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An experimental investigation on temperature distribution in high-speed milling of AZ91C magnesium alloy

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ABSTRACT: Magnesium alloys are widely used materials in industry because of their formability and low density. The machining process of these alloys; however; is a challenging problem due to their flammability. This challenge demands extensive studies on the work-piece and machining zone temperature, especially in processes with elevated temperature; such as high-speed machining. In this research, the temperature distribution of the AZ91C magnesium alloy in high-speed milling is investigated. In order to study the temperature distribution, two temperature measurement methods are employed (i.e. the infrared thermometer for measurement of the machining zone temperature, and the contact method for the work-piece temperature) and the results are presented. The experiments are carried out in different cutting speeds (both in high-speed range and normal speed range) in two different depths of cut. The results show that the work-piece temperature is reduced as the cutting speed passes the cutting speed of 452 m/min in high-speed milling, while the machining zone temperature is increased as a result of the increase in the cutting speed. The results also show that the temperature is increased 13.9% and 14.2% as the depth of cut is increased from 0.5 mm to 1 mm in the cutting zone and workpiece respectively, which is the result of an increase in the uncut chip area that results in higher cutting forces.

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1- Introduction

Magnesium is one of the widely used materials in different industries. The appropriate formability and low density of the material have extended the use of magnesium in industries such as bio-medical and aerospace industries. The main drawback of the material in manufacturing processes is that magnesium is very chemically active, and is flammable in high temperatures. While burning, it cannot be extinguished using water or other fire extinguishers in which water is used as it reacts with water, and the fire is escalated. The flammability of the material has restricted the use of material in the manufacturing processes in which the material is subjected to high temperatures (upper than 450 ˚C).

Machining is one of the manufacturing processes in which the work-piece temperature is elevated during the process. The elevated temperature is mainly caused by the high plastic strain and high friction coefficient between the tool and the chip. This elevated temperature; if not suppressed; might cause flame in the magnesium and its alloys which might result in catastrophic events. Furthermore, the water-based coolants are not applicable in the machining of the magnesium and its alloys. In machining of magnesium alloys, a great amount of effort is directed toward the selection of the appropriate machining parameters (cutting speed, feed-rate, depth-of-cut, lubricant, tool material and geometry, etc.) so that the work-piece temperature remains below the flaming temperature. It is also proved that; in most of the machining processes; the temperature is increased as the cutting speed is increased. In high-speed machining; however; the temperature is decreased as the cutting speed passes a specific amount called critical cutting speed. In another word, the temperature would reduce as the cutting speed passes this critical point. This is in fact one of the main advantages of high-speed machining. Regarding the flammability of the magnesium alloys, the study of the work-piece temperature in high-speed machining of magnesium is of great importance.

There is rich literature on the machining of magnesium and its alloys. Dinesh et al. studied the use of liquid nitrogen in machining of biodegradable ZK60 magnesium alloy using micro-structured tools and reported the excelled machinability of ZK60 alloy [1]. Danish et al. have carried out an experimental analysis on heat transfer in turning of AZ31C magnesium alloy by cryogenic cooling [2]. Abbas et al. studied the surface roughness improvement of AZ61 magnesium alloy in finish turning and optimized the process by artificial neural network [3]. Hebbar et al. [4] investigated the surface roughness in machining of AZ31 magnesium alloy. Sundar Singh Sivam et al. [5] analyzed the quality of the machined AM60 magnesium alloy using ANOVA. Kuczmaszewski and Zagórski [6] addressed the problem of temperature measurement in milling of the magnesium alloys and reviewed the different methods for temperature

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Table 1. the magnesium alloy AZ91C chemical composition [17]

