Influence of the cutting parameters on the workpiece temperature during face milling

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Abstract. This thesis presents the outcome of experimental research of the impact of changes in cutting speed and volume of material processed during a face milling process on the temperature of the processed object made of copper of M1Ez4 class. Measurement of the temperature of the processed object was conducted in six points with K-type thermocouples. The theoretical amount of released heat per unit of time for particular parameters of machining was also calculated.

1 Introduction

During the mechanical processing of the machining process, over 99.5% of machining work is transformed into heat [1-3]. The amount of heat is released per unit of time, so the stream of heat corresponds to the approximate machining power [3-6]. The source of heat in the machining process includes: work of plastic deformations and division of material (formation of chips), friction on the contact surface and rake face [2-11]. Heat generated as a result of the machining process is dissipated through chips, acquired by the tool and the processed material, and raised up to the ambient atmosphere or acquired by the cooling and lubricating liquid [4-6]. In the case of ISO N materials – so non-ferrous metals such as aluminum, copper, brass, etc. the percentage distribution of heat streams may amount to about 70% for the processed object, 20% for chips, and 2% for the cutting edge [12-14]. The uncontrolled temperature increase of the processed object may lead to a performance decrease of parts of machines, machine tools [15-19], and devices i.e. guides, proximity face seals, pneumatic valves [20-27], and precision devices used to control flying objects [28-30]. Increased temperature of the processed object during processing may lead to changes in the structure of the surface layer [31-33], decrease of processing accuracy [15-19], [34, 35] related to thermal expansion of the processed material, as well as its deformation [36, 37] resulting from uneven heating. Mistakes in performance of precision parts caused by uncontrolled heating of the processed object during face milling may result in improper operation of the device e.g. by faster wear of surfaces that work together, which may cause vibration and friction resistances [38 - 40].

2 Methods

The subject of studies was to determine temperature changes of the processed object during face milling of copper. The research was performed on samples made of M1Ez4 copper (99.95% Cu) with six predrilled holes for thermocouples. The size and placement of holes has been presented in Fig. 1.

Fig. 1. View of workpiece

The process of face milling of 30 x 30 mm surface of copper samples has been conducted on a vertical machining center AVIA VMC800 (fig. 2) with the usage of the cutting head R245-080Q27-12M manufactured by Sandvik Coromant with machining diameter of $D_c = 80$ mm, facilitated with 245-12T3M-PL4230 plates. Machining attempts have been conducted at two machining velocities $v_c = 250$ and 375 m/min, at a fixed feed rate on the edge of $f_z = 0.05$ mm/tooth and fixed depth of cut of $a_p = 0.5$ mm for which the distance from thermocouples "h" and volume of the processed material

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were variable (table 1). Detailed parameters of machining have been presented in table 2.

Table 1. Workpiece dimensions

	Length L, mm	Width W, mm	Height H, mm	Distance h, mm	Workpiece vol., mm ³
1	30	30	9.5	4.5	8550
2			9	4	8100
3			8.5	3.5	7650
4			8	3	7200
5			7.5	2.5	6750
6			7	2	6300

Measurement of the temperature of the processed object was conducted through six K-type thermocouples with diameter of 1 mm placed in six holes of 10 mm depth distributed as in fig. 1. Fig. 3 presents the measurement station and the sequence of placing thermocouples in the sample.

Table 2. Parameters of machining

Cutting speed	$v_c = 250$ m/min	$v_c = 375$ m/min
Spindle rotation	$n = 855$ rpm	$n = 855$ rpm
Feed per tooth	$f_z = 0.05$ mm/tooth	
Feed rate	$v_f = 513$ mm/min	
Depth of cut	$a_p = 0.5$ mm	
Width of cut	$a_e = 30$ mm	

Fig. 2. View of vertical machining center AVIA VMC 800

Fig. 3. Measurement station and the sequence of placing thermocouples in the sample.

3 Calculations

Total heat in machining released per unit of time (heat stream) corresponds to the approximate machining power and may be determined by the following formula:

$$Q = F_c \cdot v_c \cdot W \quad (1)$$

where: F_c - machining force N, v_c - cutting speed m/s.

Determination of the value of machining force F_c may be conducted on the basis of a formula based on knowing the specific machining resistance k_c .

$$F_c = A \cdot k_c \cdot N \quad (2)$$

where: A - cross sectional area of the machined layer mm², N , k_c - specific machining resistance N/mm².

