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Influence of Technological Parameters on the Cutting Temperature during Trochoidal Milling

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The aim of the article was to present the results of cutting temperature measurements during trochoidal milling. The investigated material was 145Cr6 (50 HRC). Three trochoidal paths were used: A– described by movement circle, B– described by arcs and straight lines, C– described by short lines between a lot of points. The main conclusions include: similar values of cutting temperatures when using paths A and C (differences between the values of about 5%), the use of a trochoidal path type B enables a significant reduction of the cutting temperature. During trochoidal milling, the maximum temperature values were about 445°C.

Keywords: Trochoidal Milling, Hard Machining, Cutting Temperature, Tool Path

1 Introduction

The cutting temperature has a significant impact on the quality of the process 1. Higher thermal values are recorded when cutting hard materials. Machining in such conditions causes accelerated wear of the cutting blades, which translates into confusion in cutting performance and a reduction in surface quality. To prevent this, abundant cooling should be used and the technological parameters of the cutting should be drastically reduced. The consequence of this will be reduced efficiency, higher process costs, and not the eco-friendliness associated with the processing of coolants 2. A possible alternative solution is the use of trochoidal milling 3. Trochoidal milling enables machining of hard materials (60 HRC) without reducing the efficiency of the process, this method significantly reduces the cutting temperature 4.

In the machining of materials in the hardened state, cutting fluids are not used due to the large thermal shocks that could have an impact on the tool. During hard milling, compressed air is usually used, the main task of which is to transport the chips away from the cutting zone, and not to cool the tool, the effectiveness of which in this case is insignificant 5. The cutting temperature can be determined experimentally or analytically 6. A more accurate method is usually the experimental determination of temperatures, because in analytical methods there are great difficulties in determining the correct boundary conditions, modeling dynamic interactions and small volumes of space in which complex phenomena of material separation occur in usually non-orthogonal cutting 7.

Cutting temperature measurement can be troublesome due to: determination of the emissivity of tool coatings, dynamic changes of the tool position in the machining space or the need to use measuring devices with a significant registration frequency 8. In the research included in the work 9, the cutting temperature distribution was analyzed in the machining process of the Ti6Al4V titanium alloy with the use of the X6540sc thermographic camera from FLIR. A cutting temperature of about 775°C was obtained in the experiment. The recorded signal from the thermal imaging camera is characterized by the repeatability of changes over time. A sudden increase was observed, followed by stabilization and another increase in temperature, which, according to the authors, can be explained as a result of heating blades during processing.

The research 10 presents the results of using the Raytek MM thermographic camera during milling of D2 steel in the hardened state with a Sandvik Coromant two-edge cutter with the manufacturer's code K390-016A16L-116. Based on the test results, it was found that the cutting temperature changes almost linearly with the increase in the cutting speed in the ranges of the cutting speed v_c from 90 to 180 m/min. The research team from the University of Stellenbosch 11 used a K-type thermocouple (NiCr-NiAl) to measure the temperature. Analyzing the obtained results, it was found that increasing the velocity cutting v_c from 20 to 40 m/min increases the temperature by about 150°C. Above v_c = 40 m/min, the temperature increase is not so significant and amounts to about 50°C for each 20 m/min increase. The cutting temperature is an important factor in the shaping of the surface layer. It is strongly related to the physical and chemical properties of the workpiece and tool material.

2 Trochoidal milling

Trochoidal milling appears also as a TPC term (Trochoidal Performance Cutting) and is defined as circular milling with simultaneous forward movements (example of generated path Fig. 1).

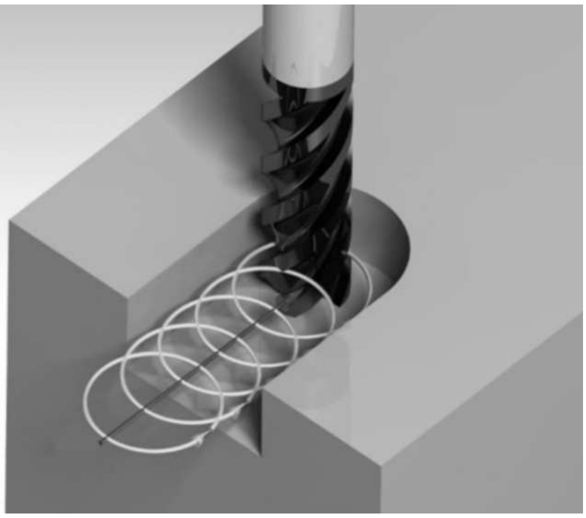

Fig. 1 *An example of generated tool path*

Trochoidal milling is a machining method that supports and optimizes high speed milling of materials in the hardened state. A characteristic feature of the presented method is the reduction of tool arc ω (peripheral engagement of the tool in machining), which translates into a reduction in the cutting width ae in favor of increasing the milling depth a_p 12.

