure, which changes the orientation of individual components orientation of both the tool and the cutting edge. At the same time, this designation is based on the coordinate system of the CNC machine tool, which allows a better understanding of the load of the machine in its individual axes.

2 Material, equipment and apparatus used during the experiment

2.1 Material used during the experiment

The Alloy 718 type material is a superalloy with a high nickel content (EN NiCr19NbMo - see table), which is used at extreme temperatures, in environments where it is exposed to corrosion and in special applications. Specific applications are mainly in components of gas turbines, aircraft engines, as part of liquid rocket engines, in mounting materials and other high-strength applications. Since this alloy contains a considerable amount of added niobium, molybdenum, aluminum and titanium, it achieves high strength, has an excellent yield strength and good corrosion resistance. It can operate in the temperature range -253 to 760 °C. Alloy 718 is precipitation hardened to achieve maximum strength and a high yield strength. It has excellent weldability, including resistance to cracking after welding. A sample of Alloy 718 used in the experiment was 120 mm in diameter and 50 mm in length.

Tab. 2 *Chemical composition of nickel alloy Alloy 718*

	Element (%)							
Nickel alloy Alloy 718	Ni	Cr	Fe	Mo	Nb	Co	Mn	Cu
	50 – 55	17 – 21	residual	2.8 – 3,3	4.75 – 5.5	1.0	0.35	0.2 – 0.8
	Element (%)							
	Al	Ti	Si	C	S	P	B	
	0.65 – 1.15	0.3	0.35	0.08	0.015	0.015	0.006	

The choice of the correct cutting parameters for the machined material of nickel alloy Alloy 718 was based on the conditions recommended by the manufacturer of monolithic ceramic milling cutter, the technical parameters of the vertical machining center HURCO VMX 30 and the principles of identification and design system. experiments (so-called DoE - design of experiments).

2.2 Solid ceramic milling cutters

Solid ceramic milling cutters are used for machining tough, heat-resistant, heat-resistant alloys and super alloys. They must withstand the heat generated by milling with high values of cutting parameters, such as high feed rates and large depth of cut. Without the use of cutting fluid, heat is generated which reduces the strength of the material and thus increases the machining efficiency. An important factor for the use of highly productive milling methods are modern CNC machines.

For the use of ceramic milling cutters, a high cutting speed (from 350 to 1000 $m.min^{-1}$) is required to generate the heat, which is necessary to soften the material without abrasion or other damage. It is recommended to use an air stream for good chip removal. When milling with a ceramic milling cutter, a continuous cut is strongly recommended, as an intermittent cut would cause damage or chipping. To maintain tool life, the cutting width should be gradually increased. The consent milling method is more suitable for this tool, non-consent milling may be unstable.

2.3 Equipment and apparatus used during the experiment

Experimental machining was performed on a HURCO VMX 30 vertical machining center. Due to its spindle and motor power and the use of the NAREX ZP 10/X auxiliary accelerator, this machining center is suitable for the high-speed machining required in the experiment.

A three-component Kistler 9255A dynamometer and a computer assembly were used to determine the results of the measured components of the cutting forces.

The cutting forces are evaluated from a practical point of view in the coordinate system of the dynamometer. The dynamometer records data by electro-analog measurement of the increase in pressure of the elastic cells, consisting of 3-component force transducers that record the values F_x, F_y and F_z.

3 Settings of the experiment

The cutting forces are evaluated from a practical point of view in the coordinate system of the dynamometer. The dynamometer records data by electro-analog measurement of the increase in pressure of the elastic cells, consisting of 3-component force transducers that record the values F_x, F_y and F_z. The stationary dynamometer was connected to the computer by A / D converters.

The principle of operation of the dynamometer is to load the crystals in the direction of the neutral axis. A static electric charge with the opposite sign is created on the neutral axis. When the crystals are lightened, the electric charge disappears. The size of the hub corresponds to the magnitude of the cutting force applied.