Specific machining resistance k_c must be calculated depending on the average thickness of the machined layer h_m .

$$k_c = \frac{k_{c1.1}}{h_m^m} \text{ N/mm}^2 \quad (3)$$

where: $k_{c1.1}$ - the value of specific resistance for the unit of thickness of the machined layer N/mm², h_m - the average thickness of the machined layer in mm, m - exponent.

The average thickness of chips (h_m) for a simple cutting edge will be determined depending on:

$$h_m = \frac{180 \cdot \sin \kappa_r \cdot a_e \cdot f_z}{\pi \cdot D_{cap} \cdot \arcsin \left(\frac{a_e}{D_{cap}} \right)} \text{ mm} \quad (4)$$

where: κ_r - setting angle °, D_{cap} - the effective machining diameter to the actual machining depth in mm.

The efficient machining diameter for the actual depth of machining and the specific setting angle is calculated depending on:

$$D_{cap} = D_c \cdot \frac{2 \cdot a_p}{\tan \kappa_r} \text{ mm} \quad (5)$$

Input data and calculation results of total heat released per unit of time during face milling for specific conditions of machining have been presented in table 3.

Table 3. Input data and calculation results

Data	Results
$D_c = 80$ mm	$D_{cap} = 81$ mm
$a_p = 0.5$ mm	
$\kappa_r = 45^\circ$	
$f_z = 0.05$ mm/tooth	$h_m = 0.034$ mm
$a_e = 30$ mm	
$k_{c1.1} = 780$ N/mm ²	$k_c = 1695.6$ N/mm ²
$m = 0.23$	
$A = 0.025$ mm ²	$F_c = 42.39$ N
$v_c = 4.16$ m/s	$Q = 176.34$ W
$v_c = 6.25$ m/s	$Q = 264.94$ W

As a result of conducted theoretical calculations, it has been determined that during face milling with a cutting head R245-080Q27-12M made of M1Ez4 copper, the amount of released heat per unit of time for machining velocity of $v_c = 250$ m/min is $Q = 176.34$ W, while for $v_c = 375$ m/min - $Q = 264.94$ W

4 Results of experimental studies

Figure 4 presents graphs for the change of temperature within the period recorded by 6 thermocouples during processing of the sample made of M1Ez4 copper with machining velocity of $v_c = 250$ m/min for the distance of the tool from thermocouples at $h = 4$ mm. By analyzing results presented in figure 4, it has been observed that the maximum temperature of the sample during the process of face milling was obtained for thermocouple no. 5 - it amounted 66.1 °C. In the case of thermocouple no. 1, the maximum temperature was 58.6 °C, which was the lowest maximum value measured for all thermocouples. Table 4 presents a comparison of results for maximum temperatures recorded by individual thermocouples for various "h" values of the tool distance from thermocouples.

Fig. 4. Graphs of temperature during processing of the sample with cutting speed of $v_c = 250$ m/min for the distance of the tool from thermocouples at $h = 4$ mm

Results presented in table 4 indicate uneven heating of the processed object during the process of face milling. For all samples, the highest temperatures were recorded in thermocouple 5 that was located in the left upper corner of the milled sample, so the cutting plates had to travel the longest distance in order to remove the material in that zone. The lowest values of the maximum temperature were recorded by thermocouple no. 1 that was located in the upper right corner. The only deviation was recorded during the 1st attempt of machining, during which the maximum temperature of 47.1 °C was recorded for thermocouple no. 6, which was caused by improper fixing of the thermocouple in the measurement hole.

Figure 5 presents charts of temperature changes of the copper sample that was face milled with machining velocity of $v_c = 375$ m/min for the tool distance from thermocouples of $h = 4$ mm. The calculated amount of released heat per unit of time for machining velocity

$v_c = 375$ m/min was $Q = 264.94$ W. When analyzing results presented in figure 5, it has been observed that the maximum sample temperature at 73.5 °C was obtained for the thermocouple no. 4. On the other hand, the lowest maximum value was recorded for thermocouple no. 2, for which the maximum temperature was 60.4 °C. Change of machining velocity from 250 to 375 m/min caused an increase of 88.6 W the amount of released heat per unit of time, which led to a change of heating zones of the processed sample.

Table 4. Maximum temperatures recorded by individual thermocouples during processing of the sample with cutting speed of $v_c = 250$ m/min

h, mm	Temperature, °C					
	T1	T2	T3	T4	T5	T6
4.5	56.7	56.8	59.3	63.3	63.6	47.1
4	58.6	58.6	61.3	65.9	66.1	56.8
3.5	60.2	60.3	63.0	67.8	68.1	62.1
3	61.6	61.7	64.7	69.9	70.3	62.9
2.5	63.4	63.6	66.8	72.3	72.6	66.3
2	64.6	64.8	68.3	73.8	74.2	63.2

Fig. 5. Graphs of temperature during processing of the sample with cutting speed of $v_c = 375$ m/min for the distance of the tool from thermocouples at $h = 4$ mm

Analogously to table 4, table 5 presents a comparison of results for maximum temperatures recorded by individual thermocouples for various "h" values of the tool distance from thermocouples.

