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An Experimental Investigation of Abrasive Jet Machining Parameters for Optimized Surface Finish of Mild Steel Components

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Abstract

Abrasive jet machining is one of the unconventional machining processes that are initiated for alternations of surface characteristics of ductile materials, like mild steel, due to the entrainment of high-velocity abrasive particles. The present experimental investigation deals with the major process parameters of the AJM process, namely air pressure, standoff dis- tance, and time of machining, on the average surface roughness (Ra) of mild steel specimens. Experiments were conducted on the self-developed AJM setup using aluminum oxide abrasive particles of an average size of 50 μm. The pressure of air is changed in three levels, 6, 7, and 8 bars. The standoff distance is taken as 2 mm constant for all the cases. The surface roughness was measured at machining times of 20, 40, and 45 seconds. The presence of the increase of air pressure from 6 to 8 bars applied for all the machining time showed an increasing influence on roughness, although always significant in Ra. For 8 bars of pressure and 45 s of machining, the minimum resulted in 1.39 μm, compared with 3.47-4.02 μm. The rate of decrease in surface roughness is sharp with increasing machining time from 20 to 40 seconds but marginal beyond that. An optimal machining time of 40–45 seconds was identified in order to obtain a minimum Ra. Capability of AJM as an effective technique to enhance the surface finish of mild steel components, and practical insight of this study is very useful toward optimization of process parameters for attaining the targeted surface quality. The results obtained may assist in expanding the industrial application of AJM toward the finishing of ductile materials in various manufacturing fields.

Keywords: Abrasive jet machining, Surface roughness, Mild steel, Process optimization, Ductile materials

Introduction

Abrasive jet machining (AJM) is an unconventional ma- chining practice that uses a high-velocity stream of abra- sive particles to eradicate material from a workpiece surface. These are hard particles of aluminum oxide or silicon carbide, which are propelled using compressed air or gas and beamed over the workpiece with the help of a nozzle. AJM does not cause any physical contact between the tool and workpiece; hence, problems such as mechanical stresses, chatter, and vi- bration, which are the common features in any conventional machining process, get eliminated by default [1].

Since AJM is an important process, it has its inherent ad- vantages that need to be studied and optimized. It is es- pecially suitable for machining hard and brittle materials that are difficult to process by other material removal tech- niques [1]- [2]. AJM can machine complicated shapes and small features in these materials without substantial thermal distortion due to the fact that the high velocity of the particles carries away the heat [3]. It can also be applied for clean- ing and deburring as well as producing matte surfaces [6]. AJM is low in cost in comparison with other unconventional machining processes, and the equipment is relatively simple; it consists of only an air compressor, a pressure regulator, a nozzle, and an abrasive particle feeder [1], [5].

However, AJM also has limitations, such as low material removal rate, nozzle wear, and surface roughness issues that require further research [3]. The process involves a large number of parameters related to the abrasive particles, noz- zle, and gas jet that influence the machining performance [7]- [10]. Therefore, it is necessary to study the effects of these input parameters and optimize them for the desired output characteristics.

This experimental study investigates the influence of AJM process parameters on the surface roughness of ductile mate- rials like mild steel. The specific objectives are:

- To analyze the effect of abrasive particle size, nozzle pressure, and standoff distance on the average surface rough- ness (Ra) produced.
- To determine the optimal combination of parameters to minimize surface roughness.
- To understand the material removal mechanism and sur- face topography evolution during AJM of mild steel.

The rest of this paper as shown in figure 1 is arranged as follows: Section 2 examines the pertinent literature on AJM, identifies research gaps, and establishes the significance of this study. Section 3 describes the experimental methodol-

ogy, including the AJM setup, workpiece material, input pa- rameters, and measurement techniques used. Section 4 out- lines the findings and examines the impact of factors on sur- face roughness. Section 5 summarizes the main conclusions. By focusing on the surface roughness characteristics of mild steel machined by AJM, this experimental study aims to generate new insights to optimize the process parameters and improve the surface integrity of ductile metals processed by this unconventional method. The findings can help to in- crease the industrial adoption of AJM for finishing operations

in automotive, aerospace, and other manufacturing sectors.

LITERATURE REVIEW

Abrasive jet machining (AJM) has been widely studied for processing various materials, especially hard and brittle ones. Numerous researchers have investigated the effects of key process parameters on the surface roughness and material re- moval mechanisms in AJM.

AJM has generated the shape of surfaces on brittle materi- als like glass [11]. The material is removed through the cre- ation and spread of horizontal fissures followed by particle collisions [11]- [17]. The erosion rate depends on the particle velocity, impact angle, and target material properties. The material response has been during AJM of alumina ceram- ics [7]. Higher particle velocities and normal impact angles resulted in more brittle fractures and higher erosion rates [7]. For ductile materials like mild steel, the material removal in AJM occurs primarily by plastic deformation and shearing action of the abrasive particles [1]. Also, surface roughness has been measured on mild steel samples machined by AJM using aluminum oxide and silicon carbide abrasives. The sur- face roughness decreased with increasing pressure and ma- chining time up to a specific limit. Beyond an optimal du- ration, the roughness started increasing again due to the re-

deposition of particles [1].

