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METHODOLOGICAL PROBLEMS OF TEMPERATURE MEASUREMENT IN THE CUTTING AREA DURING MILLING MAGNESIUM ALLOYS

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Abstract
This paper presents a literature review on temperature measurement during milling of magnesium alloys as well as other structural materials. Methodology and temperature measurement methods used in own tests are discussed in this paper. Selected test results for each method of temperature measurement in the cutting area are demonstrated.

Keywords
milling, magnesium alloys, aviation elements, machinability, temperature in the cutting area.

Introduction

Temperature in the cutting area influences, among others, thermal expansion of the workpiece affecting its shape and dimension accuracy and may cause deformations in the workpiece – tool system. Additionally, milling magnesium alloys entails risk of chip ignition, which might lead to failure of machine components. Therefore, analysing different methods of temperature measurement in the cutting area seems essential since it contributes to safe and efficient processing of those alloys.

Analysis of the issue

Literature [1, 2] offers an extensive analysis of so called ‘safe milling techniques’ of magnesium alloys including dry milling, application of water-miscible and immiscible emulsions as well as milling with the application of oil mist (minimum quantity lubrication machining). Improving material removal processing of magnesium alloys as well as widening magnesium alloys application range seem to be gaining in significance. Magnesium alloys shaping methods include [3]: casting (continuous casting and mould casting), plastic forming (rolling, forging, extrusion, sheet metal forming and superplastic forming) as well as material removal processing (turning, boring, milling, drilling, reaming, threading, grinding). In recent years, weldability of cast magnesium alloys [4] has acquired new meaning as a method of both regenerating castings after their wear resulting from exploitation and repairing casting defects.

Machinability refers to the susceptibility of the work material to processing and it is assessed using machinability indicators. Functional machinability indicators are referred to when the criteria for assessing machinability include surface roughness, cutting forces or chip shape. Physical machinability indicators include machining temperature [5] which, in the case of magnesium alloys, is critical for evaluating machining safety. When subjected to dry milling, magnesium chips and dust exhibit the tendency to self ignition. A sudden increase in machining temperature resulting from tool wear or flunk built-up causes ignition risk. It seems that assessing flammability of magnesium chips as a function of alloy chemical composition and technological parameters of the process may be key safety indicators [6]. Chip ignition may have the form of sparks, flares (rockets) and continues flares. The division has been made based on the machining speed, depth of cut and magnesium alloy composition.

Tubular helical chips formation [7] during magnesium alloy turning is triggered by increasing cutting edge inclination angle, increase in feed per tooth as well as decrease in depth of cut.

The proposed method of temperature measurement in milling [8] allows measuring so-called “mean flank face temperature” with the application of thermocouples. Test results presented in this paper were obtained during milling of AZ91 magnesium alloy with a d=10 mm carbide end mill. Type K thermocouples were used in the tests. Highest temperature recorded in the tests amounted to 302°C for cutting speed equalling $v_c = 816$ m/min which is considerably lower than ignition or melting temperature of magnesium alloy. Additionally, [9] cutting temperature increases with decreasing ‘undeformed chip thickness’ and increasing cutting speed. Ignition risk depends largely on chip size (weight). Therefore, high magnesium chip thickness should be provided for the process to be safe [10].

During turning of AISI 1117 steel [11], temperature was measured with a K type thermocouple (embedded in the cutting tool) and an infrared camera. Test results prove that an increase in cutting force, feed rate per tooth and depth of cut results in chip's ‘back face’ temperature increase. Nevertheless, cutting speed influenced temperature to the largest degree.

During turning of 6082-T6 aluminium alloy [12] temperature was measured with a K type thermocouple embedded in the workpiece (sleeve). Furthermore, temperature was measured with an infrared camera PM380E for comparative purposes. Additionally, cutting forces were registered. Cutting forces and temperature were found to decrease with the increase in cutting speed, whereas tool wear caused an increase in the observed parameters.

