DOI: 10.21062/mft.2025.011 http://www.journalmt.com

Investigation of the Wear Progression of Nozzle in Abrasive Waterjet Machining with Different Abrasive Material

Nuraini Lusi (0000-0001-9113-4976)[1,2], Mebrahitom Gebremariam (0000-0002-9430-6734)[3], Abdur-Rasheed Alao (0000-0003-4525-2685)[4], Kushendarsyah Saptaji (0000-0002-8821-5211)[5], Azmir Azhari (0000-0003-3190-6123)[1*]

[1]Faculty of Manufacturing and Mechatronic Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah, 26600, Pekan, Pahang, Malaysia. E-mail: azmir@umpsa.edu.my

[2]Department of Mechanical Engineering, Politeknik Negeri Banyuwangi, 68461, Banyuwangi, East Java, Indonesia. E-mail: nurainilusi@poliwangi.ac.id

[3]College of Engineering and Built Environment, Birmingham City University, Birmingham B47XG, United Kingdom. E-mail: mebrahitom.gebremariam@bcu.ac.uk

[4]Faculty of Engineering, Universiti Teknologi Brunei, Gadong, BE1410, Brunei Darussalam. E-mail: rasheed.alao@utb.edu.bn

[5]Department of Mechanical Engineering, Faculty of Engineering and Technology, Sampoerna University, South Jakarta, 12780, Jakarta, Indonesia.
E-mail: azmir@umpsa.edu.my

Determining the productivity and quality of precision AWJ machining requires routine and careful inspection of nozzle condition. The degradation of the inner bore of the nozzle adversely impacts the mixing efficiency and uniformity of the water jet, thereby affecting its cutting performance. In this study, new nozzle was designed and manufactured using additive manufacturing and were made of 316 L stainless steel. The new nozzle consists of two combined parts with the peculiarity of being easy to install using a screw thread. The wear behaviour of the new nozzle was examined using an accelerated wear test. An accelerated wear test was conducted on the hard abrasive silicon carbide (SiC) and compared to garnet, the abrasive commonly used in the AWJ industry. The aim of the test was to determine the wear pattern of the nozzle. The cumulative mass loss and nozzle diameter increase for different abrasives were measured. The geometric change in the nozzle is made visible through destructive examination. The findings indicated that the type of abrasives significantly affects nozzle wear. As the hardness of the abrasive increases, the diameter of the nozzle enlarges, resulting in accelerated nozzle wear. The mass loss factor of SiC abrasives is three times higher than that of garnet abrasives. This research allows practitioners to monitor the nozzle wear behaviour during the AWJ process. The results obtained were used to estimate the nozzle life based on the observed wear history.

Keywords: Wear characteristic, Accelerated wear test, Nozzle design, Focusing diameter

1 Introduction

The non-traditional machining technique known as abrasive water jet machining technology (AWJ) is extensively employed in many different industrial applications [1]. This technology exhibits reduced sensitivity to material properties due to its lack of chatter, absence of thermal effects, minimal stress application on the material, along with its exceptional machining versatility and adaptability [2]. AWJ machining is a highly effective technique commonly employed for machining hard and brittle materials, valued for its technical efficiency and cost-effectiveness. Scientific research demonstrates that waterjet technology performs well across a wide range of materials, including titanium alloys [3], aluminium alloys [4] , composites [5], and glass [6]. However, there are certain disadvantages associated with it, most notably the possibility of generating excessive noise and creating a disorganized work environment [7] . A specialized tool is used in the AWJ process to effectively machine a variety of materials without contact or inertia. This process offers several advantages, including a narrow kerf, minimal heat affected zone, less waste material, and the ability to be used in various machining processes [8]. AWJ machining significantly minimizes or eliminates the risk of environmental pollution from fibrous materials because the water jet effectively removes the eroded material from the workpiece's surface [3]. The selection of various processing parameters, including hydraulic, abrasives and machining parameters, has a great impact on the machine's ability to cut a variety of materials with different thicknesses.

Particles of abrasive material act as a remover and water as an accelerator. Fundamentally, water is released from a small opening with a diameter of

0.01-0.02 mm, which is composed of hard materials like sapphire, after it has been compressed to an ultra-high pressure of up to 400 MPa [9]. Shear, cracking, erosion, cavitation, delamination, and plastic damage are types of material degradation caused by the system's high-velocity water flow, which can attain speeds of up to 915 m.s^{-1} [9].