Several studies have focused on modeling and optimiza- tion of process parameters in AJM. Çaydas¸ and Hascalık de- veloped artificial neural networks and regression models to predict the surface roughness in AJM of AA 7075 alloy. Pres- sure, standoff distance, and abrasive grit size were the most influential factors [2]. An analytical model has been proposed considering the particle size distribution to predict the surface profile evolution in AJM [3]. Larger particles and higher jet velocities resulted in more waviness and rougher surfaces [3]. Some researchers have compared the performance of AJM with abrasive water jet machining (AWJM). In AWJM, the addition of water enhances the erosion rate and reduces dust generation compared to dry AJM. [4] However, AWJM also leads to more surface striations and kerf geometric defects at higher traverse speeds [8]. Proper control of jet pres- sure, standoff distance, abrasive mass flow rate, and traverse speed is necessary to obtain optimal surface finish in both

processes [4], [15].

While AJM has been successfully applied for various ma-chining operations like cutting, drilling, deburring and polish- ing, some challenges still remain. Particle embedding, nozzle wear, and tapered hole geometry are common issues that af- fect the surface integrity. [8] The surface roughness and ero- sion rate are also highly dependent on the properties of the target material and abrasive particles [7], [17]. More work is needed to develop predictive models that can account for these complex dependencies [8], [10]- [16].

In summary, this literature review highlights that AJM process parameters like pressure, standoff distance, abrasive type, and size significantly influence surface roughness and material removal mode. While empirical studies have been conducted on AJM of ductile materials like mild steel, fur- ther research is required to optimize the parameters for de- sired surface quality. The present experimental study aims to address this gap and provide a deeper understanding of surface roughness evolution in AJM through a systematic in- vestigation. The results can help to establish optimal process windows for finishing operations on mild steel components using this versatile machining technique.

METHODOLOGY

Experimental Setup

The experiments were conducted using a custom-built abrasive jet machining (AJM) setup. The main components of the setup include:

- Air compressor (8 bar maximum pressure)
- Pressure regulator and gauge
- Mixing chamber for abrasive particles
- Tungsten carbide nozzle (4 mm inner diameter, 15 hours life)
- Workpiece fixture with X-Y table

Abrasive particles are introduced into the mixing chamber from a hopper via a vibratory feeder. The compressed air is dried and filtered before entering the mixing chamber to carry the abrasive particles. The air-abrasive mixture exits the chamber through the nozzle as a high-velocity jet. The nozzle is mounted on a fixture allowing adjustment of the standoff distance (SOD) between the nozzle tip and the work- piece surface. The workpiece is clamped on a table that can traverse in X and Y directions to machine different areas.

Workpiece Material

Mild steel specimens of 100 mm x 50 mm x 10 mm were used as the workpiece material for this study. The initial av- erage surface roughness of the specimens was measured to be in the range of 3-4 μm Ra. Prior to the trials, the specimens were purified using acetone to eliminate any oil or debris.

Abrasive Particles

Aluminum oxide (Al2O3) abrasive particles with an aver- age grit size of 50 μm were used for the experiments. The particles have irregular shapes and sharp edges suitable for micro-cutting action. The abrasive particles were dried in an

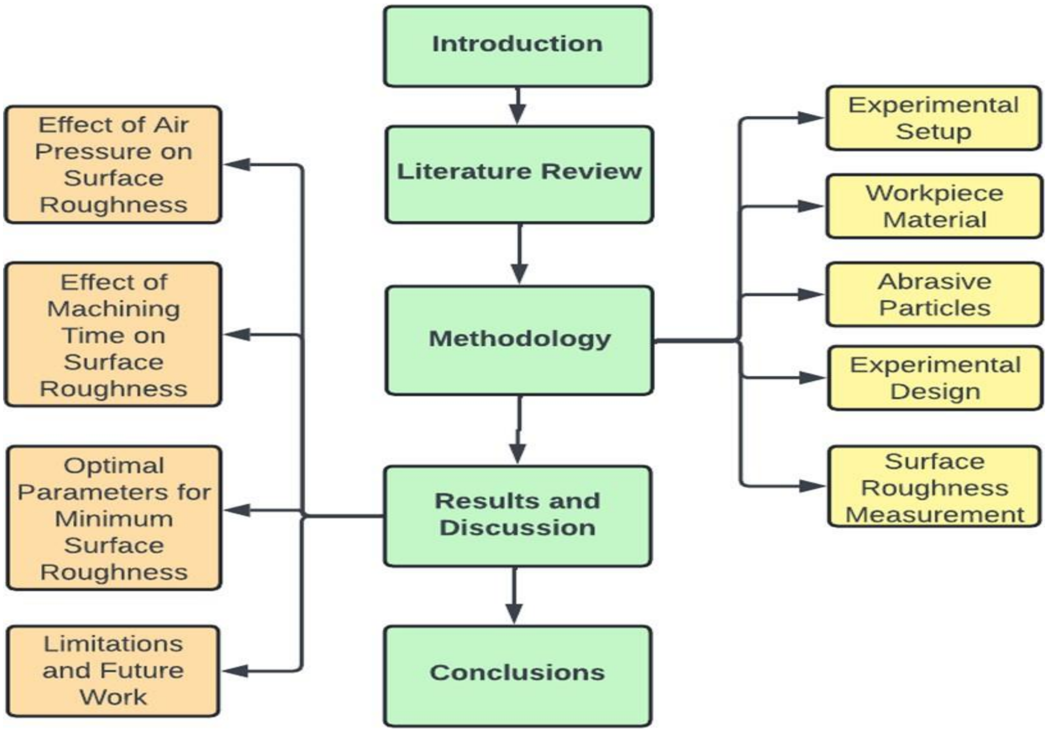

Figure-1. Illustration of Paper flow

oven at 100°C for 2 hours before use to remove any moisture.