According to [1, 13], the risk of chip ignition results from adhesion, changes in forces and friction with cutting tool path length equal to $l \geq 350$ m and $v_c = 900$ m/min, chip type (small brittle chips are dangerous) as well as low thermal conductivity of the processed material ($\lambda = 80$ W/mK). Those can occur during turning with the use of TiAlN coated or uncoated carbide end mills. Flunk build up formation results from tribochemical reactions between the cutting tool and the workpiece, which occur only after reaching the melting point of Mg-Al intermetallic phases of the machined material (for $Mg_{17}Al_{12}$ – $t_E = 437°C$). Application of [6] e.g. PCD cutting edge or tools with appropriate clearance angles, tool coating and cutting fluids seems advantageous with the view to limiting flank built-up formation. Both adhesion and flank built-up can induce high fluctuations of cutting forces as well as reduction of surface finish quality and accuracy in shape and dimension [1].

AM50A magnesium alloy ignition conditions [14] depend on machining parameters. Moreover, ignition conditions and chip morphology (form and construction) are interconnected as well. The macro morphologies of the chips were observed by optical microscope and the micro structure were obtained by scanning electron microscope (SEM). An indexable milling cutter with $d = 80$ mm in diameter was used in the tests. Sparks, flares and continuous flares were observed during magnesium alloy milling. Processing was conducted with exceptionally low depth of cut $a_p = (1 \div 1000)\ \mu$m.

In magnesium alloy milling, an increase in cutting speed has no influence on mean chip thickness. Simultaneously, such parameters as feed rate and depth of cut do demonstrate such influence. An increase in those parameters results in increased chip thickness. In addition, high-speed camera analyses revealed unstable temperature areas (in terms of temperature values), which implies the need for analysing the input and output of the tool. What is more, no partial melting on chip surface was observed for cutting speed equal to $v_c = 400$ m/min indicating that machining within these operating parameters should be safe [15].

Methodology and scope of research

Processing was performed on vertical machining centre Avia VMC800HS. The tools applied in the study were 16 mm end mills: carbide TiAlN coated, carbide Kordell design and with a PCD cutting edge.

Kordell design is characterised by three wave-shaped cutting edges. This type of tools is dedicated for processing aluminium alloys (so-called first choice) as well as magnesium alloys. Additionally, the characteristic features of Kordell geometry are helix angle $\lambda = 40°$, maximal depth of cut $a_p = (7 \div 45)$ mm, no corner radius r_ε, a positive rake angle $\gamma = (9° \div 12°)$ for reducing cutting forces [16, 17]. Characteristic features of such a carbide Kordell design tool are presented in Fig. 1.

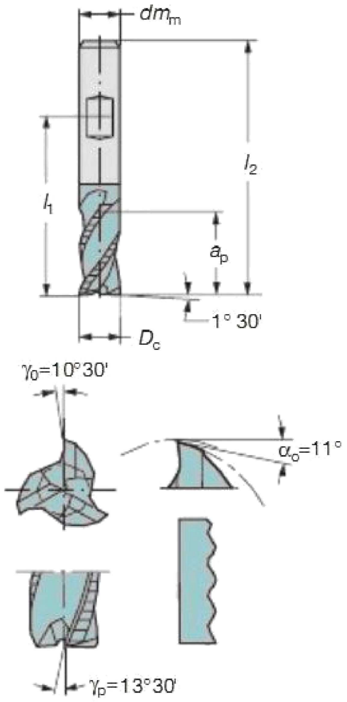

Fig. 1. Catalogue image of a Kordell end mill [17].

A constant milling width $a_e = 14$ mm and the following technological parameter ranges were adopted: $a_p = (0.5 \div 6)$ mm, $f_z = (0.05 \div 0.3)$ mm/tooth, $v_c = (400 \div 1200)$ m/min.

Temperature changes in the cutting area were investigated using the following measuring devices:

- embedded thermocouples inserted in the workpiece (K type thermocouples) compatible with UNI-T UT325 thermometer and software,
- OPTCTLCF3LT optical pyrometer with Compact Connect software,
- FLIR SC6000HS infrared camera with IR Control software.

Two types of magnesium alloys were used in the tests – AZ91HP and AZ31. These magnesium alloys are commonly used in various branches of industry.

Embedded thermocouples

Embedded thermocouples can be inserted either into the tool or the workpiece and measure respectively the temperature at the chip/tool interface or the temperature generated in the workpiece. Measured temperature is most often defined as average temperature at the chip/tool interface, i.e. when embedded thermocouple is destroyed. The thermocouples used in tests were K type thermocouples of a single thermocouple wire diameter $d = 0.13$ mm. Thermometric properties as well as tolerance are according to Polish Norms PNEN 60584-1:1997 and PN-EN 60584-2:1997. An inserted thermocouple is shown in Fig. 2.