Garnet is abrasive that most commonly used in industrial application. This material is often used as an abrasive in high-pressure water jets because it can achieve high efficiency at a rela tively low cost, which increases the durability of the focusing tube [1]. Slag [7], aluminum oxide [8], and silicon carbide (SiC) are useful alternatives to other synthetic and natural abrasives. However, other natural and synthetic abrasives, including slag [2], aluminum oxide [8], and silicon carbide (SiC), may also be utilized. Due to the high hardness and geometric aspects of the material, SiC is commonly employed for machining materials that present significant challenges during cutting processes. [3]. A slightly higher cutting speed is possible with a harder abrasive. However, the harder abrasive material also leads to wear on the nozzle. Achieving an optimal balance between extending nozzle lifespan and improving machining efficiency requires the careful selection of abrasive materials [9].

Typically, the abrasive particles are combined with a fast-moving stream of water to create a mixture that is used for cutting metals and other non-metallic materials such as ceramics, such as ceramics, glass, rock, stone, advanced composites, and superalloys [10]. The ability to cut various materials of different thicknesses largely depends on the selection of different processing methods. The major challenge affecting the effectiveness of high-velocity mud jetting is erosion of the nozzle walls. Due to the speed of the jet, which can vary between 100 and 500 m.s^{-1}, and the particle size, which can reach up to 40% of the nozzle diameter, damage to the nozzle can quickly occur [11]. Consequently, in current systems, the nozzles require frequent replacement, typically every 10 to 20 minutes. wear is an important problem analyzed in the work inAWJ processes, which significantly affect the efficiency, reliability andservice life of the high-pressure pumps. This requires ongoing maintenance and inspection and results in reduced accuracy and machine downtime [11].

Most research groups emphasis their efforts on mitigating wear issues, such as employing hard materials in the nozzle [12] , utilizing soft abrasive particle [13], and modifying nozzle geometry [14–16]. The worn nozzle may not experience a uniform wear with equal increase of internal diameter. In most cases, the erosion is more severe near the nozzle inlet than the outlet [6]. Sometimes, the region near the outlet experiences minimal or no erosion at all [7]. However, the worn has to be replaced as a whole although there is no erosion in some part of it. Worn nozzles will be thrown away like worn cutting tools in other traditional machining processes. Nozzles or cutting tools are of great importance to sustainability enhancement. They are made from many types of rare metals [17] including tungsten, boron, molybdenum, cobalt, chromium and vanadium. Therefore, it is important to design a new nozzle which its usage can be reused for a longer tool life. This study presents the latest development of a new design nozzle and conducts a laboratory wear test to illustrate the potential of this newly introduced nozzle.

2 Methods and Material

The current conventional nozzle based on industrial used in AWJ machining was taken as an initial model which consist of single solid body, and design changes have been made. A new design of the nozzle has been developed to compose of two merged parts. The nozzle has a total length of 76.2 mm, with an external focusing diameter of 3.18 mm and an internal focusing diameter of 1.27 mm. The conceptual design proposed are shown as Fig. 1. The total length of the nozzle is partitioned into 75% allocated to the inlet section and 25% designated for the outlet section. The prototype of a nozzle made using the selective laser melting (SLM) method from metal powder SS316L on the RenAM 500E 3D printer. The nozzle was produced through laser powder bed fusion (LPBF), a method of additive manufacturing (AM).

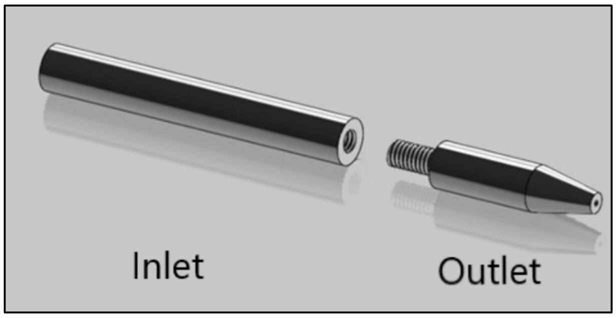


Fig. 1 *The new design of nozzle*

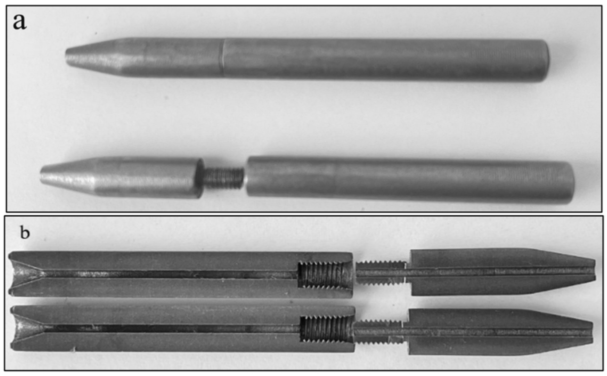


Fig. 2 *3D printed, consisting of inlet and outlet parts (a) Cross section of new printed nozzles (b)*

