The analysis of high-pressure water jet cutting of thick aluminium alloy 6061-T651 from a statistical perspective

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Abstract. The main context in which abrasive water cutting is used is the reduction of thermal deformation induced by thermal (plasma arc PAC, oxyfuel OFC, laser) or electrothermal (electroerosion EDM) cutting methods. Although it is not the cheapest or time-efficient technique it can be used on a wide variety of metallic and non-metallic materials. Among other benefits are the lack of burrs, high precision and improved surface finish, low setup time and stress-free cutting. This leads to no secondary processing required in many other applications. Depending on the material hardness the cutting thickness can reach up to 300 [mm]. The present study proposes an analysis of high-pressure abrasive water jet cutting of a 19 [mm] thick plate. The aluminium alloy used in this study was Al-6061-T651. This alloy is being used especially in the aeronautics industry due to its excellent welding properties. The experiments were conducted using multiple input and output factors. The design of experiments (DOE) takes into account input factors and offers models for responses. The study was organised according to response surface methodology, with an I-optimal design type and a quadratic design model. The input factors were: cutting pressure, standoff distance, programmed quality of the cut. The responses analysed were: entrance (I_w) and exit (O_w) width of cut, and taper angle (θ). An ANOVA analysis was performed for each response. This interpretation implies the significance (p-value) that the input factors have on the variation of the responses. For I_w and O_w a reduced 2FI model was proposed, while for θ a linear model was suggested. The p-value obtained for each response is smaller than 0.0001, which classifies the models as significant. The ANOVA fit statistics determine the R-squared error between 0.964 and 0.995, meaning that the responses are well defined by the input value variations. This high confidence in the results leads to accurate mathematical models.

1. Introduction

Abrasive Water Jet Machining (AWJM) process has proven to be successfully appliable for a wide range of materials in many industries such as aerospace, marine, robotics, construction, transportation, sporting goods, and defence applications. There is a continuous challenge to develop methods that can be generally accepted to be used in AWJM for optimal surface quality of materials. AWJM process parameters such as traverse speed, standoff distance, angle of impact, are generally investigated to optimize the quality of cutting, given by the top kerf width, kerf taper and surface roughness [1-3]. AWJ technology is widely used for composite materials machining because of several specific advantages as: lack of thermal damage, low tool wear, small cutting forces and high productivity. There is still a lack of process knowledge to develop a methodology for optimizing input parameters
for trimming with good quality each type of composite materials. This is because the machinability index of different composite materials is specific and it can’t be related to the material properties [4].

Machining of AZ91 magnesium alloy with Abrasive Water Jet (AWJ) technique was applied to investigate the effect of process parameters on depth of cut through Taguchi experimental design of L9 orthogonal array [5] and, in another study, on surface topography also [6]. The results had shown an increase of depth of cut with increasing water pressure and a decreasing with increasing traverse speed [5, 6]. Surface quality of the cut is a function of traverse speed, as lower the traverse speeds as higher the surface quality [6].

2. Experimental setup and design of experiments

While used for their higher strength to weight ratio, aluminium alloys are also easy to machine, regardless of the method of production and compared to other metallic alloys. Industries like aerospace, aviation and automotive are heavy consumers of aluminium alloys, with a wide range of manufacturing processes. In this context, any improvement is a step forward. Therefore, in this paper, the main goal is to highlight the relationship between the input factors and the outcomes of the process. The results lead to a better understanding of how this alloy behaves when using soft to aggressive cutting conditions.

The experimental setup consists of using high-pressure abrasive water jet to cut a 19 [mm] thick plate (t) of aluminium alloy 6061-T651. The resulting cuts are highlighted in figure 1, as an array, indicating the level for each standoff distance \( h \), the pressure \( P \) and quality of cut \( Q \). The entrance “\( I_w \)” and exit “\( O_w \)” width of cut (figure 2) were measured on a Mitutoyo PH-A14 profile projector, while the taper angle “\( \alpha \)” was determined analytically, using equation (1).

![Figure 1. Resulting cuts for every process parameter combination.](image-url)
\[ \alpha = \tan^{-1}\left( \frac{I_w - Q_{\infty}}{2t} \right) \] (1)

The experimental plan was generated using the surface response methodology in a design of experiments software environment (DOE). In this experimental study, the Design-Expert software was used, taking into consideration the I-optimal design type. Water pressure \( P \) (2000, 2500, 3000 [bar]) and height of cutting head \( h \) (1, 2, 3 [mm]) were defined as 3 level numeric factors, while the quality of cut \( Q \) (\( Q_1, Q_2, Q_3, Q_4, Q_5 \)) was a 5 level categoric factor. The design model generated from the input values is quadratic type, and it suggested a total number of 45 trials to be performed.