Durability and wear depend on the temperature value and durability of the cutting blade, residual stress in the workpiece and the method of chip formation. High temperature negatively affects the milling results. It is therefore important to minimize the cutting temperature value as much as possible, e.g. by changing the trajectory of the tool's movement to trochoidal machining 13. The reduced angle of contact of the tool during trochoidal milling prevents the occurrence of high temperatures (Fig. 2) 14.

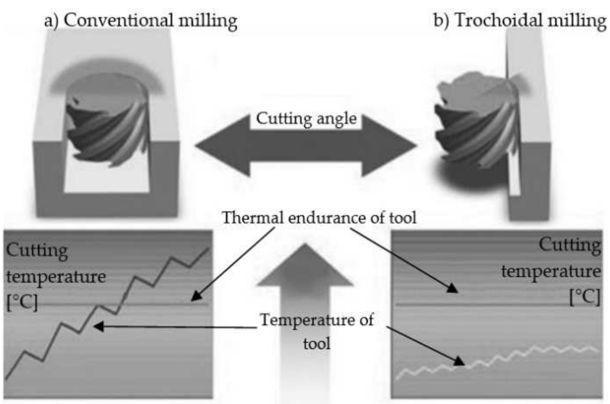

Fig. 2 *Comparison of the temperature distribution depending on the angle of contact of the tool for: a) conventional milling, b) trochoidal milling*

Heat accumulation is reduced by the circular movements of the tool. In trochoidal milling, sometimes the tool does not cut for about 50% of the programmed path 15. Movements at the exit of the tool from the material according to [6], indirectly serve to cool the cutter. In addition, only a part of the tool is involved in the machining, usually the angle of contact ω is within the range of 5° to 60°, while in conventional milling up to ω = 180° 16. A smaller angle of contact ω allows to reduce cutting forces, reduce the cutting temperature and increase the cutting depth, which may translate into an increase in cutting efficiency 17.

3 Materials and methods

In the research, the cutting temperature (T_c) was analyzed, which was defined as the highest temperature read at the point of contact of the tool with the material, measured right next to the workpiece surface (Fig. 3).

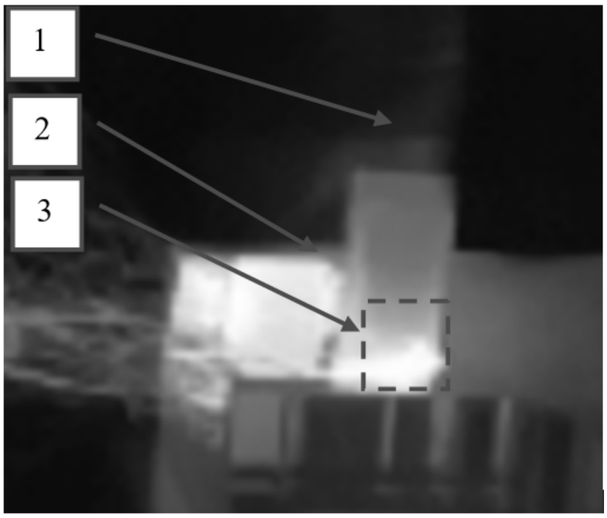

Fig. 3 *View of the measurement site*

Where:
1…Cutter,
2…Detail,
3…Thermal measurement area.

The measurement system included a Flir 7500-MB thermographic camera, matrix resolution 320x256 pixel, thermal sensitivity <0.002°C. Measurement temperature ranges: from 0 to 1200°C Measurement accuracy ± 1°C ± 1%. Objective lens 11° x 8.8° / 0.3 m, f = 2.5 ÷ 5 mm / FOV 50° Image recording frequency 1200 Hz. The area of the analyzed image was 7 x 7 pixels. The measuring system was calibrated on previously prepared samples which were heated in a furnace (the method described in the article was used 18). In this way, the emissivity factor was determined to ε = 0.93. The investigated material was 145Cr6 (1.2063) in hardened state 50 HRC. In the research, a groove with the following dimensions was milled:

width 28 mm, depth 10 mm, length 30 mm with a solid carbide milling cutter with a cylindrical shank, type:170120R050.0-MEGA-64; diameter- 10 mm, number of flutes 4, angle of major edge- 50°. The research was carried out on CNC machining centre Hermle C600u with Heidenhain iTNC530 control system.

