EVALUATING THE IMPACT OF TECHNOLOGICAL PARAMETERS ON MATERIAL REMOVAL IN ABRASIVE WATER JET MACHINING OF A STAINLESS STEEL

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Abrasive Water Jet (AWJ) machining has emerged as a promising technology for processing hard-to-machine materials like stainless steel. This paper investigates the application of low-pressure AWJ machining (50 MPa) for milling stainless steel with a controlled depth of cut. The aim is to optimize AWJ process factors to achieve desirable results in industrial applications. Experimental measurements were conducted at a constant water pressure of 50 MPa, varying the cutting head traverse speed, abrasive mass flow rate, and the number of passes to evaluate their impact on material removal efficiency. The study emphasizes material removal from the surface, surface evaluation, and potential for industrial application. The findings contribute to bridging the research gap regarding the optimization of AWJ parameters for stainless steel milling applications.

KEYWORDS

AWJ, abrasive water jet, controlled depth, stainless steel

1 INTRODUCTION

Abrasive water jet (AWJ) machining with controlled dept of cut (so called water jet milling) is variation of common process of AWJ cutting. Mentioned way of approach require to set technological parameters (traverse speed, abrasive mass flow, pump pressure etc.) to remove layers of material instead of cutting through. Pioneering researcher dealing with AWJ cutting and machining is Mohamed Hashish [Hashish 2003], who defined modern water jet machining [Hashish 1984].

There are many studies dealing with AWJ controlled depth of cut machining of different materials. Machining of planar surfaces, slots and profiles was described by Popan et al. [Popan 2015]. Investigation of pockets machining of titanium alloy was point of interest of authors Kanthababu et al. [Kanthababu 2016]. Cenac et al was dealing with machining of aeronautic aluminium alloy [Cenac 2015]. Authors Escobar-Palafox et al characterized process of AWJ pocketing od nickel-based alloy [Escobar-Palafox 2012]. Azarsa et al described micromachining of ribs with high aspect ratio [Azarsa 2020a] and creation of micro features in molds production [Azarsa 2020b].

Holmberg et al presented research of efficient AWJ machining of nickel-based superalloys for turbines. Technological parameters influence on machining process of hard to machine material was described by Krenicky et al. [Krenicky 2022]. Olejarova et al focused on vibrations monitoring during AWJ machining [Olejarova 2021]. Botko et al. [Botko 2023] performed experiments for determination of optimal technological parameter for AWJ machining of titanium alloy and Vandzura et al. [Vandzura 2024] deals with AWJ machining of alloyed and additively manufactured stainless steel.

The research presented was motivated by a lack of pocket manufacturing by the AWJ-machining produced using 50 MPa pump pressure. Most of the published papers deals with pump pressure 100 – 200 MPa.

2 MATERIAL AND METHODS

The motivation behind this study stems from the need for precise and efficient machining of hard-to-machine materials like AISI 316L stainless steel, especially in industries requiring high corrosion resistance and minimal thermal influence during processing. AWJ machining, which offers a cold-machining process, is particularly suited for such applications. This study aimed to explore how different AWJ parameters impact material removal for industrial applications. The experiment was conducted using an AWJ setup with a constant water pressure of 50 MPa. Key variables were adjusted to evaluate their influence on material removal volume: the traverse speed of the cutting head, abrasive mass flow rate, and the number of passes. The focus was on measuring the volume of material removed from the surface of AISI 316L stainless steel specimens and analysing how each parameter contributed to material removal efficiency [Dodok 2017, Cubonova 2019].

The selected experimental material, stainless steel AISI 316L, is known for its excellent corrosion resistance, mechanical properties, and weldability. It primarily consists of iron, with key alloying elements of chromium (16-18%), nickel (10-14%), and molybdenum (2-3%), enhancing resistance to pitting and crevice corrosion, especially in chloride-rich environments, such as seawater and industrial settings. The “L” in its name indicates a low carbon content (maximum 0.03%), which helps reduce carbide formation during welding, thus preventing sensitization and maintaining corrosion resistance in welded areas. This steel retains strength and toughness even at high temperatures, making it suitable for demanding applications across chemical processing, maritime, medical, food, and pharmaceutical industries. The chemical composition of AISI 316L is presented in Table 1 .

