THE INFLUENCE OF MILLING PARAMETERS ON THE SURFACE ROUGHNESS IN THE CASE OF MAGNESIUM ALLOY AZ61A

Cosmin-Constantin Grigoraş[1], Gheorghe Brabie[1]

[1]"Vasile Alecsandri" University of Bacau, Faculty of Engineering, Calea Marasesti 157, 600115, Bacau, Romania

Corresponding author: Grigoraş Cosmin-Constantin, grigorascosmin_phd@yahoo.com

Abstract: The purpose of this study is to analyse how the milling cutting parameters influence the surface roughness and hence the surface quality of biomedical implants made from magnesium alloys. Such alloys can be used as temporary bone implants. The surface roughness of AZ61A magnesium-aluminium alloy was analysed by changing different cutting parameters for milling operations, using a face mill. The total number of samples was reduced by pre-optimization, using DesignExpert software with the Box-Behnken model; after this optimization a total number of 17 samples were selected for analysis. The cutting process was performed in dry conditions, because water based cooling agents react with magnesium. It was recorded that dry cutting magnesium-aluminium alloy AZ61A with the used parameters did not lead to chip ignition. The evaluation of the surface roughness was made by measuring the roughness absolute value (Ra), with levels ranging from 0.081 [μm] to 0.269 [μm]. An ANOVA analysis for response surfaces was performed using the DesingExpert software in order to reveal which of cutting parameters were relevant for the roughness change. The obtained results showed that only the speed and feed have a significant impact in obtaining the optimal surface roughness. The Taguchi optimization method was used and applied by considering the maximization of the speeds, feeds and depth of cut and the minimization of the surface roughness. From the performed analysis it was concluded that the use of higher speeds combined with average feeds and maximum depth of cut have an important role in lowering the Ra values for the surface roughness. It was also concluded that the optimization of the cutting parameters is a technique that improves the surface quality in terms of surface roughness.
Key words: Milling, surface roughness, magnesium alloy, cutting parameters, optimization.

1. INTRODUCTION

The present orthopedically metallic implants have two major issues: stress shielding and revision surgeries, which reduce the life quality of the patient and have a major negative impact over the healthcare system [1]. Research in the field of bio-engineering has shown a growing interest in the use of biodegradable implant materials for bone fractures [2]. Some biodegradable implants are made from polymers such as poly-L-Lactic acid. This material has low mechanical strength and has driven researchers to seek for biodegradable metallic substituents. Magnesium (Mg) and its alloys are among the most interested options, [3]. However magnesium-based alloys have a high degradation rate because magnesium is an essential element to the human body. Metabolic activities requier an amont of 300-400 [mg/day] of magnesium, [4]. This element is a co-factor for removal of DNA (Deoxyribonucleic acid) damage and DNA replication [5].

Magnesium has close physical and mechanical properties to that of the human bone, in comparison to other implant materials (Table 1). However pure magnesium used as biodegradable implants leads to hydrogen gas (Eq. 1) which can create gas pockets around the implants [2].

$$Mg + 2\,H_2O = Mg(OH)_2 + H_2 \qquad (1)$$

Table 1. Summary of the physical and mechanical properties of various implant materials in comparison to natural bone, [2]

Properties	Natural bone	Magnesium	Ti alloy	Polylactide
Density [g/cm^3]	1.8-2.1	1.74-2.0	4.4-4.5	1.25-1.29
Compressive yield strength [MPa]	3-20	41-45	110-117	45.5-61.4
Elastic modulus [GPa]	130-180	65-100	758-1117	3.75

Hydrogen release occurs also when magnesium alloys is machined, using water based cooling agents, which can lead to chip ignition. A solution for this issue is high speed machining (HSM) without coolant, which is a more ecological and cost efficient. This process is an advanced surface treatment with cutting speeds from 600 to 5000 [m/min], [1, 6]. When a critical cutting speed is reached this method generates higher temperatures. This facilitate the adhesion of material on the cutting tool, also known

as flank build-up (FBU) that generates vibrations, poor dimension accuracy, chip ignition and low surface finish, [1].
In the case of magnesium alloys machining an important aspect is the surface roughness. A relation between a smoother surface and a better corrosion rate was established by using dry machining and dry burnishing, [2, 3].