![Figure 2. Schematic representation of the responses.](image)

As indicated by the DOE software, the standard error of the responses should be similar to each other in a balanced design, indicating that low standard errors are better, which is the case of this experimental study (figure 3). The values of the standard error of design are in the range of 0.20 to 0.48. Taking into account this and that the \( R^2 \)-squared factor has values, for each factor and their interaction, below 0.3 there is a high level of confidence in the accuracy of the results.

![Figure 3. Figure with short caption (caption centred).](image)

3. ANOVA results and discussions
A two-way analysis of variation (ANOVA) was performed in order to highlight and understand the effects that the input parameters have on the responses. The results can be interpreted by looking at the p-value. Along with this, in table 1 are presented all the ANOVA results (degrees of freedom, mean square, F-value / F-tests, mean, adjusted and predicted mean squared error). The p-value provides information about the statistical significance of the model by its value: smaller than 0.05 indicates that
the model is statically significant, whereas if the p-value is greater than 0.05 it indicates a strong evidence for a null hypothesis.

Looking at the values from table 1 it can be noted that the p-values are below 0.05, with values for the models well below 0.0001, which indicates that the models are significant. The p-value also ranks the input parameters and their interaction effect on the response. In the first case, of the entrance width, the main effect is assigned to h and Q, followed by P and the interaction between h and Q. In the case of the exit width of cut, the analysis implies the same order of the input parameters and appends another interaction (P×Q). The taper angle model is significant and it is strongly influenced by the cutting pressure (P) and height of the cutting head (h).

Another key factor in analysing this experimental study is the coefficient of determination, the R-Squared value that suggests the quantity of unexplained variations in the model, offering information about how many values deviate from the regression index model. If the value of R-Squared is in the range of 0.85 to 1 the regression model is reliable. As it can be observed from table 1, the responses model is above 0.96, indicating that the regression model is capable to predict almost every point from the design space. As all data present a native amount of variability that is unexplained and as R-Squared cannot explain this, the adjusted-R² and predicted R² values are calculated, and these are in reasonable agreement with one other for all responses.

Table 1. ANOVA responses result comparison.

| Source                      | df | MS     | F-value | p-value | R²   | Adjusted R² | Predicted R² |
|-----------------------------|----|--------|---------|---------|------|-------------|--------------|
| **Entrance width I_w - model** |    |        |         |         |      |             |              |
| Pressure (P)               | 1  | 0.0060 | 14.87   | < 0.0001| 0.9644| 0.9540      | 0.9353       |
| Height of cutting head (h) | 1  | 0.2995 | 739.59  | < 0.0001| 0.9644| 0.9540      | 0.9353       |
| Quality of cut (Q)         | 4  | 0.0103 | 25.33   | < 0.0001| 0.9644| 0.9540      | 0.9353       |
| h×Q interaction            | 4  | 0.0023 | 5.80    | 0.0011  | 0.9644| 0.9540      | 0.9353       |
| **Exit width O_w - model** |    |        |         |         |      |             |              |
| Pressure (P)               | 1  | 0.0018 | 12.02   | 0.0016  | 0.9957| 0.9937      | 0.9890       |
| Height of cutting head (h) | 1  | 0.0179 | 118.54  | < 0.0001| 0.9957| 0.9937      | 0.9890       |
| Quality of cut (Q)         | 4  | 0.2477 | 1642.72 | < 0.0001| 0.9957| 0.9937      | 0.9890       |
| P×Q interaction            | 4  | 0.0007 | 4.69    | 0.0047  | 0.9957| 0.9937      | 0.9890       |
| h×Q interaction            | 4  | 0.0005 | 3.04    | 0.0323  | 0.9957| 0.9937      | 0.9890       |
| **Taper angle - model**    |    |        |         |         |      |             |              |
| Pressure (P)               | 1  | 0.3851 | 277.72  | < 0.0001| 0.9662| 0.9662      | 0.9662       |
| Height of cutting head (h) | 4  | 0.3692 | 266.22  | < 0.0001| 0.9662| 0.9662      | 0.9662       |