Element	Aluminum	Manganese	Zinc	Magnesium
wt %	9	0.13	0.7	Balance

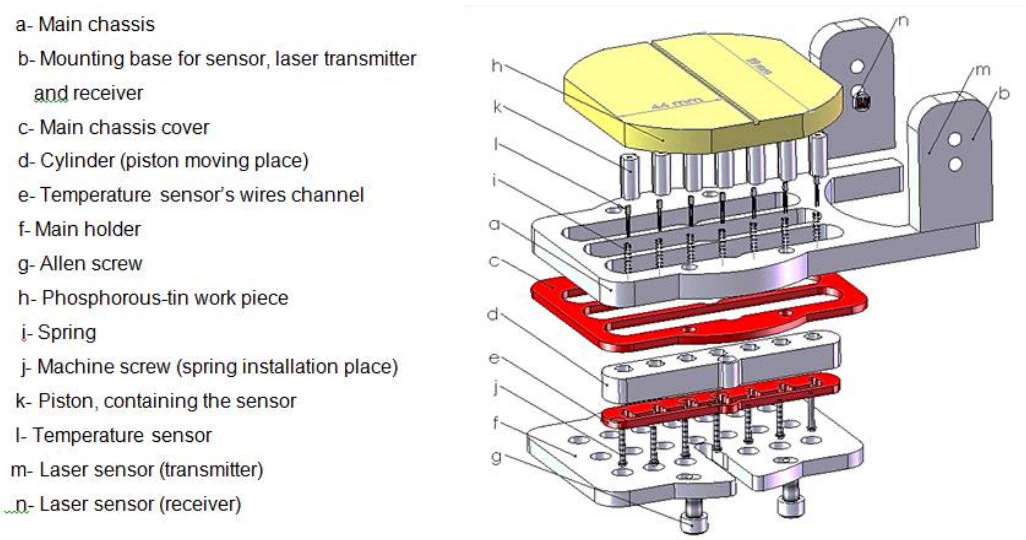

Fig. 1. The fixture for temperature measurement [16]

measurement. Viswanathan et al. [7] studied the MQL and dry turning of magnesium alloys. Hou et al. [8] performed research on the flank temperature in face milling of magnesium alloy and studied the effects of the cutting speed. Hou et al. [9] also addressed the ignition problem in machining of magnesium alloys and found the machining parameters in which the ignition of the AM50A magnesium alloy has occurred. Pu et al. [10] performed a FE analysis on the dry and cryogenic machining of AZ31B magnesium alloy. Sunil et al. studied the effect of the aluminum content in machinability of AZ31 and AZ91 magnesium alloys [11]. Shi et al. investigated the tool wear during the high-speed milling of the magnesium alloys and produced chips [12]. Kuczmaszewski et al. studied the time-to-ignition of magnesium alloy chips and the ignition-preceding stages [13]. They also investigated the chip morphology of the magnesium alloys in high-speed milling. Zgorniak and Grdulska investigated the temperature distribution during the milling of the AZ91HP magnesium alloy using the infrared temperature measurement [14]. Fang et al measured the flank temperature in high-speed machining of the magnesium alloy [15].

As it can be concluded from the literature survey, although some researchers have addressed the temperature variations in machining of the magnesium alloys, the work-piece and machining zone temperatures are not measured in the high-speed machining of the magnesium alloys and therefore, the applicability of the high-speed machining of the magnesium alloys is not extensively studied. Furthermore, AZ91C magnesium alloy is investigated in none of the abovementioned research works neither in terms of machinability nor temperature measurement.

In this research, the work-piece temperature is measured in AZ91C alloys during high-speed milling using two measurement methods (i.e. the infrared thermometer and contact method). A fixture for work-piece temperature measurement, which is fabricated in previous research works [16], is employed for the contact method. The surface roughness is also measured in the work-pieces and the results are presented in the following sections. The main objective of this research is to study the temperature elevation in machining of magnesium alloy AZ91C, in order to assure safe machining condition.

2- Experimental Procedure

The magnesium alloy AZ91C chemical composition is presented in Table 1.

This magnesium alloy has good ductility, toughness, and moderate strength [17].

The high-speed milling machine is a high-speed milling center fabricated by RAMBAUDI. The machine spindle can perform milling operations with maximum 25000 rpm rotational speed. The cutting tool is a 12 mm HSS end mill with 4 cutting flutes.