During the milling process, the individual components of the cutting force were recorded in the dynamometer system F_x, F_y and F_z for each set experiment. The dynamometer was placed under the workpiece and the cutting forces were measured in the XYZ system, with the milling cutter performing a motion related to the mathematical definition of trochoidal motion. into individual axes. At the same time, in the second part of the semicircle, the milling cutter was out of engagement, which meant a "zero" load during the components of the total cutting force. As the tool moved along the radius of the trochoid, the force increased.

To identify the monolithic ceramic milling cutter, the boundary conditions of the cutting parameters were chosen: cutting speed v_c (m.min^{-1}), feed per tooth f_z (mm), depth of cut a_p (mm) and width section a_e (mm) (Tab 2).

Tab. 3 *Marginal minima and maxima of cutting parameters for tool identification*

Parameter	Minimal value	Maximal value
cutting speed v_c (m.min^{-1})	350	750
feed per tooth f_z (mm)	0.02	0.06
depth of cut a_p (mm)	3	7
width section a_e (mm)	1.5	

Based on the design of a three-level experimental factor plan, 11 combinations of cutting conditions for experiments were developed (Tab 3). It was the summary of experimental settings according to DoE (reduced Central Composite Design) to create a response surface.

Tab. 4 *Cutting conditions used in experimental milling processes*

Order of expeiment	v_c (m.min^{-1})	f_z (mm)	a_p (mm)
1	350	0.02	7
2	350	0.04	5
3	550	0.02	5
4	550	0.04	3
5	550	0.04	5
6	550	0.04	7
7	550	0.06	5
8	750	0.02	3
9	750	0.04	5
10	550	0.04	5
11	550	0.04	5

4 Results of experiment

The dynamometer was used to directly measure the three components of the cutting force F, of which quantities are measured in the x, y and z coordinate directions. Because the movement in the milling is non-linear, the individual components were not measured with respect to force distribution (as in Fig. 1), but with respect to the dynamometer coordinate system, which axes were oriented according to the axes of the CNC machine. The measured outputs thus present above all (the orientation of the individual components of the cutting forces changing over time depending on the movement of the tool.) The orientation of the forces changes, the magnitude changes only due to the amount of material removed.

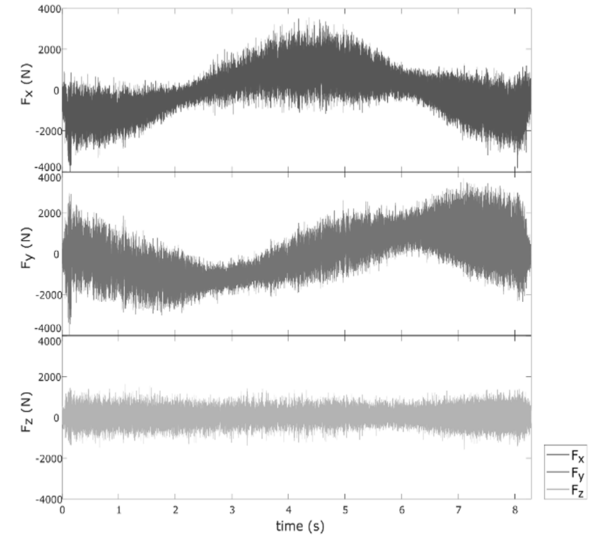

Fig. 2 *Detailed view of one cutter transition in a time record*

The cutting force F is the resultant of the forces F_x, F_y and F_z. Since these are rectangular projections of the active force component F_a and the passive component F_p into the coordinate axes in 3D space, it was necessary to measure the magnitude of the total machining force F indirectly, i.e. to calculate them as the vector sum from the measured components F_f, F_{fn} and F_p according to formula (1):

$$F = \sqrt{F_f^2 + F_{fn}^2 + F_p^2} = \sqrt{F_x^2 + F_y^2 + F_z^2} \quad (1)$$

After recording the data, the focus was on the highest tool load. Based on the measured data for the calculation of the force from the dynamometer, a mathematical-statistical model was created, which expresses the influence of the basic cutting parameters v_c, f_z and a_p on the total cutting force. Subsequently, the measured data were subjected to analysis of variance (Tab 4).

