Advances in Science and Technology Research Journal

Advances in Science and Technology Research Journal 2022, 16(2), 109–119
https://doi.org/10.12913/22998624/146851
ISSN 2299-8624, License CC-BY 4.0

Received: 2022.01.11
Accepted: 2022.02.21
Published: 2022.03.03

Chip Temperature Measurement in the Cutting Area During Rough Milling Magnesium Alloys with a Kordell Geometry End Mill

Józef Kuczmaszewski[1], Ireneusz Zagórski[1*], Piotr Zgórniak[2]

[1] Department of Production Engineering, Mechanical Engineering Faculty, Lublin University of Technology, ul. Nadbystrzycka 36, 20-618 Lublin, Poland

[2] Institute of Machine Tools and Production Engineering, Faculty of Mechanical Engineering, Lodz University of Technology, ul. Stefanowskiego 1/15, 90-537 Łódź, Poland

* Corresponding author's e-mail: i.zagorski@pollub.pl

ABSTRACT

The paper presents the results of measurements of chip temperature in the cutting zone during milling. The main aim of the research was to record and compare the maximum chip temperature in consecutive frames of thermal images. An additional goal may be the influence of changes in technological parameters on the temperature of the chips in the cutting zone. Two grades of magnesium alloys were used for the tests: AZ31 and AZ91HP. The research used a carbide milling cutter with an additional chip breaker, dedicated to effective roughing of light alloys. These tool geometries can assist in the high-performance machining of magnesium alloys by efficiently splitting the chip and consequently reducing friction in the machining zone. This can reduce the cutting area temperature. The results of the research work were showed as exemplary "time" charts, box-plot charts and a summary table, which additionally included an error analysis of the measurement method. On the basis of the tests and measurements performed, it can be concluded that despite the observed chip fragmentation, the obtained temperatures can be defined as the so-called safe milling areas. During the machining tests, the risk of chip ignition during machining was not observed, also the characteristic melting points, which clearly indicates the safety of the milling process of these alloys. It has been observed that with the increase of v_c and f_z, there was no increase in the maximum temperature of the chip in the cutting area. This situation only occurs when increasing a_p.

Keywords: magnesium alloys, milling, temperature in cutting area, chip temperature, infrared camera.

INTRODUCTION

Considering the safety of the magnesium alloys milling, the key issue seems to be the assessment of the chip temperature in the cutting area. The conducted research on various types of magnesium alloys proves that it is possible to mill without increasing the risk of ignition of chips formed during the machining process. If the cutting temperature is near to the melting point of magnesium fire ignition of chips could occur during high speed cutting. An experimental research [1] show the mean temperature on the flank face in high speed dry cutting of AZ91 magnesium alloy. Foreign thermocouples (type k) placed in the workpiece were used in the tests. In HSC process, the mean flank temperature is less than that on the rake face (cutting temperature). The undeformed chip thickness (UCT) has a very low chip thickness and comparable size as cutting edge radius. Measurements of the mean flank temperatures in various cutting conditions were taken and SEM analysis was carried out for the collected chips to analyse if there are any traces of burn marks. As a result of the analysis it was stated that below the mean flank temperature of 302 °C, there were no burn marks found on the chips (at the cutting speed of 816 m/min and at UCT of 9 μm). One way to predict the occurrence of fire during high speed cutting of magnesium alloys is the measurement of the mean flank temperature. An increase in cutting speed causes the temperature increases with, and increase is observed with a decrease in the undeformed chip thickness.

In turn, in the research [2], the temperature in the cutting zone was analyzed, determined both in the section the tool/chip interfaces (across chip) and in the subsurface. The analyzes and simulations performed show that the predicted temperatures at the tool/chip interfaces were close to the melting temperature of the Mg-Ca0.8 alloy (approximately 600 °C). Similarly, in [3], the temperature in the cutting zone was analyzed that would be generated during magnesium alloy Mg-Ca0.8 milling. The studies included simulation of five cases corresponding to five cutting speeds. The authors note that when analyzing temperature distributions two aspects should be taken into account: the size of the area covered with certain temperature and the temperature itself. Although temperatures close to 600 °C were observed in the simulation, it should be noted that the predicted temperatures would likely not be the upper limit of machining temperatures in practice at the milling parameters (heat conductivity between the tool/workpiece and workpiece/environment were not included so it means that material melting and chip ignition would not happen for the concerned machining conditions). Moreover, the temperature in almost the entire volume of the chip was approx. 150–450 °C, so it is highly probable that there will be no chip ignition and no fire hazard. The chips can only ignite if the melting point (estimated at 516.6 °C) is exceeded in the entire volume of the chips. This is confirmed by experimental research because there was no spark or chip ignition during milling.

Similarly, the article [4] analyzed the process of in high-speed milling and it's temperature distribution in the case of AZ91C alloy. Temperature distribution was measured using: the infrared thermometer (machining zone/area temperature) and the contact method (platinum temperature sensors for the work-piece temperature). The results indicate the reduction of the workpiece temperature as the cutting speed exceeds the cutting speed of 452 m/min in high-speed milling, while the temperature of cutting area increases due to an increase in the cutting speed. No ignition was observed during machining in any of the analyzed range of machining parameters.

In [5] the mean flank temperature was measured (by mounting two K-type thermocouples). Magnesium alloy AM50A was used. A milling head (80 mm) with K110M blades was used. A high cutting speed of 3014 m/min was achieved. The aim of the research was to analyse the influence of cutting speed on the temperature increase of tool flank surface was analyzed. It was observed that at the beginning the temperature increases and then decreases with increasing cutting speed. The chip ignition occurs when the mean flank temperature rise is approx. 3 °C (when the milling speed is less than 1507 m/min).