The fixture system which is used for contact method temperature measurement is depicted in Fig. 1 [16].

The work-piece is a 99 × 100 × 12 mm AZ91C magnesium

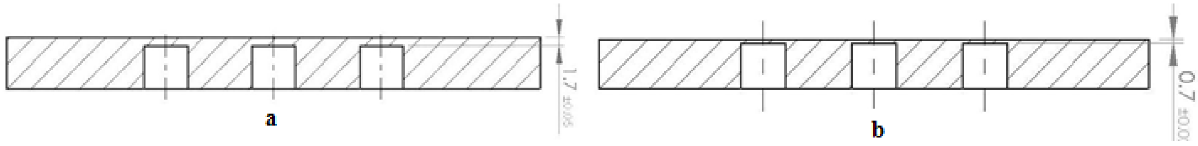

Fig. 2. holes in the work-piece [16]

Table 2. The experiments' parameters

Cutting speed (m/min)	Cutting speed (rpm)	Tool diameter (mm)	Feed-rate (mm/min)	Machining length (mm)	Depth-of-cut (mm)
37.6	1000	12	120	118	0.5-1
75.2	2000				
150.4	4000				
452	12000				
540	14300				
625	16600				
680	17800				

alloy. The temperature sensors which are employed are platinum temperature sensors. The sensors are connected to a circuit and the temperature values are read by the micro controller. The results are then transferred to the computer through a USB port. In order to measure the work-piece temperature, the work-piece has to be drilled so that the temperature sensors could be located in their positions. The work-piece should be drilled as depicted in Fig. 2 (a) and (b). The temperature sensors are located on top of the holes, which means that the sensors in Fig. 2 (a) and (b) are reading the temperature in 1.7 and 0.7 mm below the work-piece's surface respectively.

Another method for measurement of the temperature is the IR thermometer. In this research, testo 845 IR thermometer is employed for temperature measurement. The range of the thermometer is -30 to +950 ˚C. The experiments' parameters are presented in Table 2. It should be noted that the range of the high cutting speed is derived from [15].

Each of the experiments was repeated 3 times. After each machining experiment, the test setup is left idle for one hour in order to eliminate the effect of the elevated temperature resulted from the previous experiment.

3- Results and Discussion

The effects of the cutting speed on the machining zone and work-piece temperature are studied in two different speed ranges (i.e. normal speed and high-speed). The results are presented in the following sub-sections.

3- 1- The effect of the cutting speed and the depth of cut on the work-piece and cutting zone temperature in normal cutting speed range

In normal cutting speeds; generally; it has been shown previously that the increase in the cutting speed increases the generated heat [18]. The effect of the cutting speed and the depth of cut on the workpiece temperature is presented in Fig. 3. The effects of the cutting speed and depth of cut on the cutting zone temperature are depicted in Fig. 4.

The deviation in the work-piece temperature measurements was in the range of ±1˚C.

As it can be seen from Fig. 3, the work-piece temperature and the cutting zone temperature are increased as the cutting speed is increased. This is mainly due to the increase in the strain rate because of the increased cutting speed, which consequently increases the material strength and the energy needed for the cutting process.

It is also observed that the temperature is increased because of the increase in the depth of cut. This is mainly due to the increase in the uncut chip cross-section because of the increase in the cutting depth, which results in higher cutting forces and higher required energy for the cutting process.

