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SURFACE QUALITY ASSESSMENT FOLLOWING HIGH PERFORMANCE CUTTING OF AZ91HP MAGNESIUM ALLOY

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Abstract
The article presents test results of surface roughness after AZ91HP magnesium alloy machining with variable technological parameters (v_c, f_z, a_p) as well as tool geometry ($\gamma = 5°$ and $\gamma = 30°$). Two carbide end mills were applied during the tests. Roughness analysis was conveyed at the end face (Ra, Rq, RzDIN, Rt, Ry, RSm) and lateral face (Ra, Rz, RSm) of the tested sample. A decrease of roughness parameters (for increasing v_c) as well as an increase (with growing f_z) was observed in the lateral face tests. Similar interrelations were noticed for end face of the sample. Lower roughness parameters values were recorded for tool rake angle equal to $\gamma = 5°$.

Keywords
machining, magnesium alloys, roughness parameters, manufacturing processes, HSM, HPC.

Introduction

Currently, magnesium alloy elements, characterised by insignificant weight and considerable strength, find increasingly wider application in the industry. Excellent electromagnetic shielding, advantageous casting properties (in the case of cast alloys), the ability to damp vibrations, recyclability as well as accessibility (ore mining, sea water) are considered as advantageous.

Excellent mechanical properties of magnesium alloys contribute to their widespread application. Magnesium alloys are used in aviation, cosmonautics, electrotechnology, automotive and nuclear industries as well as machine building. Production of such elements as castings, brackets, dashboard elements, aeroplane and helicopter plating involves the application of magnesium alloys [1].

Commonly, aluminium, zinc and manganese are used as alloy additions due to their ability to enhance certain properties of alloys such as immediate strength, anticorrosive properties as well as hardness. Silicon, cerium and lithium can serve as additions as well. Simultaneously, reduction of copper, nickel and iron additions can be observed with the aim to achieve high purity alloys (HP).

A great majority of alloys is produced by casting (sand and metal moulds, die-casting), however, certain groups of alloys dedicated to plastic forming are most often shaped using forging or extrusion (KOBO method) or rolling (twin roll casting technology) [2].

Mg alloys machining is generally used as final processing, and consequently, surface roughness of the workpiece along with suitable efficiency of the process, are of primary importance.

Current state of knowledge

Removal machining of magnesium alloys is dominated by turning, milling, boring, drilling and reaming. Scarce cutting force and high quality surface following machining affirm excellent magnesium alloys machinability. Processing tools consist mainly

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of PCD polycrystalline diamond or fine-grained cemented carbide. Magnesium alloys have proven to be suitable for both HSC (high speed cutting) and HPC (high performance cutting) [3]. High Speed Machining (HSM) is defined as high-efficiency processing method which, among others, allows achieving high quality surface. This type of machining is characterised by high values of v_c and v_f as well as low depth of cut [4, 5]. In contrast, high performance processing is e.g. HPM (high performance machining) or HPC (high performance cutting). HPC is a process which aims at optimum exploitation of machine tool spindle force which would lead to maximum material removal in a time unit. An increase in volume efficiency is achieved through higher cutting speed v_c accompanied by higher feed rate per tooth. It is assumed that HPC is optimal for pretreatment and forming while HSC (high speed cutting) is considered suitable for finishing machining [6].

It is worth noticing that material removal processing of magnesium alloys involves a number of threats. Magnesium is characterised by inclination to self-ignite when a sudden temperature increase occurs (480°C is the ignition temperature of magnesium). Magnesium dust emerging during processing has a negative influence on both machine tool operators' health and machine tools themselves (it can damage their bearings and guideways). What seems equally dangerous is a tendency of magnesium is build-up appearing on a flank face or the cutter tooth face [3, 7].

What seems to be of great significance when considering milling is high efficiency of the process, its stability as well as the workpiece surface. Processing time can be considerably reduced (up to 4 times) without surface quality deterioration (Ra $\approx (0.25 \div 1.02)\mu$m following conventional machining and Ra $\approx (0.51 \div 1.02)\mu$m following HSM machining) or shape precision [8]. When producing innovative (biodegradable) magnesium alloy elements (Mg-Ca group) [9], special attention needs to be devoted to final surface quality. PCD cutting edge application allows to achieve (with variable v_c and a_p) roughness Ra equalling approximately 0.5 μm.

