High-pressure water jet cutting of S235JR steel alloy. Influence of process parameters on dimensional accuracy

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Abstract. This paper aims to determine the influence that water jet cutting parameters have on dimensional accuracy. The input parameters of this study were the workpiece material, that was made from 19 mm thick S235JR steel alloy plate, using a medium to high cutting pressure (2000, 2500, and 3000 bar), with a variable standoff distance (1, 2, and 3 mm) and a programmed quality of the cut from Q1 to Q5. A statistical interpretation of the results was conducted, and the experimental plan was obtained using the Response Surface Method. The samples were analysed for entrance and exit width of cut and kerf angle. A total number of 45 samples were measured, and the results were interpreted using an ANOVA analysis for statistical significance (p-value) and fit statistics (R2). The results have shown what values are optimum for the input parameters to obtain precision cutting quickly.

1. Introduction
The water jet cutting process was used around 1850 in the mining industry. It took around 80 years for the first industrial manufacturing machines to be developed and low pressure on soft material [1]. After the Second World War, rapid technological development can be observed when Luxembourg's first high-pressure water jet cutting machine was manufactured for plastics [2]. In 1958, the first high-pressure water jet equipment was developed only two years later to cut at 690 MPa hard material such as PH15 [3]. In present days water cutting using and abrasive mix is used when dealing with high strength material, complex shapes, superior surface finish and even waste reduction [4].

Water jet cutting (WJC) is considered a non-conventional but efficient process that allows cutting soft or hard, thin or thick materials with no thermal deformation than laser or plasma cutting [5]. It is also known as a "cold" process for its ability to cut without generating heat; thus, no heat-affected zones emerge, avoiding localized damage, preserving structural and chemical integrity [6]. Another advantage of the WJC is that it is an environmentally friendly process, has a low cutting price, reduces workpiece waste, and has a low setup time. Nevertheless, its key feature is the ability to cut at low or high pressure while adjusting the traverse speed, standoff distance, and angle of attack as needed, depending on the workpiece material [7-9]. The manufacturing industry benefits from this cutting process at its total capacity when using full 5-axis capabilities. This adaptation can assure that holes can be cut with chamfers included, and also complex parts such as elicoidal gear or turbine blades can be executed [10]. Like any other industrial process, the WJC presents disadvantages; one such downside is the inability to cut with high accuracy thick, rigid materials. A direct cause is generated by not accurately controlling the abrasive water jet [11]; thus, the cut surface present deviations from perpendicularity that emerge from differences resulted from how much material the water jet removes.
entering the material compared to them when it exits. Complex kinematic systems for compensation have been developed to overcome these deviations, using comprehensive geometrical cutting models implemented in the machine's software [12], but these solutions are often expensive and cannot be adapted on existing machines.

2. Research methods
While some cutting parameters, such as quality of the cut and traverse speed, are implemented in the equipment's software, others have to be programmed manually, such as water pressure, stand-off distance, material type, and thickness—this fast method for programming industrial equipment, especially if the parts do not have tight dimensional tolerances. If accuracy is needed, the process parameters can be adjusted as necessary. This viable solution is highly time-dependent, as an improved quality can be obtained when cutting with high pressure and slower traverse speeds, depending on the material [13,14]. It is essential to implement fast calculation methods that can offer optimum process parameters, starting from the part's dimensional accuracy. A statistical approach was used to obtain the necessary mathematical dependencies between the process parameters (cutting pressure, stand-off distance, and quality of the cut) and the accuracy of the cut (responses), analysing the entrance and exit width of cut and the kerf angle, as shown in figure 1.

![Figure 1. WJC process analysed parameters and material thickness.](image1)

![Figure 2. WJC input parameters as a process matrix and S235JR cut samples, highlighting the entrance (En) and exit areas (Ex).](image2)
A 19 mm thick S235JR steel alloy plate was used for the study with a total of 45 cuts executed, consistent with the Response Surface Method design of experiments (DOE) plan given by the Design-Expert software.

The design type used in this case was a central composite with a reduced cubic model. The Analysis of variance (ANOVA) for each design factor response was conducted using the automatic model selection, using a forward p-value criterion; thus, only the significant input factors and their interaction were taken into account; the Box-Cox power transformation indicated no recommended transformations. The factors taken into consideration were: the pressure (P) from 2000 up to 3000 [bar], the stand-off distance (S) of 1, 2, and 3 [mm], and all the five levels of cutting quality available presets (Q1-5). The samples' complete arrangement can be noted in figure 2, sorted as a process matrix, from where the comparison of the entrance and exit width of cut can be noted. A Mitutoyo PH-A14 profile projector was used to measure these distances with high precision. The data was inserted into Microsoft Excel, where using equation (1), the kerf angle was calculated.

\[
\Theta = \tan^{-1}\left(\frac{E_{n\text{width}} - E_{s\text{width}}}{2t}\right)
\]  \hspace{1cm} (1)

