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THERMOGRAPHIC STUDY OF CHIP TEMPERATURE IN HIGH-SPEED DRY MILLING MAGNESIUM ALLOYS

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Abstract
This paper presents an overview of the state of knowledge on temperature measurement in the cutting area during magnesium alloy milling. Additionally, results of own research on chip temperature measurement during dry milling of magnesium alloys are included. Tested magnesium alloys are frequently used for manufacturing elements applied in the aerospace industry. The impact of technological parameters on the maximum chip temperature during milling is also analysed. This study is relevant due to the risk of chip ignition during the machining process.

Keywords
machining, magnesium alloys, manufacturing processes, high efficiency, temperature in the cutting area, infrared camera.

Introduction – state of the art

Milling is used in both roughing and finishing operations. Achieving required surface finish quality as well as dimensional and shape accuracy of a workpiece is essential in manufacturing. Both surface quality and manufacturing accuracy are influenced by specific factors, defined as machinability indicators. The indicators in question include, *e.g.* cutting forces and temperature in the cutting area. Modern milling methods are applied with the aim of obtaining high efficiency while maintaining defined quality standards. High speed machining (HSM), high performance machining (HPM), high performance cutting (HPC) and high speed cutting (HSC) are among these methods. The methods described in this paper consisted in altering such parameters as cutting speed, feed rate and depth of cut. Chip temperature analysis will, to a considerable degree, allow prediction of safe machining conditions.

Safe machining of magnesium is the subject of numerous studies found in the body of literature [1, 2]. These papers describe various techniques of machining with cutting fluids, which reduce the danger of chip ignition. However, cutting fluid application generates additional costs connected with purchasing and utilising the liquid, as well as requirements concerning maintaining appropriate liquid quality within a given period of time, with the view to maintaining liquid's properties. Therefore, dry milling or minimum quantity lubrication require closer consideration. Apart from subtractive machining, casting and forming should be also recognized as basic formation methods of these alloys [3].

At present the interest in in-process measurements, which for *e.g.* can be achieved using the techniques of infrared radiation (IR), is increasing. However, they are hampered by a change of materials emissivity coefficient, not only with the temperature but also due to changes in color, roughness and contamination. The essential difference between radiation pyrometry and standard techniques consists in that here temperature of a single spot is measured, whereas thermography provides information regarding temperature distribution based on high-resolution thermographic image (thermogram) [4].

Phenomenology of primary processes in the cutting area focuses on material deformation allowance of plastic or brittle cracking and separation of the material on chip and workpiece in primary processes (the area of plastic deformation in the cutting area). The primary reason determining the nature of the cutting process can be contained in the following scientific approach to the problems of physics of cutting: the state of stress in primary deformation area (plastic deformation) depends (apart from the strength characteristics of the workpiece) on the speed of deformation processes and cutting temperature [5].

During machining structural materials, a small area over the tool workpiece interface (*e.g.* at a distance of 40 μm) [6] or the tool workpiece interface [7], in this paper referred to as cutting temperature, is subjected to thermal analysis. Infrared cameras are frequently used for measurements. An IR camera was used for measuring temperature in the cutting area in oil mist cutting [8]. Maximum recorded temperature amounted to approximately 290°C.

Frequently, temperature measurement is difficult or impossible *e.g.* due to limited access to workpiece or short duration of cutting, in which case the measurement is taken with thermocouples inserted in the workpiece [9, 10]. Depending on the type of machining process applied, temperature in the workpiece or in the machined surface may be measured at the point of destruction of the thermocouple. In the latter case, the measured temperature is described as 'mean flank temperature'.

Main concerns regarding this method include: difficulties 'setting up' a thermocouple within the workpiece (proper thermocouple installation is of great significance), the need to use an advanced measuring device able to take at least hundreds of measurements per second and measure a small cutting area (low depth of cut). Similarly, in this case [9], the maximum temperature amounted to 302°C for the cutting speed of $v_c = 816$ m/min, which is considerably lower than the ignition point of magnesium alloys. Moreover, no partial melting on the magnesium alloy chip surface was observed. The tested magnesium alloy chips [11] exhibit a distinctive structure. On the one hand, their surface is smooth (as a result of tool-chip contact), on the other hand, so-called lamellar structures are formed. Lamellas are regular structures diagonally adjacent to each other.