The following variable parameters were adopted in the research:

- Cutting speed v_c = 100; 125; 150 [m/min],
- Feed f_z = 0.03; 0.04; 0.05 [mm/tooth],
- Step over w = 0.2; 0.4; 0.6 [mm].

In order to understand the influence of the tool movement trajectory in trochoidal milling on the cutting temperature, the following parameters were taken into account as variables: cutting speed v_c, step over w (def. the distance between the forward movements of one trochoid loop) and feed f_z. The range of parameters was dictated by the recommended standards of tool manufacturers, the capabilities of the machine tool and the values used in industry. A complete three-level statistical plan was used in the research (abbreviated: PS/DK 33 acc. to 19) for each trochoidal path. Based on the obtained research results, a mathematical model in the form of a second-order polynomial was developed, where the quadratic model describes the function under study. In the study, variable factors were coded at three levels:

- Higher - marked as + 1,
- Medium - (basic) marked as 0,
- Lower - marked - 1.

The values of the levels of individual factors, the ranges of their changes and the designation of variables are presented in Table 1.

Tab. 1 *Coding of input states*

Imput factors	$x_1 = w$	$x_2 = v_c$	$x_3 = f_z$
Level 0	0.4	125	0.04
Level +	0.6	150	0.05
Level -	0.2	100	0.03
Change interval	0.2	25	0.01
Code designation of variables	$x_1 = \frac{w - 0.4}{0.2}$	$x_2 = \frac{v_c - 125}{25}$	$x_3 = \frac{f_z - 0.04}{0.01}$
Outcome factor	$y = T_c$		

In the experiments, trochoidal paths of type A, B, and C were examined. The choice of paths was conditioned by preliminary tests, in which the stability of the cutting process was determined 20. Various methods of generating the trochoidal path allow to visualize the factors determining the final milling effect, such as the influence of linear, circular and arc interpolation. Trochoidal paths were generated in three ways:

- A – quasi-trochoid (Fig. 4): described by circular movement (G-Code),
- B – stretched quasi-trochoid (Fig. 5): described by arcs and straight lines (iTNC control system),
- C – point by point quasi-trochoid (Fig. 6): described by short lines between a lot of points (CAD/CAM).

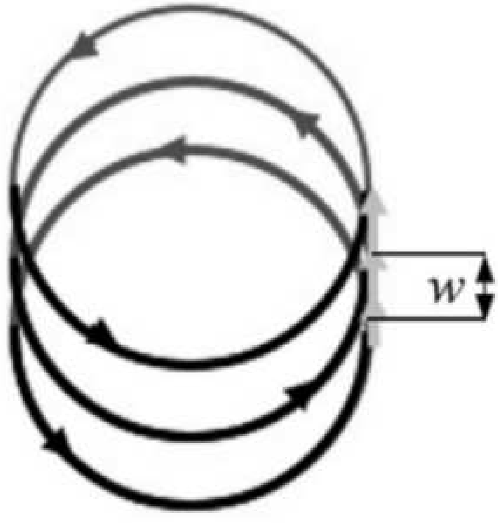

Fig. 4 *A – quasi-trochoid type*

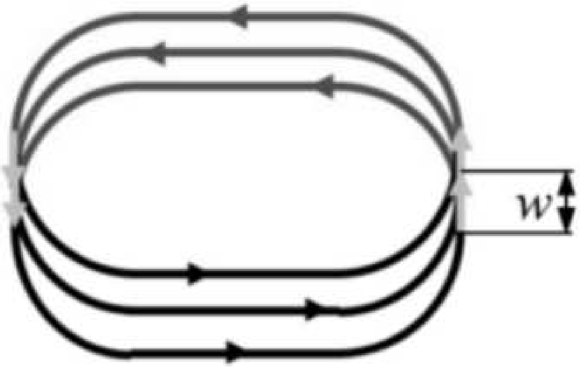

Fig. 5 *B – stretched quasi-trochoid*

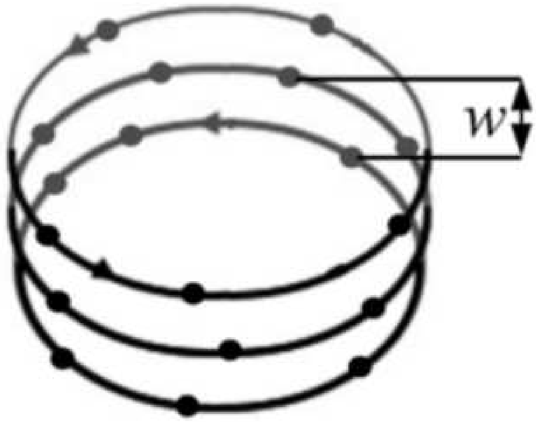

Fig. 6 *C – point by point quasi-trochoid*

4 Results

Table 2 summarizes the regression equations for the dependencies of the cutting temperature (T_c) on the cutting speed v_c, feed f_z and step over w.

