Analysis of cutting forces and surface quality during face milling of a magnesium alloy

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Abstract. This paper presents an experimental study carried out in order to assess the effects of the cutting parameters (cutting speed, feed and depth of cut) and also of cooling conditions on the cutting force and the surface quality during high speed face milling of a magnesium alloy. With its high ratio of strength to weight, good machinability and overall physico–mechanical properties magnesium has attracted a large interest upon itself, especially in fields such as automotive, aeronautics, electronics or biomaterials. On the other hand, there has been lately an increased interest for cooling techniques that are more environmentally friendly, which is why in this study two cooling systems were used: dry machining and minimum quantity lubrication (MQL). The tests have been organised according to design of experiment technique. By using the response surface methodology (RSM), a central composite experimental matrix was designed. Statistical analysis (ANOVA) has allowed to create mathematical models of the cutting force and surface roughness and to analyse the effects of the effects of the input parameters on these outcomes. It was thus revealed that the depth of cut and the feed, and the interactions feed–depth of cut and feed direction–cooling, respectively, have the most significant influence on the main cutting force, whereas when it comes to the surface roughness, the most significant factors were the feed, the feed direction and the interaction between feed direction and cooling type.

1. Introduction

Industrial production has to adapt to the current quest for a cleaner society, with a lower negative impact on the environment. Legislation concerning pollution is becoming more and more limiting. Industries such as automotive and aeronautics are highly interested in using lighter materials to produce structural parts with lower mass. In turn, this increases fuel efficiency and lowers pollutant emissions. On the other hand, consumers are demanding lighter products from the fields as electronics or sport equipment.

A part of this question may be solved by using magnesium-based alloys, which offer high specific strength at a very low density (e.g. less than 65% of aluminium density and 25% of steel density). Moreover, magnesium is a biocompatible material, which makes it useful for producing medical implants, [1].

However, there are a few caveats that prevent a more extensive use of magnesium alloys. The extent of the studies addressed to magnesium alloys machining is less compared to other materials such as steel or aluminium alloys. Most of the studies are referring to turning [2-9], while fewer studies address to drilling [10-12] and milling [13-15], respectively. One of the main problems encountered is the ignition risk, especially in the case of discontinuous machining, when small chips
are generated [16]. Magnesium is quite reactive to water and one of the byproducts is hydrogen, which is highly flammable. General advice is to avoid using water based cooling liquids. As temperature raise can be problematic, different cooling strategies were approached. Flood cooling is considered harmful to the environment [17] so alternative ways were analysed. Dry machining studies [2, 5, 6, 11, 13, 14] have showed that a superior surface integrity (low surface roughness, compressive residual stress) can be achieved, especially for high cutting speeds and low feeds, but with a downside represented by the presence of flank build-up (FBU), higher temperatures, and a more intense tool wear. Near dry machining or minimum quantity lubrication (MQL) is often regarded as environmentally friendly, but with the benefits of cooling and lubrication. This method was approached in a number of studies [2, 10, 11, 15, 16] revealing that compared to dry cutting, although in terms of surface quality the improvement can be sometimes minor, a significant gain can be achieved when it comes to reducing the cutting forces, FBU, tool wear and the cutting temperatures. To a lesser extent, some studies have oriented towards cryogenic machining [4, 5, 8] and the results revealed a good surface finish, significant grain refinement and a compressive distribution of residual stresses.

This study investigates surface roughness and the main cutting force resulted from machining of a magnesium alloy under dry cutting and by using an MQL system. The tests have been organised according to design of experiment technique.

2. Design of experiments

Modelling offers a mean to establish a relationship between the incomes and the outcomes of a system or a process, allowing a better understanding of the inner functions and opening a way to optimization. Accurate modelling is key in estimating the results of a process for a given combination of input parameters and also for process optimization. Different modelling techniques were used across studies. Design of experiments (DOE) are amongst the most used methods. Using a certain amount of specific combinations among a series of input variables (aka factors) DOE-s are capable to establish their influences upon the output variables (aka responses). Statistical tests, such as analysis of variance (ANOVA), are employed to assess the importance (significance) of the input factors and to quantify how the variation of the factors is reflected upon the variation of the responses. Mathematical relations (e.g. linear or quadratic equations) can be formulated and combined with certain boundary conditions, an optimization of the problem may be achieved.