2. MATERIAL AND EXPERIMENT SETUP

This study implies executing the following steps: pre-optimization, experimental setup, data acquisition, data analysis, result interpretation, optimization and conclusions.
The experimental setup of face milling is shown in figure 1. The study was performed using a 3 axes CNC milling machine Knuth Rapmill 700. The machine was equipped with a Sandvik Coromant 490 tool with a diameter of 50[mm] and CCMT 0.8 [mm] radius inserts.
A round bar of AZ61A magnesium alloy, with the chemical composition given in Table 2, was cut in samples having 74[mm] diameter and 30[mm] thickness. On each side of the sample two groves were made for grip as shown in figure 1. The samples were fixed in a vise and dry cutting conditions were performed, to avoid chip ignition.

Table 2. Chemical composition of AZ61A magnesium alloy

Al [%]	Cu [%]	Fe [%]	Mg [%]	
5.5-6.5	≤0.1	<0.005	92.3	**Other [%]**
Ni [%]	**Si [%]**	**Zn [%]**	**Mn [%]**	≤0.1
<0.005	≤0.2	0.5-1.5	0.05-0.4	

Table 3. Face milling parameters

Cutting speed [m/min]	Feed [mm/min]	Depth of cut [mm]
200	500	0.15
350	1000	0.25
500	1500	0.35

The entire range of the cutting condition given in Table 3 was used to determine the influence of the milling parameters on the surface roughness. Measurements were performed using the roughness measuring equipment Namicon Roughness Tester TR-200.
The milling parameters given in Table 3 were chosen so that they are linked one another by the same ratio, to facilitate the optimization calculation.
The experimental plan was pre-optimized using DesignExpert software. The total number of samples was reduced from 27 to 17 by applying the Box-Behnken model. Combinations of the milling parameters performed by Design Expert software and roughness measurements are given in Table 4.

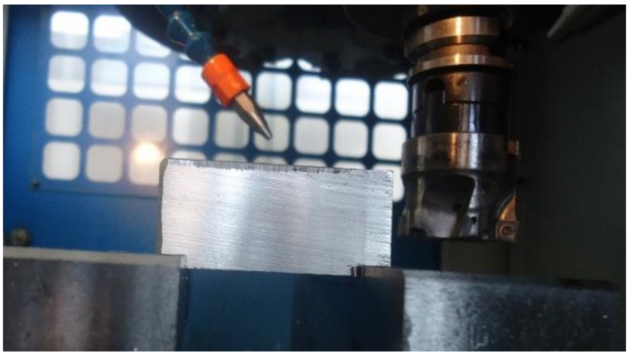


Fig. 1. Experimental setup of face milling

Table 4. Face milling parameter combinations performed by DesignExpert software and surface roughness measurements

Sample No.	Cutting speed [m/min]	Feed [mm/min]	Depth of cut [mm]	Roughness values [µm]
1	500.00	500.00	0.25	0.108
2	500.00	1500.00	0.25	0.081
3	350.00	1000.00	0.25	0.202
4	350.00	500.00	0.15	0.082
5	200.00	1000.00	0.15	0.235
6	200.00	1500.00	0.25	0.300
7	500.00	1000.00	0.35	0.107
8	500.00	1000.00	0.15	0.118
9	350.00	1500.00	0.15	0.269
10	350.00	1500.00	0.35	0.267
11	350.00	500.00	0.35	0.093
12	350.00	1000.00	0.25	0.216
13	350.00	1000.00	0.25	0.117
14	350.00	1000.00	0.25	0.089
15	350.00	1000.00	0.25	0.167
16	200.00	1000.00	0.35	0.264
17	200.00	500.00	0.25	0.168