In [6] attempts were made to ignite during the processing of chips from AM50A and AZ91D magnesium alloys. Influence of cutting parameters on ignition of chips during face milling was analyzed. The research included also chips morphology to understand mechanisms of ignition. The types of observed ignition are described as: sparks, flares and ring of sparks. It was found that AZ91D is more inflammable than AM50A in dry face milling. The significant ring of sparks was noticed about 754 m/min during dry milling AZ91D. The big flares are observed when the cutting speed is about 754 m/min during milling AM50A. First the probability of ignition of magnesium alloy chips increases and then decreases with increasing cutting speed.

In [7], the typical problems that occur when measuring the temperature in the cutting area during milling of metal alloys are discussed. Selected results of temperature measurements with the use of three measurement methods are also presented: k-type thermocouple, optical pyrometry and infrared camera. The research [8] presents the results of the measurement of chip temperature in the cutting area with the use of a carbide tool with a TiAlN coating and magnesium alloys AZ31 and AZ91HP. The influence of machining parameters on the maximum chip temperature in the cutting zone during dry milling was analyzed. Noticed that measured chip temperature in the cutting zone is significantly lower than temperature needed to ignite the chip or the melting point of magnesium alloys. However, in [9] the so-called time to ignition, ignition temperature and chip morphology after milling with used TiAlN coated carbide tool. Additionally presented the so-called successive stages preceding chip ignition for magnesium alloys (AZ31 and AZ91HP) In the article [10], the chip temperature in the cutting area was also analyzed using of the previously mentioned magnesium alloys, in this case a high-class cutter with polycrystalline diamond PCD blades was used as the tool. Also presented are exemplary chip fractions and the mass of chips obtained during machining (taking into account different chip fractions). The paper presents chip temperature results as box-plot charts and a summary table with various temperature values (including the entrance and the exit of the workpiece, including the so-called “outliers” which differ from other measured values, including the stable region only). In addition, it was presented metallographic photographs of magnesium alloy chips and the so-called “cauliflowers” area in the magnesium chips ignited on a heating plate of a specially designed test stand. Equally important and helpful in the analysis of temperature changes in the cutting area may be the analysis of the temperature distribution in the area directly related to the undeformed chip [11], especially during the machining of magnesium alloys. An interesting issue also seems to be aspect risk of legal liability in the experiment with challenges in machining of magnesium alloys [12].

Infrared measurement of temperature in the cutting area are also often used in the machinability analysis of other construction materials [13], often including titanium alloys, as a material often used both in industry and in research conducted on these alloys. In addition to magnesium alloys, titanium and nickel alloys also pose a significant risk related to damage to machine elements and devices by chips that may ignite and burn during machining. The material grade Ti6Al4V [14–18] is commonly used in research, which is also widely used in automotive and aviation industry.

Unfortunately, research works are often carried out under the conditions of machining parameters (mainly depth of cut), which are unlikely to be found in widely understood industrial practice. Small depths of cut, on the order of a few or a dozen or so micrometers [19], may be important from the point of scientific understanding of the cutting process phenomena. Nevertheless, due to industrial applications, research work carried out in machining conditions similar to those used in the machinery industry, carried out in a safe and at the same time effective and efficient manner, is valuable.

METHODOLOGY, AIMS AND SCOPE OF THE STUDY

During the milling process, dynamic temperature changes on the chip surface were recorded using a FLIR SC6000HS infrared camera. The camera was located at a distance of 0.9 m from the tested workpiece. Using the IR Control software, the necessary changes were made to the camera settings and its parameters were adapted to the research. The software enables the visualization of photos taken with the camera, as well as obtaining data for both the entire sequence and a single frame. The IR Control program is compatible with the MatLab software enabling more detailed data processing and its visualization in graphic form. The ambient temperature and the cutter temperature before each test were 22 °C. In order to obtain the maximum data collection frequency, the field of view of the camera has been narrowed. With a resolution of 320 × 256, a frequency of 400 Hz was achieved. The Preset Sequencing method was used in order to increase the measuring range of the camera, which resulted in the reduction of the frequency of the pictures taken to 100 Hz. This was due to the way the camera worked, which had to take four frames to obtain one with an extended measuring range.

When measuring temperature with a camera, it was very important to determine the emissivity of the source. When analyzing the working space of the milling center, it is easy to notice that the size of the processed workpiece sample was a small part of the area “seen” by the camera. Therefore, it is difficult to clearly define the emissivity of the target, as it consists of many components. In such cases, it is necessary to establish the so-called Emissivity Calculator the estimated emissivity of the area. This definition includes the emissivity of the workpiece, milling cutter, and the entire workspace. The Emissivity Calculator specifies the Target Temperature and the Calculated Mean Temperature. On this basis, the program has calculated the emissivity of the visible area for the camera. To obtain the actual temperatures occurring in the milling process, the average emissivity of magnesium was taken into account, which for the temperature of 260 °C was 0.13 [20]. During the temperature analysis in the IR Control software, the entire area of the cutting zone was analyzed and the maximum temperature that appeared in this area in all frames of the recorded data sequence was determined. Their average number is nearly 400 frames per test. In order to make a reliable assessment of the generated temperature in the cutting area, it was decided to generate reports for each test and on this basis determine the value of the generated temperature in the cutting process.

The temperature of objects was measured using infrared cameras, the following types of errors should be taken into account [7, 8]: method errors (e.g. error in estimating the emissivity ε of the object, error caused by the influence of the ambient radiation reflected from the object and the influence of the radiation of the environment itself), calibration errors (errors related to the actual conditions of thermal imaging measurement), electronic path errors (e.g. detector noise, instability of the cooling system, limited resolution and non-linearity of analog-to-digital converters). Measurement errors related to the use of a thermal imaging camera can result from the change (along with temperature) of the emissivity coefficient and errors resulting from measurement accuracy.