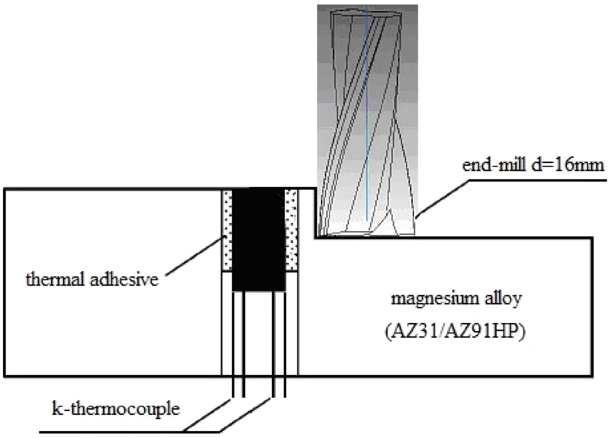

Fig. 2. K type thermocouple inserted into workpiece (AZ31 and AZ91HP magnesium alloy).

K type thermocouple was plugged in a UNI-T digital thermometer (model UT-320) of the following parameters: the measuring range with K type thermocouple −200.0°C to +1372°C; measurement accuracy with K, J, T and E type thermocouples: 0.2% ± 0.6°C; display resolution 0.1°C; temperature scale in C/F/K; input T1, T2.

Optical pyrometry

Pyrometers are measuring devices for measuring temperature of inter alia workpiece surface. What is important is to assume fixed focal length for a given model of pyrometer. In the case of this research and OPTCTLCF3LT type pyrometer this parameter is equal to $L = 200$ mm. For the spectral range (8...14) μm, with accordance to [18] the emission coefficient was set to 0.1. The CF3 optical head of the applied pyrometer is presented in Fig. 3.

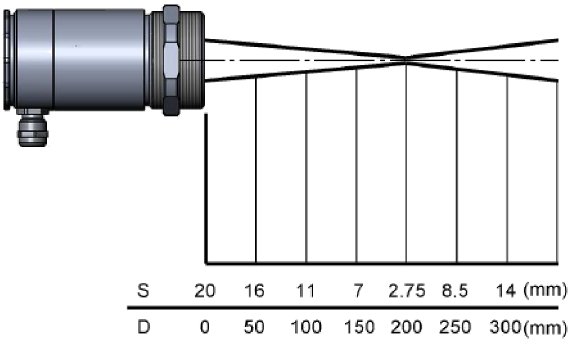

Fig. 3. CF3 optics with the focal length [18].

Laser sensors in CTlaser pyrometers are non-contact temperature sensors, providing measurements based on infrared radiation emitted by the object. Integrated double laser system marks accurate measuring spot regardless of the distance. Compact Connect Software enables, e.g.: CT sensors setup, defining parameters of the sensor according to requirements of a particular application, displaying and recording temperature changes [18].

Computer thermography

Temperature distribution during milling process, their peak values as well as dynamic temperature variations were recorded with an infrared camera, FLIR SC6000HS. The distance between the camera and the observed workpiece was 0.9 m [19].

IR Control software enables configuration of camera settings and adjusting its parameters to conducted tests. Moreover, it allows recording thermal data, processing it and generating the final report. In addition, visualisation of images from the camera, both individual and sequence images is supported by the software. Finally, the compatibility of IR Control with MatLab enables development and detailed data processing as well as its graphic visualisation [19]. Table 1 presents experimental test conditions.

Table 1
Selected experimental test conditions [19].

Parameter	Value
Ambient temperature	22°C
Milling cutter temperature before test	22°C
Lens distance from the workpiece	0.9 m

Camera's factory presets allow to measure temperatures between −20°C and 120°C. Filter application was impossible as minimum temperature values required for their application equal 250°C. With the view to achieving maximum frequency of data collection, the camera's visual field was limited. Frequency reached 400 Hz with resolution equal to 320 × 256. With the application of Preset Sequencing method, the measuring range was extended to 360°C.