Table 1. Chemical composition of AISI 316L

Element	% Present	Element	% Present
C	0.3	**Cr**	16.5-18.5
Si	1	**Ni**	10-13
Mn	2	**N**	0.10
P	0.045	**Mo**	2-2.5
S	0.015	**Fe**	balance

The dimensions of the experimental specimens from AISI 316L material were 150 x 20 mm with a thickness of 10 mm.

The experimental procedures were carried out utilizing the Water Jet 3015 RT – 3D apparatus, manufactured by Kov-ostrojservis, Ltd., based in the Czech Republic. The device features a worktable with dimensions of 3000 mm by 1500 mm, providing ample space for processing large materials. A key component of the machine is its 3D cutting head, capable of tilting up to 45 degrees in both the X and Y axes, allowing for complex geometrical cuts with high precision. Water pressure for the cutting process is supplied by a high-performance pump, the PTV Jets 3.8/60. This pump can generate a maximum water pressure of 415 MPa, with a flow rate reaching 3.8 liters per minute, ensuring sufficient power for cutting a wide range of materials under high-pressure conditions. This setup offers a robust and versatile solution for precision cutting in various applications. The experiment process involved linear passes with set process parameters of the abrasive waterjet machining head over the experimental material. The process is illustrated in Figure 1.

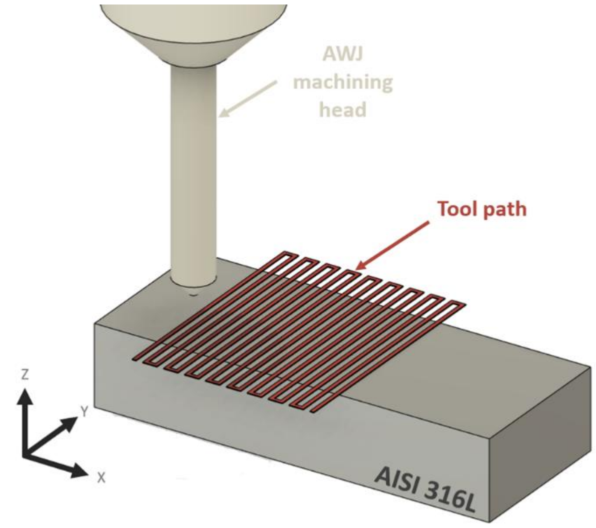

Figure 1. Schematic representation of machining during the experiment

The process parameters used in the experiment can be categorized as fixed and variable. The fixed parameters of the machining head and the abrasive nozzle used are shown in Table 2.

Table 2. Parameters of cutting head

Nozzle diameter Dv (mm)	Diameter of focusing tube Df (mm)	Length of focusing tube Dl (mm)	Tilt angle of cutting head γ (°)
0.33	1.02	76.2	90

The experiment was conducted at a low water pressure of 50 MPa. The standoff distance (SoD) was set to a standard 4 mm. The overlap of the cutting head paths was set to 0.5 mm. The variable process conditions of the experiment included the traverse speed (v_f) was set to 100 mm.min^{-1}, 200 mm.min^{-1}, and 300 mm.min^{-1}, with an abrasive mass flow (m_a) of 35 g.min^{-1}and 50 g.min^{-1}, using one or two passes of the machining head. The individual combinations of conditions, along with the specimens' designations, are presented in Table 3.

Table 3. Specimens marking and technological parameters

Specimen No.	Number of passes	Abrasive mass flow m_a (g.min^{-1})	Traverse speed v_f (mm.min^{-1})
1	1	35	100
2			200
3			300
4		50	100
5			200
6			300
7	2	35	100
8			200
9			300
10		50	100
11			200
12			300

A total of 12 specimens of the experimental material were prepared from the various combinations of process conditions. The control program for the movement of the CNC AWJ machine was designed using the CAM software IGEMS. The CNC AWJ machine movement was programmed in IGEMS CAM software to provide smooth, continuous movement across the dimensions of the experimental specimens, eliminating issues with acceleration and deceleration on short distances (Figure 2).

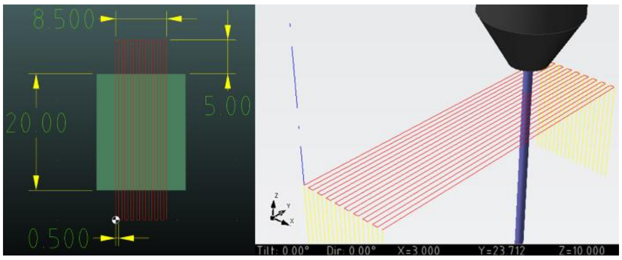

Figure 2. The programming of the program in IGEMS

3 RESULTS AND DISCUSION

In evaluating the machining results of AISI 316L stainless steel using low-pressure abrasive waterjet, the main parameter observed was the material removal volume. Based on adjustments in the traverse speed of the cutting head, the abrasive mass flow and the number of passes over the material, an analysis was conducted on their effect on the volume of material removed.

