# Optimization of Process Parameters in Abrasive Water Jet Drilling of D2 Steel to Produce Minimum Surface Roughness Using Taguchi Approach

Deepak D*, Anjaiah D, Sawan Shetty

***Abstract—*** Abrasive Water Jet (AWJ) machining is one of the non-traditional machining methods popular for machining of hard, heat sensitive and brittle materials. The present work investigates the effect of feed rate, operating pressure and standoff distance (SOD) on surface roughness produced while machining of D2 steel. It is found that increase in operating pressure reduces the surface roughness. Other parameters such as SOD and feed rate (Percentage contribution 6.2 % and 6.4 % respectively) were found to be statistically insignificant within the ranges of experimental settings. Further, during the erosion of material, the abrasive loose its kinetic energy leading to formation of wear tracks and burrs as well as peaks and valley on the machined surface. At optimum levels of the process parameters the surface roughness obtained is 2.46 µm.

***Keywords—*** Abrasive Water Jet, Design of experiments, Surface roughness, Drilling

## I. Introduction

Tool and die making industries generally use D2 steel for its applications. This steel contains high percentage of carbon, chromium and possess high wear resistance. Corrosion resistance of this material is enhanced due to the presence of chromium in higher percentage. Machining of such material by traditional machining methods is challenging due its high hardness. The heat generated in the cutting zone is absorbed by the cutting tool while machining, thus resulting in higher surface roughness, formation of white layer and residual stress on the cut surface (Gaitonde et al. 2009). Machining industries are more sensitive to quality and productivity of machining process. There are varieties of non-traditional machining processes such as AWJ machining, electric discharge machining, chemical machining, laser machining etc., which overcome the problems associated with traditional machining. The suitability of the non-traditional machining process depends on material properties and precision of machining. AWJ machining is one of the non-traditional machining method which is generally insensitive to material properties (Folkes, 2009).

In abrasive water machining mixture of abrasive particles such as garnet, silicon carbide, etc., and water is directed on the target material. Erosion takes place due to rapid and repetitive action of the AWJ. There have been cited literatures with regards to the effect of AWJ machining parameters on quality of cutting. From work of Momber (1998) and Hashish (1982), Kovacevic et al. (1997), Kantha Babu et al. (2002) and Srinivasu et al. (2009), Deepak et al. (2015, 2016) it is observed that the kerf geometry, material removal rate and surface roughness were the significantly affected by operating pressure, feed rate and SOD. Khan et al. (2007) found that better machining performance was exhibited by silicon carbide particles followed by aluminum oxide and garnet. The influence of abrasive morphology was investigated by Boud et al. (2010) on machining of a titanium alloy. Higher material removal rate was shown by irregular shaped abrasive particles and good surface finish was produced by spherical shaped particles. Chithirai et al. (2011) and Wang (2007) studied the effect of process parameters on the responses for cutting of copper as well as alumina ceramic materials and also developed response prediction models. Similar studies were also made by Far-had et al. (2009) on Al 6063-T6. Shanmugam et al. (2008) found that the surface taper produced on alumina ceramic can be substantially reduced by adopting kerf compensation technique. Deepak et al. (2014) studied the effect of SOD and feed rate as well as multi-pass machining on kerf width and surface roughness on D2 material. This being an important engineering material, there is a need to study the effect of operating parameters on AWJ machining. Considering this, the present work aims at investigating the effect of operating pressure, SOD and feed rate on the surface roughness produced in drilling operation.

## II. Materials And Methods

### A. Experimental Setup

Figure 1 shows the 3-axis AWJ machine used for conducting experimental work. It consists of an intensifier which generates high pressure water up-to 400 MPa, abrasive feeding system and a cutting head which generates AWJ by

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abrasive injection. The movement of the cutting head on the work piece is controlled by a 3-axis computer numerical control system. The material which is eroded during machining is collected at catcher tank in which the remaining energy of the spent AWJ gets dissipated. Garnet Abrasive of size 80 mesh and the nozzle having exit diameter of 0.76 mm (Make: Kennametal) is used in experimental work.