3. RESULTS

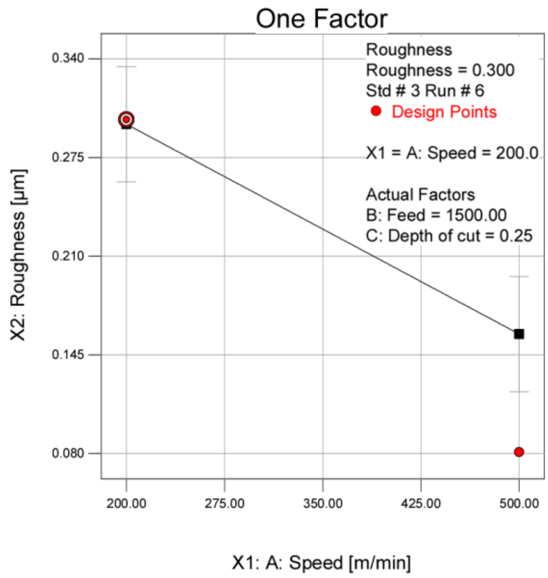
The roughness arithmetic averages (R_a) measured 17 samples (Table 4) were inserted into DesignExpert software. Performing the ANOVA analysis, for response surface, shows that results are significant with a p-value of 0.0002.
The correlation between the surface roughness and feed and speed is given in figure 2 (a), (b). It is noted a tendency of low roughness values as the speed value is higher.
The higher value for the surface roughness is 0.300 [µm] obtained by using a speed of 200 [m/min] and a feed of 1500 [mm/min] at a cutting depth of 0.25 [mm]. Combining the maximum speed of 500 [m/min] with the same feed and depth of cut produces the lowest value for surface roughness of 0.081 [µm], in the case dry face milling of AZ61A magnesium alloy. An improvement of 370.37 [%] in surface roughness is noted, as a result of a higher speed, up to 250 [%].

Table 5. ANOVA surface response analysis results performed with DesignExpert

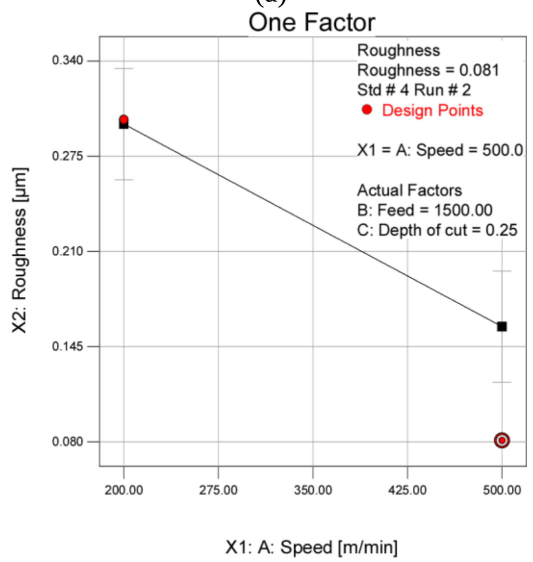
ANOVA for Response Surface Reduced Linear Model						
Analysis of variance table [Partial sum of squares - Type III]						
	Sum of		Mean	F	p-value	
Source	Squares	Df	Square	Value	Prob > F	
Model	0.065	2	0.033	16.09	0.0002	significant
A-Speed	0.038	1	0.038	18.82	0.0007	
B-Feed	0.027	1	0.027	13.37	0.0026	
Residual	0.028	14	2.031E-003			
Lack of Fit	0.017	10	1.661E-003	0.56	0.7905	not significant
Pure Error	0.012	4	2.956E-003			
Cor Total	0.094	16				

An increase of the feed value leads to rougher surfaces. In Fig. 3 (a) and (b) it is shown that for a speed of 350 [m/min] and a depth of cut of 0.15 [mm] the surface roughness varies from 0.082 [μm] to 0.269 [μm] by changing the feed value from 500 [mm/min] to 1500 [mm/min].