However, using presets caused a decrease in frequency from 400 Hz to 100 Hz, as the method involved taking four frames in order to obtain one frame with extended measuring range by the camera. Each preset was characterised by a different frequency range equalling up to 400 Hz for resolution equivalent to 320 × 256 [19].

Determining emissivity of the investigated object was among the aims of IR camera temperature measurement. The analysis of the milling centre working area indicated that the size of the tested material constitutes only a small part of the area 'seen' by the camera. Hence, establishing emissivity of the object poses considerable difficulties, as it is composed of various elements. In such cases, an emissivity calculator should be used for establishing so called 'estimated emissivity' of the area. Term 'area' comprises multiple elements: the workpiece, the milling cutter and all the workspace. The program estimated emissivity based on temperatures, as shown in Fig. 4 [19].

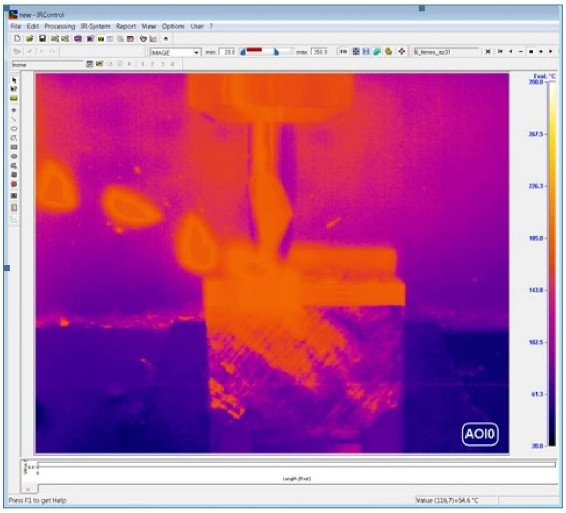

Fig. 4. IR camera image obtained with IR Control software [19].

Emissivity calculator served to determine target temperature as well as calculated mean temperature. Based on that data, the program estimated emissivity of the area seen by the camera. Emissivity evaluated using emissivity calculator equalled 0.92 in conducted tests. All image sequences were taken for this emissivity value. Mean magnesium emissivity equalling 0.13 for 260°C was taken into consideration with the view to obtaining real milling temperatures [19]. This value was assumed based on emissivity tables [20].

Image of the program interface operating on IR camera showing one frame of milling AZ31 magnesium alloy with a Fenes end mill is presented in Fig. 4. During temperature measurements conducted using IR Control program, entire cutting area and maximum temperature occurring in this area in every frame of the data sequence were taken into consideration [19].

The amount of frames in each thermal image sequence was different due to differences in test duration. The average amount is approximately 400 frames per test. In order to produce a reliable evaluation of temperature generated in the cutting area, reports for each test were created with the view to determining temperature generated in the milling processes.

Selected the test results and their analysis

The presented test results will provide basis for selecting supreme temperature measurement method in the cutting area. Tests were conducted with the application of: K type thermocouples embedded in the workpiece (mean chip/tool interface temperature), optical pyrometry (work surface and machined surface temperature measurement), computer thermography (maximum temperature measurement in a given thermal image sequence).

Embedded thermocouples

Own test results as well as those presented in this paper [8] indicate that measuring mean chip/tool interface temperature is valid only during machining with low depth of cut values (equalling approximately cutting edge radius of the tool).

Figure 5 presents 'mean tool/workpiece interface temperature measurement' using K type thermocouple.

a)