Experimental Design

The experiments were designed to scrutiny the effect of three key AJM process parameters on the surface roughness:

- Air pressure (6, 7, 8 bar)
- Standoff distance (2 mm)
- Machining time (20, 40, 45 seconds)

For each pressure level, experiments were conducted at a constant 2 mm SOD for 20, 40, and 45 seconds. Three repli- cates were performed at each experimental condition. The experiments were randomized to minimize any systematic er- rors. A total of 27 experiments (3 pressure x 1 SOD x 3 time x 3 replicates) were carried out.

Surface Roughness Measurement

The machined specimens' surface roughness was mea- sured using a portable stylus-type profilometer (Mitutoyo Surftest SJ-410). The profilometer was calibrated before the measurements using a standard roughness specimen. The center-line average roughness parameter (Ra) was used to quantify the surface finish. Ra represents the arithmetic aver- age of the absolute values of profile deviations from the mean line. Measurement of roughness for each specimen was done at five different places, i.e., the four corners and the center of the specimen of 4 mm evaluation length. For the speci- men, the surface roughness is the arithmetic average of the 5 Ra values. Measurements were taken with a 0.8 mm cut- off length and a 0.8 mm sampling length, as defined by ISO 4288. Accordingly, systematic changes in process parameters are followed by measuring surface roughness in order to look at its effects and interactions with input variables. These re- sults should be able to offer optimum parameters to achieve the desired surface finish level on the work material: mild steel machined by AJM.

RESULTS AND DISCUSSION

Effect of Air Pressure on Surface Roughness

Figure2 below, respectively, show the results of the ex- periment on the effect of air pressure on the average surface roughness (Ra) of the machined mild steel specimen by AJM with a constant 2 mm standoff distance.

The bar graph shows the effect of air pressure and time on the roughness of the surface.

As is evident from Table 1 and Figure 2, increasing the air pressure from 6 bar to 8 bar has decreased the average value of the surface roughness (Ra) for all the machining times tested. For example, at a machining time of 20 seconds, Ra decreased from 2.36 μm at 6 bar to 2.19 μm at 8 bar pressure. Similarly, at 45 seconds, Ra reduced from 1.61 μm to 1.39 μm when pressure was increased from 6 bar to 8 bar. Figure 3 shows the Sample Before and After Finishing at 6 Bar Pressure, and Table 2 presents the experimental data used at 6 bar pressure. Figure 4 shows the line diagram of average roughness at 6 bar pressure at different time intervals.

Table-1. Effect of air pressure and machining time on average surface roughness (Ra)

Pressure (bar)	Initial Ra (μm)	Ra (μm) at 20 s	Ra (μm) at 40 s	Ra (μm) at 45 s
6	3.64	2.36	2.00	1.61
7	4.02	2.30	1.37	1.34
8	3.47	2.19	1.57	1.39