3- 2- The effect of the cutting speed and the depth of cut on the work-piece and cutting zone temperature in high cutting speed range

In high-speed machining, the temperature increases because of the increase in the cutting speed up to a certain

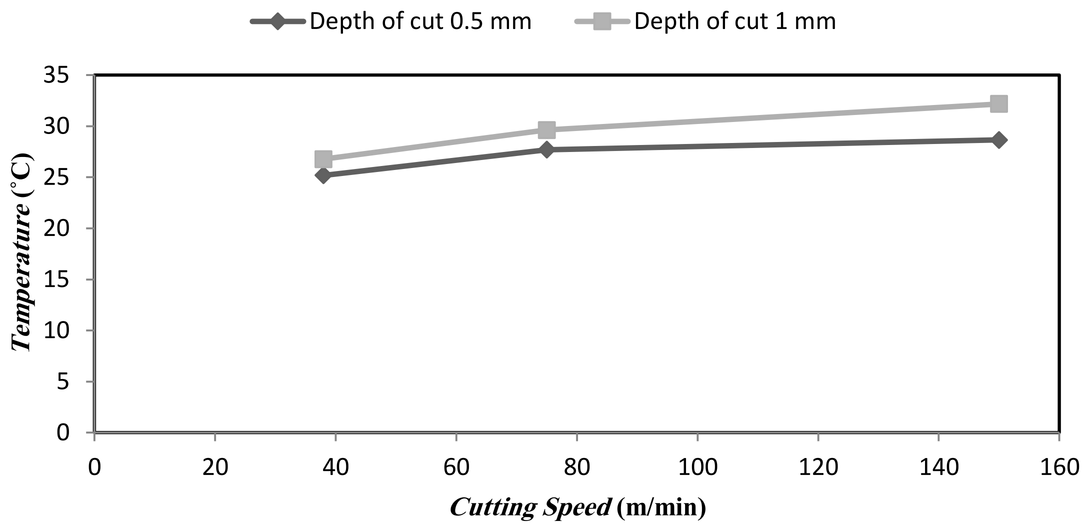

Fig. 3. the effect of the cutting speed and depth of cut on the work-piece temperature in the normal cutting speeds using thermocouples

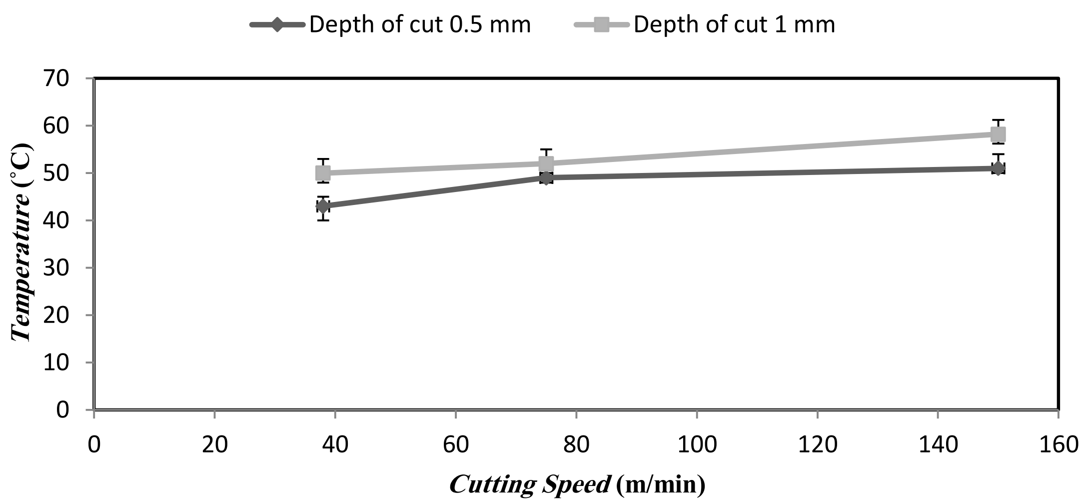

Fig. 4. The effects of the cutting speed and depth of cut on the cutting zone temperature in the normal cutting speeds using IR thermometer

point, over which the temperature decreases because of the increase in the cutting speed. This point is called the transition point. This transition point is very important in high-speed machining technology, because the reduced temperature would decrease the cutting tool wear and increases the tool life.

The main cause is that a greater share of the energy is dissipated by the chip from the machining zone in comparison to the normal speed machining. in the other world, the material removal rate is so high that the heat cannot be transferred to the machining zone and workpiece, and therefore is dissipated by the chip.