Rapid temperature growth in the cutting area is frequently related to FBU formation (flank built up formation) as well as considerable cutting force fluctuations [12]. These phenomena normally occur in continuous metal cutting processes such as turning, however, in certain conditions they may be observed in milling [11].

Appropriate chip formation in milling through proper selection of cutting data is vital. In turning, an attempt was made to find a method for chip control with the view to obtaining the chip which would not be susceptible to ignition (tubular helical chip). This chip is formed at increased cutting speed and decreased cutting depth [13].

In milling, increased cutting speed (up to $v_c = 400$ m/min) has no influence on mean chip thickness. Simultaneously, such parameters as feed per tooth and cutting depth do demonstrate such impact. Increase in those parameters results in increased chip thickness. In addition, a high-speed camera analyses revealed unstable temperature areas, which may indicate the need for analysing the areas of entrance and exit of the tool. What is more, no partial melting on the chip surface was observed for cutting speed equal to $v_c = 400$ m/min, which indicates that machining at these cutting data should be safe [14].

In recent works on magnesium alloys machinability, observation of chip ignition conditions for lower depth of cut values is recommended [15, 16]. Flares, sparks as well as rings of flares (continuous flares) were observed during cutting.

When measuring workpiece temperature with infrared cameras, the following errors may occur [17]: error of method (*e.g.* error in calculating emissivity, error caused by background radiation reflected from the object or background radiation itself), calibration errors (errors concerning actual environmental conditions during thermovision measurements), electrical circuit error (detector's noise, unstable cooling system, low pixel numbers as well as non-linearity of analog-to-digital converters).

Infrared camera measurement errors may be divided into errors resulting from emissivity change (influenced by temperature) and errors resulting from measurement inaccuracy. As mentioned in previous paragraphs, emissivity value was determined for 260°C and equalled $\varepsilon = 0.13$ [18, 19]. This issue is further discussed in this paper.

Methodology, aims and scope of research

Machining was performed on a Vertical Machining Centre Avia VMC800HS. The tool applied was a 16 mm TiAlN coated carbide end mill. The radial depth of cut was equal to $a_e = 14$ mm, and the remaining cutting data was as follows: $a_p = (0.5 \div 6)$ mm, $f_z = (0.05 \div 0.3)$ mm/tooth, $v_c = (400 \div 1200)$ m/min. An infrared thermovision camera, FLIR SC6000HS, was applied to monitor temperature changes in the cutting area.

In tests, thermal images were taken with a resolution of 320×256 dpi. Total recording frequency set to the value of 100 Hz accounted for dynamic extension of the measuring range in value 360°C and time of recorded sequences. Schematic diagram of test setup is shown in Fig. 1.

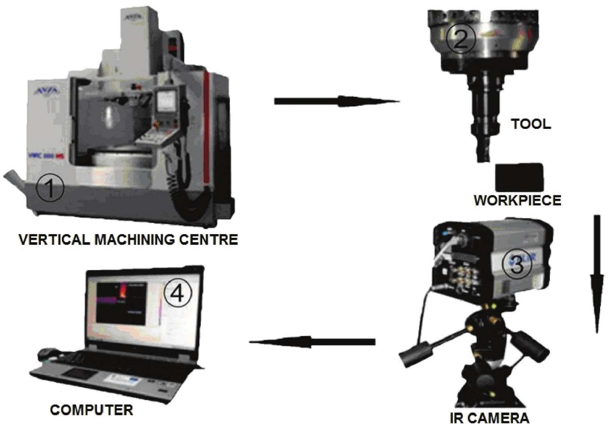


Fig. 1. IR measurement setup.

Admittedly, even excellent infrared camera parameters cannot guarantee sufficient accuracy of measurements. There arises the necessity to evaluate measurement unreliability, which mainly comprises emissivity estimation error and other random conditions affecting the end result. In camera error evaluation method, several assumptions were made for the sake of study.