Taguchi method, sometimes combined with grey relational analysis (GRA), was used for studying the influence of the machining parameters upon responses like surface roughness, cutting forces, tool wear and cutting temperature [9, 18, 19]. Factorial designs were used to determine the most appropriate cutting parameters in order to achieve an improved surface quality [2, 10, 15]. Central composite designs (CCD), particularly response surface method (RSM), are also very efficient for modelling and optimization of machining processes [20-22].

Newer studies related to machining have resorted to methods such as artificial neural networks (ANN), which mimic the functions of the human brain, genetic algorithms (GA), which are based on the natural selection mechanism, particles swarm optimization (PSO) or fuzzy logic [15, 23-25]. The objective is mainly the achievement of a minimum surface roughness (Ra) and often the results are benchmarked against DOE results.

In the current study, the experiments were organised following a central composite matrix, according to the response surface methodology (RSM). Statistical analysis (ANOVA) was used to assess the effects of the input parameters upon the outcomes of the process. The responses taken into consideration for analysis in this paper are surface area roughness \((S_a)\) and the main cutting force \((F_c)\). Besides the usual cutting parameters (cutting speed, feed, depth of cut), which are numerical, two other categorical factors were taken into considerations: feed direction and cooling method.

In a central composite design (CCD), the design points consist of three groups:

- two level factorial points, which are all the combinations of the +1 and -1 levels of the factors;
• the central points corresponding to the average value of the factors, which are repeated four times for a better estimation of the error;
• the axial (star) points resulted by multiplying the factorial levels with +/-\( \alpha \) (alpha), which is calculated in order to assure the rotatability of the design.

The levels of each experimental factor are presented in table 1. The values of the cutting parameters have been chosen in order to obtain a stable machining process and to comply with the indications of the cutting inserts manufacturer. A set of 60 experiments was carried and the results are given in table 2.

### Table 1. Experimental factors and levels.

| Factor                  | Measurement unit | -\( \alpha \) | -1 | 0   | +1  | +\( \alpha \) |
|-------------------------|-----------------|--------------|----|-----|-----|------------|
| A. Cutting speed, \( v_c \) | m/min           | 500          | 573.22 | 750  | 926.78 | 1000 |
| B. Feed per tooth, \( f_z \) | mm/tooth       | 0.08         | 0.11   | 0.19 | 0.27 | 0.30 |
| C. Depth of cut, \( a_p \) | mm             | 0.40         | 0.58   | 1.00 | 1.42 | 1.60 |
| D. Feed direction       |                | Direct       | Reversed |
| E. Cooling              |                | Dry cutting  | MQL     |

