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EXPERIMENTAL INVESTIGATION OF HIGH SPEED MILLING OF ALUMINIUM ALLOY

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Original scientific paper
The customer´s growing demand for higher quality products has forced manufacturing industry to continuously progress in quality control and machining technologies. One of the fundamental metal cutting processes is milling. The aim of this study is to investigate optimum cutting parameters of AlMgSi alloy (EN-AW 6060), which is one of the most commonly used aluminium alloys, using uncoated cemented carbide end mills. The influence of tool geometry (helix angle) and cutting conditions (cutting velocity, and feed rate) on the surface finish produced during high speed milling of aluminium alloy have been investigated. The significance of the parameters on surface roughness has been established with analysis of variance (ANOVA). The cutting parameters regarding surface roughness performance indexes are analysed, and the findings are discussed and evaluated.

Keywords: *aluminium alloy, end mill, high speed milling, surface roughness*

Eksperimentalno istraživanje brzog glodanja aluminijske legure

Izvorni znanstveni članak
Sve veći zahtjevi kupaca za kvalitetnijim proizvodima prisilili su proizvodnu industriju da neprestano usavršava kontrolu kvalitete i tehnologije obrade. Jedan od osnovnih postupaka rezanja metala je glodanje. Cilj ovoga rada je istražiti optimalne parametre rezanja legure AlMgSi (EN-AW 6060), jedne od najčešće korištenih legura aluminija, primjenom čeonih glodala od neobloženog cementnog karbida. Analizirao se utjecaj geometrije alata (ugao zavojnice) i reznih uvjeta (brzina rezanja i veličina posmaka) na površinsku obradu tijekom brzog glodanja aluminijske legure. Djelovanje parametara na površinsku hrapavost ustanovljeno je analizom varijance (ANOVA). Analizirano je djelovanje parametara rezanja na indekse hrapavosti površine. Rezultati su prodiskutirani i procijenjeni.

Ključne riječi: *aluminijska legura, čeono glodalo, brzo glodanje, površinska hrapavost*

1 Introduction

Surface roughness plays an important role in determining the product quality since it strongly influences the performance of mechanical parts as well as production cost. Many machining processes impose characteristic irregularities on a work piece surface.

End milling process belongs to the one of the most commonly used metal cutting operations for machining parts because of its ability to remove materials in great amount and fast with a reasonably good surface quality.

Nowadays, computer numerically controlled (CNC) machine tools have been widely used to provide the full automation in manufacturing process. They significantly improve the productivity, increase the quality of the machined parts and require minimal operator intervention. The aim of high speed machining (HSM) on CNC machine tools is to achieve a significant increase in material removal rate (MRR), which can expressively reduce production cost and increase production rate.

Aluminium alloys are widely used in engineering, especially in automotive industry, cosmonautics, aeronautics and medicine [1, 2]. As written in [3], cutting tools made of uncoated cemented carbide are the most commonly used cutting materials for machining aluminium alloys. Cemented carbides are used as cutting tool materials for machining wrought alloys due to their wear resistance and hardness.

A wrought alloy with low silicon contents is a soft, ductile, and homogeneous material, which causes a minimum of tool wear. Kauppinen [4] stated that the tool wear rates of the cutting tools do not normally play a significant role in the machining of aluminium alloys. As mentioned in [5], in the case of wrought alloys, the tool life is measured in number of shifts or days rather than in minutes. Moreover, the relative machinability rankings are of less interest since these materials are relatively easy to machine.