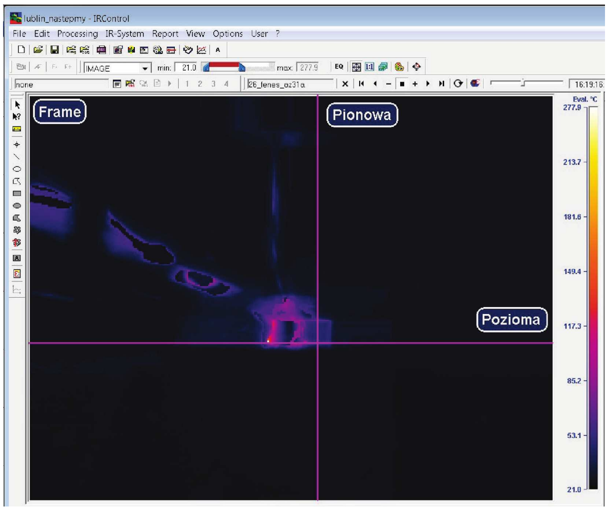
Total infrared camera measurement error is influenced by multiple factors, such as emissivity, the distance of the camera from the object, atmospheric opacity, optical path parameters *etc* [17]. A number of factors influencing total infrared camera measurement error necessitated limiting the issue in this article to the data received from the Flir camera manufacturer, who assessed measurement accuracy for SC6000HS camera to be at ±2 [°C] or ±2% of the measuring range [20]. Attempts to assess total temperature measurement error with the use of infrared camera will be the subject of further research works. Due to the application of the dynamic extension of the measuring range, the measurement error of ±2% of the measuring range was adopted.

Test results and analysis

The figures below show examples of infrared images taken during milling AZ31 and AZ91HP magnesium alloys with TiAlN coated carbide tool. In order to determine the impact of particular cutting parameters, single frames from the sequence of thermal images of the milling cutter in mid-position of AZ31 workpiece.

Thermal images of chips machined at the highest cutting speed and feed rate applied in the tests are shown in Fig. 2.

a)



b)

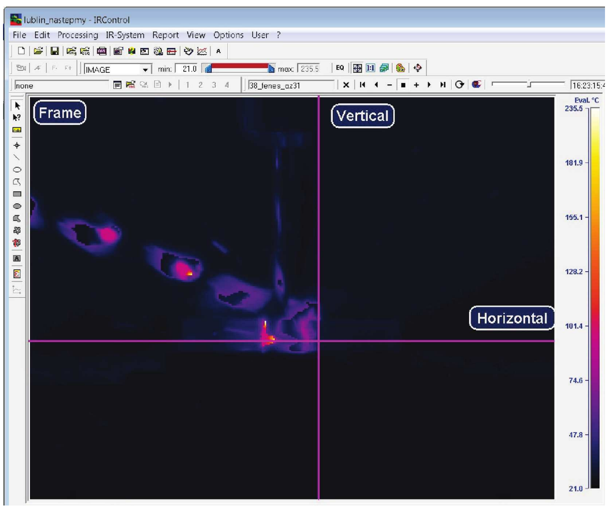
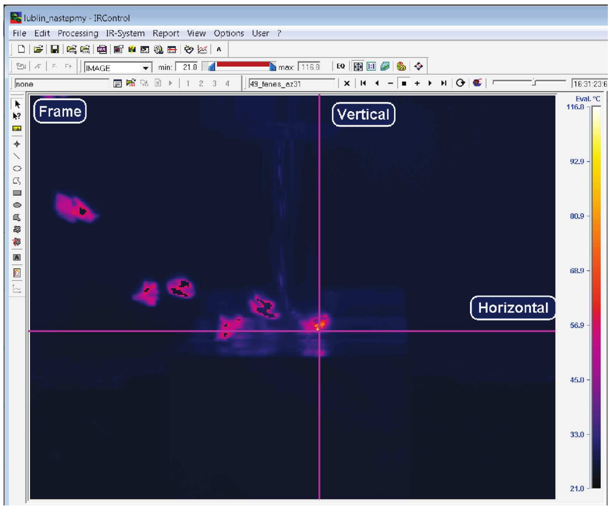


Fig. 2. Thermal images of AZ31 magnesium alloy cutting process: a) maximum cutting speed $v_c = 1200$ m/min, $a_p = 6$ mm, $f_z = 0.15$ mm/tooth; b) maximum feed per tooth $f_z = 0.3$ mm/tooth, $v_c = 800$ m/min, $a_p = 6$ mm.