Therefore, the total measurement error with a thermal imaging camera is influenced by many factors, such as: emissivity, object distance from the detector, atmospheric transmittance, optical path parameters, etc. [7, 8]. Due to the large number of factors influencing the total error of measurement with a thermal imaging camera, this study was based on the data of the Flir camera manufacturer, which for the SC6000HS camera type used, estimated the value at ± 2 °C or ± 2% of the measured temperature range. Because of the use of the function of dynamic extension of the measuring range of the camera, a worse possibility was assumed and the measurement error was determined at the level of ± 2% of the measuring range [21]. The next step was to create charts of the chip temperature time history and collective box-plot charts, among others to illustrate the maximum temperatures in the cutting area.

Scheme of test setup is shown in Fig. 1. Milling of magnesium alloys was carried out on a vertical machining center Avia VMC800HS. A carbide milling cutter with a Kordell geometry (Fig. 2) with a diameter of d = 16 mm was used. It was a three-flute cutter with part number R216.33-16040-AJ20U. A characteristic feature of the Kordell geometry (U type Kordell geometry) is the wave-shaped cutting edges. This tool is dedicated to machining aluminum alloys (so-called "first choice") as well as magnesium alloys. Furthermore, this geometry is characterized by: the helix (inclination) angle $\lambda_s = 40°$, maximum axial depth of cut $a_p = 45$ mm, lack corner

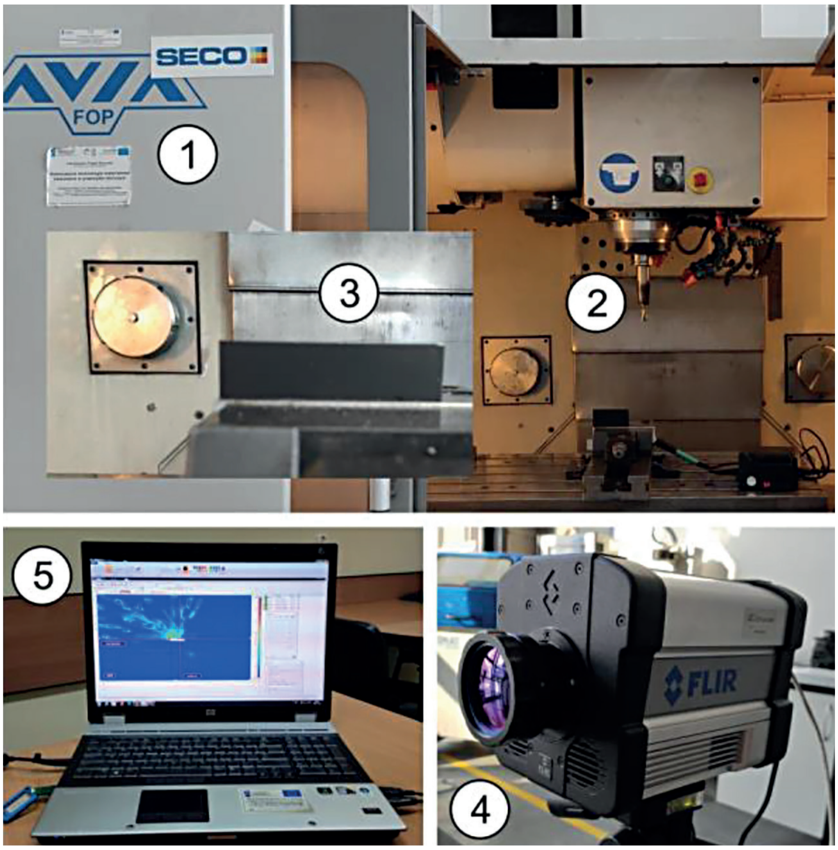

Fig. 1. Chip temperature experimental and measurement set-up: 1 – milling machine, 2 – tool, 3 – magnesium workpiece, 4 – FLIR SC6000HS infrared camera, 5 – computer with IR Control software

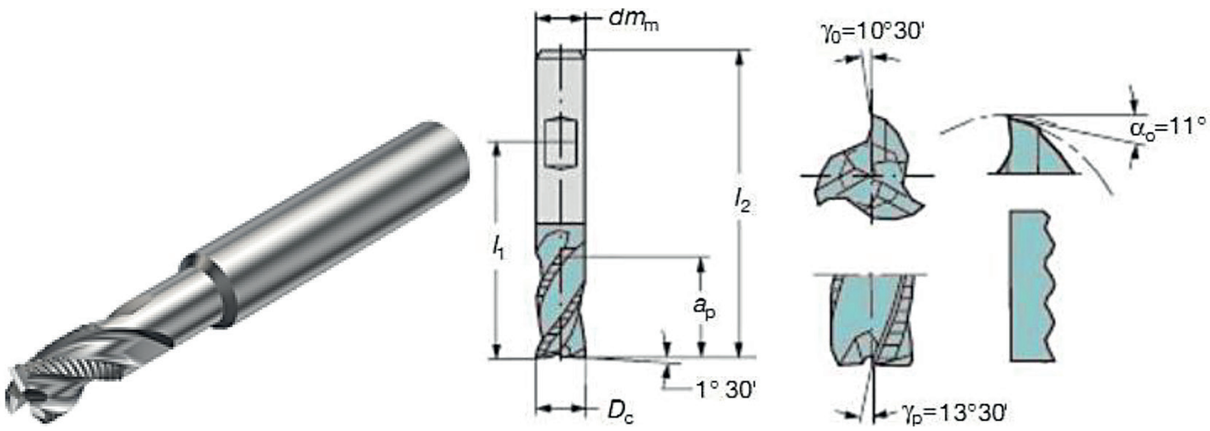

Fig. 2. Catalogue image of a Kordell end mill [22]

radius r_ε, positive rake angle γ = 9÷12° (to reduce the cutting force). A constant milling radial depth of cut was adopted a_e = 14 mm. The following range of technological parameters was adopted: v_c = 400÷1200 m/min, f_z = 0,05÷0.3 mm/tooth, a_p = 0.5÷6 mm.

Two magnesium alloys, frequently used in both industrial and research applications, were used in the research: casting magnesium alloy AZ91HP and from the group of alloys intended for use in metal forming applications AZ31.

