The influence of milling parameters on the material hardness in the case of magnesium alloy AZ61A

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Abstract. This study was conducted in order to determine the material hardness value due to modification of the milling cutting parameters. The alloy hardness was analysed as a function of different cutting parameters for milling operations (speed, feed and depth of cut), using a face mill. A total number of 17 samples were machined using parameters obtained by combining the input parameters. The total number of combinations is reduced by a pre-optimization, using the DesignExpert software. The cutting process was performed in dry conditions, and it was recorded that dry cutting magnesium-aluminium alloy AZ61A with the used parameters did not lead to chip ignition. The surface hardness was determined based on the Vickers scale (HV), its values ranging from 110.59 [HV] to 121.37 [HV]. The obtained results showed that the feed has a significant contribution in the surface harness modification. The application of the Taguchi method reveals that the material hardness can be improved, together with the manufacturing time, by means of the speed, feed and depth of cut maximization.

1. Introduction
The use of some magnesium alloys [1] as biodegradable orthopedically implants as temporary bone implants is a present topic among bio-engineering research.

In comparison to other implant materials (table 1) magnesium alloys have closer physical and mechanical properties to those of the natural bone [2]. While magnesium and its alloys are among the most interested options [3] low corrosion resistance can be a major step-back.

The low corrosion resistance is consistent to the fact that magnesium and its alloys have a high surface electrochemical activity or high susceptibility to corrosion attack [4]. In the human body, metabolic activities require an amount of 300-400 [mg/day] of magnesium [5], chemically reacting with water according to equation (1) [2].

\[
\text{Mg} + 2 \text{H}_2\text{O} = \text{Mg(OH)}_2 + \text{H}_2
\]  

(1)

The hydrogen gas arising from the chemical reaction demands a higher attention when magnesium alloys are machined, if water based cooling agent is used. This issue can be overcome by dry or high speed machining (HSM). However this method, at a critical speed, generates high temperatures that facilitates the adhesion of material in the cutting tool (FBU – flank build-up) [6].

The material hardness in the case of magnesium alloy orthopedically implants is related to the wear resistance mechanism [4]. Research in this field [1, 3, 4, 6] leads to advanced chemical and/or mechanical surface treatments to improve the corrosion rate.
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        |

2. Material and experiment setup

The study implies the execution of the following steps:

- **Pre-optimization**
- **Experimental setup**
- **Data acquisition**
- **Data analysis**
- **Result interpretation**
- **Optimization**
- **Conclusions**

The AZ61A magnesium alloy was used for the current study in the shape of a round bar. A total number of 17 cylindrical samples, each having 70 [mm] diameter and 30 [mm] thickness, were obtained by cutting the bar. The samples were fixed in a vise and for better grip two groves were made on each sample (figure 1). In order to reduce the risk of chip ignition, dry cutting conditions were used. The chemical composition of the magnesium alloys is given in table 2.

The face milling experiment was conducted on a 3 axes CNC milling machine Knuth Rapmill 700. The cutting tool used was a Sandvik Coromant 490 face mill, having 50 [mm] in diameter and CCMT 0.8 [mm] radius inserts. The materials hardness was measured on the Vickers scale [HV] using the hardness measuring equipment Innovatest Ultramatic 2.

![Figure 1. Experimental setup of face milling.](image)

Table 2. Chemical composition of AZ61A magnesium alloy.

| Element | Composition [%] |
|---------|-----------------|
| Al      | 5.5-6.5         |
| Cu      | $\leq 0.1$      |
| Fe      | $\leq 0.005$    |
| Mg      | 92.3            |
| Mn      | 0.05-0.4        |
| Ni      | $\leq 0.005$    |
| Si      | $\leq 0.2$      |
| Zn      | 0.5-1.5         |
| Other   | $\leq 0.1$      |

Given in table 3 are indicated the speed, feed and depth of cut values used in this experiment. The values were chosen so that they are linked one another by the same ratio to ease the pre-optimization and optimization analysis. The total number of samples was calculated by combining all the parameter values ($3^3 = 27$). Thereby having the total number of possible combinations and using DesignExpert software by applying the Box-Behnken model, the number of samples was reduced from 27 to 17. The
pre-optimization results given in table 4 where together with the feed, speed and depth of cut are the hardness values, obtained as average of a five point’s measurement.