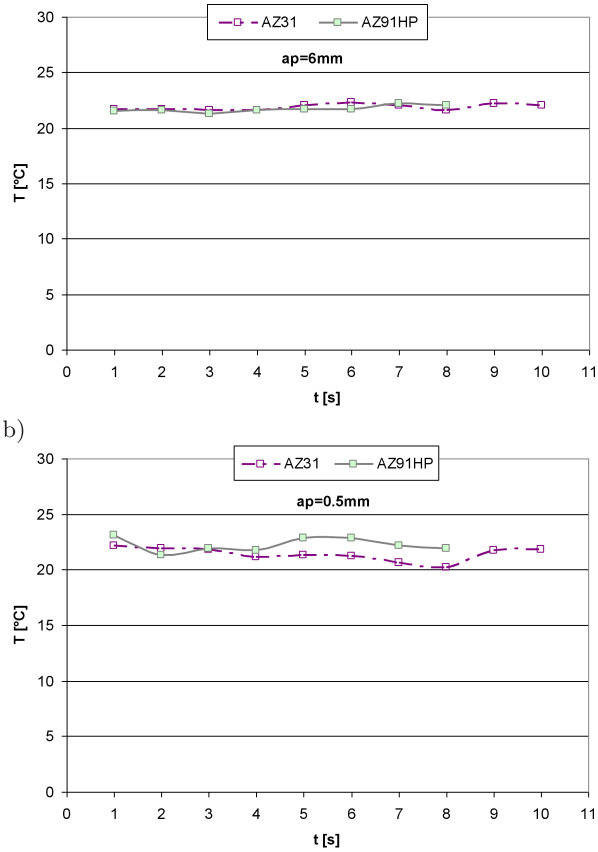

Fig. 5. Changes in mean tool/workpiece interface temperature for the following parameters: $v_c = 800$ m/min, $f_z = 0.15$ mm/tooth: a) $a_p = 6$ mm, b) $a_p = 0.5$ mm.

Temperature scarcely increases during machining, which allows to assume that the applied method proves useless in this parameter range. Measured temperature is equal to the initial temperature of the workpiece. As notices before [8] this temperature measurement method is effective only with low depth of cut values, which does not find application in real industrial conditions. Moreover, temperature values did not resemble the results presented in [8] (despite corresponding thermocouple location).

Optical pyrometry

Changes in cutting speed v_c were analysed for two magnesium alloys. Changes in temperature measured on the edge of the workpiece as well as maximum recorded temperature values are presented in Fig. 6.

a)

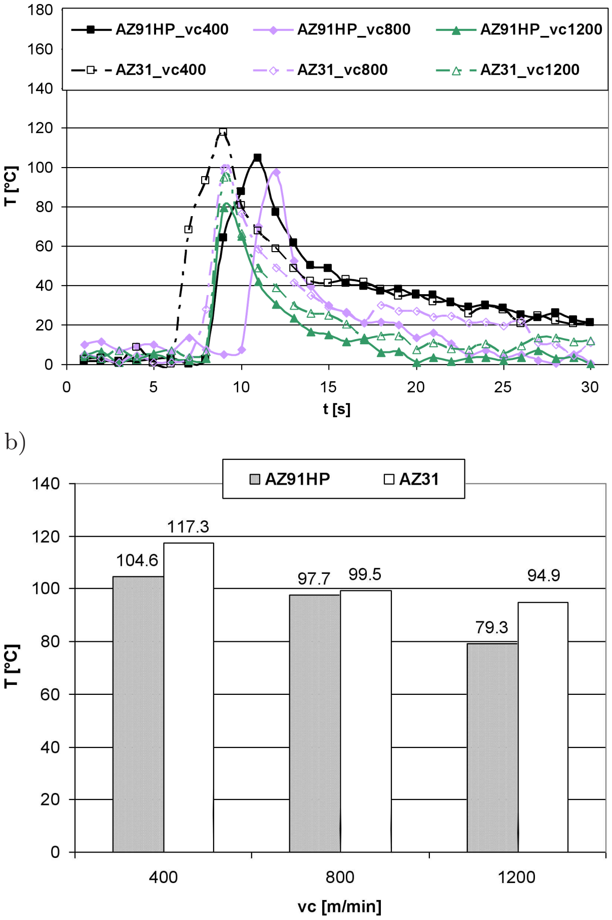

Fig. 6. Changes in temperature in the cutting area measured using optical pyrometry: a) time runs of temperature changes, b) maximum temperature values.

Temperature values obtained in the test indicate that temperature in the cutting area reached lowest values when the tool/interface contact was shortest (short machining time). The presented test results can serve comparative purposes, since determining cutting area temperature using this method is unobtainable. This method can be used for monitoring surface temperature of the workpiece. AZ31 alloy demonstrated higher temperature values, however, the difference is scarce. The highest temperature was observed for AZ31 alloy with cutting speed equalling $v_c = 400$ m/min, and it amounted to $T = 117.3$°C. This value is considerably lower than temperature observed in identical conditions using an IR camera. This is most probably caused by the fact that the latter method measures chip temperature, and 80% of heat during machining is transferred to chips [21].