Lowering the cutting temperature is possible not only by using a cooling medium (e.g. in the form of an emulsion), but also by changing the trajectory of the tool's movement. Trochoidal milling lowers the cutting temperature, especially in extremely severe cutting conditions at high speeds. Table 3 presents a comparison of various trochoidal paths in terms of the recorded cutting temperature.

Analyzing the results in table 3, it was found that the cutting temperature values during trochoidal milling using paths A and C are very close to each other. The differences between the trochoidal tool paths are no more than 5% with no tendency to indicate the path.

The lowest cutting temperature values for all paths were observed for the lowest parameters used in the process: v_c = 100 mm/min, f_z = 0.03 mm/tooth, w = 0.2 mm, the temperature values for trochoid types A and C: 223°C and 250°C and for B T_c = 219°C. The highest cutting temperature values were recorded for the parameters: v_c = 150 m/min, f_z = 0.03mm/tooth, w = 0.6 mm using paths A and C and are respectively 439°C and 445°C. The extreme values of cutting temperature (T_c = 382°C) using path B were recorded for the parameters: v_c = 125 m/min, f_z = 0.05 mm/tooth, w = 0.6 mm. A significant increase in the cutting temperature was observed during the change of the trochoid pitch w for the parameters v_c = 100; 125; 150 m/min and f_z = 0.03 mm/tooth. For the parameters listed: a three-fold increase in the step over from w = 0.2 mm to w = 0.6 mm increases the cutting temperature by about 40% when paths A and C were used, and by about 30% for B. Based on the obtained test results, it was observed that the cutting temperatures during trochoidal milling are not high. In the population of measurement results obtained, thermal values range from 219 to 445°C. These values are not high for carbide tools, because their operating temperature is up to 800°C and more.

Tab. 2 *Cutting temperature regression equations Tc, for a = 0.05*

Trochoidal tool path type	Regression equation - relationship $T_c = T_c(w, v_c, f_z)$	R^2	F
A	T_c= 352.3112 + 501.3309w + 3.1642v_c – 0.005v_c^2 + 14703.6296f_z – 95851.7519f_z^2 – 0.6717wv_c - 6041.6667wf_z – 37.6667$v_c f_z$	0.931	0.0005
B	T_c= 220.3 + 375.2383w + 4.0363vc – 0.0231v_c^2 - 3320.9012f_z + 44008.8339f_z^2 – 2.0131wv_c – 4399.9997wf_z – 13.5353$v_c f_z$	0.921	0.0023
C	T_c = 215.2999 + 506.1722w + 3.5521v_c – 0.0095v_c^2 + 169.1168f_z + 8826.6696f_z^2 – 2.5001wv_c – 5783.4545wf_z- 17.2313$v_c f_z$	0.913	0.0049

Tab. 3 *Cutting temperature regression equations T_c, for a = 0.05*

Feed fz	**Cutting speed v_c**	**Step over w**	**Temperature T_c [°C]**		
[mm/tooth]	[m/min]	[mm]	Type of paths		
			A	B	C
0.03	100	0.2	223	219	250
		0.4	319	275	311
		0.6	345	341	373
	125	0.2	288	258	286
		0.4	325	287	341
		0.6	391	359	420
	150	0.2	329	299	378
		0.4	367	327	341
		0.6	439	371	445
0.04	100	0.2	309	268	319
		0.4	372	282	372
		0.6	345	295	350
	125	0.2	301	261	331
		0.4	346	300	346
		0.6	399	371	432
	150	0.2	356	334	359
		0.4	403	329	373
		0.6	399	359	390
0.05	100	0.2	272	270	299
		0.4	348	309	346
		0.6	385	345	371
	125	0.2	335	299	330
		0.4	375	350	392
		0.6	400	382	407
	150	0.2	371	325	371
		0.4	345	317	345
		0.6	378	345	391

5 Conclusions

The possibilities of modern thermographic cameras make it impossible to measure the temperature distribution on quickly rotating individual tool blades. The results only show the average values of the cutting edge of the milling cutter that participatein machining.

Slight temperature differences noted during machining with A and C trochoidal paths were caused by a similar value of tool arc of engagement. When machining with the B type trochoidal path, the cutting temperature values were lower by an average of about 13% (compared to machining with A and C paths). This can be explained by a longer cutting path. In the initial stage of machining, the tool cut the material along a small arc, and then it cut along a straight line, which translated into a reduction in the angle of contact with the tool thus reducing the cutting temperature.

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