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              |

Table 4. Face milling parameter combinations performed by DesignExpert software and material hardness measurements.

| Sample | Cutting speed | Feed [mm/min] | Depth of cut | Hardness [HV] |
|--------|---------------|---------------|--------------|---------------|
| 1      | 500.00        | 500.00        | 0.25         | 113.5         |
| 2      | 500.00        | 1500.00       | 0.25         | 118.5         |
| 3      | 350.00        | 1000.00       | 0.25         | 118.5         |
| 4      | 350.00        | 500.00        | 0.15         | 114.8         |
| 5      | 200.00        | 1000.00       | 0.15         | 114.8         |
| 6      | 200.00        | 1500.00       | 0.25         | 117.2         |
| 7      | 500.00        | 1000.00       | 0.35         | 117.5         |
| 8      | 500.00        | 1000.00       | 0.15         | 117           |
| 9      | 350.00        | 1500.00       | 0.15         | 117.2         |
| 10     | 350.00        | 1500.00       | 0.35         | 116.8         |
| 11     | 350.00        | 500.00        | 0.35         | 114.2         |
| 12     | 350.00        | 1000.00       | 0.25         | 119.7         |
| 13     | 350.00        | 1000.00       | 0.25         | 121.37        |
| 14     | 350.00        | 1000.00       | 0.25         | 118.5         |
| 15     | 350.00        | 1000.00       | 0.25         | 117.5         |
| 16     | 200.00        | 1000.00       | 0.35         | 114.2         |
| 17     | 200.00        | 500.00        | 0.25         | 110.59        |

3. Results

The initial value for the material hardness was 102 [HV]. After the cutting process the measurements (table 4) shown an increase to a maximum value of 121.37 [HV], meaning 18.9 [%].

The hardness measurements from table 4 were inserted intro DesignExpert software and an ANOVA analysis for response surface was performed. The results given in table 5 show that the model used for this study is significant, with a p-value of 0.0004. The analysis also indicates that the depth of cut is not a major factor in the material hardness modification.

The variation of the material hardness at a constant depth of cut of 0.25 [mm] is given in figure 2. A minimum value of 110.59 [HV] is registred when using a low speed of 200 [m/min] with a feed of 500 [mm/min]. When combining average values for the speed and feed, meaning 350 [m/min] and 1000 [mm/min] the hardness value is 121.37 [HV]. This maximum value indicates an increase of 9.74 [%] in the case of dry face milling of the magnesium alloy AZ61A.

The use of higher speeds and feeds leads to a slight decrease of the material hardness value. When cutting with a speed of 500 [m/min] and a feed of 1500 [mm/min] it is registered a drop of 2.36 [%],
corresponding to a value of 118.5 [HV]. It is also noted that the smallest hardness values are concentrated between speeds of 200-275 [m/min] and feeds of 500-750 [mm/min]. An increase of 5.97 [HV] in the magnesium alloy hardness from 110.59 [HV] to 117.2 [HV] corresponds to a variation of the feed from 500 [mm/min] to 1500 [mm/min] at constant a depth of cut of 0.25 [mm] and a speed of 200 [m/min]. For the same values of the feed and depth of cut an increase of 4.40 [%], from 113.5 [HV] to 118.5 [HV], is noted when dry cutting with a speed of 500 [m/min]. The percent in which the material hardness is enhanced is higher for the smaller speeds, but the improvement is in the numerical value that corresponds to the use of higher speed and feeds.