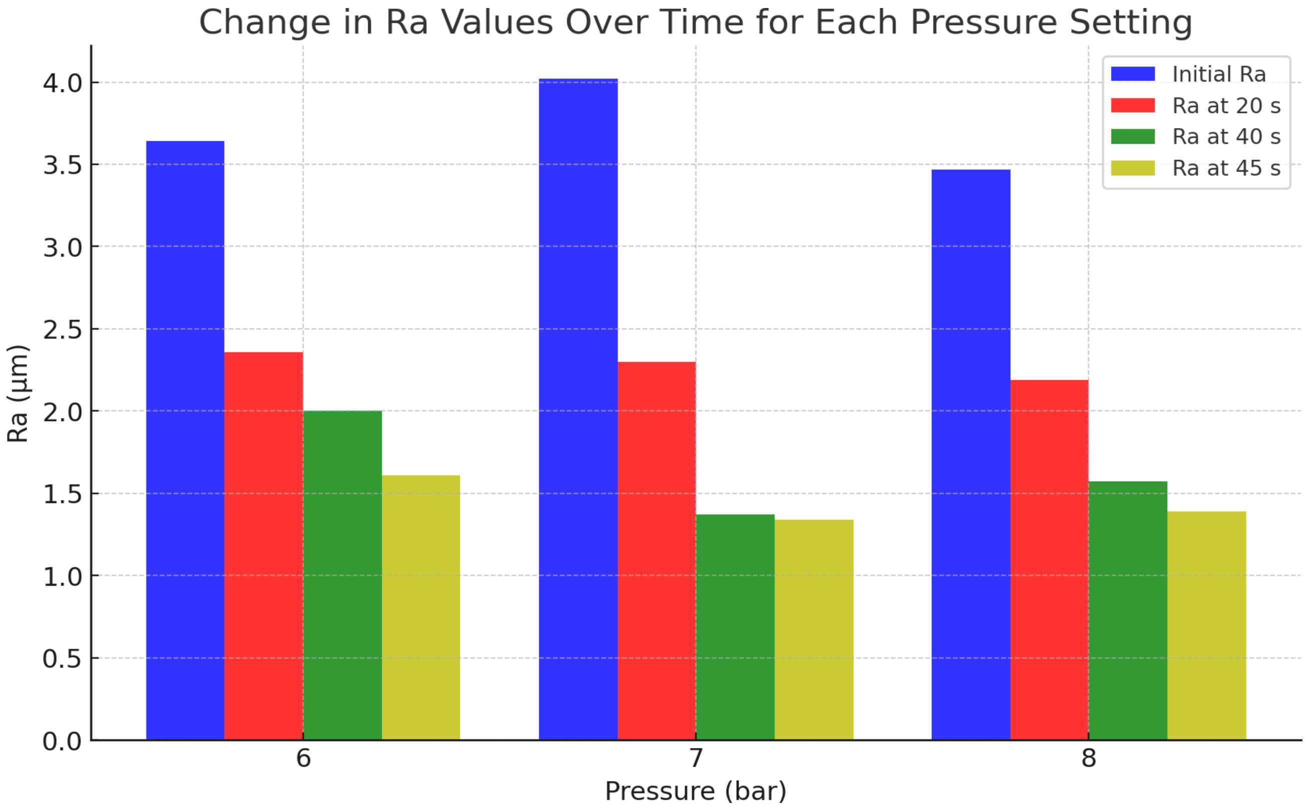

Figure-2. Effect of air pressure and machining time on average surface roughness (Ra)

The decrease in surface roughness with increasing air pres- sure can be attributed to the higher velocity and kinetic energy of the abrasive particles impacting the workpiece surface at elevated pressures. Higher particle velocities lead to increased erosion rates and more effective removal of surface asperities, resulting in a smoother surface finish [7], [18].

These results are consistent with the findings of previous researchers. It has also been reported that the surface roughness of mild steel decreased with increasing air pressure during AJM [1]. It has been observed that higher particle velocities resulted in more brittle fracture and material removal in AJM of alumina ceramics [7]. The trends in surface roughness are also in agreement with the erosion rate models, which predict higher erosion rates at increased particle velocities [1], [3].Effect of Machining Time on Surface Roughness

The influence of machining time on the average surface roughness at different air pressures is also evident in Table 1 and Figure 2. For all pressures tested, Ra initially decreased with an increase in machining time from 20 seconds to 40 seconds. However, beyond 40 seconds, the reduction in Ra was less pronounced, especially at higher pressures.

For instance, at 6 bar pressure, Ra reduced sharply from

2.36 μm after 20 seconds to 2.00 μm after 40 seconds of machining. A further increase in time to 45 seconds resulted in a smaller decrease in Ra to 1.61 μm. At 8 bar pressure, Ra decreased from 2.19 μm at 20 seconds to 1.57 μm at 40 seconds, but only marginally to 1.39 μm after 45 seconds. Figure 5 shows the Sample Before and After Finishing at 7 Bar Pressure, and Table 3 presents the experimental data used at 7 Bar pressure.

Figure 6 shows the line diagram of average roughness at 6 bar pressure at different time intervals. The initial steep reduction in surface roughness with machining time can be explained by the rapid removal of surface peaks and asperities by the impacting abrasive particles. As machining pro-

Figure-3. Sample Before and After Finishing At 6 Bar Pressure

Table-2. Experimental details at 6 Bar Pressure

Time (in second)	Standoff distance	Average Roughness (**μm)**
20	2mm	2.361μm
40	2mm	2.006 μm
45	2mm	1.61 μm