3. Statistical interpretation results
The interdependency of the process parameters gives the complexity of the WJC. These parameters tend to deviate during the manufacturing process; therefore, the final part may result out of tolerances. Thus we consider that the significance of the data represents an important step in any analysis. A procedure that can be easily implemented using an ANOVA analysis determines if the process parameters impact the result and to what extent. This method has as main outputs the mean square (the sum of squares divided by the degrees of freedom), F-value (test for comparing the source’s mean square to the residual mean square), p-value (the probability of getting a result at least as extreme as the one that was observed), coefficient of determination (R2, measures the amount of variation around the mean explained by the model) with its particular forms (adjusted-R2, predicted- R2, adequate precision) and the mathematical models. Among these parameters, the most important for this experimental study is the p-value, which indicates if we can reject a null hypothesis, if its value is smaller than 0.05, and the R2 value that has to be greater than 0.85 so that one can be confident that a prediction of this model offers accurate results.

3.1. ANOVA results and mathematical models
The ANOVA analysis results for the p-value are highlighted in table 1; the data is divided into groups based on the responses that indicate that each model (entrance, exit width of cut, and kerf angle) is significant if the p-value is lower than 0.0001. The analysis considered the process parameters and their interaction concerning the responses; therefore, the p-value was calculated for each one. It can be noted that the cutting pressure (P) has less influence on the entrance width of the cut compared to the exit width and kerf angle. This result is predictable, as the minimum pressure of 2000 bar is more than sufficient for cutting steel; the high pressure being instead of a way of cutting thick plates, as it can be observed the exit width of cut, where this parameter is highly significant, therefore for the kerf angle. Taking into consideration that the conical shape of the water jet changes with the distance, the analysis finds that the stand-off distance (S) model predicts that the entrance width of cut and kerf angle is affected, while the exit width is significant when in interaction with the pressure, as the p-value indicated being 0.0063. The quality of the cut (Q) for each response is very significant, with values below 0.0001, data that indicates a strong correlation between the process parameters and the dimensional accuracy of the final part, in terms of the entrance, exit width of cut, and kerf angle.
As with any statistical data interpretation, the variance analysis offers predictions, as the effects of the process parameters on the responses have been determined. The confidence in the predictions is given by the coefficient of determination and its particular form. In this experimental study, the result, highlighted in table 2, indicates, with a high degree of trust, that the mathematical connections are accurate and can consequently describe the process with precision, as it can be noted from the R2 values of each response, that is between 0.9535 and 0.9868. For every response, the Adjuster R2 is in reasonable agreement with the Predicted R2, with a difference smaller than 0.2, while the adequate precision that measures the signal to noise ratio indicates that, if a ratio greater than four is obtained, the results offer an adequate signal; the overall status given by the Design-Expert software is that the model can be used to navigate the design space.

Table 1. WJC ANOVA results in terms of the p-value for each response.

| Source | Model | P | S | Q | PS | PQ | SQ | P^2 | S^2 | PSQ | PS^2 | P^2S |
|--------|-------|---|---|---|----|----|----|-----|-----|-----|------|------|
| E_n    | <0.0001 | 0.3789 | <0.0001 | <0.0001 | 0.2832 | 0.5929 | 0.0536 | - | 0.0105 | 0.0147 | 0.0062 | - |
| E_s    | <0.0001 | 0.7668 | <0.0001 | <0.0001 | 0.0063 | 0.0916 | 0.16 | - | - | 0.0312 | - |
| k_o    | <0.0001 | <0.0001 | <0.0001 | <0.0001 | 0.0872 | - | - | - | - | - | - | - |

| Table 2. ANOVA results in terms of R^2, Adj. R^2, Pred. R^2 and Adeq. Precision of each response. |
|---|---|---|---|---|
| Source | R^2 | Adjusted R^2 | Predicted R^2 | Adeq. Precision |
| E_n   | 0.9816 | 0.9648 | 0.8985 | 27.8712 |
| E_s   | 0.9868 | 0.9813 | 0.9710 | 45.0139 |
| k_o   | 0.9535 | 0.9447 | 0.9329 | 35.2979 |

Takin into consideration that the measured values of the entrance width of cut are between 0.92-1.25 [mm], the ones for the exit width are from 0.62 to 1.08 [mm], and the kerf angle is in the range of 0.106 to 0.588 [°], the mathematical models for the responses are highlighted from equation (2) to equation (8). The models are specific for each quality level as this factor was declared as a categoric discrete type. The mathematical models describe the relationship between the entrance width of the cut concerning the process parameters equations (2), (3), (4), (5), and (6). It can be noted that the stand-off distance (S) has a major impact on the result, as a single parameter and in interaction with the cutting pressure, at any quality level. The exit width of the cut mathematical model, presented in equation (5), highlights that changes in this response for each quality level, are influenced by coefficients c1,5 and k1,5 (c1 = 0.042, c2 = -0.119, c3 = 0.045, c4 = 0.112, c5 = 0.254, k1 = 4.91, k2 = 5.48, k3 = 5.31, k4 = 5.35, k5 = 5.11). This response can be obtained at a required value as minor changes have to be applied. This is available also for the kerf angle as the mathematical model from equation (8) indicates that it’s values has minor variations with coefficient c1,5 (c1 = 0.538, c2 = 0.498, c3 = 0.383, c4 = 0.311, c5 = 0.227).

