Modelling Drilling Experiments on Al7075 Using the Response Surface Methodology

P Kyratsis1*, N Efkoidis1 and K Kakoulis1

1Western Macedonia University of Applied Sciences, Department of Mechanical Engineering and Industrial Design, Kila Kozani GR50100, Greece

*Corresponding author: pkyratsis@teiwm.g

Abstract. The current research deals with the mathematical simulation of the drilling manufacturing process using the response surface methodology (RSM). The workpiece used was made of aluminium alloy 7075 and the tools used were manufactured from Kennametal. A number of different drilling tool diameters were used, with variable cutting speeds and feed rates. The thrust force (Fz) and the cutting torque (Mz) were measured using a Kistler dynamometer, while the mathematical models in both cases were proved to be sufficient, in order to describe the effect of the drilling parameters on both the thrust force and the cutting torque.

1. Introduction
Drilling is an extremely popular manufacturing process in a variety of industries i.e. structural, automotive, aerospace, manufacturing. Its simulation and the development of mathematical models are used for the prediction of its result i.e. surface quality, cutting force and torque, geometrical characteristics [1, 2]. A number of different methodologies have been applied (response surface methodology, genetic algorithms, fuzzy logic) based on experimental results for different drilling tools and workpiece materials, or validated simulations with finite elements and CAD based methods [3, 4]. They resulted in documenting the drilling manufacturing process outputs for use in industry and in academia. Those results are used for predicting the drilling behavior in different cases studies and can lead in drilling optimizations [5, 6].

The current paper aims to present mathematical models for the thrust force and the cutting torque based on the response surface methodology (RSM), when drilling Al7075 with solid carbide tools commercially available. For this reason, a full factorial set of 27 experiments were used and their results were handled following the RSM methodology and the analysis of variance (ANOVA). The derived mathematical models are very accurate and can be used directly for predicting both the thrust force and the cutting torque within the limits of the manufacturing parameters used.

2. Experiments set up
A HAAS VF1 machining center was used for performing a number of experiments. The material of the specimen used was Al7075, since it is one of the most popular materials in industry i.e. automotive, aerospace, constructions. As a result, the outcome of the present research is expected to be adopted from a variety of researchers and industry engineers.

A Kistler type 9123 dynamometer was used for acquiring the thrust force (Fz) and the cutting torque (Mz), while both signal were processed by a multichannel signal conditioner (5223) and data
acquisition unit (5697). Fig.1 depicts the research workflow followed for delivering the mathematical models.

![Research Workflow](image)

| Cutting Conditions | Solid Carbide Tool and Al7075 plate | Hardware for measurements |
|--------------------|-------------------------------------|---------------------------|
| Feed rate - \( f \) [mm/rev] | [image] | Kieller dynamometer |
| Cutting speed - \( V \) [m/min] | [image] | Data acquisition |
| Tool diameter - \( D \) [mm] | [image] | |

**Mathematical models using the Response Surface Methodology (RSM)**

| Thrust Force | Cutting Torque |
|--------------|---------------|
| \( F_z = -764 + 143D + 0.615V + 1275f - 2.15D^2 + 0.0193V^2 - 69f - 0.151DV + 76.2DF - 0.597VF \) (N) | \( M_z = 9.79 - 1.73D - 0.00697V - 8.94f + 0.0855D^2 - 0.00004V^2 - 1.87f^2 + 0.000479DV + 1.89DF + 0.0209VF \) (Nm) |

**Figure 1.** Research flowchart

Kennametal is the manufacturer of the drilling tools used (solid carbide -KC7325). Their diameters were 10mm, 12mm and 14mm, while the feed rates and cutting speeds selected were 0.20mm/rev, 0.40mm/rev and 0.60mm/rev and 10m/min, 40m/min and 70m/min, respectively. Table 1 depicts these drilling parameters together with their notations and values. The levels were selected to be relative wide in order to be able to increase the derived models usability.

27 experiments were performed, while all the combinations of the drilling parameters were achieved. As a result a full factorial set of data for both the \( F_z \) and \( M_z \) were measured and used for the calculation of the mathematical models based on the response surface methodology and the analysis of variance.

**Table 1.** Cutting parameters and tools

| Manufacturing parameter | Notation | Unit | LEVELS |
|-------------------------|----------|------|--------|
| Tool diameter           | \( D \)   | mm   | 10 12 14 |
| Feed rate               | \( f \)   | mm/rev | 0.20 0.40 0.60 |
| Cutting speed           | \( V \)   | m/min | 10 40 70 |

Figure 2 offers an overview of the total set of measurements acquired for the thrust force and the cutting torque. When the tool diameter increases, both the thrust force and the cutting torque increase to a great extent as expected. The same is the case every time the feed rate is increased. On the other hand, increasing the cutting speed does not affect substantially the required thrust force and cutting torque. This is expected to affect the statistical definition of the cutting speed significance during the application of the response surface methodology.
3. Mathematical models proposed for both the $F_z$ and $M_z$

A full factorial set of experiments was used in order to develop mathematical models for both the thrust force and the cutting torque during this research. All 27 experiments were performed in order to be able to describe the influence of the cutting parameters and the tool diameter to the thrust force and cutting torque measured. A second order polynomial model was the basis in both cases and the equations derived are presented:

$$F_z = -764 + 143D + 0.615V + 1275f - 2.15D^2 + 0.0193V^2 - 69f^2 - 0.151DV + 76.2Df - 0.597Vf \ (N)$$

and

Figure 2. Drilling experiments in Al7075
\( M_z = 9.79 - 1.73D - 0.00697V - 8.94f + 0.0855D^2 - 0.00004V^2 - 1.87f^2 + 0.000479DV + 1.89Df + 0.0209Vf \) (Nm)  

(2)

where:

- \( F_z \) is the thrust force (N),
- \( M_z \) is the cutting torque (Nm),
- \( D \) is the tool diameter (mm),
- \( f \) is the feed rate (mm/rev) and
- \( V \) is the cutting speed (m/min).