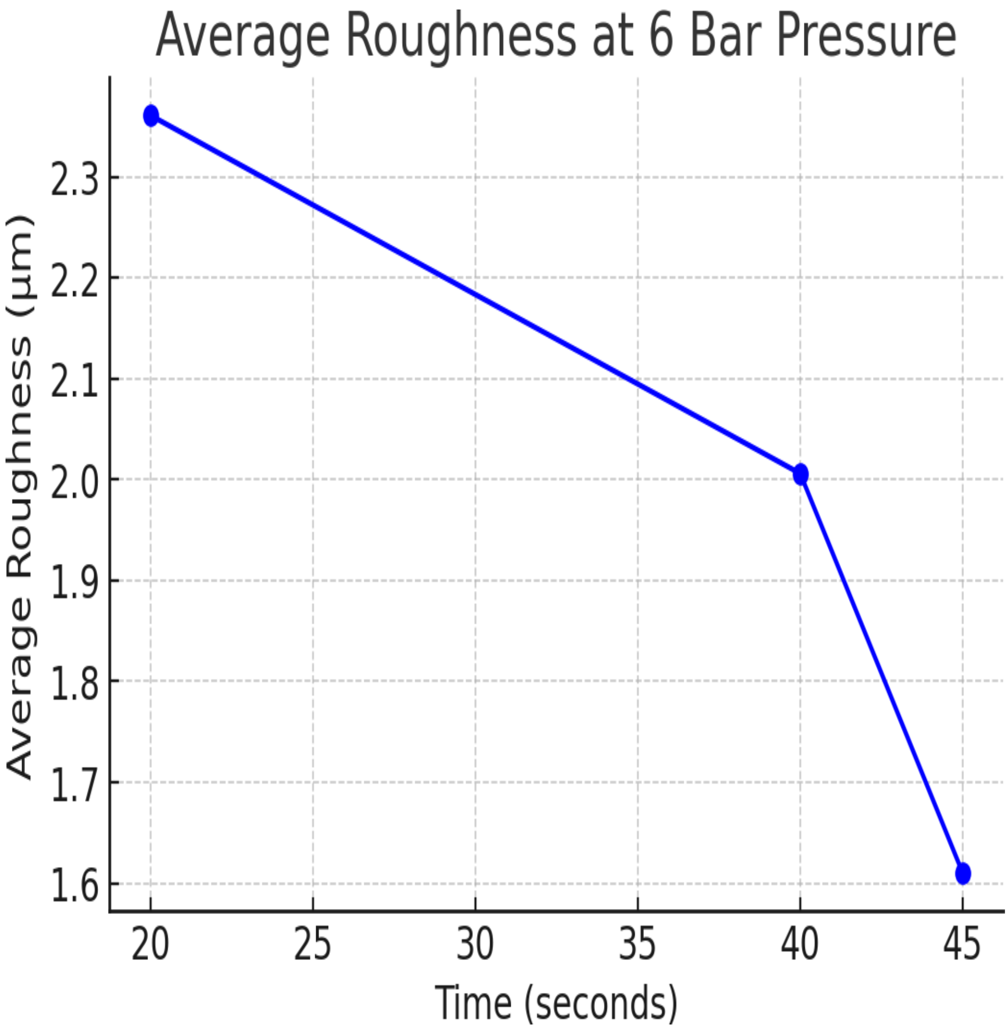

Figure-4. Line Diagram Showing Average Roughness at 6 Bar Pressure at Different Time Intervals