The experimental results were analyzed using a 4K microscope, which allowed for the creation of detailed three-dimensional scans and provided highly accurate visualization of the specimens.

To assess the observed parameters, the machined specimens were scanned using a Keyence VHX-7000 4K optical microscope. This advanced 3D microscope is engineered for high-resolution surface analysis, offering non-invasive three-dimensional imaging and precise measurement capabilities. By leveraging multiple magnifications, automatic focusing, and the flexibility to analyze specimens from various angles, the VHX-7000 delivers highly accurate and reliable results.

The experimental data were captured using a 20-200x objective lens at 150x magnification in 3D optical scanning mode with reflection reduction. Figure 3 shows the processed surface scan of Specimen No. 8.

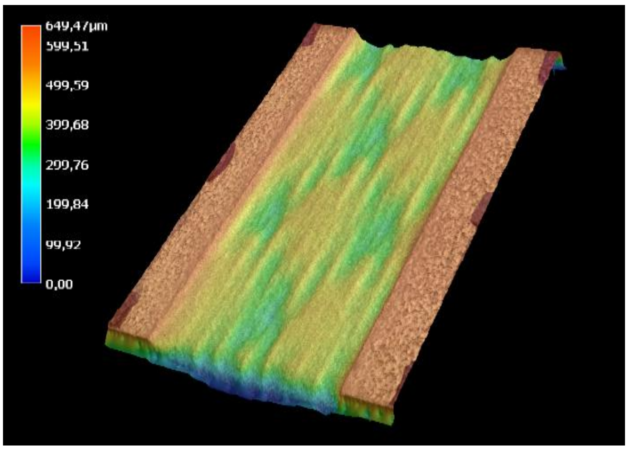

Figure 3. 3D scan specimen No. 8.

Scanning and data acquisition were performed for all 12 specimens. To ensure the relevance of the results, the settings for conditions, imaging, scanning, and image processing were kept consistent across all evaluated specimens. Figure 4 shows the scanned surfaces of the machined material specimens.

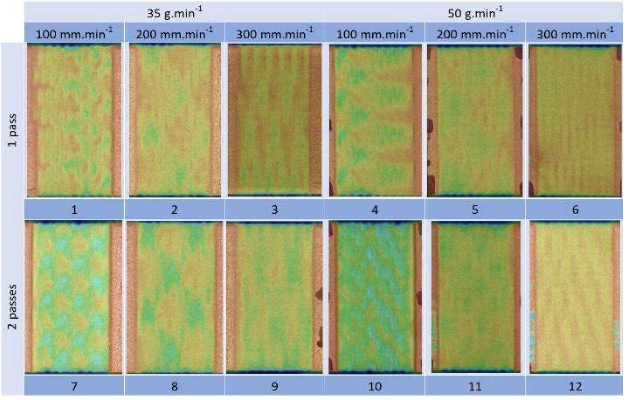

Figure 4. Surfaces of scanned specimens

The experimental specimens were subjected to various combinations of traverse speeds (v_f), abrasive mass flow (m_a), and the number of passes. These combinations had a significant impact on the amount of material removed, which was subsequently quantified by the parameter material volume removed (M_{VR}). The volume of removed material was obtained from 3D scans. To eliminate the influence of material removal at the corners of the specimen, measurements were conducted on a 12x15 mm area at the center of the specimen. Figure 5 illustrates the measurement on specimen No. 7.

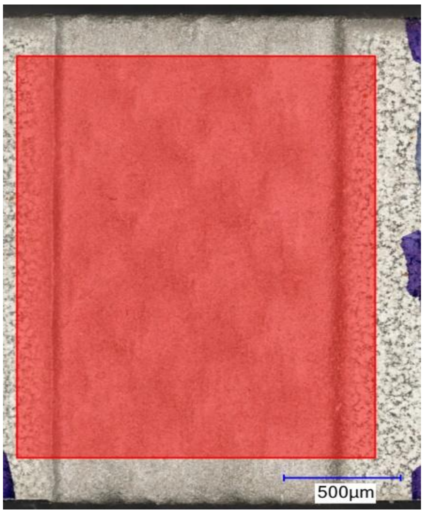

Figure 5. Area of measurement

The measured volumes of the removed material represented by the variable Material volume removed (M_{VR}) for each specimens are in Table X.