TEST RESULTS AND ANALYSIS

Figure 3 shows an exemplary time waveform chart of the change in chip temperature in the cutting area during milling of magnesium alloys. The presented example time waveform chart of the chip temperature in the cutting area relate to the machining conditions during which the cutting speed v_c was variable. The waveforms charts include all data from the thermal image sequence. Already based on the analysis of the time course diagram, it can be seen that the change in the cutting speed in the given range does not remarkably affect the increase or decrease of the temperature of individual chips in the cutting zone.

It is worth noting that in the time series of temperature values there are periodic rapid changes in temperature, this is an increase of several dozen °C. Temperature fluctuations recorded in successive frames of thermal images are caused by the effect of intermittent cutting of successive cutter blades and the cooling effect of individual machining blades.

Figures 4–6 show the influence of change technological parameters on temperature in

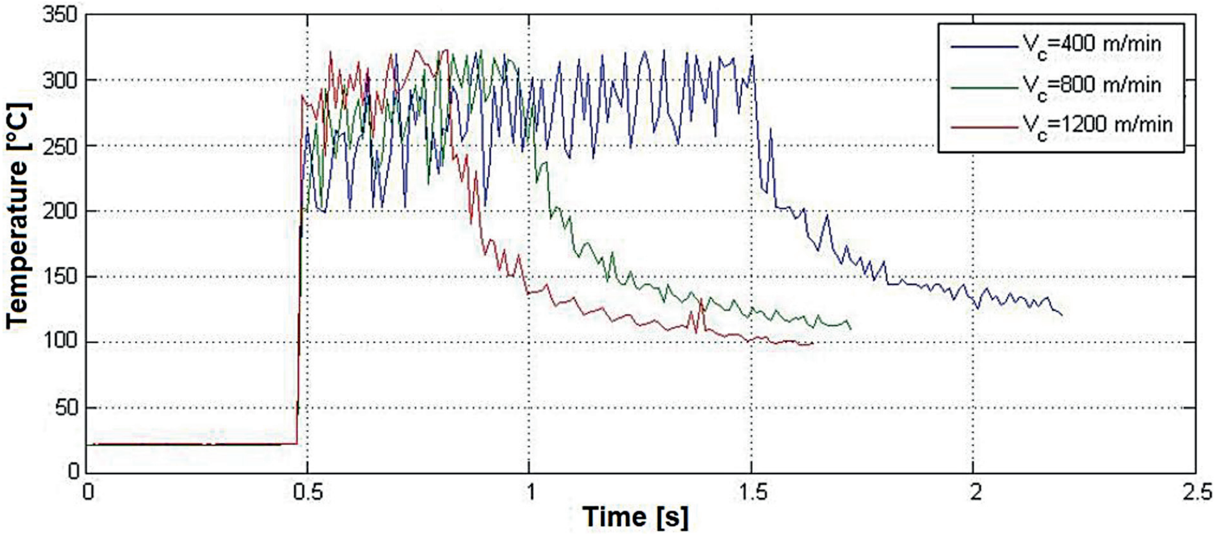

Fig. 3. Time waveform chart of cutting speed v_c change on chip temperature in milling: AZ91HP magnesium alloys (f_z = 0.15 mm/tooth, a_p = 6 mm)

the cutting area. These results are presented in box-plot charts (box-whisker plot). A horizontal line with a point in the middle of the "box" marked on it represents the median, the limits of the "whiskers" indicate the range of variability of the analyzed parameter (temperature), while "rectangles inside the figures" define the limits in which 50% of the obtained results can be found. These charts show the influence of changing technological parameters (v_c, f_z, a_p) on the chip temperature observed in the cutting area.

The obtained results allow to conclude that the increase in the cutting speed v_c does not cause a sudden increase in chip temperature in the cutting area. There is only noticeable reduction of the observed chip temperature scatter area (the lower part of the box-plot plot moves closer to the area where 50% of the obtained measurement results are located - rectangular areas inside the drawing). The results of the chip temperature measurement in the case of a cutting speed of v_c = 1200 m/min, can be explained by the phenomenon of the so-called "transition" in the scope of HSM/HPC machining, because along with the increase in cutting speed, the value of most commonly analyzed machinability indices (cutting force components, vibrations) decreases, which probably also affects the temperature drop in the cutting zone. In this situation, one could use the statement that there is a certain stabilization of the machining process and a narrowing of the temperature field observed during cutting with given machining parameters. The maximum chip temperature values are similar and amount to approx. 322 °C.

On the basis of the presented results, it can be stated that a temperature range exceeding 350 °C, should be used for the measurement in the case of determining the maximum chip temperatures. Evidently, the signal cut-off was achieved, which may indicate the presence of higher chip temperatures. Presets calibrated with and without a filter cannot be used in the dynamically extended measuring range, as this involves removing the lens and physically mounting the filter. The higher temperature ranges were calibrated with the filter. The only solution would be to extend the research by registering the sequences in a preset calibrated with the filter separately, and then processing the results to enable their mutual comparison. In this case, the accuracy of the assessment would drop significantly. Therefore, to evaluate the trend in the event of a change in individual cutting parameters, one should look at the temperatures represented by the median and the 75 percentile values. In this case, with an increase in the cutting speed, we observe an increase in chip temperature for material AZ31. In the case of AZ91HP material, the trend is also increasing, although for the speed of 800 m/min a slight decrease in temperature was observed for the 75th percentile. In the case of the median analysis, the temperature value increases.