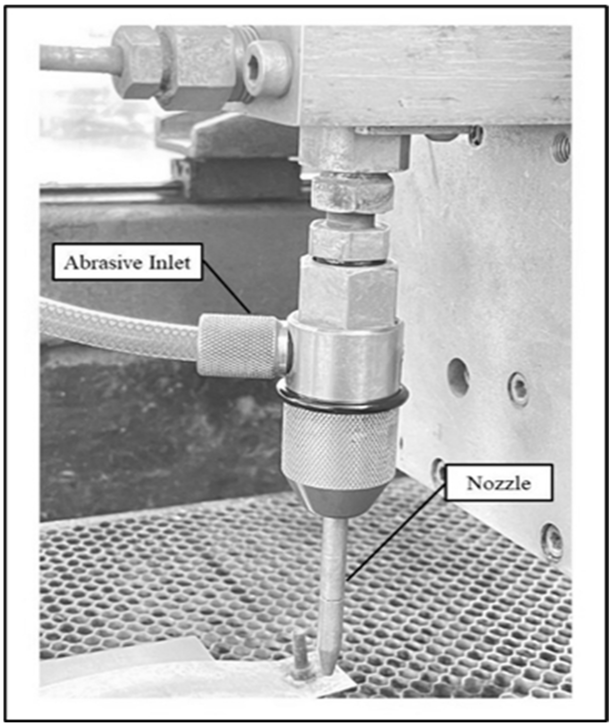


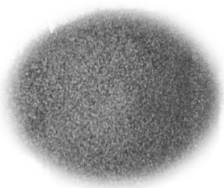
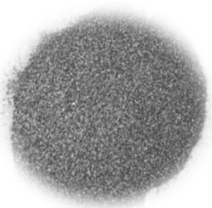
Fig. 3 *The installation of nozzle attached to the cutting head*

The fabricated new nozzles and a cross-sectional view of a waterjet nozzle is illustrated in Fig. 2. The entire nozzle does not need to be discarded after it has worn out, as it is designed with separate components. The outlet component is easily installed using a screw thread mechanism and can be repurposed. Additionally, this novel reusable nozzle design has the potential to minimize waste, thereby promoting environmental conservation. The new design nozzle is compatible to be used in all commercial waterjet machines. It can conveniently fit to any commercial abrasive waterjet machines which uses a commercial nozzle. Furthermore, the life of the nozzle of the outlet part can be extended since it will be reused by replacing the nozzle with a new inlet part. Fig. 3 shows the nozzle installation in AWJ cutting head.

2.1 Nozzle Wear Test and Experimental Setup

The wear performance of nozzles analyzed through two types of tests [18]. Accelerated wear tests and actual wear tests are commonly utilized to investigate the wear behavior of nozzles materials [19] and quickly identify wear trends using less wear-resistant mixing tubes made of steel or harder abrasives like garnet, Silicon carbide and Aluminum oxide [20]. Using the newly developed nozzle, an experiment conducted using selected processing parameters including water pressure, diameter of orifice, abrasive mass flow rate, abrasive particle size and abrasive materials. In order to conduct the accelerated wear test, two type of abrasive particles silicon carbide and garnet were used to accelerate the wear of nozzle. The test is to wear the nozzles intensively within few minutes which represents the use of nozzles beyond the allowed threshold [19–21]. The properties of these abrasive particles listed in Tab 1. The increase in diameter and the mass reduction of the nozzle were documented at specified intervals of 5 minutes. The accelerated test conducted for offset nozzles up to 25% to confirm the trends [20]. A digital scale was utilized to accurately determine the mass of the nozzle both before and after the experiment, ensuring precise measurement of material loss due to wear. The nozzle was subjected to longitudinal sectioning using wire electrical discharge machining (wire EDM) to analyze its internal geometry. This technique offered an accurate cross-sectional perspective, facilitating thorough examination of wear patterns and material deterioration within the nozzle.

Tab. 1 *Abrasive particle properties [10,22]*

Abrasive particle types	Particle size (μm)	Hardness (MOHS)	Grain Shape	Density ($g.cm^{-3}$)
 Garnet	200	6.5 -7.5	Granule, Irregular sharp-edged	4.1-4.3
 Green Silicon Carbide (SiC)	200	> 9	Granule, Irregular sharp-edged	3.15

The wear test was conducted on a self-developed CNC water jet cutting machine, as illustrated in Fig. 4. This machine is equipped with an air-driven liquid pump capable of generating water pressures of up to 100 MPa. The operation of the system is controlled by a computer numerical control (CNC) unit, which precisely regulates the movement of the machine. The table's motion is governed along two axes (X and Y), while the nozzle's movement is controlled along the Z-axis, allowing for accurate depth adjustment. The specific machining conditions used for the nozzle wear test are detailed in Tab 2.