Table 2. Volume of removed material

Specimen No.	Material volume removed M_{VR} [mm³]
1	23.659
2	11.713
3	4.732
4	26.467
5	12.664
6	8.686
7	52.909
8	21.388
9	10.669
10	66.462
11	23.704
12	12.335

The largest material volume removal was recorded with the parameter combination of traverse speed v_f=100mm.min^{-1}, abrasive mass flow, m_a=50g.min^{-1}, and two passes in specimen No. 10. The smallest material removal, M_{VR}=4.732mm^3, was observed with the parameter combination of v_f=300mm.min^{-1}, m_a=35g.min^{-1}, and a single pass of the cutting head in specimen No. 3.

Increasing the number of passes from one to two resulted in a significant rise in the removed volume across all examined cases. Specimens with two passes achieved nearly double the material removal volume compared to those with a single pass under identical conditions for the other parameters. From the measured MVR data, it can be concluded that the number of passes has the greatest impact on the volume of material removed. This observation underscores the critical role of pass count in enhancing the efficiency of the material removal process.

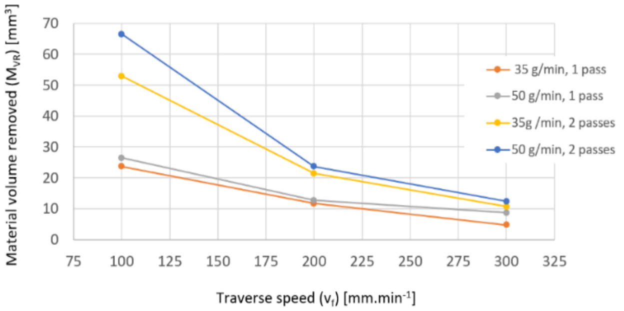

Figure 6. Graph of Material volume removed (M_{VR}) vs traverse speed (v_f)

From the analysis of the graph (Figure 6) showing the dependence of traverse speed v_f on material volume removal M_{VR}, it can be concluded that increasing the feed rate reduces the erosive effect, thereby decreasing the effective impact of abrasive particles on the material, which is reflected in a lower volume of material removed. Reducing the traverse speed v_f to 100 mm.min^{-1} yields the highest material removal values, indicating that lower traverse speeds are more favorable for maximizing material removal.

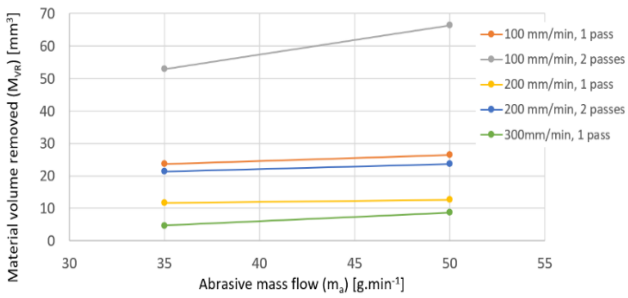

Figure 7. Graph of Material volume removed M_{VR} vs Abrasive mass flow m_a

The abrasive mass flow rate m_a also significantly affects the material volume removed M_{VR}. Increasing m_a from 35 g.min^{-1} to 50 g.min^{-1} resulted in a higher volume of material removal, with this effect being more pronounced at lower traverse speed v_f. A higher abrasive mass flow rate ensures a more intense impact of abrasive particles on the material, leading to more efficient material removal (Figure 7).

4 CONCLUSION

Experimental AWJ machining of stainless steel AISI 304 shows promising results for 50 MPa pump pressure. As is evident from the obtained results:

- highest material removal for single transition of water jet with 0,5 mm overlap was achieved for 50 g.min^{-1} of abrasives mass flow and 100 mm.min^{-1} of traverse speed

- highest material removal for two transitions was also observed for combination 50 g.min^{-1} of abrasives mass flow and 100 mm.min^{-1} of traverse speed
- most significant factor affecting the material removal is traverse speed in the range 100 – 300 mm.min^{-1}

Using abrasive water jet for milling like operations shows application potential for machining of hard to machine materials and for heat sensitive materials due to absence of heat affection. Surface topography after abrasive water jet machining predetermines it for roughing operations with subsequent finishing using milling or EDM.

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