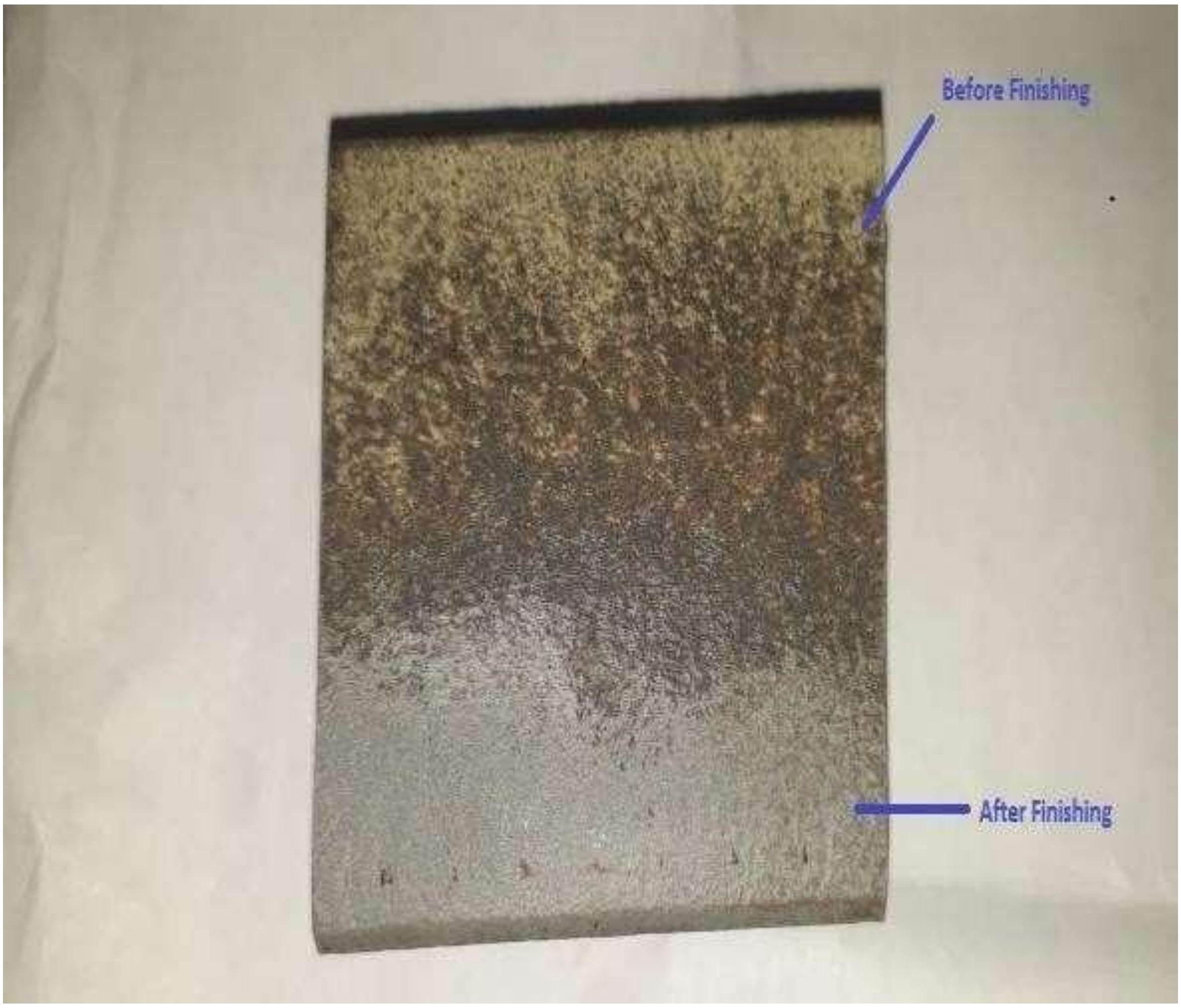

Figure-5. Sample Before and After Finishing At 7 Bar Pressure

Table-3. Experimental details at 7 Bar Pressure

Time (in second)	Standoff distance	Average Roughness (μm)
20	2mm	2.3 μm
40	2mm	1.37 μm
45	2mm	1.34 μm

gresses, the surface becomes smoother, and the material re- moval rate decreases. Beyond an optimal time, re-deposition of fractured abrasive particles and debris can occur, which hinders further improvement in surface finish.

It has been found that the surface roughness of mild steel decreased with increasing machining time up to a certain duration, beyond which roughness started increasing again due to particle re-deposition. Ghobeity et al. also observed that the surface waviness and roughness initially decreased rapidly with time in AJM of glass, but the rate of change re- duced at longer times [3].

Optimal Parameters for Minimum Surface Roughness

Based on the experimental results, the optimal AJM pa- rameters to achieve minimum surface roughness on mild steel are:

- Air pressure: 8 barStandoff distance: 2 mm
- Machining time: 40-45 seconds

Under these conditions, an average surface roughness (Ra) between 1.39-1.57 μm could be obtained, which is a signif- icant improvement compared to the initial Ra of 3.47-4.02

μm. The optimal pressure of 8 bar is the highest value tested in this study. Even lower Ra values may be possible at pres- sures beyond 8 bar, but this needs to be confirmed through further experiments.

The recommended machining time of 40-45 seconds repre- sents the point beyond which the reduction in Ra is marginal. Increasing the machining time further may not be beneficial as it can lead to increased processing cost and time without significant gain in surface quality. Figure 7 shows the Sam- ple Before and After Finishing at 8 Bar Pressure, and Table 4 presents the experimental data used at 8 Bar pressure. Fig- ure 8 shows the line diagram of average roughness at 6 bar pressure at different time intervals.

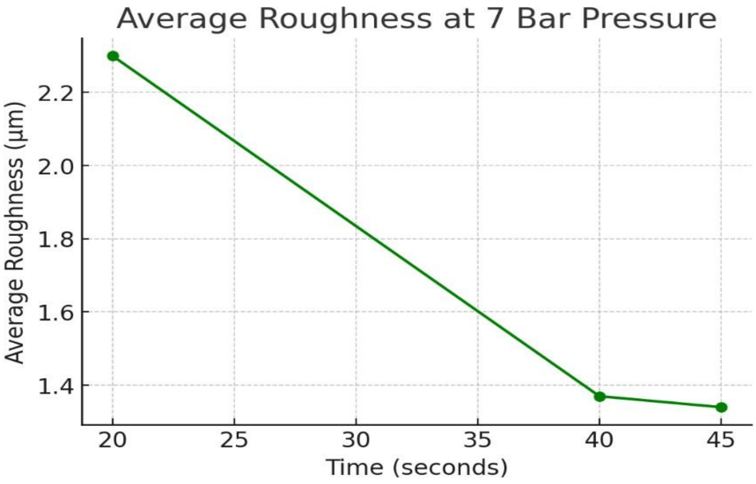

Figure-6. Line Diagram Showing Average Roughness at 7 Bar Pressure at Different Time Interval s

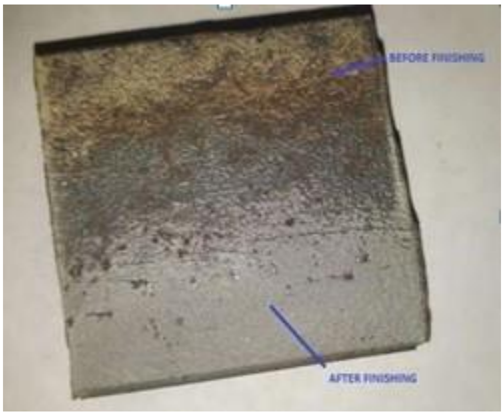

Figure-7. Sample Before and After Finishing at 8 Bar Pressure Table-4. Experimental details at 8 Bar Pressure

Time (in second)	Standoff distance	Average Roughness **(μm)**
20	2mm	2.19μm
40	2mm	1.57μm
45	2mm	1.39μm

t should be noted that these optimal parameters are spe- cific to the mild steel workpiece and aluminum oxide abra- sive particles used in this study. The results may vary for different material-abrasive combinations and need to be de- termined through separate experiments [7], [19]- [20].

