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Effect of Abrasive Water Jet (AWJ) Parameters on Materials Removal Rate for Low Carbon Steel

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HIGHLIGHTS

- The effect of jet pressure, feed rate, and standoff distance on material removal rate throughout abrasive water jet cutting of carbon steel metal workpieces were studied.
- The experimental results showed that feed rate and pressure jet had the most effect on material removal rate.
- The most influencing factors for getting a better material removal rate are pressure jet and feed rate.

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ABSTRACT

Abrasive water jet (AWJ) is one of the most advanced and valuable non-traditional machining processes because of its massive advantages of removing metal from hard and soft metals. This paper has studied the effect of jet pressure, feed rate, and standoff distance on material removal rate throughout abrasive water jet cutting of carbon steel metal workpieces. The material removal rate was assessed using a precision balance device by performing sixteen experiments to identify the ratio of weight loss to total cutting time. The Taguchi method was introduced to implement the experiments and indicate the most influential process parameters on material removal rate. The experimental results showed that feed rate and pressure jet had the most effect on material removal rate. The best material removal rate value was 3.71 g/min at jet pressure 300 MPa, feed rate 30 mm/min, and standoff distance 4mm.

1. Introduction

Abrasive Water Jet (AWJ) is a non-traditional machining technique that belongs to the mechanical machining processes [1-2]. Material is removed from the target material by impinging a highly accelerated abrasive jet, which causes the material to be cut by the sharp abrasive edges [3-4]. Abrasive water jet machining can be used to cut materials that are difficult to cut using traditional methods. Abrasive water jet machining is used in various fields and products, including metals, ceramics, polymers, and composite materials [5-6], with many distinct advantages such as no heat-affected zone, no thermal distortion, and higher flexibility [7]. Besides, the process is more economical, and the Material Removal Rate (MRR) is higher than those of non-traditional machining processes [8]. The material removal rate is dependent on the mechanical properties and abrasive attack of the workpiece. The Abrasive water jet machining process is defined by several parameters, which govern the material removal rate and the development of the characteristics of the surface. A considerable effort was made to understand the influence of the system operation process parameters such as water jet pressure, standoff distance, feed rate, traverse speed, and angle of cutting on the material removal rate. The investigations revealed that the abrasive water jet machining is importantly affected by the process parameters variation.

However, the degree of influence of parameters depends on the magnitude of parametric variation and machinability of the material. The feed rate of the jet has a strong influence on the surface finish of the workpiece and material removal rate [9–12]. Joel [13] investigated the AWJ machining of AA7075. The Grey-Taguchi method is used for determining the predicted optimal parametric combinations by varying the level of Abrasive feed rate, Nozzle Speed, and Standoff distance on the cutting of AA7075. Results revealed that the abrasive feed rate contributed to abrasive cutting operation by 46.52%, and the second-highest influencing factor showed nozzle speed with 36.76% and a standoff distance of 15.05%. Hashish [14] observed that the power required for cutting gets reduced drastically as the pressure increases. This suggests that cutting at higher pressure is more efficient than at low pressure for the same power consumption.

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The increased pressure also reduced the cost due to a reduction in abrasives usage and increased cutting speed. The study shows that the depth of the cut increases with jet pressure. Ojmertz [15] has shown that low feed rates result in irregular surface morphology and significantly increased material removal rates from titanium alloy, but despite this, lower surface roughness values are observed. Samson [16] studied the abrasive water jet machining input parameters such as pressure, flow rate, and Standoff distance on Beryllium copper grade C25 to get the optimum values of response parameter's like Material removal rate. The result revealed that pressure and standoff distance are the most influencing factors for getting better material removal rates. Fowler et al. [17] have shown that low feed rate results in high material removal rates and high surface waviness for Ti–6Al–4V alloy. In the previous literature, MRR is notably affected by feed rate and abrasive pressure jet. The present research investigates the influence of the input parameters on cutting process performance with the AWJ machine technique. The study's objective is evaluated in terms of MRR to get the best optimization results. Hence, a full factorial experimental design consisting of four levels of each input process parameter has been employed. Analysis of Variance (ANOVA) has been carried out to recognize the input parameters' statistical significance on the responses.