Table 5. ANOVA surface response analysis results performed with DesignExpert.

| Source       | Sum of Squares | Df | Mean Square | F Value | p-value Prob > F |
|--------------|----------------|----|-------------|---------|-----------------|
| Model        | 87.53          | 4  | 21.88       | 11.98   | 0.0004          |
| A-Speed      | 11.79          | 1  | 11.79       | 6.45    | 0.0259          |
| B-Feed       | 34.49          | 1  | 34.49       | 18.18   | 0.0010          |
| A²           | 18.35          | 1  | 18.35       | 10.05   | 0.0081          |
| B²           | 20.62          | 1  | 20.62       | 11.29   | 0.0057          |
| Residual     | 21.92          | 12 | 1.83        |         |                 |
| Lack of Fit  | 13.13          | 8  | 1.64        | 0.75    | 0.6648          |
| Pure Error   | 8.79           | 4  | 2.20        |         |                 |
| Cor Total    | 109.46         | 16 |             |         |                 |

The tendency of higher values for the surface hardness can be observed when average and above average speeds and feed are used. From a certain point, near to the maximum values for the input parameters, the hardness value slightly decreases. In this particular case the results shown that the decrease is notable after a speed and feed of over 425 [m/min] respectively 1250 [mm/min].

![Figure 2.](image)

Figure 2. The influence of speed and feed at constant depth of cut on the material hardness.
Significant changes in the material hardness aren’t noticed when the depth of cut is modified. In figure 3 (a), (b), (c) and (d) is reported the hardness dependency with respect to the following input parameters: speed of 350 [m/min], feed of 500-1500 [mm/min] and depth of cut of 0.15-0.35 [mm].

The comparison between the results from figure 3 (a) and (c) shows that the depth of cut has a minor impact over the hardness, with a change of only 0.52 [%]. The same insignificant change in the hardness value is noted when comparing the results from figure 3 (b) and (d); a variation of only 1.71 [%], with the change in depth of cut from 0.15 [mm] to 0.35 [mm].

As stated above the depth of cut does not have a major role in the material hardness change, when AZ61A magnesium alloy is machined, using the parameters from table 3. However the use of a higher depth of cut ensures a reduced machined time and an increase productivity.

The ANOVA analysis gives the final equation in term of actual factors. It shows the relation between the input parameters and the material hardness. From equation (2) it can be noted that the depth of cut does not have any significant role.

\[
HV = 91.426 + 0.072 \cdot Speed + 0.021 \cdot Feed - 9.266E^{-5} \cdot Speed^2 - 8.839E^{-6} \cdot Feed^2
\]  

(2)

4. Optimization
In order to enhance the material hardness considering the optimization of the input parameters (feed,
speed and depth of cut) the Taguchi method was used. It was taken into account the maximization of the hardness value regarding the intervals for speed and feed in which improvements were noted. By using speeds ranging from 350 [m/min] to 425 [m/min] and feeds from 1000 [mm/min] to 1250 [mm/min] and a maximum depth of cut the optimization predicts a surface hardness of 119.265 [HV]. Having a desirability factor of 0.982 (figure 4) the optimization indicates the use of the following parameter values: speed of 393.5 [m/min], feed of 1233.61 [mm/min] and depth of cut of 0.35 [mm].

![Figure 4. Optimized milling parameters using the Taguchi method.](image)

5. Conclusions
The variation in the material hardness by changing the milling parameters was analyzed in this study.

The pre-optimization indicates that, by reducing the total number of samples from 27 to 17, conclusive results were obtained. The ANOVA analysis points out the relation between the input parameters and material hardness. It was noted that the average and above average speeds and feed offer an increase in the material hardness. Another conclusion was that high speeds and feeds lead to a slight decrease in the hardness value and the depth of cut does not have a significant role.

The optimization, using the Taguchi method, confirms the conclusion drawn from the analysis. The material hardness can be improved by changing the speed and feed until a certain value.

In the case of AZ61A magnesium-alloys the material hardness can be enhanced by using the model resulted in this study.

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