Various studies have been conducted on the surface roughness in end milling using different materials, cutting tools, and experimental and optimization methods. The research of Rao and Shin [6] was concerned with the analytical and experimental study on the high-speed face milling of 7075-T6 aluminium alloys with a single insert fly-cutter. They analysed the results in terms of cutting forces, chip morphology, and surface integrity of the work piece machined with carbide and diamond inserts. Fuh and Wu [7] studied the influence of tool geometries (nose radius and flank width) and cutting parameters (cutting speed, depth of cut, feed) on surface roughness *Ra* in end milling of Al alloy using RSM method. Yang and Chen [8] studied the effect of spindle speed, feed rate and depth of cut on *Ra* in end milling of Al work piece. Benardos and Vosniakos [9] used Taguchi method to consider prediction of *Ra* in CNC face milling of Al alloy. The factors considered in the experiment were the depth of cut, the feed rate per tooth, the cutting speed, the engagement and wear of the cutting tool, the use of cutting fluid and the three components of the cutting force. Brezocnik et al. [10] used genetic programming for prediction of *Ra* in CNC end milling of 6061 Al alloy in terms of machining parameters and vibrations. Wang and Chang [11] investigated surface roughness in slot end milling of Al2014-T6. Simunovic et al. [12] and Saric et al. [13] presented researches on machined surface roughness prediction in the face milling process. The data for modelling have been collected by the central composite design of experiment. Input variables are cutting speed, feed and depth of cut. In the modelling process the authors used regression modelling and Neural Networks. Cukor and Jurkovic [14, 15] examined the influence of cutting parameters (cutting speed, feed and depth of cut) on the tangential component of cutting force in the rough longitudinal turning operation using rotatable central composite design and Taguchi method. They also presented and discussed different optimization methods to improve the surface roughness obtained in the finish longitudinal turning operation.

Krolczyk et al. [16, 17] developed a mathematical model to determine the influence of cutting parameters (cutting speed, feed and depth of cut) onto surface roughness and tool life after turning of duplex stainless steel. Puh et al. [18] applied the Taguchi method and ANOVA to study performance characteristics of cutting parameters (cutting speed, feed and depth of cut) with consideration of surface roughness after hard turning process. Reibenschuh et al. [19] focused their research on the cost effectiveness of using dry cutting in comparison with the use of cutting fluids and the use of different tool geometry in turning of high quality aluminium alloys.

In this contribution, ANOVA is carried out using commercial software Statistica v.10 for a level of confidence of 95 %. ANOVA is the most widely utilized method of statistical analysis of quantitative data. It is used to determine the impact independent variables have on the dependent variable in a regression analysis. ANOVA calculates the *F*-ratio, which is calculated as the ratio of between-treatments variance divided by error variance. It measures the significance of model under investigation with respect to the variance of all the terms included in the error term at the desired significance level.

The aim of this study is to investigate the influence of tool geometry and cutting conditions on the quality of work piece surface produced in HSM of an aluminium alloy. The direct as well as interactive effects of cutting parameters on surface roughness have been examined quantitatively by the analysis of variance (ANOVA). The cutting parameters regarding surface roughness performance indexes are analysed, and the findings are discussed and evaluated.

2 Material and methods

To evaluate which parameters affect the surface roughness in high speed milling of aluminium alloy, a number of experiments have been carried out.

This research was conducted using AlMgSi aluminium alloy with a T6 heat treatment, namely the EN AW-6060 alloy. It is a low strength heat treatable wrought alloy, which is widely used in many different engineering and architectural applications due to its very good corrosion resistance, very good weldability and good cold formability. It is an ideal alloy for very complex cross sections and has a very good anodising response. Its chemical composition is described in Tab. 1.

Table 1 Chemical composition of the EN-AW 6060 alloy (in wt. %)

Si	Mg	Mn	Fe	Cr	Zn	Cu	Ti	Other
0,3 ÷ 0,6	0,35 ÷ 0,6	0,1	0,1 ÷ 0,3	0,05	0,15	0,1	0,1	0,15

The test specimens of 32 pieces were cut with the dimensions of 10 × 15 × 100 mm. The work piece was clamped on the worktable as shown in Fig. 4.

Four different helix angles (0°, 10°, 20°, 40°) for 3-flute uncoated carbide end mills were used (Fig. 1). The diameter of 12 mm and tool length of 42 mm was fixed. The tools were clamped into shrink fit holders and the arrangement was balanced by Haimer Tool Dynamic 2009 with G levels according to ISO 1940-1 standard (Fig. 2). Out of balance level was less than G2.

Figure 1 End mills

The experiments have been carried out on a CNC machining centre DMG HSC 105 Linear manufactured by the German company DeckelMahoGildemeister – DMG.

Figure 2 Cutting tools balancing

Fig. 3 illustrates the kinematic structure of the machine tool. Spindle moves to the portal structures in the *Y* and *C* axes. Turntable with a diameter of 900 mm moves in the direction of axis *X*. The fourth axis is turner the spindle in the range of −10° to 110°. Machine tool design in five axes is equipped with water-cooled high-performance spindle with an air release/gripping held HSK E50 tool holder. Spindle maximum speed reaches 42000 min^{-1} and maximum power 13 kW. Machine control provides a modern management system HeidenhainiTNC 530 (or Siemens 840D) in five axes with security packets.