2. Experimental work

2.1 Machine

The experimental setup for the abrasive water jet machine (Model No. 3020; YONODA, China) is shown in Figure 1. The machine uses a 3-stage plunger-type high-pressure pump to generate high pressures of 413 MPa. At this rated pressure, the machine has a 2.6 litters/min water discharge capacity. The machine's maximum traverse speed is limited to 1200 mm/min, and the motion is controlled by a CNC, a motorized Z-axis for vertical movement. The working and technical specifications of the machine are given in Table 1.

All the experiments were conducted at 90^o jet impingement angles only. The cutter head consists mainly of two nozzles, one of them is primary (jewel orifice), and the other is secondary (Focusing or mixing tube). The primary nozzle is the orifice that exits water from the cutting stream. Typically, jewels are created from ruby, diamond, or sapphire, a "jewel" mounted in a steel insert. Its diameter ranges from (0.178 – 0.51) mm [18], notice figure 2. A secondary nozzle is sometimes referred to as a mixing tube or Focusing tube. This tube is manufactured from a tough material that concentrates the water and abrasive into a coherent beam for cutting. Typically, a mixing tube has a diameter of 0.76 mm [18], notice figure 2, to the abrasive water jet nozzle to cut efficiently and improve the life of components. The jewel orifice must be accurately aligned with the nozzle body.

2.2 Materials

Abrasive water jet (AWJ) experiences were carried out on a sample of carbon steel of (10 x 40 x 118) mm dimensions with the following chemical composition according to the standard BS EN10025-2:

Carbon steel is non-alloy steel in which carbon is a fundamental component that determines its grade. Carbon steel is strong, has good formability and weldability, is shock-resistant, and is strengthened by cold work; this metal is often the most practical choice. And it is widely used in various fields for various purposes, such as constructing bridges and buildings, automobile industries, and the oil industry [19]. According to BS EN 10025-2, the sample has the name and number S355J2 and 1.0577, respectively, in addition to the following mechanical properties:

Abrasives used in this study are red garnet with an average particle size of 80 mesh (0.178 μm). This type is the most popular abrasive utilized in AWJ cutting machines because of the facts: (1) It is an inert material that does not interact with the material to be cut. (2) It is widely available, thus relatively inexpensive. (3) When hitting the target, it breaks down, forming sharp edges, thus improving cutting performance [20].

Figure 1: Experimental setup for abrasive water jet machining

Figure 3: Orifice and mixing tube

2.3 Experimental procedure

The machining was done by considering the jet pressure, standoff distance, and feed rate, and each process parameter was varied over four levels, as shown in Table 4. Based on Taguchi's design philosophy, standard orthogonal array L16, as shown in Table 5, has been selected to complete the experiment and estimate its impacts on the material removal rate (MRR). Cutting was performed on a carbon steel sample having dimensions (10 x 40 x 118) mm. Before and after machining was completed, the MRR on the workpiece was measured.

Table 1: Technical specifications of AWJM

Machine	YONODA, China
Maximum transverse speed	1200 mm/min
Jet Impingement Angle	90^o
Mixing Tube Length	76.2 mm
Focusing/Mixing Tube Diameter	1.02 mm
Orifice Diameter	0.3 mm
Maximum Working Pressure	413 MPa
Maximum distance from the workpiece	10 mm
Table size	3000 x 2000 mm
Operation program	Nc studio V10

Table 2: Chemical composition of low carbon steel (measured)

C%	Mn %	Si %	P %	Cu %	Mo %	Cr %	S %	AL %	Co %	Ni %	Fe %
0.14	1.30	0.47	0.028	0.18	0.045	0.16	0.017	0.004	0.012	0.15	97.4