The ANOVA analysis performs numerical regression that offer numerical models that link the responses to the input parameters. As the quality of cut was defined as a categoric factor, the analysis gives an equation for each of its levels. The results, presented in table 2, show that in the case of the entrance width varies constantly with the cutting pressure, and also with the quality of cut and the standoff distance. For the exit width of cut, the cutting pressure and height of cutting head have a similar impact. The difference between the entrance and exit width indicates the shape of the cut, straight or angled. In the case of the taper angle, this fact is also indicated by the quality of the cut factor (Q). As Q1 and Q2 are specific to rough cutting with higher cutting speeds the angle has positive values, meaning that I_w > O_w. Q3 is specific for parallel cuts, while Q4 and Q5 lead to I_w < O_w. This indicates that lower cutting speeds allow the water jet to remove more material in the lower side of the material. The variance of the angle leads to variance in the deviation from the perpendicularity.

The statistical analysis also generates graphs that indicate the relationship between the input parameters and the responses. As highlighted in figure 4 the variation in cutting pressure doesn’t lead to significant changes in the responses. As expected, the modification in height of the cutting head
causes the entrance width of cut to a sharp increase; this fact applies to the other responses, but not with the same intensity. Changing the quality of cut from Q1 to Q5 has a significant impact on the variation of all the responses. In the case of the entrance and exit width of cut a higher cutting quality leads to a larger cut, while the tapper angle presents positive values.

| Quality of cut | Entrance width \(I_w\) [mm] | Exit width \(O_w\) [mm] | Taper angle \(\alpha\) [°] |
|---------------|-------------------------------|------------------------|--------------------------|
| Q1            | \(1.175 - 3.1 \times 10^{-3} P + 0.069 h\) | \(1.019 - 9.6 \times 10^{-4} P + 0.013 h\) | \(0.112 + 0.108 h\) |
| Q2            | \(1.133 - 3.1 \times 10^{-3} P + 0.085 h\) | \(1.002 + 1.6 \times 10^{-3} P + 0.013 h\) | \(0.012 + 0.108 h\) |
| Q3            | \(1.139 - 3.1 \times 10^{-3} P + 0.102 h\) | \(1.221 - 2.1 \times 10^{-3} P + 0.033 h\) | \(-0.17 + 0.108 h\) |
| Q4            | \(1.155 - 3.1 \times 10^{-3} P + 0.104 h\) | \(1.390 - 4.2 \times 10^{-3} P + 0.024 h\) | \(-0.29 + 0.108 h\) |
| Q5            | \(1.156 - 3.1 \times 10^{-3} P + 0.116 h\) | \(1.440 - 3.5 \times 10^{-3} P + 0.030 h\) | \(-0.37 + 0.108 h\) |

Figure 4. The effect of the input parameters on the responses for \(Q_1\) and \(Q_5\).

4. Conclusions
This paper presents an experimental study upon abrasive water jet cutting of aluminium alloy 6061-T651 using soft to aggressive cutting techniques. The process was discussed from a statistical
perspective, taking into consideration the evaluation of both the input parameters and the responses. As this aluminium alloy is considered a soft material it led to a series of phenomena of which the following were noted:

- lower values in the standard error of design can be assigned to the correct preparation of the experimental setup;
- the ANOVA analysis indicates that unexplained error was insignificant, leading to a high confidence process, meaning that expectations can be achieved;
- it was noted that the entrance width of cut was highly influenced by the height of the cutting head and the quality of the cut; this aspect is highlighted by ANOVA as an interaction between these factors, but also in the mathematical models and plots.
- the exit width of cut varies significantly with the quality of cut; it was noticed an increase of 40% when cutting with high-quality parameters.
- for both the entrance and exit width of cut, this tendency is valid; this is due to the fact that the cutting speed is lower and the material is soft thereby the material removal rate increases.
- in the case of the taper angle, a particular aspect was observed: it does not vary with the change in pressure, regarding the level of the quality of cut;
- an increase in the taper angle was observed when cutting from a higher distance; the reverse occurrence takes place when cutting with low-quality levels; negative angles were also observed when cutting with low-quality levels.
- this study indicates that Q3 is the most balanced quality level, offering similar values for the responses; in the case of the taper angle, it led to values close to zero. This indicates that the cut is straight, the deviation from perpendicularity being also null.

A key aspect of every industrial process is repeatability in time, which can be only achieved when the process is fully understood. The ANOVA analysis can lead to an increase in the confidence of an industrial process, helping its shortcomings, by highlighting its strong and low points.

5. References

| Reference | Details |
|-----------|---------|
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