\[
E_{n\text{Width}(Q1)} = 1.042 - 5.3 \times 10^{-5} P - 0.267 S + 1.12 \times 10^{-4} PS + 0.109 S^2 - 3.8 \times 10^{-5} PS^2 \quad (2)
\]
\[
E_{n\text{Width}(Q2)} = 1.008 - 3.0 \times 10^{-5} P - 0.248 S + 1.07 \times 10^{-4} PS + 0.109 S^2 - 3.8 \times 10^{-5} PS^2 \quad (3)
\]
\[
E_{n\text{Width}(Q3)} = 1.483 - 2.0 \times 10^{-4} P - 0.248 S + 1.77 \times 10^{-4} PS + 0.109 S^2 - 3.8 \times 10^{-5} PS^2 \quad (4)
\]
\[
E_{n\text{Width}(Q4)} = 1.343 - 1.47 \times 10^{-4} P - 0.370 S + 1.62 \times 10^{-4} PS + 0.109 S^2 - 3.8 \times 10^{-5} PS^2 \quad (5)
\]
\[
E_{n\text{Width}(Q5)} = 1.373 - 1.5 \times 10^{-4} P - 0.363 S + 1.62 \times 10^{-4} PS + 0.109 S^2 - 3.8 \times 10^{-5} PS^2 \quad (6)
\]
\[
E_{x(Q_5)} = c_{1,5} + k_{1,5} \times 10^{-4} P + 0.491 S - 3.44 \times 10^{-4} PS - 9.47 \times 10^{-8} P^2 + 6.4 \times 10^{-8} P^2 S \quad (7)
\]


\[ K_{a(Q_s)} = c_{1-5} - 5.9 \times 10^{-5} P + 9.1 \times 10^{-5} S + 2.4 \times 10^{-5} PS \]  

(8)

3.2. Models graph interpretation

The dependency of the dimensional accuracy of the responses concerning the process parameters is presented in figure 3. The values are displayed as average over the quality levels, using a blue to a red gradient, specific for small to high numerical values. As mathematical models resulting from the ANOVA analysis, the graphs can predict with high confidence, the responses presented are for pressures in the range of 1500 - 3500 [bar] and stand-off distances up to 4 [mm]. As the stand-off distance increases, the entrance width increases more than the exit width, leading to kerf angles greater than 0.5 [°]. The ideal results are obtained when using very high pressure with a stand-off distance smaller than 1 [mm]; this can be problematic to implement in practice as it is complicated to be obtained; thus, the indicated value for this parameter is around 2 [mm], to avoid any nozzle damage. Therefore, an entrance width of cut of 1.1 [mm] is in reasonable limits with an exit width of 0.85 [mm] when using cutting pressure of 2500 [bar] with a stand-off distance of 2 [mm]; this lead to an approximate kerf angle of 0.35 [°]. Estimations show that when cutting with a pressure of 3500 [bar], the improvement in dimensional accuracy is minimal.

![Figure 3](image.png)

**Figure 3.** Entrance, exit width of cut and kerf angle values distribution function of the stand-off distance and cutting pressure, displayed as average over the quality levels.

4. Conclusions

Abrasive particles from the water jet gain kinetic energy at the exit from the nozzle but are dissipated as the traveling distance increases, leading to a drop in the quality cut, when comparing the entrance and exit width of cut, therefore a higher kerf angle that results in a higher deviation from perpendicularity. It was noted that with the increase of this distance, the kerf angle increase above 0.5 [°]. A smaller kerf angle is ideal but hard to implement; this can be accomplished using a height sensor to avoid any nozzle damage. Analysis of the experimental data indicated an optimum stand-off distance of 2 [mm].

The optimum cutting pressure is in the range of 2300 and 2700 [bar], considering that this parameter is best interpreted in interaction with the stand-off distance. Minor deviations are obtained when cutting with a 1500 [bar] pressure at 1 [mm] stand-off distance, thus improving dimensional accuracy.

The quality level has a significant impact on the results, as superior edge finish was observed at the exit cut when using Q5, compared to when using the Q1 quality that leaves indentations in the cut surface. The result's analysis indicated that a clean-cut could be obtained when using the Q3 level, as it also assures an optimal cutting time.
The stability of the WJC process in terms of part accuracy can be reduced to the kerf angle's value, as it shows the deviation of the entrance width from the exit width. Therefore, a minor kerf angle leads to minor deviations from perpendicularity, reducing the need for further machining. As indicated in this paper, the optimum process parameters are indicated in terms of part dimensional accuracy. The mathematical models ensure that the parameters can be calculated so that a minor kerf angle can be obtained, leading to the desired entrance and exit widths. Thus we consider that is an efficient way of deducing the process parameters for high part accuracy.

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