It is worth emphasizing the fact that as the cutting speed increases, the range of temperature variation decreases, the machining is more heat-stabilized. This is not observed in the case of feed. As in the case of the cutting speed v_c analysis, observing the increase in feed per tooth f_z we can see that with a change in f_z there is no rapid increase in chip temperature in the cutting area. When machining AZ31 alloy, points are observed that can be defined as the so-called outliers / extreme points. This is the case in the following range of feed per tooth: f_z = 0.05 mm/tooth and f_z = 0.30 mm/tooth). The highest chip temperature values were observed at f_z = 0.30 mm/tooth and it was approx. 405 °C. It is worth noting, however, that the given value of chip temperature applies to only two measurement frames, hence these values should be defined as the already mentioned outliers / extreme points. In the given case, the value of the medians is only approx. 315 °C, while the scope of the chart frame-whiskers covers the temperature of approx. 330 °C.

Observing the change in the axial depth of cut, it can be observed that with the increase of a_p the temperature of the chip generated in the cutting zone also increases. It is interesting that the outliers / extremes are observed in large numbers only for machining conditions where a_p = 1.5 mm, in the case of both magnesium alloys. In other cases, they practically do not occur (basically one such point at a_p = 0.5 mm and AZ91HP alloy). The chip temperature increases and reaches its maximum values at a_p = 6 mm, they are approx. 322 °C for both magnesium alloys. It is also interesting that with a small axial depth of cut temperature, the maximum chip is only about 200 °C. It should be emphasized the opposite tendency in terms of changes in the area of temperature variation with an increase in the axial depth of cut in relation to the analysis

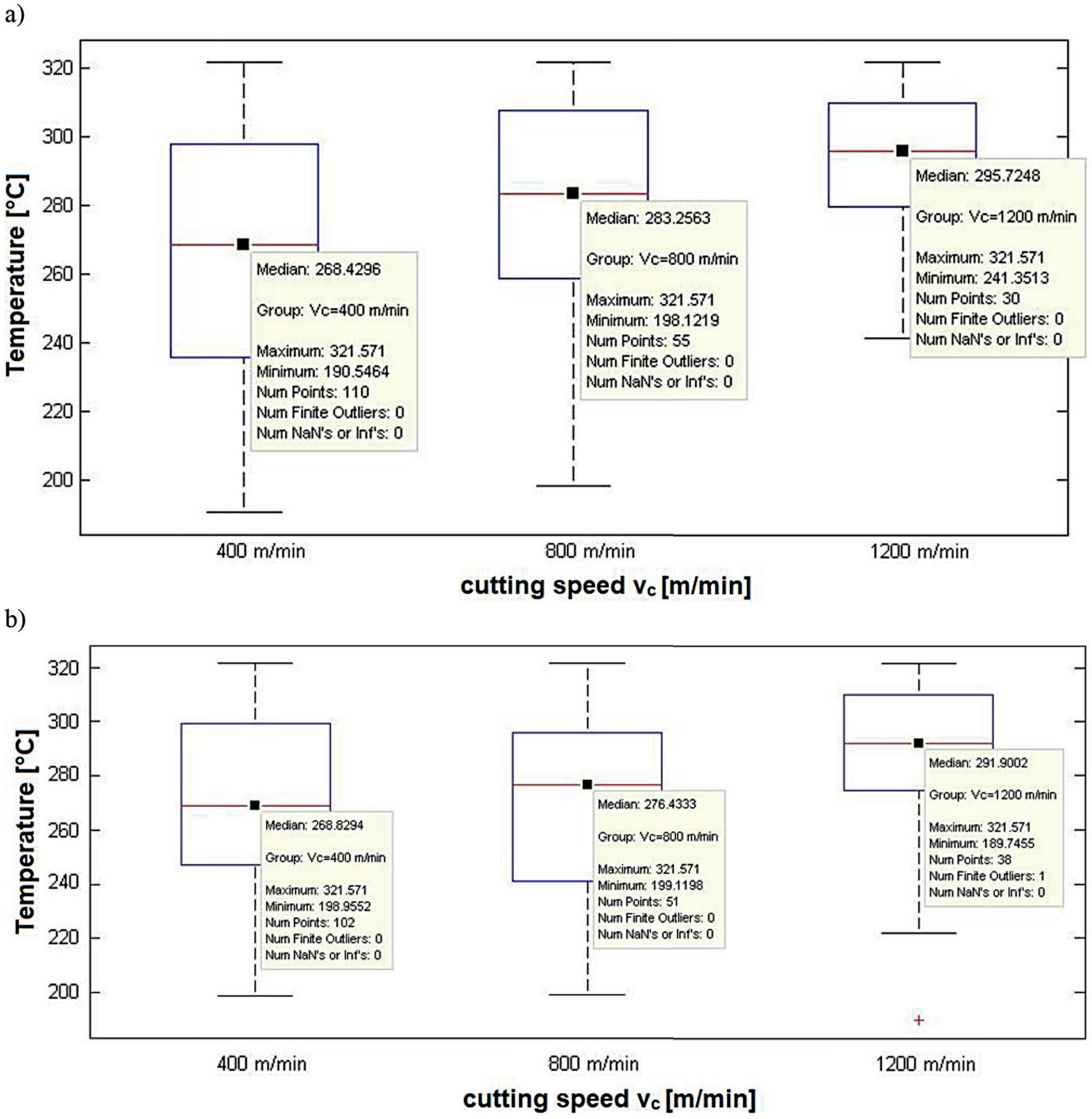

Fig. 4. Relation between the cutting speed v_c change and chip temperature in milling: a) AZ31 and b) AZ91HP magnesium alloys (f_z = 0.15 mm/tooth, a_p = 6 mm)

of the influence of cutting speed. In this case, increasing the depth of cut not only increases the median value, but also increases the area of temperature variation. The process is therefore less heat stable.

It is worth noting that both the cutting speed and the feed do not significantly affect the chip temperature value. This increase is more significant as the depth of cut is increased. This is an important observation, taking into account the chip ignition, it is advisable to increase the feed and cutting speed rather than the depth as an important measure of machining safety. However, it should be remembered that it is also dangerous to reduce the depth of cut too much, very fine chips may be more susceptible to ignition due to their lower unit weight.