### Table 2. Experimental data.

| A   | B   | C   | D   | E       | \( S_a \) [\( \mu m \)] | \( F_c \) [N] |
|-----|-----|-----|-----|---------|------------------------|-------------|
| 926.78 | 0.27 | 0.58 | Direct | Dry     | 0.482                 | 561.1       |
| 926.78 | 0.11 | 1.42 | Direct | Dry     | 0.142                 | 547.5       |
| 573.22 | 0.27 | 1.42 | Direct | Dry     | 0.795                 | 1084        |
| 573.22 | 0.11 | 0.58 | Direct | Dry     | 0.17                  | 212.2       |
| 500.00 | 0.19 | 1.00 | Direct | Dry     | 0.535                 | 691.7       |
| 1000.00 | 0.19 | 1.00 | Direct | Dry     | 0.264                 | 704.3       |
| 750.00 | 0.08 | 1.00 | Direct | Dry     | 0.174                 | 272.2       |
| 750.00 | 0.30 | 1.00 | Direct | Dry     | 0.4                   | 702         |
| 750.00 | 0.19 | 0.40 | Direct | Dry     | 0.363                 | 148.1       |
| 750.00 | 0.19 | 1.60 | Direct | Dry     | 0.194                 | 909.6       |
| 750.00 | 0.19 | 1.00 | Direct | Dry     | 0.236                 | 323.3       |
| 750.00 | 0.19 | 1.00 | Direct | Dry     | 0.337                 | 568.7       |
| 750.00 | 0.19 | 1.00 | Direct | Dry     | 0.28                  | 563         |
| 750.00 | 0.19 | 1.00 | Direct | Dry     | 0.223                 | 691.9       |
| 750.00 | 0.19 | 1.00 | Direct | Dry     | 0.243                 | 702.6       |
| 926.78 | 0.27 | 0.58 | Reversed | Dry | 0.469 | 552.5 |
| 926.78 | 0.11 | 1.42 | Reversed | Dry | 0.329 | 598.2 |
| 573.22 | 0.27 | 1.42 | Reversed | Dry | 0.571 | 1241 |
| 573.22 | 0.11 | 0.58 | Reversed | Dry | 0.306 | 311 |
| 500.00 | 0.19 | 1.00 | Reversed | Dry | 0.508 | 741.4 |
| 1000.00 | 0.19 | 1.00 | Reversed | Dry | 0.353 | 673 |
| 750.00 | 0.08 | 1.00 | Reversed | Dry | 0.205 | 374.3 |
| 750.00 | 0.30 | 1.00 | Reversed | Dry | 0.209 | 887.1 |
| 750.00 | 0.19 | 0.40 | Reversed | Dry | 0.545 | 349.1 |
| 750.00 | 0.19 | 1.60 | Reversed | Dry | 0.305 | 971.2 |
| 750.00 | 0.19 | 1.00 | Reversed | Dry | 0.471 | 645.6 |
| 750.00 | 0.19 | 1.00 | Reversed | Dry | 0.524 | 681.5 |
| 750.00 | 0.19 | 1.00 | Reversed | Dry | 0.585 | 770.2 |
| 750.00 | 0.19 | 1.00 | Reversed | Dry | 0.324 | 714.6 |
Experimental procedure

3.1. Material
The cylindrical workpieces, Ø80 mm, used in this study were made of a magnesium-aluminium-zinc alloy, graded AZ61A, which is frequently used in aeronautics applications. Chemical composition of the magnesium alloy is presented in Table 3.

Table 3. Chemical composition of AZ61 magnesium alloy.

| Elements | Al   | Zn   | Mn   | Si  | Cu   | Fe   | Ni   | others |
|----------|------|------|------|-----|------|------|------|--------|
| Content (%) | 5.80-7.20 | 0.40-1.50 | 0.15-0.50 | <0.10 | <0.05 | <0.005 | <0.005 | <0.3 |

3.2. Equipment
Face milling tests were carried on a Rapimill 700 CNC machining centre, with a 50 mm diameter Sanvik CoroMill tool, equipped with uncoated carbide inserts. Two different environmentally friendly cooling conditions were taken into considerations. First, a set of dry cutting experiments was carried according to the experimental plan. Second, the milling tests were performed using a SKF MQL cooling system.
The measurement chain for the cutting force comprised a Kistler 9272 dynamometer, upon which the part was mounted, a signal amplifier (Kistler charge amplifier type 5073), data acquisition system (Dewesoft Sirius Mini), and Dewesoft X3 software for data processing. Surface roughness was measured with a Zygo ZeGage™ 3D optical profiler using Mx™ software. The results are expressed as surface area roughness $S_a$ (figure 1).