Limitations and Future Work

While this experimental study provides useful insights into the impact of AJM factors on the surface roughness of mild steel, there are a few limitations that need to be addressed through future research:

- The study considered only three levels of air pressure and machining time. Testing more intermediate levels can help generate a more comprehensive understanding of the param-eter effects and optimize the process settings further.

- The experiments were performed at a single standoff dis- tance of 2 mm. The influence of standoff distance on surface roughness needs to be evaluated in detail.

- Only one type of abrasive particle (aluminum oxide) with a single average size was used. Future studies should exam- ine the effects of different abrasive materials, sizes, and size distributions on the surface roughness.

- The surface roughness was characterized using only the Ra parameter. Other roughness parameters, such as Rz, Rq, and others related to characteristics of the surface topography, have to be reviewed for a complete realization of the surface quality.

- This machining was carried out with a fixed nozzle head

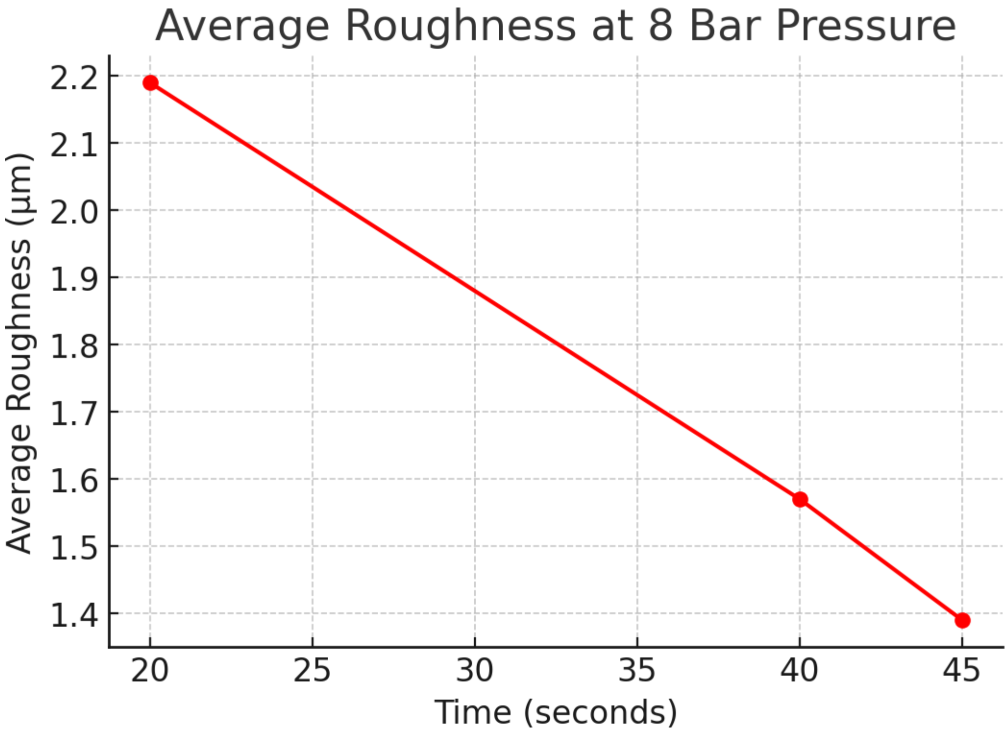

Figure-8. Line Diagram Showing Average Roughness at 8 Bar Pressure at Different Time Interval s

and no oscillation or movement of the workpiece. With such strategies in combination and related parameters optimized, surface uniformity will be improved over large area coverage.

- Mechanism of material removal and evolution of surface morphology in AJM of mild steel are to be studied in detail through scanning electron microscopy and profilometry mea- surements. That should bring out a fundamental understand- ing of this process and help to establish models for predictive surface roughness.
- Study the effect of abrasive particle material, size, and shape on the surface roughness and morphological evolution of mild steel in the course of AJM.
- Investigation on residual stress, microhardness, and mi- crostructural alteration surface integrity aspects due to AJM and ensure functional performance of produced components.
- Development of physics-based and data-driven models for the prediction of surface roughness in AJM under varied processing conditions. Such models may be used for the op- timization of the process and the control of the process. The roughness values were obtained at 20 sec, 40 sec, and 45 sec for a 6 bar pressure.
- The feasibility of sought-after new abrasives could be biodegradable and environmentally friendly media, which will give AJM a more sustainable nature.

Such set limitations can be addressed by properly designed experiments, and they can contribute massively to the knowl- edge base of AJM for ductile materials like mild steel. This could form the basis for the determination of optimal process windows and control strategies in the pursuit of the attain- ment of the intended surface quality in the industrial use of

this versatile machining technique.