Table 3: Mechanical properties of low carbon steel

Yield strength (MPa)	Tensile strength (MPa)	Elongation after fracture (mm)	Hardness (HB)
355	470 to 630	22 l 20 t	146 -187

Table 4: Process control parameters and levels

Parameters	Units	Level1	Level2	Level3	Level4
Pressure jet	MPa	225	250	275	300
Feed rate	mm/min	30	50	70	90
Standoff distance	mm	1	2	3	4

Table 5: Experimental design by Taguchi method

No.	Pressure (MPa)	Feed Rate (mm/min)	Standoff Distance (mm)
1	225	30	1
2	225	50	2
3	225	70	3
4	225	90	4
5	250	30	2
6	250	50	1
7	250	70	4
8	250	90	3
9	275	30	3
10	275	50	4
11	275	70	1
12	275	90	2
13	300	30	4
14	300	50	3
15	300	70	2
16	300	90	1

2.4 Measurement of MRR

The mass of the workpiece specimen is weighed before and after the experiment using an electronic balance having a resolution of 0.01 g. The sample is weighed in dry condition before experimentation. After the piecework is cut, the abrasive particles are washed off; the cut specimen is cleaned with compressed air and thoroughly dried before being weighed again. MRR is calculated as the weight loss ratio to the total cutting time. The following formula is used to estimate the MRR for a single channel [16]:

$$\text{Material removal rate (MRR)} = (W_2 - W_1 / T) \quad (1)$$

W_1: Weight after machining
W_2: Weight before machining
T: Time is taken to a machining

2.5 The Design of Experiments (DOE)

When considering process parameters at different levels, designing experiments is known as the design of experiments (DOE). Taguchi's method for experimental design offers a simple, systematic, and efficient approach to determining the efficiency, expense, and quality of an experiment (Aydin et al., 2010). Statistically designed experiments are conducted more efficiently as they consider many parameters simultaneously. Unlike conventional experimentation, they can identify significant interactions with a minimum number of experiments. A factorial experimental set consisting of pressure jet, standoff distance, and feed rate as process parameters, each at 4-levels (4^3) with all possible combinations, totaling 16 experiments, was chosen based on the above. The process parameters range is specified in Table 5.

2.6 Analysis Data

Taguchi analysis, drawing control charts for processes, plotting time series plots, multivariate tests, and other very simple tasks and time-saving. It is the most effective method for quality improvement initiatives based on results. MINITAB (version 17) was used in this study for ANOVA analysis and plotting various graphs [21].

In the analysis of variance (ANOVA), the F ratio was applied to calculate the important process parameter on the material removal rate and average surface roughness. First, an F ratio is estimated from the experimental results and then compared to the critical value. If the F ratio estimated is larger than the F critical value, it is an indication that the statistical test is important at the confidence level selected [22].

In this work, an analysis of variance was carried out for the confidence level of 96.1 %. It was found that the factors feed rate (t) and pressure (p) was the most significant factor impacting the assessment of the material removal rate. To observe the impact of important factors, the results of the response parameters are displayed through graphs. The experimental tests are designed for four levels and three parameters.

3. Results and discussion

This section examined the influence of the process parameters such as jet pressure, feed rate, and standoff distance on the material removal rate during AWJ cutting of carbon steel.

Table 6 shows the predicted and measured results of material removal rate for the target material samples by (Taguchi design). Figure 3 explains the measured and predicted value for MRR, and figure 4 explains the Main effects plot of process parameters on the material removal rate.