![Experimental setup](image)

**Figure 1.** Experimental setup.

4. Results and discussion

Analysis of variance (ANOVA) is a statistical tool used in DOE to establish the significance of the factors or their interactions. As a general rule, total variance of a model is attributed to the factors and to the random error, respectively. The significance of a factor is assessed by performing statistical (F-tests) under a null hypothesis: large values of F-ratios imply a high influence of the factor on the response. Significance is determined according to a confidence interval, which is established for a certain $p$-value. The $p$-value represents the probability that the results of the tests (or more extreme ones) could have occurred by random chance. This study uses $p = 0.05$ (corresponding to a 95% confidence interval), which means that a factor is considered significant only if $p$ value is less than 0.05. An algorithm is used to eliminate the insignificant factors from the final model.

The accuracy of a model can be estimated using the residual value ($R^2$), which is calculated as the ratio between the explained variation and the variation of the model. The interval for this coefficient is ranging from 0 to 1 and the closer $R^2$ is 1, the more accurate are the model predictions.

Next, a quadratic mathematical model is formulated as in equation (1), offering a mean to establish a relationship among the results (responses) and the input parameters (factors) of the process:

$$ Y = a_0 + \sum_i a_i x_i + \sum_j a_{ij} x_i x_j + \sum_i a_{ii} x_i^2 + \varepsilon $$

where, $Y$ is the response, $x_i$ are the factors, $a_0$ is the free term of the equation, $a_i$ and $a_{ij}$ are the the coefficients for the linear and quadratic terms, respectively, $a_{ii}$ are the coefficients of the interaction terms, and $\varepsilon$ is the error of fit.

4.1. Surface roughness analysis

The results of the analysis performed for surface roughness are illustrated in table 4. A natural logarithm transformation was applied to the results in order to obtain a better fitted model.
Table 4. Analysis of variance for surface roughness.

| Source | df | Sum of Squares | Mean Squares | F-value | p-value | Contribution |
|--------|----|----------------|--------------|---------|---------|---------------|
| Model  | 9  | 5.00           | 0.5551       | 7.14    | < 0.0001| 56.31         |
| A. Cutting speed | 1  | 0.0450         | 0.0450       | 0.5790  | 0.4503  | 0.51          |
| B. Feed per tooth | 1  | 2.58           | 2.58         | 33.17   | < 0.0001| 29.05         |
| D. Feed direction | 1  | 0.3784         | 0.3784       | 4.87    | 0.0320  | 4.26          |
| E. Cooling      | 1  | 0.0002         | 0.0002       | 0.0030  | 0.9567  | 0.00          |
| AE              | 1  | 0.3690         | 0.3690       | 4.74    | 0.0341  | 4.16          |
| BD              | 1  | 0.3800         | 0.3800       | 4.89    | 0.0317  | 4.28          |
| DE              | 1  | 0.4438         | 0.4438       | 5.71    | 0.0207  | 5.00          |
| A²              | 1  | 0.3424         | 0.3424       | 4.40    | 0.0410  | 3.86          |
| B²              | 1  | 0.4295         | 0.4295       | 5.52    | 0.0228  | 4.84          |
| Residual       | 50 | 3.89           | 0.0778       |         |         |               |
| Total          | 59 | 8.88           |              |         |         |               |

The most significant factor is B - feed per tooth (with a 29.05% contribution), followed by the C - feed direction (with 4.26% contribution). The following interactions and quadratic terms were also found significant: AE (cutting speed × cooling), BD (feed per tooth × feed direction), DE (feed direction × cooling), A² (cutting speed²), and B² (feed²). It must be remarked that some of the factors are not significant, they can be involved in significant interactions or have significant quadratic terms.

The surface roughness increases when feed values raise and also when feed direction changes from direct to reversed (figure 2). However, it may be noticed that for the direct feed direction the measured values of surface roughness are scattered across a larger interval compared to the reversed direction (figure 3).

The interaction term DE (feed direction × cooling), illustrated in figure 4, offers an interesting insight into the process. It can be noted that for dry cutting the modification of feed direction produces an important variation of surface roughness, whereas when MQL cooling is utilised, the surface roughness becomes virtually unaffected by the direction change.