Table 1 contains the estimation of the so-called measurement error, which for the used SC6000HS camera type is (as already described in the test methodology) ± 2% of the measurement range.

Based on Table 1, we can see that the measurement error determined on the basis of the camera manufacturer's data was a maximum of about ± 8 °C, while the variation limit characterized as the error range was 4–8 °C, analyzing all data for the influence of technological parameters of the machining.

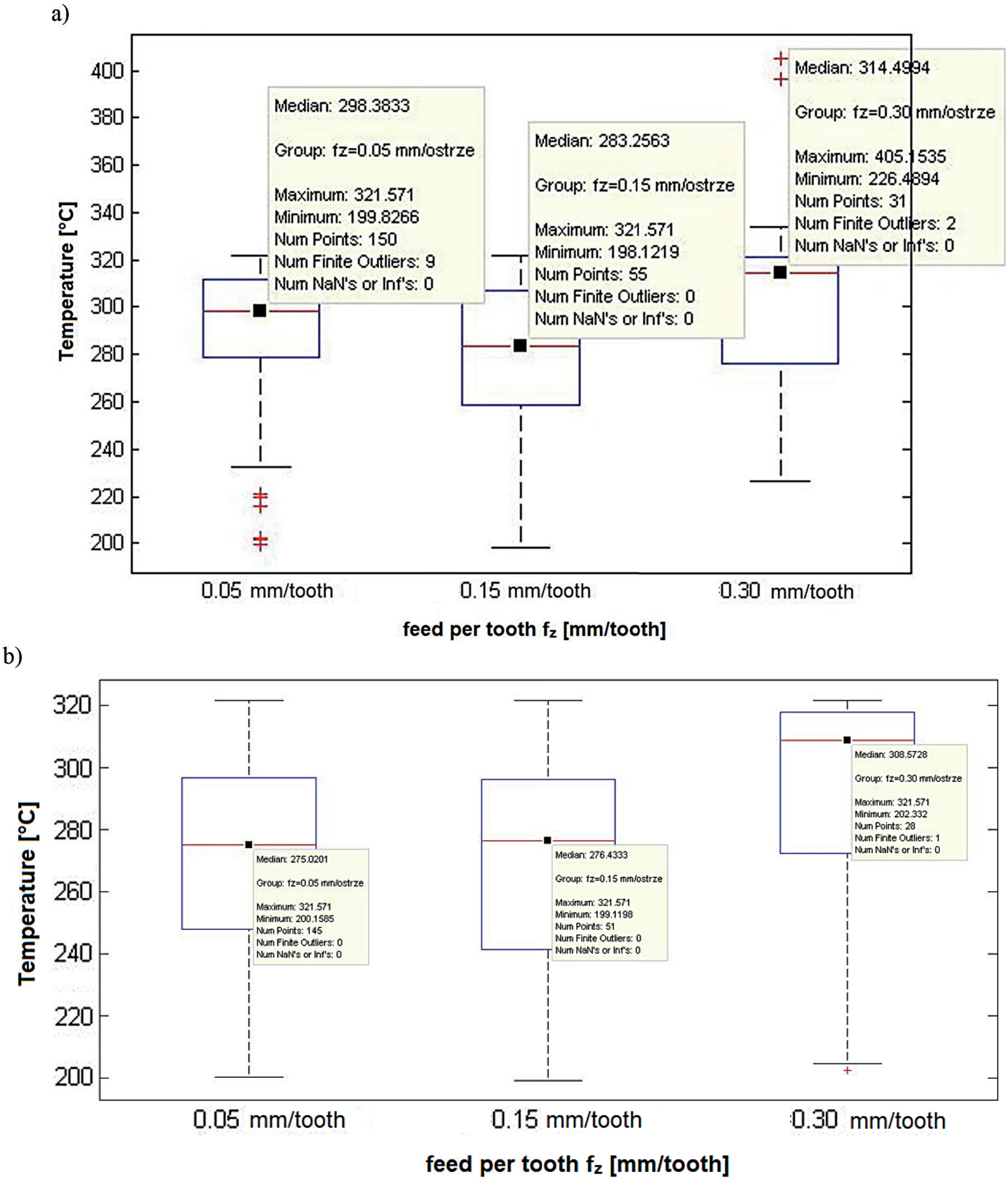

Fig. 5. Relation between feed per tooth f_z change and chip temperature in milling: a) AZ31 and b) AZ91HP magnesium alloys (v_c = 800 m/min, a_p = 6 mm)

SUMMARY AND CONCLUSIONS

The following main conclusions can be drawn on the basis of the carried out research. The observed chip temperature in the cutting area, in principle for the entire range of the analyzed technological machining parameters, is much lower than the temperature at which chip ignition is possible, or the melting point of magnesium alloys. Analyzing the shape of the chips, it can be concluded that in the entire analyzed range of variability of technological machining parameters, no characteristic melting of the sharp edges of the chips was observed, which confirms the correctness of the temperature estimation in the cutting zone. It should be noted that the melting point of the analyzed Mg alloys is higher than the temperature considered dangerous due to ignition.