Table 6: Measured and predicted material removal rate

No.	Pressure (MPa)	Feed Rate (mm/min)	Standoff Distance (mm)	Measured MRR (g/min)	Predicted MRR (g/min)
1	225	30	1	3.35	3.45
2	225	50	2	2.89	2.81
3	225	70	3	2.06	2.23
4	225	90	4	1.98	1.78
5	250	30	2	3.43	3.39
6	250	50	1	3.42	3.43
7	250	70	4	2.44	2.43
8	250	90	3	2.13	2.16
9	275	30	3	3.62	3.64
10	275	50	4	2.97	3.26
11	275	70	1	3.34	3.04
12	275	90	2	2.36	2.34
13	300	30	4	3.71	3.62
14	300	50	3	3.64	3.41
15	300	70	2	2.63	2.76
16	300	90	1	2.57	2.75

The predicted material removal rate values were compared with the measured values, as presented in Table 5. The material removal rate (MRR) results were close between predicted and measured. The ability of independent value to predict the material removal rate was 93.3% (R^2). This means that the correlation coefficient between the dependent variable's measured and expected values are good.

Figure 4 shows the effect of pressure (P), feed rate (F), and standoff distance (SOD) on MRR. Increasing in P leads to an increase in MRR. Conversely, increasing F leads to a decrease in MRR, and increasing in SOD leads to a decrease in MRR, as shown below.

3.1 Influence of pressure jet on Material Removal Rate

The material removal rate was measured during the experiment and plotted in Figure 5. The influence of pressure jet on material removal rates, a parameter, was tested under pressures from 225 to 300 MPa. Figure 5 shows a significant impact of pressure on the material removal rate. The rise in the pressure jet increases jet velocity, which directly impacts the abrasive particle kinetics of impinging on the workpiece material, leading to higher material removal [23]. Considering the standoff distance, as is evident at pressure 275 MPa and feed rate 50 and 70 mm/min.

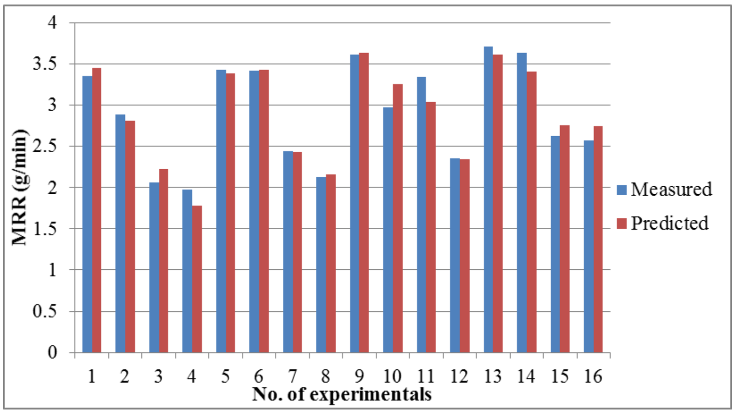

Figure 4: The measured and predicted value for MRR

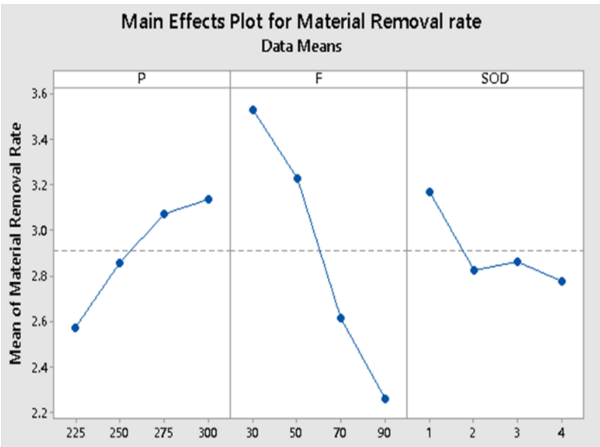

Figure 5: A plot of the main effect for means of material removal rate (MRR)