The effects of the cutting speed and the depth of cut on the work-piece and cutting zone temperatures are depicted in Figs. 5 and 6.

The deviation in the work-piece temperature measurements was in the range of ±1˚C.

The results presented in Figs. 5 and 6 show that the temperature in the work-piece is increased as the cutting speed is increased from 452 to 540 m/min. However, the temperature has remained constant in higher cutting speeds (540, 625 and 680 m/min). This shows that the transition point in machining of the magnesium is in this range, and the temperature would not increase further.

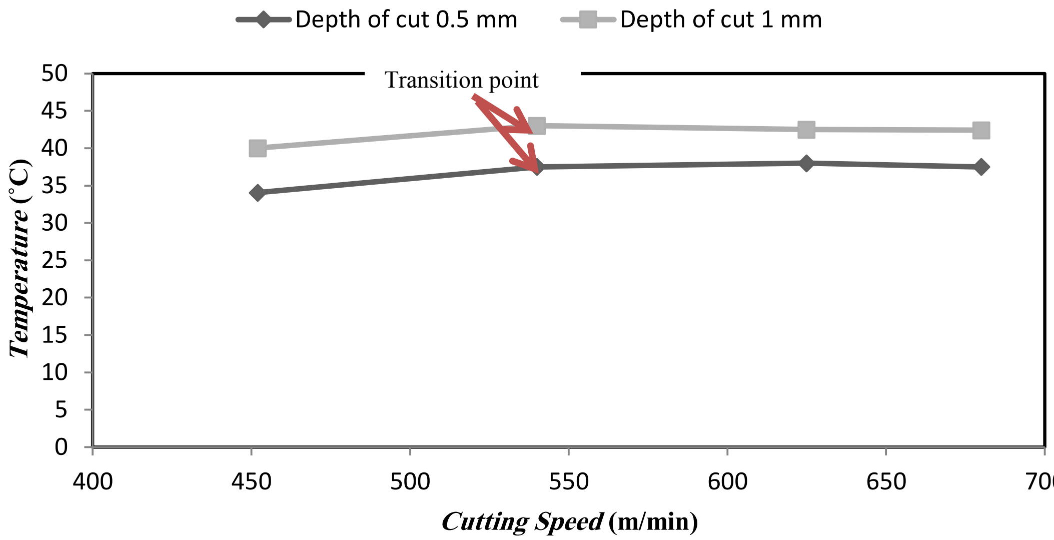

Fig. 5. the effect of the cutting speed and depth of cut on the work-piece temperature in high cutting speeds using thermocouples

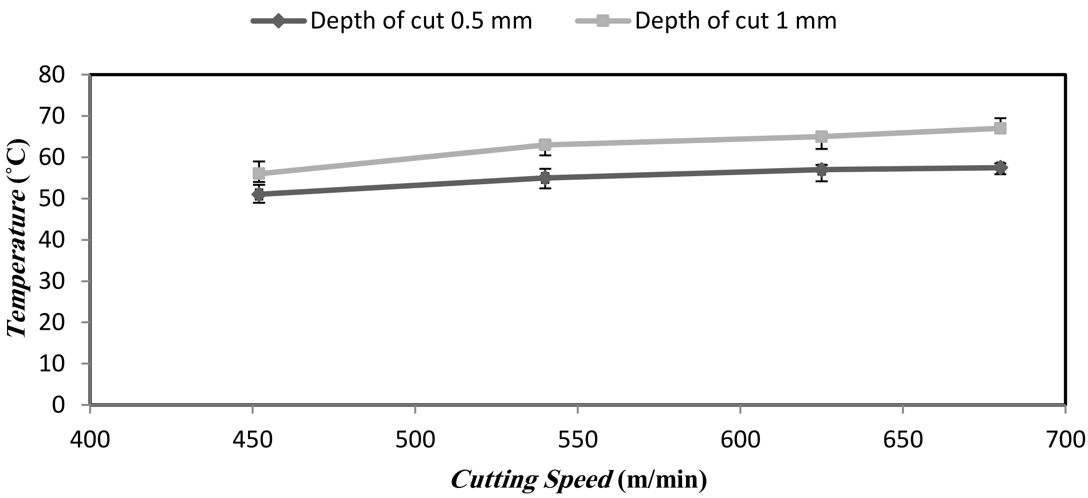

Fig. 6. The effects of the cutting speed and depth of cut on the cutting zone temperature in the high cutting speeds using IR thermometer