Thermal images for various depths of cut, constant feed rate and cutting speed are shown in Fig. 3.

a)



b)

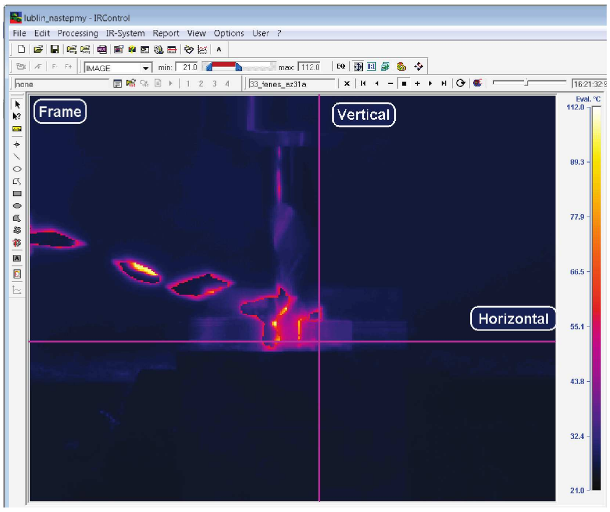


Fig. 3. Thermal images of AZ31 magnesium alloy cutting process: a) $a_p = 0.5$ mm, $v_c = 800$ m/min, $f_z = 0.05$ mm/tooth; b) $a_p = 6$ mm, $v_c = 800$ m/min, $f_z = 0.05$ mm/tooth.

Constant emissivity value for magnesium, equal to 0.13, was adopted in tests [18, 19]. Maximum temperature was determined with the use of data analysis tool – a rectangle reflecting thermal image frame dimensions called 'Frame'. Maximum temperature observed was determined from that square.

The aim of the study was to compare maximum temperature in subsequent frames during cutting. Frames with maximum temperature were chosen for the analysis. The frame selection method is shown in Fig. 4.

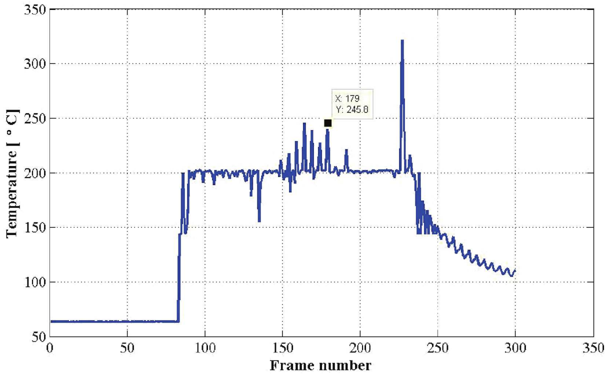


Fig. 4. Frame selection method for evaluation of relationship of cutting parameters.

In order to compare relationship of selected cutting parameters, several cutting test were carried out. The frames located approximately in the middle of the recorded thermal image sequence where the greatest value of temperature was detected were chosen for subsequent analysis. What is more, in a recorded frame chips must be detected. Frames in which extreme values were not observed, were not taken into consideration in analysis. Examples of experimental data concerning AZ31 magnesium alloy samples are shown in Table 1. Values of maximum temperatures detected in frames, taken from different cutting tests, are arranged in column T (Table 1). Column T Max is the sum of T and Error +2%, whereas T Min is equal to the sum of T and Error −2%.

Table 1
Results (for chosen frames) where milling cutter is approximately in mid-position.

v_c [m/min]	a_p [mm]	f_z [mm/tooth]	T [°C]	T Max [°C]	T Min [°C]	Error ±2%	Frame
400	6	0.15	245.8	250.3	241.3	4.50	179
800	6	0.15	321.6	327.6	315.6	6.01	78
1200	6	0.15	341.1	347.5	334.7	6.40	83
800	6	**0.05**	320.4	326.4	314.4	5.99	259
800	6	**0.15**	321.6	327.6	315.6	6.01	78
800	6	**0.3**	311.3	317.1	305.5	5.81	98
800	**0.5**	**0.05**	201.8	205.4	198.2	3.62	271
800	**1.5**	**0.05**	313.3	319.1	307.4	5.85	212
800	**3**	**0.05**	321.6	327.6	315.6	6.01	153
800	**6**	**0.05**	320.4	326.4	314.4	5.99	259
800	**0.5**	**0.15**	224	228.1	219.9	4.06	117
800	**1.5**	**0.15**	285.4	290.7	280.1	5.29	48
800	**3**	**0.15**	320.2	326.2	314.2	5.98	79
800	**6**	**0.15**	321.6	327.6	315.6	6.01	78

The estimation method involving comparison of frames where the cutting process was applied is presented in Table 1.

Error values were calculated from technical parameters provided by the manufacturer of FLIR SC6000HS thermal camera [20]. Based on recorded sequences the ranges of temperatures were defined, and next 2% of evaluated range for each test was calculated and put in Table 1. Measured temperatures and values of camera errors are shown in Fig. 5.