Computer thermography

All data collected from thermal image sequence were analysed. This approach was adopted with the aim of finding maximum temperature occurring in the cutting area since they pose the risk of ignition. The analysis of all data allows to detect so called unstable areas at the input and output of the tool.

Example of infrared image taken during milling AZ31 magnesium alloy are presented in Fig. 7.

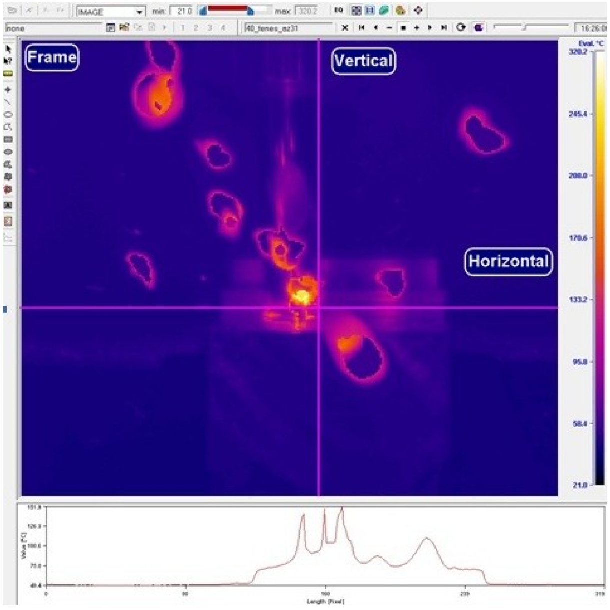

Fig. 7. Example of infrared image taken during milling AZ31 magnesium alloy with TiAlN coated carbide end mill; $v_c = 800$ m/min, $f_z = 0.15$ mm/tooth, $a_p = 6$ mm [19, 22].

Characteristic correlations presenting changes in the time function of the observed temperature values depending on the depth of cut during milling with the use of TiAlN coated carbide end mill are presented in Fig. 8.

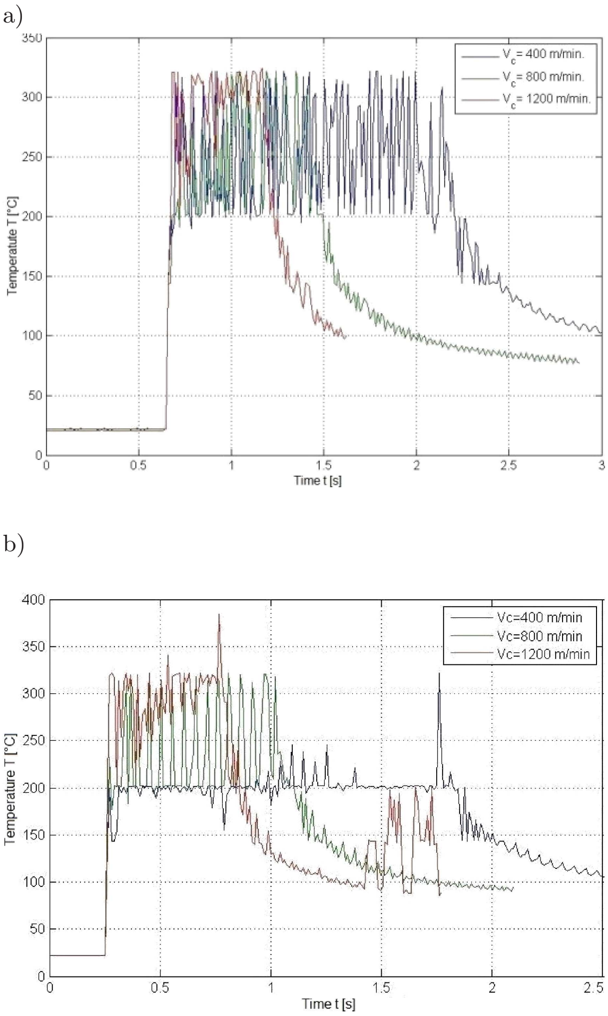

Fig. 8. The influence of cutting speed of cut on temperature in the cutting area during milling of: a) AZ91HP alloy, b) AZ31 alloy, with a TiAlN coated carbide end mill; $a_p = 6$ mm, $f_z = 0.15$ mm/tooth [19].