The same results can also be observed in the cutting zone temperature, in which the slope of the graph is reduced significantly as the cutting speed is increased from 452 to 540. The graph is almost horizontal after the cutting speed 452 m/min.

The effect of the depth of cut is similar to that in normal cutting speeds. The temperature in both the cutting zone and the work-piece is increased as the depth of cut is increased. This is similarly due to the increase in the uncut chip cross-section, which is described above.

The presented results are also in good agreement with the results presented in [6], which has investigated the cutting zone temperature in different magnesium alloys. The workpiece temperature which is measured in this research is in good agreement with the results presented in [8, 13], which shows the validity of the results and method.

The results of the cutting zone temperature are roughly in agreement with the previous results presented by [12]. The differences are mainly due to the difference in magnesium alloy chemical composition, machining parameters such as cutting speed, feed-rate, depth of cut, tool diameter and tool material.

4- Conclusions

The work-piece temperature and cutting zone temperature in normal cutting speeds and high cutting speeds of the AZ91C magnesium alloy are studied in this research. Since magnesium is a flammable material, the study of the work-piece temperature as well as the temperature of the cutting zone is of great importance. As a general trend, the temperature in the machining processes is increased as the cutting speed is increased. However, in high-speed machining, there is a transition point, over which the temperature is decreased as the cutting speed is increased. In this research, the temperature of the work-piece and the cutting zone temperature are measured in normal speeds and high-speed machining of the AZ91C magnesium alloy. The results of this research are concisely outlined as follows:

• The temperature both in the cutting zone and the work-piece in high-speed machining of the magnesium alloys are higher than that in normal machining. In all of the experiments in the normal cutting speed zone, the increase in the cutting speed resulted in the increase in the work-piece and cutting zone temperature values, which is due to the increase in the strain rate during the machining process. The increase of the depth of cut also resulted in the increase in the increase of the work-piece and cutting zone temperature values, which is mainly due to the increase in the uncut chip cross-section.

• In the high-speed machining experiments, the effect of the depth of cut is similar to that in normal cutting speed zone. However, since the transition point in high-speed machining lies after the cutting speed of 452 m/min, the temperature graphs show that the temperature does not have an increasing trend like that in the normal cutting speed zone. Although the determination of the exact transition point is not possible due to the limitation of the tests, the results show that after 452 m/min, the temperature in both cutting zone and work-piece is almost constant.

• In none of the experiments, the magnesium alloy was flamed. This shows that the cutting zone and the work-piece temperature values are not dangerously high, and therefore, the high-speed milling of the magnesium alloy is possible. However, precautions should be considered about other factors that may increase the cutting zone and/or work-piece temperature values; such as the worn cutting tools, the water-based coolants, etc.

References

[1] S. Dinesh, V. Senthilkumar, P. Asokan, Experimental studies on the cryogenic machining of biodegradable ZK60 Mg alloy using micro-textured tools, Materials and Manufacturing Processes, 32(9) (2017) 979-987.

[2] M. Danish, T.L. Ginta, K. Habib, A.M. Abdul Rani, B.B. Saha, Effect of Cryogenic Cooling on the Heat Transfer during Turning of AZ31C Magnesium Alloy, Heat Transfer Engineering, 40(12) (2019) 1023-1032.