Tab. 4 *Output from analysis of variance for total machining force F*

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	8	8242775	1030347	31.25	0.118
Linear	3	3332376	1110792	33.69	0.029
vc	1	812691	812691	24.65	0.038
fz	1	10145	10145	0.31	0.635
ap	1	2509539	2509539	76.11	0.013
Square	3	2414702	804901	24.41	0.040
vc* vc	1	1966477	1966477	59.64	0.016
fz*fz	1	1005976	1005976	30.51	0.031
ap*ap	1	1199110	1199110	36.36	0.026
2-Way Interaction	2	493989	246994	7.49	0.118
vc*fz	1	7669	7669	0.23	0.677
vc*ap	1	486320	486320	14.75	0.062
Error	2	65949	32974		
Total	10	8308724			

The table of variance analysis shows that the most significant influence on the total cutting force is mainly the cutting speed vc and the depth of cut ap. Statistically significant members are those whose p-value is less than 0.05, but this is not in the table. Therefore, it is necessary to find the lowest possible value. The lowest p-values have a cutting speed vc and a depth of cut ap, both in the linear and quadratic models and also in their mutual interaction. The weight of the effect is also shown by the column of Sequence Squares Adj SS.

$$\boldsymbol{F_{max} = -29084 + 54.39 \cdot v_c + 164811 \cdot f_z + 4937 \cdot a_p - 0.032 \cdot v_c^2 - 2288986 \cdot f_z^2 - 249.9 \cdot a_p^2 + 26.8 \cdot v_c \cdot f_z - 3.413 \cdot v_c \cdot a_p} \quad (2)$$

The response area is defined as the area of the three variables by the polynomial of the second scale. The accuracy of the model reached R^2= 99.21% in the performed experiments with a prediction coefficient of

Rp^2= 86.30%, in terms of statistical significance of individual members, this model can be considered correct and sufficiently accurate for further research, simulation and verification of the machining process and subsequent applications in professional practice. The equation represents the created model.

Based on the created equation, it is possible to show the influence of basic cutting parameters also graphically. Due to the fact that it is a 4-dimensional graph, it is not possible to create a complex response surface. The equation that defines the model can be used for any of the set cutting parameters. The effect of changing parameters can be illustrated by keeping one parameter constant. The figure shows the influence of individual parameters when the value of the third parameter is in the middle of the range of changed values. The figure shows that the greatest tool load occurs at high a_p and low v_c and f_z. When applying the tool to a given material, dark red areas should be avoided.

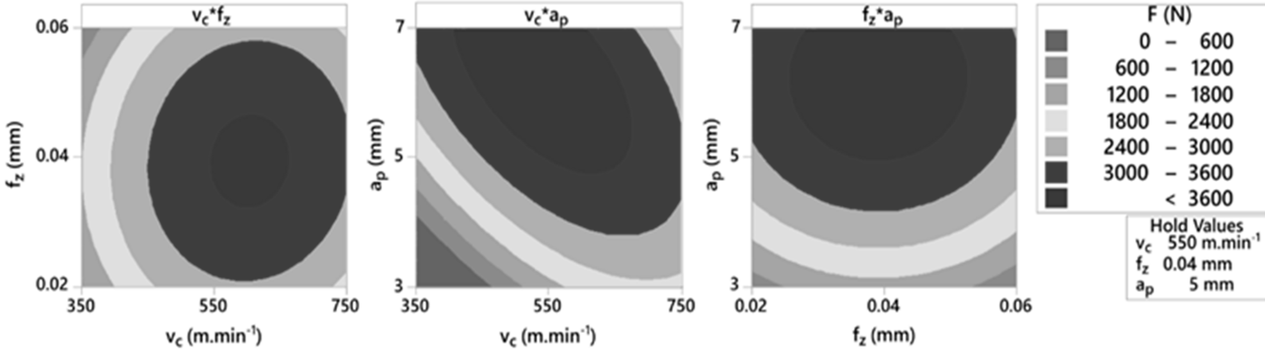

Fig. 3 *Influence of individual parameters when the value of the third parameter is in the middle of the range of changed values*

The accuracy of the created model from the development of the total cutting force is declared in Tab.5., where the calculated and measured values are compared.