Table 5. Maximum temperatures recorded by individual thermocouples during processing of the sample with cutting speed of $v_c = 375$ m/min

h, mm	Temperature, °C					
	T1	T2	T3	T4	T5	T6
4.5	58.90	58.60	61.20	71.40	70.20	62.40
4	60.60	60.40	63.20	73.50	72.50	64.20
3.5	62.30	62.00	64.90	75.80	74.80	66.00
3	63.40	63.10	66.50	79.90	77.40	67.80
2.5	65.10	64.80	68.40	81.60	79.80	69.70
2	66.60	66.30	70.30	84.30	82.50	71.70

In the case of all samples, the highest temperature was recorded for thermocouple no. 4 that was located in the

left lower corner of the milled sample. while the lowest values of the maximum temperature were recorded by thermocouple no. 2 that was located in the right lower corner. When comparing data presented in tables 4 and 5, it has been determined that the increase of machining velocity from 250 to 375 m/min resulted in an increase of the maximum temperature of the machined object by 10.1 °C.

Figure 6 presents the charts of temperatures recorded during the process of face milling on copper samples with two machining velocities for $h=4.5$ mm. The continuous line stands for temperatures recorded for machining velocity of 250 m/min. while dotted line - for machining velocity equal 375 m/min.

When analyzing the chart presented in figure 6, we may notice that the increase of machining velocity results in an increase of the flow of released heat. which heats the processed object faster and to higher temperatures.

Fig. 6. Graph of maximum temperatures for different cutting speed

Table 6 presents example results of the impact of the change in machining velocity on the temperature of the processed object for $h=4.5$ mm. Change of machining velocity from 250 to 375 m/min caused an increase of 88.6 W the amount of released heat per unit of time. which in the case of the distance of the tool from thermocouples $h=4.5$ resulted in an increase of the maximum temperature of the processed object by $\Delta T = 8.1$ °C in comparison to processing at a lower machining velocity.

Table 6. Comparison of maximum temperature for different cutting speed

v_c , m/min	Temperature, °C					
	T1	T2	T3	T4	T5	T6
250	56.7	56.8	59.3	63.3	63.6	47.1
375	58.9	58.6	61.2	71.4	70.2	62.4
ΔT	2.2	1.8	1.9	8.1	6.6	15.3

Figure 7 presents the comparison of lists of temperatures (maximum. average. and minimum) of milled samples depending on machining velocity and the distance of the tool from thermocouples. When analyzing data from figure 7, it has been observed that together with the decrease of the "h" value of the tool distance from thermocouples. the maximum values of recorded

temperatures were increasing. which also resulted from the decrease of volume of processed samples after each cycle of the tool, which has been presented in table 1. For machining velocity equal 250 m /min, loss of material of 450 mm³ caused an increase of the maximum average temperature of the sample by 2.12 °C, while for $v_c=375$ m/min by 2.58 °C.

Fig.7. Comparison of temperatures (maximum, average, and minimum) of milled samples

5 Summary

Conducted research allowed to analyze the impact of changes in cutting speed and volume of material processed during a face milling process on the temperature of the processed object made of copper of M1Ez4 class.

Conducted research proves that:

1. Increased machining velocity during the process of face milling causes an increase of performance of the process itself, but also results in an increased amount of released heat per unit of time, which may lead to uncontrolled heating of the processed object to high temperatures.
2. The process of face milling with $v_c=250$ m/min, $f_z=0.05$ mm/tooth, $a_p=0.5$ mm, $a_e=30$ mm led to heating of the processed object to a maximum temperature of 74.2°C.
3. Increase of the machining velocity from 250 to 375 m/min resulted in an increase of the maximum temperature of the processed object from 10.1 °C to 84.3°C.
4. During the process of face milling, the processed object was heated unevenly.
5. Along with the decrease of the volume of processed samples and, consequently, of the "h" value of tool distances from thermocouples, the maximum values of recorded temperatures increased.
6. For machining velocity of 250 m/min. loss in material of 450 mm³ caused an increase of the average maximum temperature of the sample by 2.12 °C. while for $v_c=375$ m/min - 2.58 °C.

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