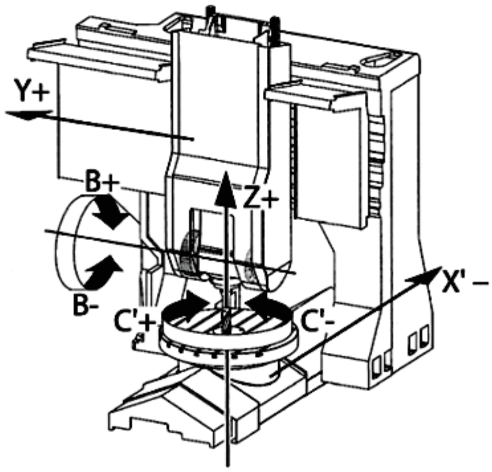

Figure 3 Kinematic structure of HSC 105 Linear

Fig. 4 shows the photo of the specimen fixture and the side milling operation with a cutting fluid.

Figure 4 Milling the specimen

Table 2 Process parameters with their levels

	Level 1	Level 2	Level 3	Level 4
Helix angle λ_s, °	0	10	20	40
Cutting speed v_c, m/min	500	800	1000	1500
Machining	dry	wet	-	-

Table 3 Experimental design matrix

No.	Helix angle λ_s / °	Cutting speed v_c / m/min	Machining
1	0	500	dry
2	0	800	dry
3	0	1000	dry
4	0	1500	dry
5	10	500	dry
6	10	800	dry
7	10	1000	dry
8	10	1500	dry
9	20	500	dry
10	20	800	dry
11	20	1000	dry
12	20	1500	dry
13	40	500	dry
14	40	800	dry
15	40	1000	dry
16	40	1500	dry
17	0	500	wet
18	0	800	wet
19	0	1000	wet
20	0	1500	wet
21	10	500	wet
22	10	800	wet
23	10	1000	wet
24	10	1500	wet
25	20	500	wet
26	20	800	wet
27	20	1000	wet
28	20	1500	wet
29	40	500	wet
30	40	800	wet
31	40	1000	wet
32	40	1500	wet

To develop the design of experiment we used the Taguchi's approach. The experimental design proposed by Taguchi involves using orthogonal arrays to organize the parameters affecting the process and the levels at which they should be varied. The parameters levels were chosen within the intervals recommended by the cutting tool manufacturer.

In our study, four levels were specified for two process parameters as given in Tab. 2. The orthogonal array chosen was L_{16} for dry and L_{16} for wet machining. This led to a total of 32 tests (Tab. 3).

Cutting velocity (v_c) was determined as controllable cutting parameter to be used in the experiments. Radial depth of cut (a_e) was kept 1 mm, axial depth of cut (a_p) 10 mm, and feed per tooth f_z was fixed to 0,1 mm for all the experiments. The helix angle (λ_s) varied between 0 to 40°. The up milling was applied. Every specimen was milled with (wet machining/CF) and without the cutting fluid (dry machining) to determine the influence of cutting fluid on the surface roughness. The used cutting fluid was an emulsion of soluble oil and water at a 1:15 ratio.

Surface roughness of the milled surface was measured using a surface texture measuring instrument Surfcom 130A, Carl Zeiss (Fig. 5). Three measurements were made on each surface and the arithmetical means of them were calculated.

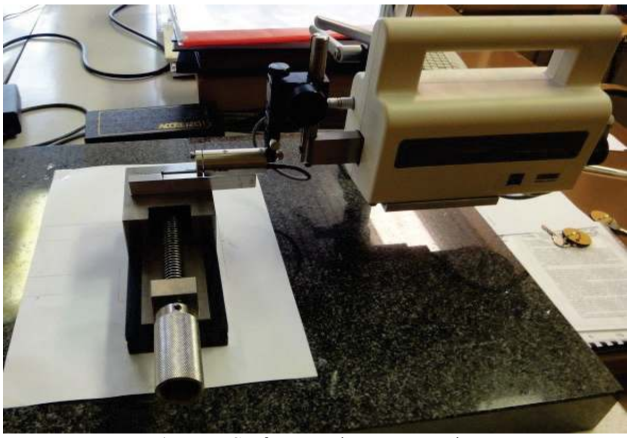

Figure 5 Surface roughness measuring

3 Results and discussion

A statistical analysis of variance (ANOVA) was performed to see which cutting parameters were statistically significant. To check if there was normality in the experimental errors, the Shapiro-Wilk test was performed. The test proved the variances normality of experimental errors for application of variance analysis. The results of ANOVA are summarized in Tab. 4.