The dependence of cutting speed, feed per tooth and depth of cut on temperature in frame, where the milling cutter is in mid-position of the workpiece is shown in Fig. 5.

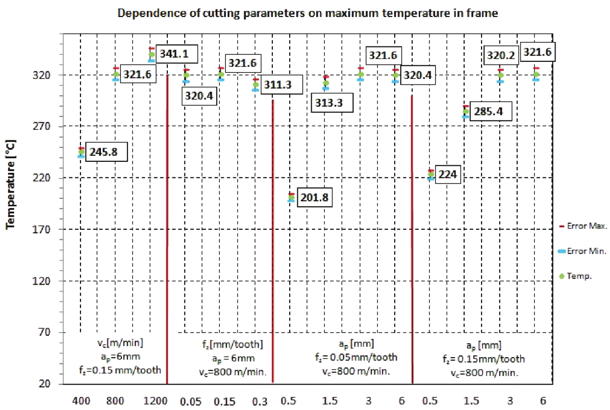


Fig. 5. Overall comparison of the relationship between cutting parameters and temperature with measurement error at ±2% of measuring range.

Authors are fully aware that actual error values might be different. During this study, real error values were not evaluated. The main reason for that fact is lack of special equipment which would enable authors to conduct reliable temperature measurements. The dependence of changes in emissivity coefficient with the increase of temperature or oxidation phenomena of work material should be the subject of future investigation.

Test results indicate that an increase in cutting speed induces a significant increase in temperature measured in a frame. The same relationship was observed for different feed per tooth rates in three variants (Fig. 5). A slight temperature decrease was observed at low feed per tooth in cutting conditions with depth of cut equal to $a_p = 6$ mm, as compared with $a_p = 0.5$ mm. In the former, an increased friction could have occurred causing an increase in temperature. Temperature difference was insignificant and equalled 5°C. Based on Table 1, presenting the correlation between depth of cut and temperature, it was proved that measurement error amounted to maximum ±2°C, as estimated by the camera manufacturer.

a)

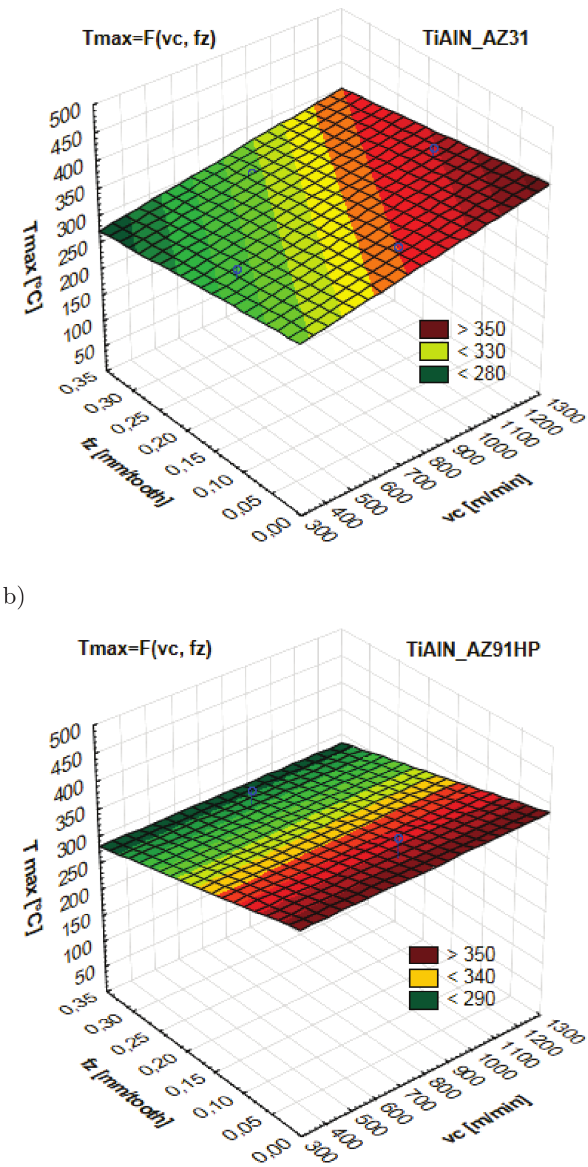
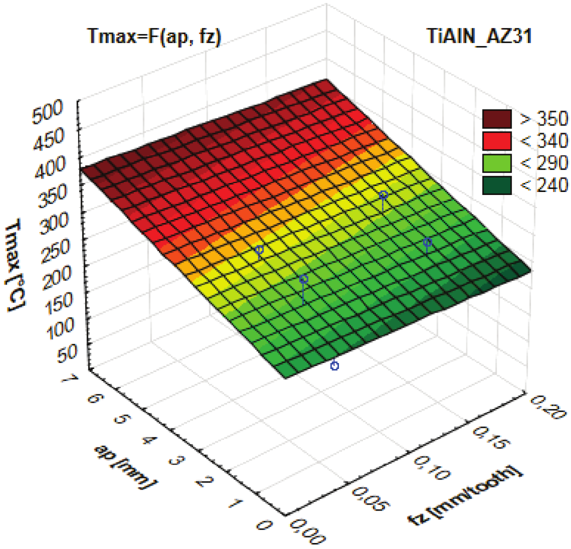