[3] A.T. Abbas, D.Y. Pimenov, I.N. Erdakov, M.A. Taha, M.S. Soliman, M.M. El Rayes, ANN Surface Roughness Optimization of AZ61 Magnesium Alloy Finish Turning: Minimum Machining Times at Prime Machining Costs, Materials (Basel), 11(5) (2018) 808.

[4] G. Hebbar, G. D'Mello, P.S. Pai, Surface Roughness Optimization in Machining of Biodegradable Magnesium Alloys, Materials Today: Proceedings, 5(5, Part 2) (2018) 11787-11793.

[5] S.P.S.S. Sivam, S.M. Karuppaiah, B.K. Yedida, J.R. Atluri, S. Mathur, Multi Response Optimization of Setting Input Variables for Getting Better Product Quality in Machining of Magnesium AM60 by Grey Relation Analysis and ANOVA, Periodica Polytechnica Mechanical Engineering, 62(2) (2018) 118-125.

[6] J. Kuczmaszewski, I. Zagórski, Methodological Problems of Temperature Measurement in the Cutting Area During Milling Magnesium Alloys, Management and Production Engineering Review, (No 3) (2013).

[7] R. Viswanathan, S. Ramesh, V. Subburam, Measurement and optimization of performance characteristics in turning of Mg alloy under dry and MQL conditions, Measurement, 120 (2018) 107-113.

[8] J. Hou, N. Zhao, S. Zhu, Influence of Cutting Speed on Flank Temperature during Face Milling of Magnesium Alloy, Materials and Manufacturing Processes, 26(8) (2011) 1059-1063.

[9] J.Z. Hou, W. Zhou, N. Zhao, Effect of Cutting Parameters on Ignition of AM50A Mg Alloy during Face Milling, Materials and Manufacturing Processes, 25(10) (2010) 1048-1051.

[10] Z. Pu, D. Umbrello, O.W. Dillon, T. Lu, D.A. Puleo, I.S. Jawahir, Finite element modeling of microstructural changes in dry and cryogenic machining of AZ31B magnesium alloy, Journal of Manufacturing Processes, 16(2) (2014) 335-343.

[11] B.R. Sunil, K.V. Ganesh, P. Pavan, G. Vadapalli, C. Swarnalatha, P. Swapna, P. Bindukumar, G. Pradeep Kumar Reddy, Effect of aluminum content on machining characteristics of AZ31 and AZ91 magnesium alloys during drilling, Journal of Magnesium and Alloys, 4(1) (2016) 15-21.

[12] K. Shi, J. Ren, D. Zhang, Z. Zhai, X. Huang, Tool wear behaviors and its effect on machinability in dry high-speed milling of magnesium alloy, The International Journal of Advanced Manufacturing Technology, 90(9) (2017) 3265-3273.

[13] J. Kuczmaszewski, I. Zagórski, A. Dziubinska, Investigation of ignition temperature, time to ignition and chip morphology after the high-speed dry milling of magnesium alloys, Aircraft Engineering and Aerospace Technology: An International Journal, 88(3) (2016) 389-396.

[14] G.A. Zgorniak P., Investigation of Temperature Distribution during Milling Process of Az91hp Magnesium Alloys, Mechanics and Mechanical Engineering, 16(1) (2012) 33-40.

[15] F.Z. Fang, L.C. Lee, X.D. Liu, Mean flank temperature measurement in high speed dry cutting of magnesium alloy, Journal of Materials Processing Technology, 167(1) (2005) 119-123.

[16] S. Faramarzi, R. Nosouhi, M. Homanfard, Design and manufacturing of a new apparatus and fixture for studying the generated heat in high speed machining,

mdrsjrns, 15(13) (2016) 501-505.

[17] C. Moosbrugger, Introduction to Magnesium Alloys, in: M. C. (Ed.) Engineering Properties of Magnesium Alloys, ASM International, Materials Park, OH 44073-0002, 2017, pp. 1-10.

[18] B. Davoodi, H. Hosseinzadeh, A new method for heat measurement during high speed machining, Measurement, 45(8) (2012) 2135-2140.

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