Tab. 5 *Comparison of measured and calculated values*

Nr. of experiment	v_c (mm.min^{-1})	f_z (mm)	a_p (mm)	F (N)	$F_{(v)}$ (N)	Difference
1	350	0.02	7	2547	2553	0.24%
2	350	0.04	5	1798	1803	0.28%
3	550	0.02	5	2871	2878	0.24%
4	550	0.04	3	1596	1601	0.31%
5	550	0.04	5	3216	3722	13.59%
6	550	0.04	7	3836	3844	0.21%
7	550	0.06	5	2728	2735	0.26%
8	750	0.02	3	1367	1374	0.51%
9	750	0.04	5	3073	3081	0.26%
10	550	0.04	5	3757	3722	0.94%
11	550	0.04	5	3872	3722	4.03%

It is clear from the table that there are minimal differences between the calculated and measured values. The aim of the experiment was to find the smallest number of experiments, but experiments were also performed whose values were repeated to verify accuracy. The highest deviations occurred at the midpoints, the repetition of which was included for the mentioned verification of accuracy. In the first implementation, a deviation of 13.59% was found, the other differences found did not reach a difference of even 1%.

5 Evaluation and conclusion

The presented article was focused on the analysis of the influence of cutting conditions on the size of the total cutting force, as the total tool load in the field of high-speed machining. After defining the effects, a mathematical-statistical prediction model was created, which was successfully verified on the basis of experimental settings.

Based on experimental results of direct measurements of machining force components with a dynamometer during high-speed milling of nickel alloy, it can be stated:

- The total machining force was measured and evaluated indirectly.
- The results of 11 experiments performed for combinations of three basic cutting parameters were statistically processed and a predictive equation of the total machining force and the corresponding response area of the total machining force were subsequently created.
- The response area and the comparative regression equation of the total machining

force, depending on the cutting parameters, indicate that the most significant influence is the cutting speed and depth of cut, both in the linear and quadratic model. The response area is defined as the area of the three variables by the polynomial of the second scale. The accuracy of the model reached R^2= 99.21% in the performed experiments with a prediction coefficient of R_p^2= 86.30%.

Based on the calculated model, verification was also performed by comparing the measured (F) and calculated ($F_{max\ (v)}$) values. There are minimal differences between the calculated and measured values. The highest deviations occurred at the midpoints. In the first implementation, a deviation of 13.59% was found, the others did not make a difference of even 1%.

The achieved model was limited mainly in the used material and tools, which were chosen according to practical requirements. Based on the proven results, it can be stated that the created model has the potential for further research, as well as possible use in real conditions of practice.

For the model design, it was necessary to mathematically express the load of the cutting tool. The tool load values change and increase as the tool enters the material. The magnitude of the tool load is also affected by the shape of the material being machined. The proposed development model does not include all the changing factors that affect the resulting modeled values. The cutting components acting in the x-axis and y-axis were simulated in the models. The tool is subjected to less load during the milling process in the z-axis than in the x-axis and y-axis. The component of the cutting force F_z is a passive component, has several times smaller magnitude than F_x and F_y, and therefore the modeling and evaluation was focused only on the cutting components of the forces F_x and F_y - the assumption of a higher load.

Based on the simulation and the result of the modeled calculation of cutting forces, it allows to determine what load will act in the real milling process. It is possible to assume how much load will be applied to the machine system, tool, workpiece and what power of the machine tool will be required to perform the required machining operation. Another benefit is the use of data for adaptive machining and for its further research.

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