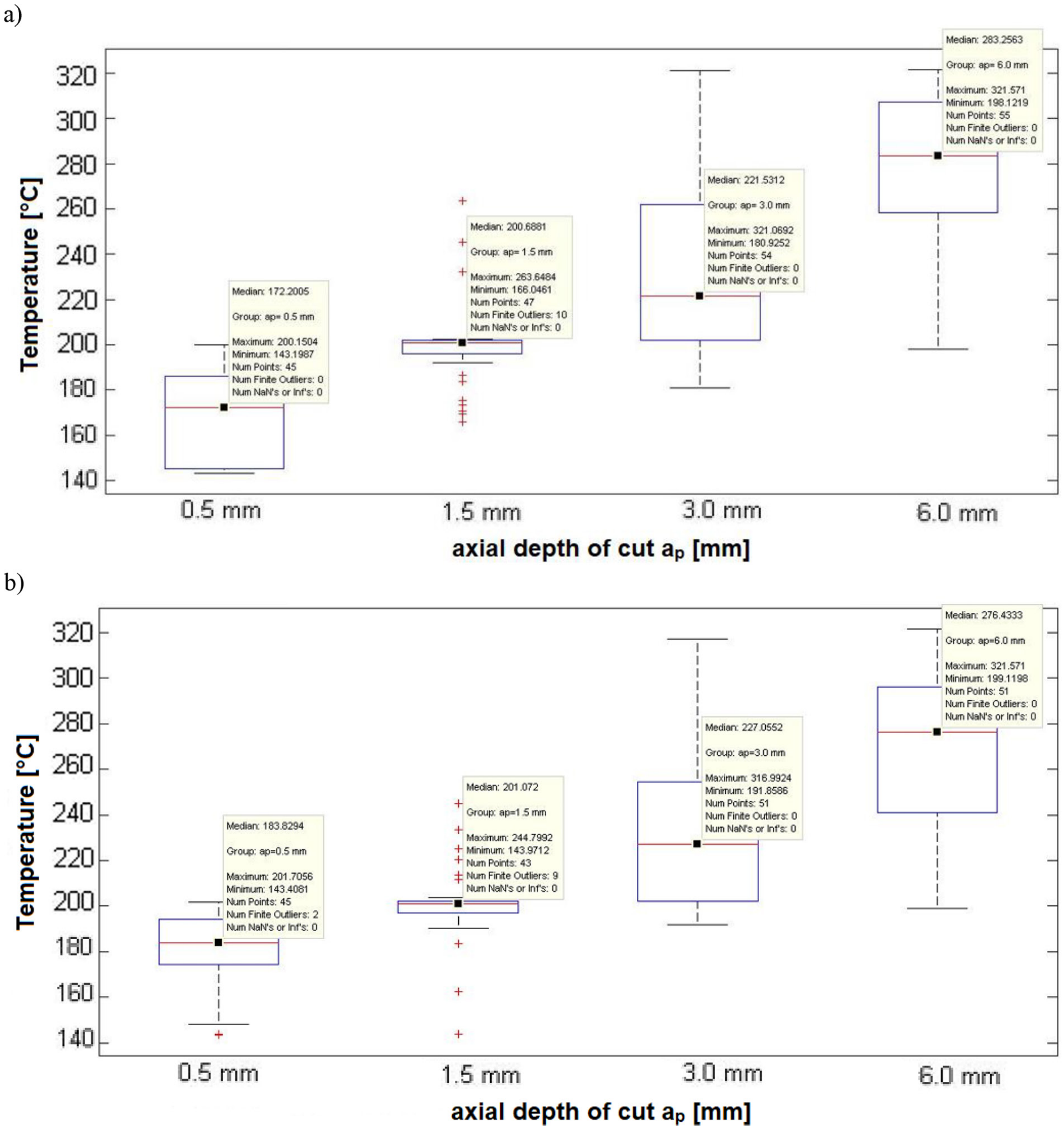

Fig. 6. Relation between axial depth of cut change and chip temperature in milling: a) AZ31 and b) AZ91HP magnesium alloys (v_c = 800 m/min, f_z = 0.15 mm/tooth)

The highest temperatures obtained from measurements with a infrared camera are much lower than those observed in the study of chip ignition outside the machine tool or in studies on the degree of oxidation of magnesium alloys. Changing the cutting speed and feed per tooth does not significantly increase the temperature of the chip in the cutting zone. The highest chip temperature value was observed at f_z = 0.3 mm/tooth, with a cutting speed of 800 m/min, and it was for the AZ31 alloy approx. 405.5 °C. Increasing the cutting speed thermally stabilizes the process, and the temperature variation range is significantly reduced. An increase in the axial cutting depth causes an increase in the maximum value of the chip temperature in the cutting area, an increase in the temperature variation range is also observed. When analyzing the obtained time series of chip temperature courses, local and short-term temperature increases can be noticed, which requires more detailed analyzes concerning both the assessment of the causes of this phenomenon as well as the assessment of its impact on the risk of chip ignition. The presented range of cutting technological parameters can be defined as the so-called safe processing area.

Table 1. The results of estimating the measurement error in the case of the analysis of the maximum chip temperature observed in the cutting zone during milling of magnesium alloys

alloy grade	v_c [m/min]	f_z [mm/tooth]	a_p [mm]	T [°C]	Error +2%	Error −2%	T max [°C]	T min [°C]
AZ31	400	0.15		321.571	6.43142	6.43142	328.00	315.14
	800			321.571	6.43142	6.43142	328.00	315.14
	1200			321.571	6.43142	6.43142	328.00	315.14
	800	0.05		321.571	6.43142	6.43142	328.00	315.14
		0.15		321.571	6.43142	6.43142	328.00	315.14
		0.30		405.5135	8.11027	8.11027	413.62	397.40
		0.15	0.5	200.1504	4.003008	4.003008	204.15	196.15
			1.5	263.6484	5.272968	5.272968	268.92	258.38
			3.0	321.0692	6.421384	6.421384	327.49	314.65
			6.0	321.571	6.43142	6.43142	328.00	315.65
AZ91HP	400			321.571	6.43142	6.43142	328.00	315.14
	800			321.571	6.43142	6.43142	328.00	315.14
	1200			321.571	6.43142	6.43142	328.00	315.14
	800	0.05		321.571	6.43142	6.43142	328.00	315.14
		0.15		321.571	6.43142	6.43142	328.00	315.14
		0.30		321.571	6.43142	6.43142	328.00	315.14
			0.5	201.7056	4.034112	4.034112	205.74	197.67
			1.5	244.7992	4.895984	4.895984	249.70	239.90
			3.0	316.9924	6.339848	6.339848	323.33	310.65
			6.0	321.571	6.43142	6.43142	328.00	315.14