The coating type influence on surface roughness following light alloys (eg. Al. 6082) milling seems to be remarkable. TiB_2 and TiAlCN carbide tool coating types are usually subjected to such analysis [10]. The lowest roughness values for v_c and f_z were obtained for coated tools. Magnesium alloys machinability tests compare TiAlN coated tools with tools without any coating. Tools without coating are characterised by a 'sharper' geometry and they allow achieving higher quality surface in comparison with coated tools [11]. Carbide TiN coated tools, carbide tools with no coating and PCD tools are applied also in Mg alloy turning (AZ91HP and Mg alloy containing SiC particles) [12].

Cutting fluids (emulsions) and compressed air (used as a cooling agent) [13] are frequently implemented during surface quality tests [10]. Customarily, tests focus on the cooling agent delivery angle, the number of cutting edges as well as technological parameters and their influence on surface roughness [13].

It has been noted that cutting speed does not influence surface roughness significantly during both conventional machining and HSM. The greatest influence on surface quality has been assigned to changes in feed rate per tooth f_z [9, 11, 14]. Kordell geometry strongly differentiates roughness parameters for Mg alloys, however, it does not change their values significantly in comparison to 'classical' geometry tools. Nevertheless, a dangerous process (in respect of machining safety) of chip fineness can be observed for Kordell geometry tools. Considering magnesium alloy machining tools, the greatest universality is assigned to a PCD cutting edge, which achieved highest surface quality in the course of tests and can be used in HPC and HSC machining [11, 15].

Methodology, aims and scope of the research

The aim of the conducted research was to determine surface quality changes following machining relative to changes in parameters values. The research plan is presented in Fig. 1. Variable parameters are as follows: cutting speed $v_c = 400 \div 1200$ [m/min], feed rate per tooth $f_z = 0.05 \div 0.3$ [mm/tooth], depth of cut $a_p = 0.5 \div 3$ [mm] and a tool rake angle γ (5°; 30°). A constant milling width $a_e = 14$ mm and a type of workpiece material (AZ91HP alloy) are constant.

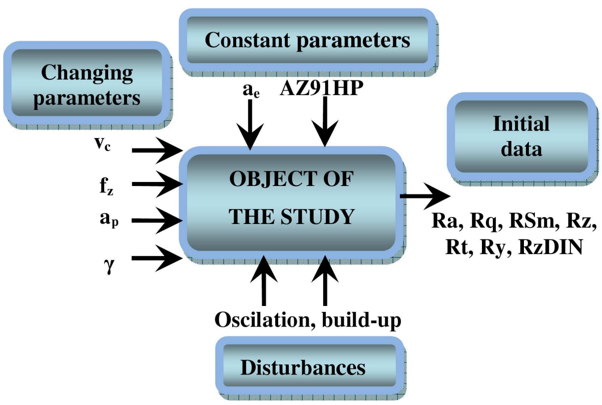

Fig. 1. Research plan for the analysis surface quality.

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Chemical composition of AZ91HP magnesium alloy is presented in Table 1.

Table 1
Chemical composition of AZ91HP alloy [1, 14].

AZ91HP – chemical composition [%]							
Cu	Mn	Mg	Zn	Si	Fe	Al	Ni
0.016	0.17	rem.	0.72	0.03	0.002	9.45	0.025

Tests were conducted on a vertical machining centre AVIA VMC 800HS. Two 3-flute (∅ = 16 mm) carbide cutting edges were used as cutting tools with two different rake angles $\gamma = 5°$ and $\gamma = 30°$.

A Hommel Tester T1000 profilometer was used for measuring roughness values on the lateral face of sample, while for the end face roughness measurement a Tylor Hobson Surtronic 3+ profilometer was used. The measurements were taken repeatedly directly after milling performed with previously established parameters. Each measurement was repeated five times, which allowed assessing mean values as well as standard deviation. Additionally, roughness maps were prepared (for selected parameters) using a 3D Hommel-Etamic t800 profilometer. The device is compatible with Turbo Wave V7.55 and Hommel Map Basic software.

The essence of this research is the analysis of technological aspects of depth of cut, feed per tooth, cutting speed and cutting edge geometry values in relation to surface roughness occurring after milling of AZ91HP casting magnesium alloy. Technological processes are usually designed with the aim of achieving highest efficiency provided that it does not significantly change defined surface parameters. For this reason, research should analyse such values of independent variables which allow achieving the goal to the highest degree.

Test results and their analysis

Surface roughness tests were conducted on the lateral face and the end face of the sample. Cutting speed v_c and feed per tooth f_z were the variable technological parameters whose influence on surface roughness was analysed in the tests. By contrast, changes in a_p were measured only for the end face.

The influence of changes in v_c and feed rate per tooth f_z on roughness values (Ra, Rz, RSm) on the lateral face are presented in Fig. 2.