A decrease of 328.04[%] in the surface roughness is noted when the cutting feed is increased. However, lower feeds can produce continuous chip that can enwrap around the tool and facilitates the installation of build-up edge (BUE), affecting the tool geometry [7]. This issue leads to a higher manufacturing time by means of tool cleaning and changing the insert.

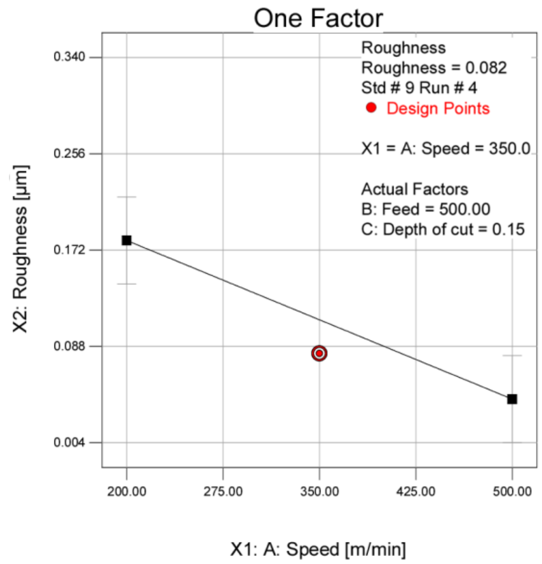


(a)

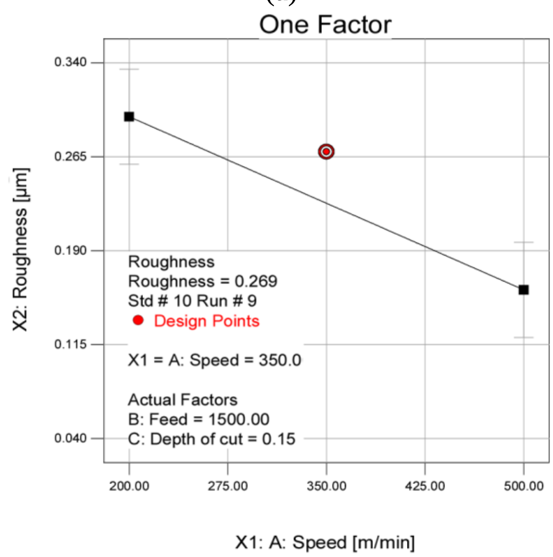


(b)

Fig. 2. The influence of speed and depth of cut at constant feed on the surface roughness



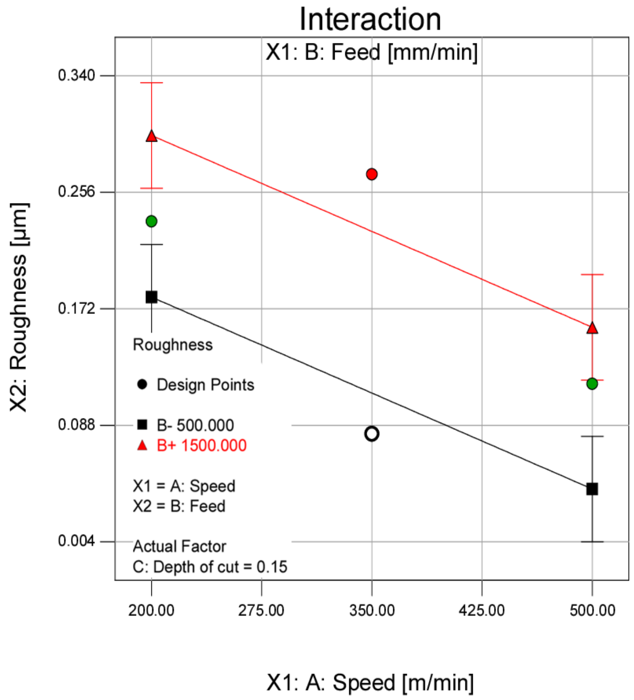
(a)