What seems worth noticing is that cutting speed increasing to 1200 m/min did not cause any substantial temperature increase in the cutting area. Maximum temperatures for AZ91HP alloy were similar, that is within the range $T(321.6 \div 324.3)$°C, and the maximum temperature was observed for maximum cutting speed. Maximum temperatures for AZ31 alloy equalled $T = (321.6 \div 384.6)$°C, and the maximum temperature was observed for maximum cutting speed.

Figure 9 presents Boxplot diagrams. The horizontal line with the point marked in the centre of the ‘box’ denotes a median, ‘whiskers’ indicate the analysed parameter (temperature) variability range and ‘rectangles inside the box’ comprise 50% of the data. Because maximum temperatures occurring in the cutting area are of primary importance in the tests, all data collected from a thermal image sequence was analysed. The diagrams present the influence of feed rate per tooth on chip temperature in the cutting area.

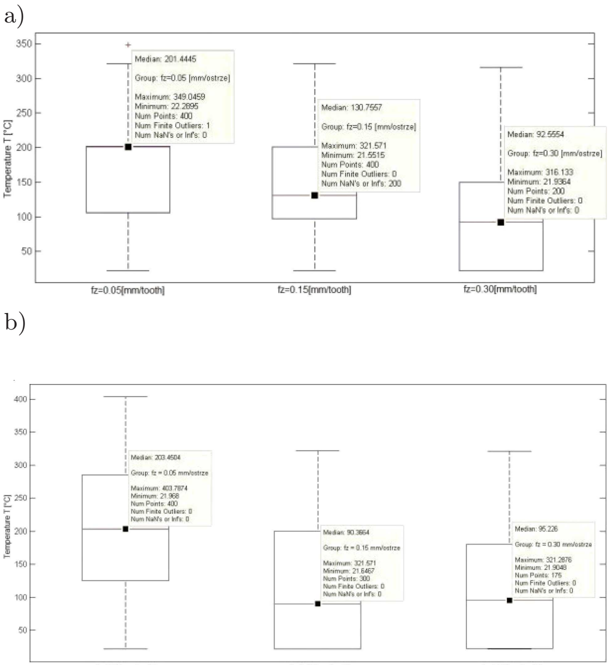

Fig. 9. Influence of feed rate per tooth on changes in temperature: a) AZ31 alloy, b) AZ91HP alloy [19].

Maximum recorded temperature (with changing feed rate per tooth) equalled approximately 404°C with $f_z = 0.05$ mm/tooth for AZ91HP alloy. The observed temperature is lower than melting point of magnesium alloys or temperature required for ignition to occur.

Measuring error resulting from the application of infrared camera can be divided into errors resulting from change in emissivity (as well as temperature) and errors resulting from measurement accuracy. Emissivity coefficient was adopted for temperature 260°C and it equalled $\varepsilon = 0.13$. Overall error of method was assessed to equal ±2% of the measuring range in the conducted tests.

Summary and conclusions

The conducted analyses as well as experimental tests allow to formulate the following conclusions:

1. Changes in cutting speed do not cause any significant temperature increase in the cutting area in magnesium alloys face milling.
2. Temperature analysis in the cutting area using optical pyrometry is suitable only for monitoring surface temperature of the workpiece.
3. Temperature measurement using thermocouples is not suitable for temperature measurement in the cutting area, especially with depth of cut reaching values applied in industrial conditions. This method is effective only with low depth of cut values, which does not find application in real industrial conditions.
4. Temperature measurement method involving infrared camera proves to be most suitable in terms of recorder temperature values. Nevertheless, this method can entail dealing with inaccuracy due to changing emissivity coefficient.
5. Recorded temperature in the cutting area was considerably lower than ignition chip temperature or magnesium alloy melting point.
6. The conducted tests allow to believe that there is no risk of chip ignition in face milling of the tested magnesium alloys within the assumed measuring range of technological parameters, which were equal to those applied in industrial conditions.
7. High local temperature values in the input and output of the tool were detected in the conducted tests, which in the future should be regarded as potential ignition areas.

Conducted study works as well as own research allow to formulate the following primary conclusion: high quality thermography equipment offers most acceptable level of accuracy of the assessment, with technological parameters of the process equal to real industrial conditions, therefore is most suitable. The remaining methods can be used selectively in particular situations.

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