Based on Fig. 2 it appears that both tools applied in the tests induce similar interrelations between cutting speed, feed rate per tooth and surface roughness. An increase in cutting speed caused a decrease in Ra value, whereas an increase in feed rate per tooth had an opposite effect. Comparable results were obtained for both Rz and RSm. Ra parameter (even with standard deviation included) did not exceed 1 μm during the experiment and it reached its highest value for tool rake angle equal to $\gamma = 30°$ at $v_c = 400$ m/min, whereas the lowest values were obtained for feed rate per tooth equalling $f_z = 0.05$ mm/tooth. Rz values were comparable for both tool types, however, the greatest variation was observed at $v_c = 400$ m/min, where the difference between the analysed tool types in Rz values equalled approximately 1 μm. RSm values fluctuations for variable feed per tooth were not as great as for changes in cutting speed, where for rake angle equal to $\gamma = 30°$ RSm values dropped almost twice from 426.4 μm at $v_c = 400$ m/min to 237.4 μm at 1200 m/min. The effect on RSm values was much lesser in the case of tool rake angle equal to $\gamma = 5°$.

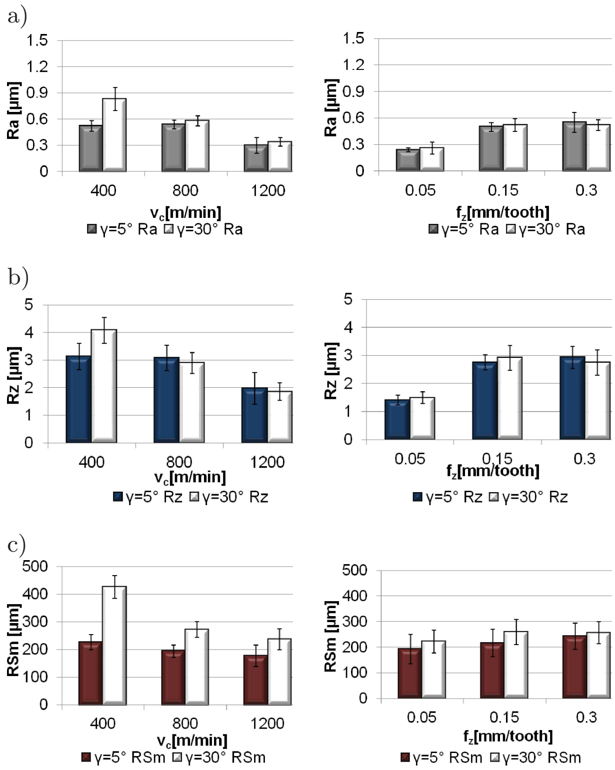

Fig. 2. The effect of changes in cutting speed v_c and feed rate per tooth f_z on the value of surface roughness parameters: a) Ra, b) Rz, c) RSm a) measured on the lateral face following milling with the application of carbide cutting edges with feed rate per tooth equalling $\gamma = 5°$ and $\gamma = 30°$.

Figure 3 presents the influence of cutting speed v_c, feed rate per tooth f_z and depth of cut a_p on surface roughness parameters (Ra, Rq) measuret at the end face of the sample.

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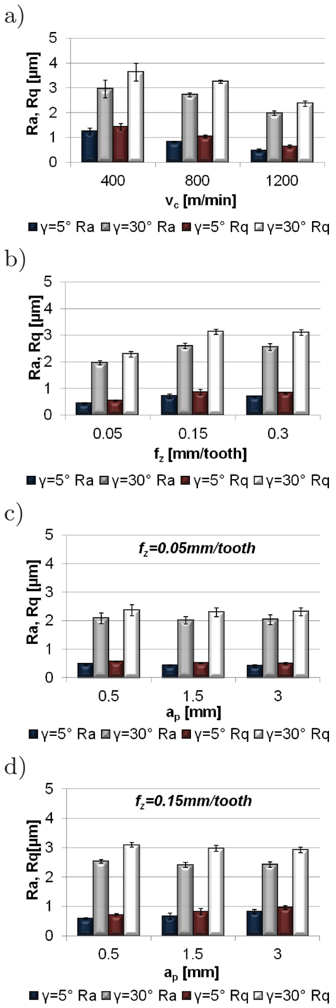

Fig. 3. Changes in roughness parameters Ra and Rq measured at the end face of the sample induced by changes in the following parameters: a) v_c, b) f_z, c) a_p ($f_z = 0.05$ mm/tooth), d) a_p ($f_z = 0.15$ mm/tooth).