Fig. 6. The dependence of cutting speed v_c and feed per tooth f_z on the maximum chip temperature in the cutting area: a) AZ31 alloy, b) AZ91HP alloy.

Noticeably, high local temperature values (differences amounting to several dozens °C) occur temporarily in the time history of temperature. Temperature fluctuations recorded in subsequent frames result from discontinuous cutting processes as well as cooling. Temperature peaks could result from heterogeneous material properties, chip entering the frame within the distance equal to focal length of the lens or the exposure of cutting edges of the tool.

Test results shown in previous figures (*e.g.* maximum values of temperatures detected for frames where cutting took place) were subsequently analysed. This approach was adopted with the aim of finding maximum temperature occurring in the cutting area since they pose the risk of ignition. Maximum temperatures are shown in Fig. 6 and Fig. 7.

a)



b)

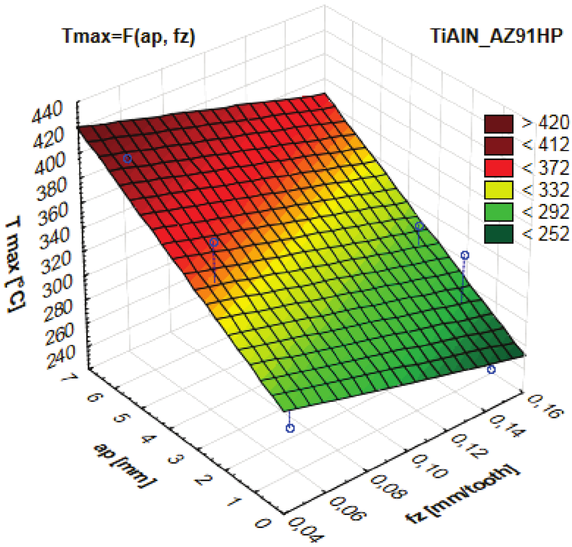


Fig. 7. Relationship between depth of cut a_p and feed per tooth f_z and maximum chip temperature in the cutting area: a) AZ31 alloy, b) AZ91HP alloy.

The relationship between cutting speed v_c and feed per tooth f_z on chip temperature in the cutting area is presented in Fig. 6, and the relationship between depth of cut on chip temperature in the cutting area is presented in Fig. 7.

Neither cutting speed nor feed rate significantly influence chip temperature. Temperature growth is more significant for higher depths of cut. This observation seems vital as far as chip ignition is concerned, as for the machining safety it seems well-founded to increase feed rate and cutting speed rather than depth of cut. It should be, nevertheless, kept in mind that too extensive reduction of depth of cut is dangerous, as fine chips are more susceptible to risk of ignition.

Conclusions

Key findings of experimental tests are as follows:

- Observed chip temperature in the cutting area is substantially lower than temperature needed for chip ignition or the melting point of magnesium alloys for virtually all the analysed parameters.
- The highest temperatures obtained during infrared camera measurement are much lower than observed in chip ignition tests performed outside the machine.
- Cutting speed modifications do not induce any significant temperature growth in the cutting area.
- Feed rate modifications do not substantially influence maximum temperature in the cutting area.
- An increase in depth of cut causes an increase in maximum temperature in the cutting area.
- Time histories of chip temperature show local temporary temperature growth. This phenomenon should be further analysed as far as its causes and chip ignition hazard are concerned.
- The presented range of cutting technological parameters may determine so called safe milling.

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