Table 4 ANOVA table for surface roughness *Ra*

	SS	*MS*	*F*-test	*p*-level
Intercept	35,8767	35,8767	6000,25	0,00000
λ_s	0,80737	0,26912	45,010	0,00000
v_c	0,66236	0,22079	36,926	0,00000
Machining	0,05965	0,05965	9,976	0,00242
$\lambda_s \cdot v_c$	1,12644	0,12516	20,933	0,00000
$\lambda_s \cdot Mach$	0,23661	0,07887	13,191	0,00000
$v_c \cdot Mach$	0,47769	0,15923	26,631	0,00000
$\lambda_s \cdot v_c \cdot Mach$	0,56811	0,06312	10,557	0,00000
Error	0,38267	0,00598		

The *F*-ratio value of 45,01 for the helix angle shows that this parameter is the most influential. This angle is defined as the angle of the flutes relative to the axial centreline of the tool and influences tool performance mainly by affecting chip flow and cutting forces. A helix angle of 30º has always been the most general-purpose design that works well in the broadest application area for the most common materials and cutting conditions. This study examines the helix angles which are not common to determine the influence of the other helix angles.

We observed (Fig. 6) that the *Ra* values by lower helix angles (0 to 20°) are very similar (between 0,48 to 0,72 μm). The difference is only in helix angle of 40º, at which are *Ra* values the highest. This shows that the end mill with a helix angle of 40° is not suitable for milling AlMgSi by the selected cutting conditions.

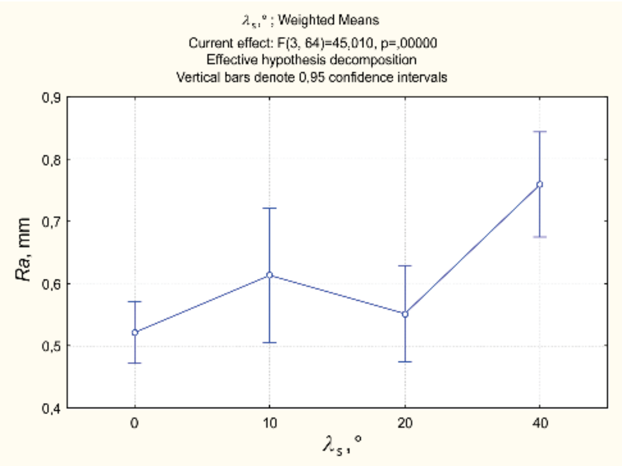

Figure 6 Influence of helix angle on surface roughness

The second parameter, which influences the *Ra*, is the cutting speed with *F*-test value 36,9. The graph in Fig. 7 partially confirms the fact that a lower cutting speed unfavourably influences the quality of surface finish. Despite it, the lowest cutting speed (v_c = 500 m.min^{-1}) gives the lowest values of *Ra*, but the variance is very wide (between 0,47 to 0,67 μm). Machining with the highest cutting speed (v_c = 1500 m/min) is considered as the most stable, because the variance of the *Ra* values by this cutting speed is the smallest. Moreover, the productivity is the highest (because of the shortest time), therefore this cutting speed is recommended.