**Figure 2.** Influences of the main factors on surface roughness: feed per tooth and feed direction.
From the interaction AE (cutting speed \( \times \) cooling) illustrated in figure 5, it can be remarked that the increase of the cutting speed has an overall positive effect in reducing surface roughness. This effect is more visible for the dry cutting and is highly affected by the feed direction.

A quadratic model of the surface roughness was formulated in the form of four equations (2–5), one for each specific combination of categorical (non-numeric) factors:

- **Direct feed, dry cutting**
  \[
  \ln(S_a) = -0.392249 - 0.005872 v_c + 12.45691 f_z + 3.36854 e - 0.06 v_c^2 - 19.48771 f_z^2 \quad (2)
  \]

- **Direct feed, MQL**
  \[
  \ln(S_a) = -1.13536 - 0.004658 v_c + 12.45691 f_z + 3.36854 e - 0.06 v_c^2 - 19.48771 f_z^2 \quad (3)
  \]

- **Reversed feed, dry cutting**
  \[
  \ln(S_a) = 0.470993 - 0.005872 v_c + 9.65485 f_z + 3.36854 e - 0.06 v_c^2 - 19.48771 f_z^2 \quad (4)
  \]

- **Reversed feed, MQL**

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**Figure 3.** Variation of surface roughness with feed values and feed direction.

**Figure 4.** Evolution of surface roughness determined by the interaction of feed direction with cooling.
\[ \ln(S_a) = -0.616146 - 0.004658 v_c + 9.65485 f_z + 3.36854 e - 06v_c^2 - 19.48771 f_z^2 \] (5)

**Figure 5.** Interaction cutting speed - cooling and its influence on surface roughness.

4.2. Cutting force analysis

The results of ANOVA carried for the main cutting force \(F_c\) are shown in table 5. The model is significant.

The significant factors in this case are the C - depth of cut (which is the most important, with a contribution of 54.45%) and B - the feed (with a 16.38% contribution). Although there are other significant terms, their contribution is very reduced compared to the former ones: interactions BC (feed \( \times \) depth of cut) and DE (feed direction \( \times \) cooling) and the quadratic terms A\(^2\) (cutting speed\(^2\)), and B\(^2\) (feed\(^2\)).

**Table 5.** Analysis of variance for the main cutting force.

| Source      | df | Sum of Squares | Mean Squares | F-value | p-value | Contribution % |
|-------------|----|----------------|--------------|---------|---------|----------------|
| Model       | 10 | 2.645E+06      | 2.645E+05    | 69.92   | < 0.0001| 93.69          |
| A. Cutting speed | 1  | 5.78           | 5.78         | 0.0015  | 0.9690  | 0.00           |
| B. Feed per tooth | 1  | 4.624E+05      | 4.624E+05    | 122.26  | < 0.0001| 16.38          |
| C. Depth of cut  | 1  | 1.537E+06      | 1.537E+06    | 406.35  | < 0.0001| 54.45          |
| D. Feed direction | 1  | 14976.89       | 14976.89     | 3.96    | 0.0524  | 0.53           |
| E. Cooling    | 1  | 13250.78       | 13250.78     | 3.50    | 0.0675  | 0.47           |
| AC           | 1  | 9745.11        | 9745.11      | 2.58    | 0.1152  | 0.35           |
| BC           | 1  | 35413.57       | 35413.57     | 9.36    | 0.0037  | 1.25           |
| DE           | 1  | 68822.64       | 68822.64     | 18.20   | < 0.0001| 2.44           |
| A\(^2\)      | 1  | 22617.29       | 22617.29     | 5.98    | 0.0183  | 0.80           |
| B\(^2\)      | 1  | 20408.12       | 20408.12     | 5.40    | 0.0246  | 0.72           |
| Residual     | 47 | 1.778E+05      | 3782.31      | 6.30    |         |                |
| Total        | 57 | 2.823E+06      |              |         |         |                |
Figure 6. Influences of the main factors on surface roughness: feed per tooth and feed direction.