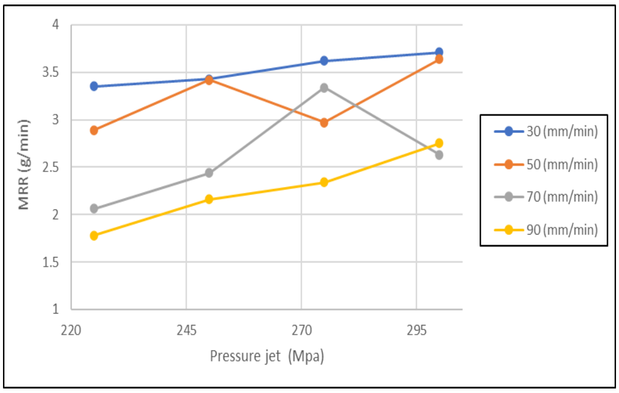

Figure 6: A plot of the impact of pressure on material removal rate (MRR)

3.2 Influence of standoff distance on Material Removal Rate

The distance between the tip of the nozzle and the target work surface is termed SOD. It is another important parameter in the AWJM process. In low SODs, the abrasive flow is damped or decelerated by the target surface, leading to a poor surface and enhanced MRR. Conversely, an increase in SOD increases the jet diameter leading to a decrease in the energy density. The reduction in energy density generates more random peaks and valleys on the surface leading to higher surface roughness and reduced MRR [23]. Figure 6 illustrates the influence of SOD on MRR.

3.3 Influence of feed rate on material removal rate

Feed rate is another process parameter that influences the machining process. This is a typical result of several effects that determine the number of impacting particles and their kinetic energies. The influence of feed rate on MRR is plotted in Figure 7.

As the Feed rate increases, the MRR reduces because of a decrease in the abrasive flow velocity. As a result, a limited amount of kinetic energy of a jet obtains distributed over a large number of particles, leading to a decline in the kinetic energy of the specific particle. This also leads to an increase in turbulence [24].

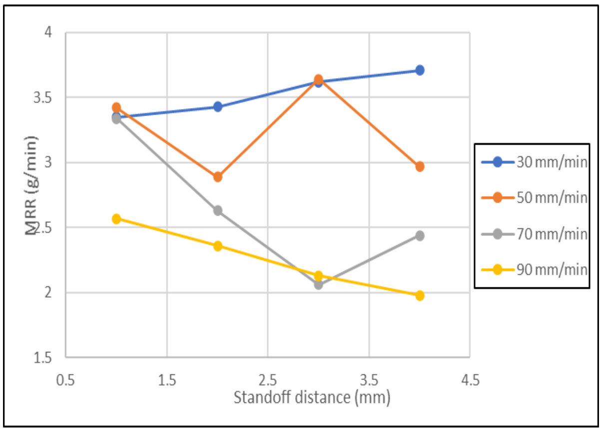

Figure 7: A plot of the impact of standoff distance (at 225-300 MPa) on material removal rate (MRR)

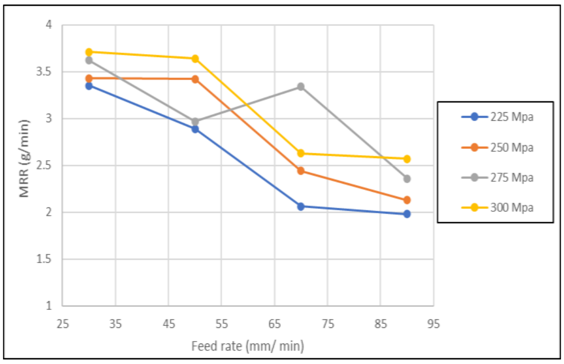

Figure 8: A plot of the influence of feed rate on material removal rate (MRR)

4. Conclusions

1) Material removal rate increases with the increase of pressure jet and decrease with an increase of feed rate and standoff distance. This is because the high standoff distance increases the jet focus point, and the loss of energy happens because of the scattering of the jet.
2) High feed rate results in lower material removal rates in the material due to reduced abrasive flow velocity and limited kinetic energy.
3) The most influencing factors for getting a better material removal rate are pressure jet and feed rate. The best material removal rate value was 3.71 g/min at jet pressure 300 MPa, feed rate 30 mm/min, and standoff distance 4mm.

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Author contribution

All authors contributed equally to this work.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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