In accordance with the data presented in Fig. 3, much higher values of roughness parameters can be observed for $\gamma = 30°$ geometry tools. Based on the lateral face measurements it can be noticed that an increase in cutting speed resulted in a decrease of Ra and Rq parameters, whereas their increase could be observed for changing feed rate per tooth. Depth of cut did not seem to have any influence on surface roughness whatsoever. With changing cutting speed v_c Rq parameter values did not exceed 4 µm for $\gamma = 30°$ and 2 µm for $\gamma = 5°$. The greatest scatter of results was detected for $\gamma = 30°$ at the lowest cutting speed. When analysing feed rate per tooth changes, it is apparent that Ra parameter reached the highest values for $\gamma = 30°$ at $f_z = 0.15$ mm/tooth. For $\gamma = 5°$ surface roughness values were almost three times lower and did not exceed 1 µm. In accordance with the expectations, the analysis of depth of cut a_p proved that best results can be achieved at $f_z = 0.05$ mm/tooth.

Figure 4 presents the influence of cutting speed v_c, feed rate per tooth f_z and depth of cut a_p on surface roughness parameters (RzDIN, Rt and Ry) measured at the end face of the sample.

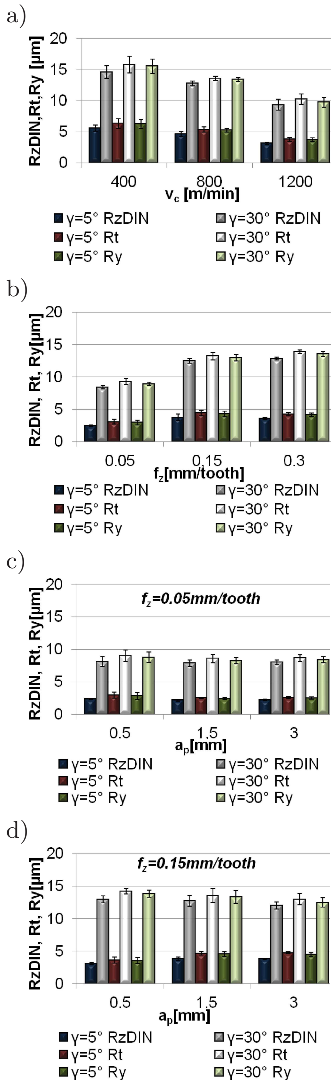

Fig. 4. Changes in roughness parameters RzDIN and Rt and Ry measured at the end face induced by the change in the following parameters: a) v_c, b) f_z, c) a_p ($f_z = 0.05$ mm/tooth), d) a_p ($f_z = 0.15$ mm/tooth).

Figure 4 shows that in the case of both variations of feed rate pert tooth values ($\gamma = 5°$ and $\gamma = 30°$) the change in cutting speed caused a decrease in roughness parameters. RzDIn parameter reached 5.58 µm ($\gamma = 5°$) and 14.56 µm ($\gamma = 30°$) for cutting speed equal to $v_c = 400$ m/min, whereas for $v_c = 1200$ m/min the results amounted to 3.14 µm ($\gamma = 5°$) and 9.34 µm ($\gamma = 30°$). An increase in

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feed rate per tooth caused an increase in roughness parameters, with most prominent changes observed for $\gamma = 30°$. Depth of cut did not influence RzDIN, Rt or Ry significantly. Lower values of these parameters were noticed for $f_z = 0.05$ mm/tooth and $\gamma = 5°$ and were under 4 μm, while for $\gamma = 30°$ they reached 10 μm. Slightly higher values of feed rate per tooth $f_z = 0.15$ mm/tooth generated 5 μm for $\gamma = 5°$, and 15 μm for $\gamma = 30°$.

The inflence of cutting speed v_c, feed rate per tooth f_z and depth of cut a_p on roughness parameter (RSm) measured on the end face of the samle is presented in Fig. 5.

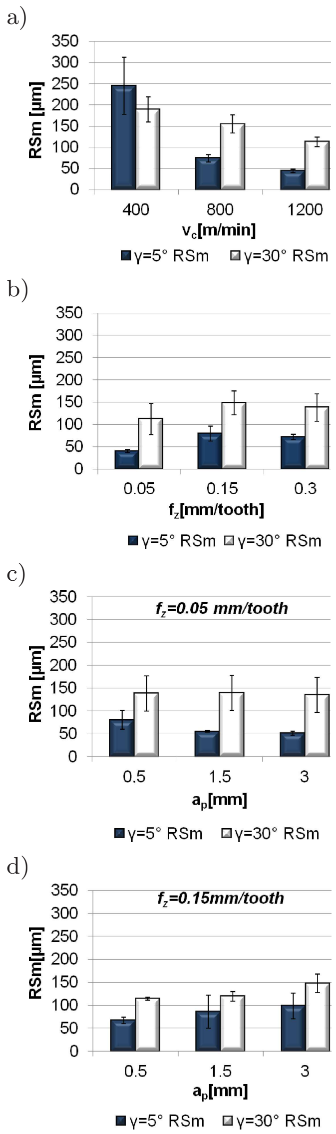

Fig. 5. The influence of technological parameters: a) v_c, b) f_z, c) a_p for $f_z = 0.05$ mm/tooth, d) a_p for $f_z = 0.15$ mm/tooth on RSm measured on the end face of the sample during milling with tool rake angle equall to $\gamma = 5°$ and $\gamma = 30°$.