Conclusions

This research experimentally studied the influence of AJM process parameters such as air pressure, standoff distance, and machining time over surface roughness in the case of mild steel specimens. An increase in air pressure from 6 to 8 bar showed a significant decrease in the average sur- face roughness, Ra, for all machining times tested, with the lowest Ra of 1.39 μm obtained at 8 bar pressure and 45 sec- onds machining time from an initial value of 3.47 to 4.02

μm. The surface roughness dropped by a very high percent- age at the beginning by increasing the machining time from 20 to 40 s for all the pressures; however, thereafter, the fall was marginal after 40 s, showing an optimum machining time of 40–45 s for the minimum surface roughness. Based on these results, the recommended AJM parameters for getting the best surface finish in mild steel are air pressure—8 bars, standoff—2 mm, and machining time of 40-45 seconds. The paper, therefore, enunciates AJM as an efficient process for enhancement in the surface finish of mild steel components and provides insight into process optimization to get the de- sired surface quality for many industrial applications.

References

[1] Melentiev, R. and Fang, F., Recent advances and challenges of abrasive jet machining. *CIRP Journal of Manufacturing Science and Technology*, *22*, 1-20, 2018.

[2] A Yadav and M L Jain. Abrasive jet machining- re- search review. *SSRN Electronic Journal*, 2014.

[3] Jiang, M., Cai, J., Liao, Z., Lv, X., & Huang, C., Research progress in abrasive water jet processing technology. Frontiers in Materials, 10, 2023. https://doi.org/10.3389/fmats.2023.1141275

[4] R V Rao and P S Rao. Abrasive jet machining pro- cess parameters optimization by using the Jaya algorithm. *International Journal of Engineering Research and Applications*, 9(1):24–29, 2019.

[5] A Yadav and M L Jain. A sustainable challenges of abrasive jet machining (AJM): Art of review. *International Journal of Engineering Research & Technology*, 7(5):1–4, 2018.

[6] M JVenkatesh, V. C., Goh, T. N., Wong, K. H., & Lim, M. J., An empirical study of parameters in abrasive jet machining. *International Journal of Machine Tools and Manufacture*, *29*(4), 1989.

[7] R V Rao and P S Rao. Abrasive jet machining process parameters optimization using the Jaya algorithm. *IOP Conference Series: Materials Science and Engineering*, 1193, 2022.

[8] Uthayakumar, M., Khan, M. A., Kumaran, S. T., Slota, A., & Zajac, Machinability of nickel-based superalloy by abrasive water jet machining. *Materials and Manufacturing Processes*, *31*(13), 1733-1739, 2016.

[9] R V Rao and P S Rao. Abrasive jet machining process parameters optimization using teaching-learning-based optimization algorithm. *International Journal of Me- chanical Engineering and Technology*, 9(4):202–211, 2018.

[10] M Uthayakumar, P Marimuthu, V Muthuraman, V Jayaseelan, A Tzotzis, L Tzounis, and G D Panagiotou. Investigating the machining performance of abrasive water jet machining on Inconel 718 alloy. *Met- als*, 11, 2021.

[11] R V Rao and P S Rao. Abrasive jet machining process parameters optimization using Jaya algorithm. *Interna- tional Journal of Mechanical and Production Engineer- ing Research and Development*, 8(6):1–10, 2018.

[12] M Uthayakumar, P Marimuthu, V Muthuraman, V Jayaseelan, A Tzotzis, L Tzounis, and G D Panagiotou. Investigating the machining performance of abrasive water jet machining on Inconel 718 alloy. *Ma- terials Today: Proceedings*, 18:2125–2130, 2019.

[13] R V Rao and P S Rao. Abrasive jet machining process parameters optimization using Jaya algorithm. *IOSR Journal of Computer Engineering*, 20(4):84–89, 2018.

[14] R V Rao and P S Rao. Abrasive jet machining process parameters optimization using Jaya algorithm. *Journal of Advanced Manufacturing Systems*, 21(4):1–10, 2022.

[15] R Varun and T Nanjundeswaraswamy. A Literature Re- view on Parameters Influencing Abrasive Jet Machining and Abrasive Water Jet machining. *Journal of Engineering Research and Application*, 9(1):24–29, 2019.

[16] K Venkatesan, S Devendiran, D Sachin, and J Swaraj. Investigation of machinability characteristics and

comparative analysis under different machining conditions for sustainable manufacturing. *Measurement*, 154:107425–107425, 2020.

[17] R Balasubramaniam, J Krishnan, and N Ramakrishnan. An experimental study on the abrasive jet deburring of cross-drilled holes. *Journal of Materials Processing Technology*, 121(2-3):360–368, 2002.

[18] M Uthayakumar, P Marimuthu, V Muthuraman, V Jayaseelan, A Tzotzis, L Tzounis, and G D Panagiotou. Investigating the machining performance of abrasive water jet machining on Inconel 718 alloy. *Materials Today: Proceedings*, 18:2125–2130, 2019.

[19] M Uthayakumar, P Marimuthu, V Muthuraman, V Jayaseelan, A Tzotzis, L Tzounis, and G D Panagiotou. Investigating the machining performance of abrasive water jet machining on Inconel 718 alloy. *Materials Today: Proceedings*, 56:2125–2130, 2022.

[20] A K Chaitanya, D K Babu, and K G Kumar. Experimental study on surface roughness by using abrasive jet machine. *Materials Today: Proceedings*, 23:453–457, 2020.