Fig. 1 Experimental set up

### B. Experimental Methodology

The average hardness of the test specimen is 58 HRC. Table 1 shows the variable process parameters which are chosen in the present work and their settings at different levels. Experiments were planned at 3 levels of each process parameter with two replications. Hence Taguchi L9 orthogonal array is chosen for experimental design. Investigation is carried out to find the effect of operating pressure, SOD and feed rate on the surface roughness produced on the surfaces of the drilled holes. Single pass drilling is made on the test specimen for a diameter of 8 mm at different experimental settings (Table 2). The surface roughness (Ra) is measured along the depth of the drilled holes using Taylor Hobson Surtronic 3+ instrument for sampling length of 6 mm. Table 3 also shows the Ra values obtained at different experimental conditions for two replications. Since, low surface roughness is expected on the surfaces of the drilled holes, the analysis of the response data is carried out using mean response to get the optimum settings for the process parameters.

Fig. 2 Drilled holes on the work-piece

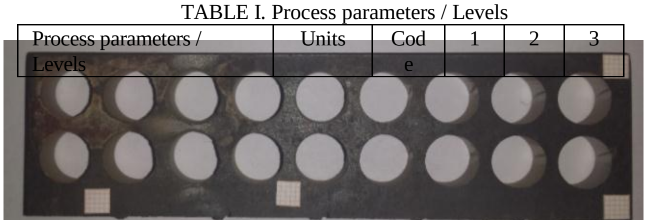

TABLE I. Process parameters / Levels

| Process parameters / Levels | Units | Code | 1 | 2 | 3 |
|---|---|---|---|---|---|
| Pressure | MPa | A | 200 | 250 | 300 |
| Standoff distance | mm | B | 1 | 3 | 5 |
| Feed Rate | mm/min | C | 50 | 75 | 100 |

TABLE II. Experimental plan and results

| Expt. no | Pressure | SOD | Feed Rate | $R_a$ |
|---|---|---|---|---|
| 1 | 200 | 1 | 50 | 3.37 |
| 2 | 200 | 3 | 75 | 4.02 |
| 3 | 200 | 5 | 100 | 4.69 |
| 4 | 250 | 1 | 75 | 3.65 |
| 5 | 250 | 3 | 100 | 3.94 |
| 6 | 250 | 5 | 50 | 3.63 |
| 7 | 300 | 1 | 100 | 2.64 |
| 8 | 300 | 3 | 50 | 2.96 |
| 9 | 300 | 5 | 75 | 2.85 |

## III. Results and Discussion

### A. The Effect of Process Parameters on Surface Roughness

Figure 2 shows the holes drilled on the work piece at various test conditions and Table 3 shows the experimental results at different test conditions. The surface roughness thus obtained was subjected to analysis of variance to determine the effect of process parameters. Figure 3 shows the main effects plot of response data. It is seen that the surface roughness decrease with increase in operating pressure due to increase in the jet kinetic energy at higher operating pressure. The smaller gap between the nozzle exit and work-piece as well as low feed rate shows lesser surface roughness compared to their higher levels. Increase in SOD results in jet expansion leading to reduction in jet coherence thus promoting rechochiation of abrasives in random directions. Also, higher feed rates reduces the exposure time for the machining of the work piece. Thus increase in SOD and feed rate produces higher surface roughness. Table 3 shows the Analysis of Variance (ANOVA) for the response data. The mean square variance values were subjected to F test at 95 % confidence level to identify the factors which have significant influence on the response. It is observed that operating pressure is the most significant factor influencing the surface roughness. Whereas, SOD and feed rate were found to be insignificant.

TABLE III. ANOVA of $R_a$ (Un-pooled)

| Source | Degree of freedom | Sum of | Mean Square | F |
|---|---|---|---|---|
| Press | | | | 9.24 |
| SOD | | | | 1.68 |
| Feed | | | | 1.11 |
| Error | | | | |
| Total | | | | |

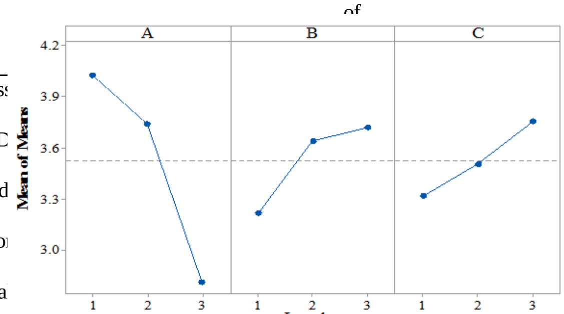


Fig. 3 The main effect plot of response data

### B. Optimization of Process Parameters

The average surface roughness obtained at different levels of the process parameters are shown in Table 4. It shows that lower surface roughness is obtained at the process settings operating pressure at 300 MPa, SOD – 1 mm and feed rate 50 mm/min (i.e., A3B1C1) and these settings is considered as optimum settings within the experimental range. Using equations (1), (2), (3) and (4), the optimum surface roughness is found to be 2.26 µm at settings A3B1C1. Confirmation experiments were conducted at optimum conditions. The Ra values obtained from these experiments were in close agreement with the predicted results within 7 % variations. Further, based on the influence of process parameters on Ra values, the process parameters are ranked as pressure –I, SOD - II and the feed rate – III