According to data presented in Fig. 5, an increase in cutting provokes a decrease in RSm. At cutting speed equal to 400 m/min RSm reached higher values for $\gamma = 5°$ cutting tool (greater scatter of results), whereas for 800 m/min and 1200 m/min $\gamma = 30°$ induced higher values of RSm. With changing feed rate per tooth, RSm (with scatter of results included) did not exceed 100 μm for $\gamma = 5°$ and 200 μm for $\gamma = 30°$. Changes in depth of cut did not have any significant influence on the value of this parameter.

Figure 6 presents a 3D topographic map and roughness parameters values in accordance with ISO 25178.

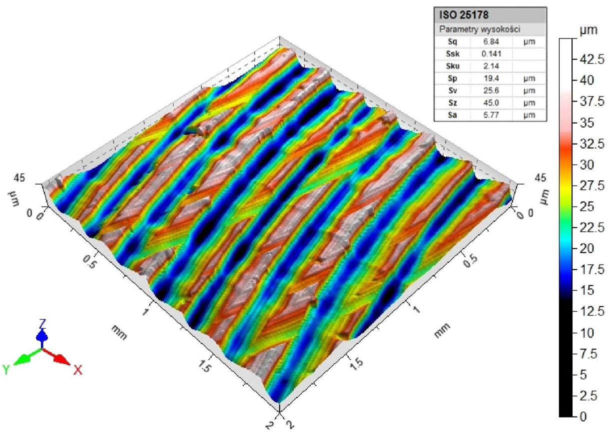

Fig. 6. 3D map and roughness parameters for tool rake angle equal to $\gamma = 5°$ and the following technological parameters values: $vc = 800$ m/min, $f_z = 0.3$ mm/tooth, $a_p = 6$ mm, $a_e = 14$ mm.

The presented 3D map was prepared for surface obtained with the following machining conditions: $\gamma = 5°$, $f_z = 0.3$ mm/tooth. Additionally, 3D surface roughness parameters values were given. Sample values: Sa = 5.77 μm, Sz = 45 μm, Sq = 6.84 μm.

Summary and conclusions

In appliances and machine elements manufacturing particular attention is given to such selection of machining parameters so as to ensure highest repeatability and quality of results. In the analysed case this refers to machined surface roughness. With regard to finish milling, what should be considered as the priority is to produce an object of accurate (required) dimensions and shapes, as well as surface quality within acceptable surface roughness. Simultaneously, any effectiveness maximisation must not be implemented at the expense of process stability or surface quality.

This study analysed the relation between surface roughness after machining AZ91HP magnesium alloy

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and changing technological parameters (v_c, f_z, a_p) as well as tool rake angle γ. A numerous group of roughness parameters, examined in the present study, enables a more effective assessment of surfaces under analysis. Based on the obtained results the following conclusions can be drawn:

1. Superior quality of surface following machining (lower values of roughness parameters) was obtained at tool rake angle $\gamma = 5°$.
2. In the analysed range of feed per tooth, *i.e.* $f_z = 0.05 \div 0.3$ [mm/tooth], the lowest surface parameter was noted for the lowest feed per tooth, whereas in the analysed range of cutting speed, $v_c = 400 \div 1200$ [m/min], the lowest surface roughness parameter value was obtained in the highest cutting velocity.
3. Depth of cut was of negligible impact on the surface parameters measured on the end face of the analysed sample, which indicates that an attempt to improve volumetric efficiency of machining should consist in increasing the depth of cut rather than feed per tooth.
4. In the analysed range of depths of cut, lower values of roughness parameters were obtained at lower feed per tooth ($f_z = 0.05$ mm/tooth). Nevertheless, reducing feed per tooth should be conducted within reasonable limits as insufficient feed rate may cause the cutting edge to slide across the machined material.
5. Conducted study indicates that, if necessary, volumetric efficiency can be increased through increasing the depth of cut and not the feed rate, as the rate of growth of surface roughness in increasing feed rate is higher when compared with the change of cutting depth alternatively, cutting velocity could be increased.

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