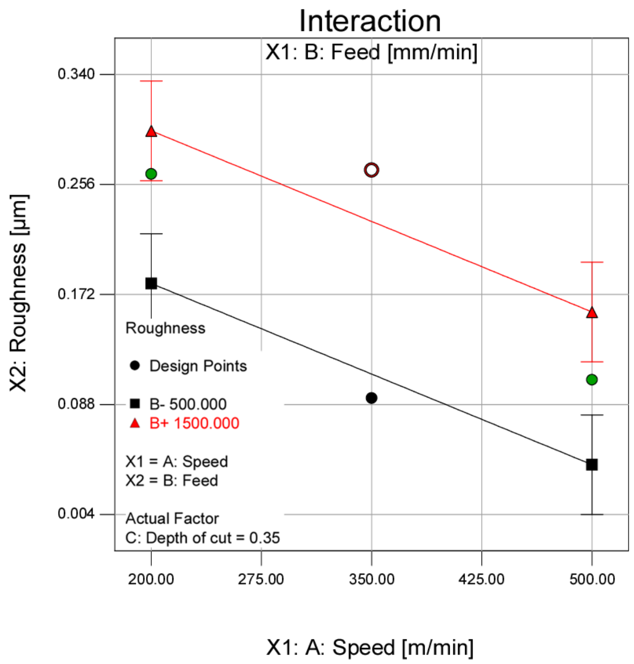
(b)

Fig. 3. The influence of feed at constant speed and depth of cut on the surface roughness

Major variations in the surface roughness, at constant speed and feed, cannot be notable when changing the depth of cut, as shown in figure 4 (a) and (b). The difference in surface roughness from 0.082 [μm] to 0.093 [μm] corresponds to 0.15[mm] and 0.35[mm] in depth of cut, at a speed of 350[m/min] and feed of 500[mm/min]. An insignificant difference from 0.269[μm] 0.267[μm] can be observed in the same conditions, but at a feed of 1500[mm/min].
The results in this study are similar to results in other literature from this field. It is stated that the build-up edge tendency during machining of ductile materials at low and intermediate cutting speed is considerably high. The best way to reduce the BUE tendency is to create a flow zone between the cutting tool and chip by increasing the cutting speed within an acceptable range, [7].



(a)



(b)

Fig. 4. The influence of the depth of cut at constant speed and feed on the surface roughness

Face milling in dry conditions in the case of AZ61A did not lead to chip ignition, using the parameters from Table 4.

4. OPTIMIZATION

The Taguchi method was used for optimizing the input (feed, speed and depth of cut) and output (surface roughness) milling parameters. The general criteria refer to minimizing the surface roughness. Considering the fact that a higher cutting speed generates a smoother surface the goal is to maximize it, along with the feed and depth of cut.
With a desirability factor of 0.968 the software predicts a surface roughness of 0.116[μm]. The optimized results from Fig. 5 indicate the use of the following parameters: speed of 500[m/min], feed of 1132.49[mm/min] and a maximum depth of cut.