TABLE IV. Mean response at different levels

| Level | Operating Pressure | Stand-off Distance | Feed Rate |
|---|---|---|---|
| 1 | 4.027 | 3.220 | 3.320 |
| 2 | 3.740 | 3.640 | 3.507 |
| 3 | 2.817 | 3.723 | 3.757 |
| Delta | 1.210 | 0.503 | 0.437 |
| Rank | 1 | 2 | 3 |

$$n_{eff} = \frac{\text{Total trials}}{1+\text{degree of freedom}} \quad (1)$$

$$T = \frac{\sum \text{Response}}{\text{Total trials}} \quad (2)$$

$$R_{a\ optimum} = R_a [A_3 + B_1 + C_1] - 2T \quad (3)$$

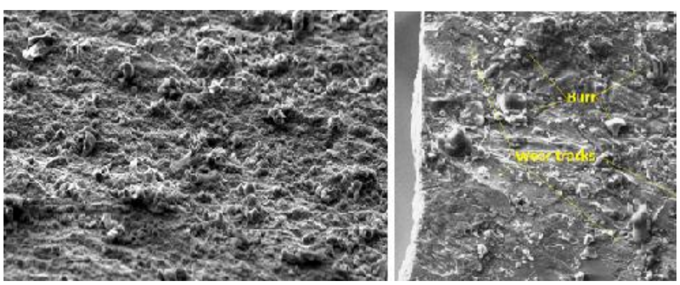


Fig. 4 Surface morphology of the hole

Further, the surface of the drilled hole was investigated using scanning electron micrographs (SEM). Figure 4 shows the holes surface drilled at optimum settings of the process parameters i.e., A3B1C1. It is seen that, the complete cut surfaces exhibits burr and wear tracks. Due to the impact of abrasives on the target, material erosion takes place. During the erosion process the abrasives loose its kinetic energy leading to formation of wear tracks. When the particle energy is completely utilized, the material being eroded remain intact with the wear track leading creation of burrs as shown in the figures. Thus, the wear tracks and burrs formed results in creation of peaks on and valley on the cut surface resulting in higher surface roughness.

### C. Development of Regression Model

A model is developed to predict the surface roughness developed at different settings of the process parameters using regression method. The model includes pressure, SOD and feed rate as model parameters. R2 values of the model is found to be 94.48 %. The accuracy of the models is tested by confirmation experiments which were conducted in the range shown in Table 1. The predicted results from the model is in close agreement with the surface roughness values measured from the experiments with a maximum error of 6.17 %. Normal probability plot of residuals is shown in Figure 5. Standard errors of coefficient are found to be distributed around the line of fit.

$$R_a = 6.126 - 0.01477 \times A + 0.1583 \times B + 0.00987 \times C \quad (4)$$

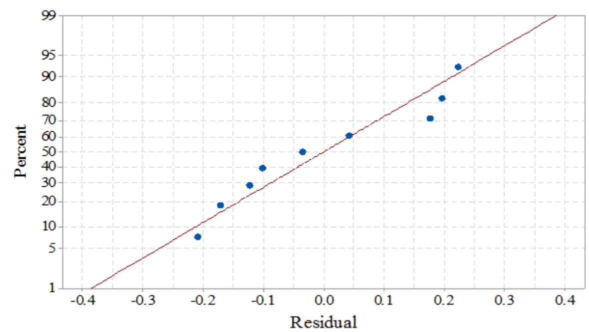


Fig. 5 Normal probability chart

## IV. Conclusion

Following conclusions are drawn from the present experimental work on AWJ drilling of D2 grade heat treated steel on surface roughness.

- Operating pressure is the most influential parameter (contribution 81.48 %) that affects surface roughness.
- Percentage contribution of SOD and feed rate are 6.2 % and 6.4 % respectively and hence the effect of these parameters are found to be insignificant within the experimental range.
- Optimum settings for the process parameters were established as operating pressure at 300 MPa, SOD - 1 mm and feed rate - 50 mm/min.
- During the erosion process the abrasives loses its kinetic energy leading to formation of wear tracks and burrs. At optimum setting of the process parameters the surface roughness obtained is 2.46 µm.

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