**Table 2.** Analysis of variance for the thrust force mathematical model

| Source of variation (Fz) | DF | SS    | MS    | F        | P     |
|--------------------------|----|-------|-------|----------|-------|
| Regression               | 9  | 4182029 | 464670 | 2729,14  | 0     |
| Residual error           | 17 | 2894  | 170   |          |       |
| Total                    | 26 | 4184924 |       |          |       |
| R-sq(adj)                |     | 99,90\%|       |          |       |

| Predictor | Coef. | SE Coef. | T    | P     |
|-----------|-------|----------|------|-------|
| Constant  | -763,60 | 198,100 | -3,86 | 0,001 |
| D         | 142,69  | 32,320  | 4,42  | 0,000 |
| V         | 0,62    | 0,930   | 0,66  | 0,517 |
| f         | 1275,00 | 158,100 | 8,07  | 0,000 |
| D^2       | -2,15   | 1,332   | -1,62 | 0,124 |
| V^2       | 0,02    | 0,006   | 3,26  | 0,005 |
| f^2       | -69,40  | 133,200 | -0,52 | 0,609 |
| D*V       | -0,15   | 0,063   | -2,41 | 0,027 |
| D*f       | 76,25   | 9,417   | 8,10  | 0,000 |
| V*f       | -0,60   | 0,628   | -0,95 | 0,355 |

**Table 3.** Analysis of variance for the torque mathematical model

| Source of variation for Mz | DF | SS    | MS    | F        | P     |
|----------------------------|----|-------|-------|----------|-------|
| Regression                 | 9  | 217,386 | 24,154 | 3533,56  | 0,000 |
| Residual error             | 17 | 0,116  | 0,007 |          |       |
| Total                      | 26 | 217,503 |       |          |       |
| R-sq(adj)                  |     | 99,9%  |       |          |       |

| Predictor | Coef. | SE Coef. | T    | P     |
|-----------|-------|----------|------|-------|
| Constant  | 9,79300 | 1,25500 | 7,80 | 0,000 |
| D         | -1,72650 | 0,20480 | -8,43 | 0,000 |
| V         | -0,00697 | 0,00589 | -1,18 | 0,253 |
| f         | -8,94100 | 1,00200 | -8,93 | 0,000 |
| D^2       | 0,08547  | 0,00844 | 10,13 | 0,000 |
| V^2       | -0,00040 | 0,00004 | -1,06 | 0,304 |
| f^2       | -1,86530 | 0,84380 | -2,21 | 0,041 |
| D*V       | 0,00048  | 0,00040 | 1,20  | 0,245 |
| D*f       | 1,88646  | 0,05967 | 31,62 | 0,000 |
| V*f       | 0,02093  | 0,00398 | 5,26  | 0,000 |
The adequacy of all mathematical models is provided at a level of significance of 5%. The analysis of variance provided proofs of validity for the developed mathematical models. Based on the methodology principles, the calculated values of the F-ratio (Table 2 for the Fz and Table 3 for the Mz), are significantly high compared to the tabulated values provided by the F-table for 95% confidence level (2729.14 for the Fz and 3533.56 for the Mz). The P values are equal to zero, which proves that both the developed mathematical models are adequate at a 95% confidence level.

The validity of the fit of the models can also be proved, by the adjusted R-sq coefficient, which provides a measure of variability of the output. The coefficient in both cases is 99.9 %, which means that the mathematical models have adequate predictive capacity. In addition, the significant terms of the models can be recognized by the magnitude of their P-values. They should be less than 0.05 due to the confidence level used. With respect to the Fz model the following factors are statistically significant: D (P-value = 0.000), f (P-value = 0.000), V² (P-value = 0.005), D×V (P-value = 0.027), D×f (P-value = 0.000), while for the Mz model the significant factors are: D (P-value = 0.000), f (P-value = 0.000), D² (P-value = 0.000), f² (P-value = 0.041), D×f (P-value = 0.000) and V×f (P-value = 0.000).

![Residuals' analyses](image)

**Figure 3.** Residuals analysis graphs for the Fz and Mz
Figure 3 depicts the normal probability plots of the calculated residuals for the Fz and the Mz. The residuals closely follow straight lines (blue line) and their distribution follows the normal distribution pattern. Both the scatter diagrams of the residuals vs the fitted values provide evidence that the residuals are evenly distributed on both sides of the reference line and randomly scattered. The same is the case for the residuals vs the order of the experiments, which proves that the order of performing the experimental work does not affect the quality of the mathematical models. All the statistical results were acquired with the use of the statistical software Minitab. The regression analysis was accompanied with the residuals’ analysis in order to secure that all the hypotheses of the theory are met.

The above mentioned methodology provided a solid basis for concluding that the prediction models sufficiently explain the relationship between the Fz and Mz with the drilling parameters used (diameter, feed rate and cutting speed) in the case of drilling Al7075 with the abovementioned drilling tools.

4. Conclusion
The current paper presents mathematical models for both the thrust force and cutting torque, when drilling Al7075 with solid carbide tools. Those tools were selected by the catalogue of one of the greater tool manufacturers and commercially available. The response surface methodology was followed and the proposed models were established to be accurate to a great extent. All the significant manufacturing parameters were identified in both cases and the high R-sq(adj) coefficient lead to excellent fitting results.

5. References
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