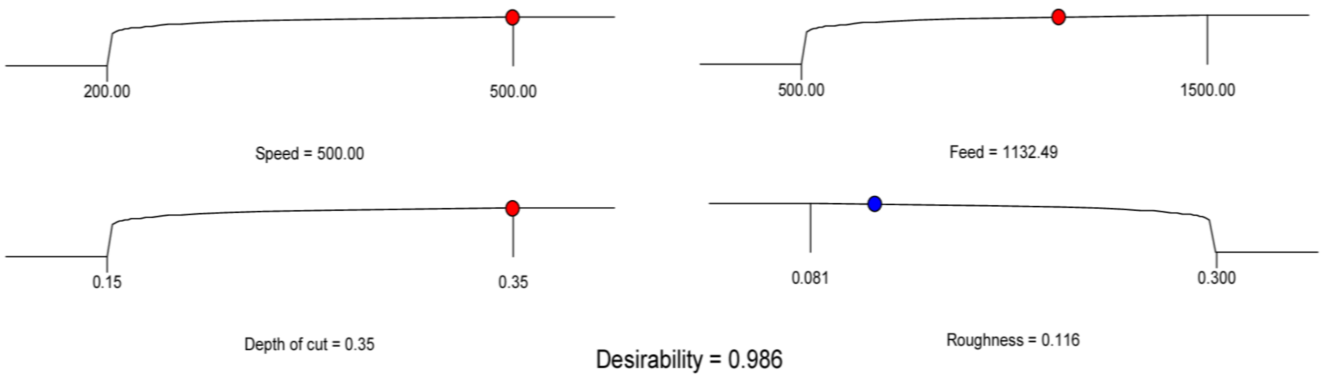


Fig. 5. Optimized milling parameters using the Taguchi method

5. CONCLUSIONS

This experimental study has shown the surface roughness improvement with respect to the influence of the milling parameters. The cutting process was performed by the variation of the speed, feed and depth of cut.

The DesignExpert software was used in pre-optimization, to improve the optimum/minimum number of samples that are required to be machined for extracting the correct and complete data.

When low speeds and feeds were used the cutting process did not lead to chip ignition.

The ANOVA analysis also indicates that the depth of cut does not have a significant contribution to the surface roughness variation. This result is shown in Eq. 2 with reference to the input factors.

$$R_a = 0.21438 - 4.60833E\text{-}0.04Speed + 1.165E\ 0.05Feed \quad (2)$$

Statistical analysis highlights the relation between the input parameters and the surface roughness. Furthermore, it was shown that the depth of cut does not have a significant influence on the roughness. However, a higher speed is shown as a major factor in obtaining a smoother surface, along with a low feed-rate.

The optimization results emphasize the statements above. The predicted low roughness can be achieved by using a higher speed and average feed. A higher depth of cut can be used for an optimum machining time.

It can be concluded from this study, that in the case of dry face milling magnesium alloy AZ61A, the model resulted can be used for obtaining the optimum values for feed and speed regarding the surface roughness.

6. REFERENCES

1. Guo, Y. B., Salahshoor, M., (2010). *Process mechanics and surface integrity by high-speed dry milling of biodegradable magnesium–calcium implant alloys,* CIRP Annals - Manufacturing Technology, Vol. 59, pp. 151-154.

2. Walter, R., Kannan, M. B., He, Y., Sandham, A., (2013). *Effect of surface roughness on the in vitro degradation behaviour of a biodegradable magnesium-based alloy*, Applied Surface Science, Vol. 279, pp. 343-348.

3. Salahshoor, M., Guo, Y. B., (2011). *Surface integrity of biodegradable Magnesium–Calcium orthopedic implant by burnishing*, Journal of the Mechanical Behavior of Biomedical Materials, Vol. 4, pp. 1888-1904.

4. Hindmarsh, J. T., (1988). Clinica Chimica Acta, Handbook of Toxicity of Inorganic Compounds: Hans G. Seiler, Helmut Sigel, Astrid Sigel Marcel Dekker (Ed(s)), Vol. 175, pp. 119-120, Inc., New York.

5. Hartwig, A., (2001). *Mutation Research / Fundamental and Molecular Mechanisms of Mutagenesis*, Role of magnesium in genomic stability, Vol. 475, pp. 113-121.

6. Salahshoor, M., Guo, Y. B., (2011). *Cutting mechanics in high speed dry machining of biomedical magnesium–calcium alloy using internal state variable plasticity model*, International Journal of Machine Tools and Manufacture, Vol. 51, pp. 579-590.

7. Korkut, I., Donertas, M. A., (2007). *The influence of feed rate and cutting speed on the cutting forces, surface roughness and tool–chip contact length during face milling*, Materials & Design, Vol. 28, pp. 308-312.

Received: July 28, 2015 / Accepted: December 10, 2015 / Paper available online: December 20, 2015