The effects of the significant factors are presented in figure 6, and the interactions in figure 7. It can be observed that the cutting force raises rapidly with the increase of the depth of cut. To a lesser extent, feed growth also leads to larger cutting forces. The combined effect of these two factors can be better observed using a 3D plot representation. The graph of feed direction - cooling interaction reveals that for the direct sense of the feed, dry cutting requires lower cutting forces, whereas for the reversed feed the forces are almost constant for either cooling conditions. In the case of MQL cooling, the cutting forces have a narrow variation interval.

The regression equations (6)-(9) for the cutting force are as follows:

- Direct feed, dry cutting

\[ F_c = -1.28472 - 0.826045v_c + 1714.21274f_c + 498.7285a_p - 0.482925v_\alpha a_p + 2102.734 f_\alpha a_p + 0.000875v_c^2 - 4292.80243 f_c^2 \]  

(6)

- Direct feed, MQL

Figure 7. Interaction plots for the cutting force.
\[ F_c = 98.42682 - 0.826045v_c + 1714.21274f_c + 498.7285a_p - 0.482925v_c a_p + 
+ 2102.734f_c a_p + 0.000875v_c^2 - 4292.80243 f_c^2 \]  
(7)

- Reversed feed, dry cutting
\[ F_c = 100.34682 - 0.826045v_c + 1714.21274f_c + 498.7285a_p - 0.482925v_c a_p + 
+ 2102.734f_c a_p + 0.000875v_c^2 - 4292.80243 f_c^2 \]  
(8)

- Reversed feed, MQL
\[ F_c = 61.45349 - 0.826045v_c + 1714.21274f_c + 498.7285a_p - 0.482925v_c a_p + 
+ 2102.734f_c a_p + 0.000875v_c^2 - 4292.80243 f_c^2 \]  
(9)

4.3. Model diagnostics
A diagnostic of the models can be formulated by examining the residuals. The normal probability plots from figure 8 follow a straight line, which means that the errors are normally distributed. The plots of residuals vs predicted show a random scatter, with no evident patterns, equally distributed across positive and negative directions (figure 9).

Based on the calculated F-values it can be argued that both surface roughness and cutting force models are significant, with only a chance of 0.01% that these results could occur due to noise. There is also a good agreement between the predicted and the adjusted \( R^2 \) values, as presented in table 6. Therefore, the models are well fitted and able to offer a good overview of the process.

Table 6. Fit statistics.

| model            | Predicted \( R^2 \) | Adjusted \( R^2 \) |
|------------------|---------------------|--------------------|
| Surface roughness| 0.3541              | 0.4835             |
| Cutting force    | 0.9114              | 0.9236             |

![Figure 8. Normal probability plots for surface roughness \( S_a \) and cutting force \( F_c \).](image)
5. Conclusions
In this study, the RSM method was used to investigate the high-speed milling process of a magnesium alloy (AZ61A). The work was organised to establish how surface quality and the main cutting force are affected by the choice of the machining conditions: cutting speed, feed, depth of cut, feed direction, cooling conditions. The most relevant conclusions of this study are as follows:

- Surface roughness is influenced the most by the feed (expressed in this study as the feed per tooth, \( f_z \)) and the feed direction. Smaller influences were exerted by the interactions of the aforementioned factors, but also by the interactions cutting speed \( \times \) cooling and feed direction \( \times \) cooling. The most favourable conditions for a good surface quality, under the studied circumstances, are a combination of high cutting speed, small feed and depth of cut, dry cutting and direct feed orientation.
- Feed is also an important factor of influence for the main cutting force. However, a more important effect has the depth of cut, with a contribution of 54.45%. To a much lesser extent, the cutting force is influenced by their interaction and also by feed direction \( \times \) cooling interaction.
- It was found that machining with MQL cooling is less prone to variations; both the surface roughness and the cutting force showed less scattering under MQL.
- The developed mathematical models are accurate enough to predict the outcomes of a certain factor combination.

This study will further develop to include the rest of the cutting force components, machining temperature and also take into consideration more factors of influence.

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