It should be emphasized that the research were carried out under dry machining conditions. Parameters typical for high-performance machining were used. Despite this, the machining was carried out under temperature conditions in the cutting zone considered safe. It can be assumed that in production conditions, where cooling lubricants are usually used, the level of safety will be much higher. Further research should focus on precision machining, in the conditions of this machining there is a tendency to a strong increase in the temperature of the shredded chips. It is particularly interesting to what extent the flares occurring under such conditions may constitute a chip ignition hazard. It is also interesting to analyze the mechanisms of chip formation and its form. It is also worth extending the research work by registering sequences in a preset calibrated with the filter separately, and then processing the results enabling their mutual comparison. In workshop practice, it may be most useful to define the presented machining conditions, under which milling can take place under conditions defined as safe. Often, industrial companies do not have the appropriate research equipment, and above all, the time needed to carry out tests and research on the measurement of chip temperature in the cutting zone, it is also impossible to stop the production in progress. It should be emphasized that in industrial practice, low technological parameters are often used, justifying it with safety reasons. The proposed values of technological parameters allow for a significant increase in the metal removal rate without increasing the risk of chip ignition. Kordell geometry end mill, as shown by research, can be used in such conditions. Hence, the presented research works may be valuable due to the possibility of implementing the presented ranges of machining parameters in industrial practice.

Acknowledgements

This work was financed from the funds of the Ministry of Education and Science by Agreement No. DNK/SP/513880/2021 of 22 December 2021, the project "14th School of Machining and the 43rd Scientific School of Abrasive Machining", under the programme "Perfect Science".

REFERENCE

1. Fang F.Z., Lee L.C., Liu X.D. Mean flank temperature measurement in high speed dry cutting. Journal of Materials Processing Technology. 2005; 167: 119–123.

2. Guo Y.B., Salahshoor M. Process mechanics and surface integrity by high-speed dry milling of biodegradable magnesium–calcium implant alloys. CIRP Annals – Manufacturing Technology. 2010; 59: 151–154.
3. Guo Y., Liu Z. Sustainable High Speed Dry Cutting of Magnesium Alloys, Materials Science Forum Online. 2012; 723: 3–13.
4. Karimi M., Nosouhi R. An experimental investigation on temperature distribution in high-speed milling of AZ91C magnesium alloy. AUT Journal of Mechanical Engineering. 2021; 5: 1–5.
5. Hou J., Zhao N., Zhu S. Influence of Cutting Speed on Flank Temperature during Face Milling of Magnesium Alloy. Materials and Manufacturing Processes. 2011; 26: 1059–1063.
6. Hou J.Z., Zhou W., Zhao N. Methods for prevention of ignition during machining of magnesium alloys. Key Engineering Materials. 2010; 447–448: 150–154.
7. Kuczmaszewski J., Zagórski I. Methodological problems of temperature measurement in the cutting area during milling magnesium alloys. Management and Production Engineering Review. 2013; 4: 26–33.
8. Kuczmaszewski J., Zagórski I., Zgórniak P. Thermographic study of chip temperature in high-speed dry milling magnesium alloys. Management and Production Engineering Review. 2016; 7: 86–92.
9. Kuczmaszewski J., Zagórski I., Dziubińska A. Investigation of ignition temperature, time to ignition and chip morphology after the high-speed dry milling of magnesium alloys. Aircraft Engineering and Aerospace Technology. 2016; 88: 389–396.
10. Zagórski I., Kuczmaszewski J. Temperature measurements in the cutting zone, mass, chip fragmentation and analysis of chip metallography images during AZ31 and AZ91HP magnesium alloy milling. Aircraft Engineering and Aerospace Technology. 2018; 90: 496–505.
11. Zgórniak P., Grdulska A. Investigation of temperature distribution during milling process of AZ91HP magnesium alloys, Mechanics and Mechanical Engineering. 2012; 16(1): 33–40.
12. Habrat D., Stadnicka D., Habrat W. Analysis of the legal risk in the scientific experiment of the machining of magnesium alloys. Lecture Notes in Mechanical Engineering. 2019; 421–430.
13. Zgórniak P., Stachurski W., Ostrowski D. Application of thermographic measurements for the determination of the impact of selected cutting parameters on the temperature in the workpiece during milling process, Strojniški vestnik. Journal of Mechanical Engineering. 2016; 62(11): 657–664.
14. Kłonica M., Kuczmaszewski J. Modification of Ti6Al4V titanium alloy surface layer in the ozone atmosphere. Materials. 2019; 12: 1–14.
15. Du Y., Yue C., Li X., Liu X., Liang S.Y. Research on breakage characteristics in side milling of titanium alloy with cemented carbide end mill. International Journal of Advanced Manufacturing Technology. 2021; 117(11–12): 3661–3679.
16. Yang Z., Zhang D., Huang X., Yao C., Ren J. The simulation of cutting force and temperature in high-speed milling of Ti-6Al-4V. Advanced Materials Research. 2010; 139–141: 768–771.
17. Nieslony P., Grzesik W., Bartoszuk M., Habrat W. Analysis of mechanical characteristics of face milling process of Ti6Al4V alloy using experimental and simulation data. Journal of Machine Engineering. 2016; 16(3): 58–66.
18. Sun J., Wong Y.S., Rahman M., Wang Z.G., Neo K.S., Tan C.H., Onozuka H. Effects of coolant supply methods and cutting conditions on tool life in end milling titanium alloy. Machining Science and Technology. 2006; 10(3): 355–370.
19. Akyuz B. Machinability of magnesium and its alloys. The Online Journal of Science and Technology. 2011; 1: 31–38.
20. Wolfe W.L. Handbook of Military Infrared Technology. Office of Naval Research, Department of Navy, Washington, D.C.
21. Flir System Inc. http://www.flir.com/PL/, access 1.12.2021.
22. Sandvik Coromant Catalogue. Metalcutting Technical Guide: Milling. http://www.sandvik.coromant.com/, access 1.12.2021.