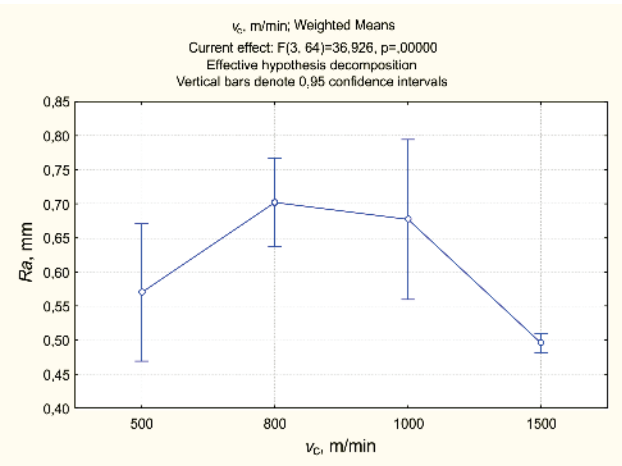

Figure 7 Influence of cutting speed on surface roughness

Fig. 8 shows a multifactorial interaction plot between helix angle and surface roughness by dry and wet machining. The difference between the *Ra* values by both types of machining is unimportant, what means that similar *Ra* values are achieved by wet machining as well as by dry machining. Because of the higher costs of a cutting fluid and its negative impact on health of workers and environment, dry machining is highly recommended in this case.

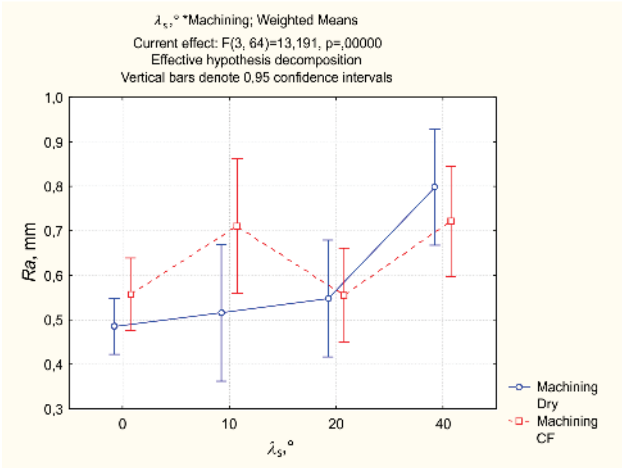

Figure 8 Influence of helix angle and dry/wet machining on surface roughness

Fig. 9 shows another multifactorial interaction plot which demonstrates the influence of cutting speed and helix angle on surface roughness. The combination of these two variables is the most homogenous and stable by the cutting speed of 1500 m/min, by which are the values of *Ra* independent from helix angle size.

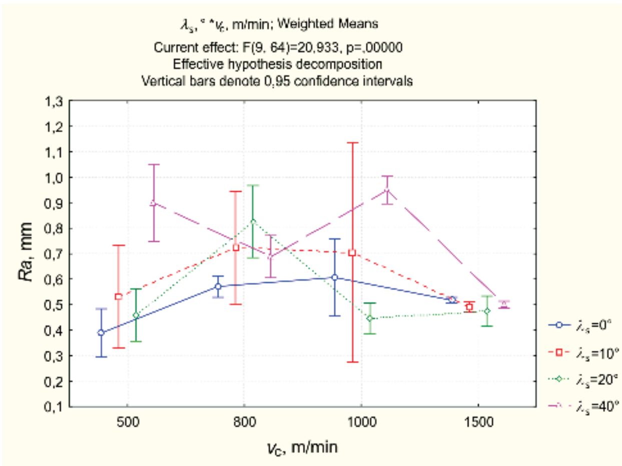

Figure 9 Influence of cutting speed and helix angle on surface roughness

4 Conclusion

The result of the experiments has shown the importance of proper tool geometry and cutting parameters selection in machining of aluminium alloys. The parameters should be designed optimally in order to reach the prescribed quality of surface finish by minimal costs. In this contribution, the influence of tool geometry and selected cutting parameters on surface roughness after high speed milling of aluminium alloy has been analysed and examined.

Based on the experimental investigations the following concluding remarks can be made:

- The most important parameter, which influences the surface roughness values, is the helix angle λ_s.
- The surface roughness decreased with the increase of the cutting speed.

- The use of a cutting fluid is not important. The values of *Ra* are similar by wet and dry machining.
- High speed milling is more suitable for this type of tool, work piece material and cutting parameters, because better surface quality was achieved.

Nomenclature

v_c − cutting speed, m/min
f_z − feed per tooth, mm
a_e − radial depth of cut, mm
a_p − axial depth of cut, mm
λ_s − helix angle, °
Ra − arithmetical mean deviation of the roughness profile, μm
ANOVA − Analysis of Variance
CF − Cutting Fluid
CNC − Computer Numerical Control
MS − Mean Square
MRR − Material Removal Rate
RSM − Response Surface Methodology
SS − Sum of Squares

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