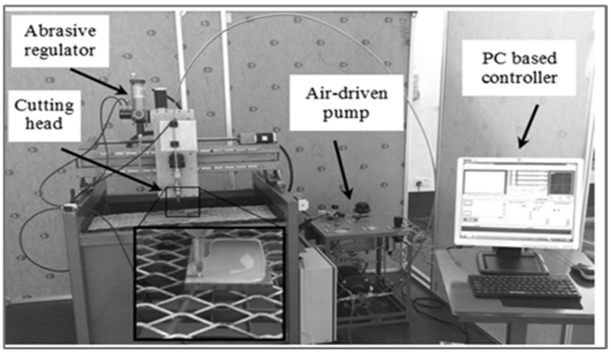


Fig. 4 *The self-developed CNC AWJ machine and [23]*

Tab. 2 *Parameters for AWJ machining process*

System Parameters	Value	Units
Water pressure	69	MPa
Abrasive mass flow rate	10	$g.min^{-1}$
Type of abrasives	Garnet, Silicon carbide (SiC)	200 μm
Particle grit number	#80	mesh
Orifice diameter	0.1016	mm

The nozzle's diameter was measured with a video measurement device. The nozzles were viewed under 10x magnification, and coaxial lighting from above was used to illuminate them. Three points were chosen on the inner edge of the nozzle to ascertain the diameter, after which the software computed the radius. Each nozzle diameter was measured a minimum of four times. The number of measurements increased with the amount of wear on the nozzle. Fig. 5 show the experimental set up of the wear test of the nozzle. Focusing tubes made of tool steel have an effective working life of 15 minutes when using garnet abrasive at a pressure of 207 MPa and an abrasive flow rate of 7.5 $g.min^{-1}$ according to Hashish's research on focusing tube wear [19]. The use of a softer focusing tube material in this experiment compared to Hashish's resulted in significantly accelerated effective working time of the focusing tube.

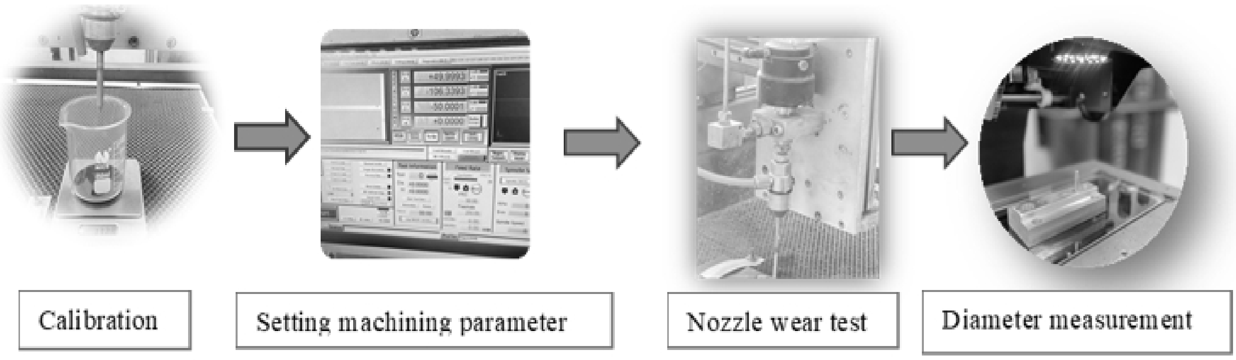


Fig. 5 *The steps of experiment*

3 Results and Discussion

3.1 Wear Progression of Outlet Diameter

The durability of a nozzle is contingent upon its intended application. The permissible maximum increase in exit diameter in this context is 0.3 mm. A significant degree of wear was permissible if this increase reached 25% of the original diameter (1.57 mm). Certain applications clearly endure greater wear than others, allowing a worn tube to be employed in contexts that accommodate larger mixing tube diameters. Fig. 6 depict a diagram demonstrating the correlation between focusing tube wear and cutting time. The figure illustrates that an extended cutting duration correlates with a wider diameter of the focusing tube outlet. The nozzle's contact with garnet abrasive for 15 minutes leads to a minor increase in the outlet diameter, measuring only 0.24 mm. In contrast, when the nozzle encounters silicon carbide (SiC) abrasive, the erosion process transpires significantly more swiftly. After merely 5 minutes of exposure, the outlet diameter expands by 0.36 mm. The notable disparity in erosion rates indicates the more aggressive characteristics of SiC relative to garnet. The elevated abrasion rate of SiC not only accelerates nozzle wear but also diminishes the overall durability of the nozzle under comparable operational conditions. The diameter of the worn nozzle for the #80 garnet and SiC abrasive types is depicted in Fig. 7. The images illustrate that a recently developed nozzle has an opening size that is nearly ideal in terms of circularity. The roundness, on the other hand, gradually decreases as the amount of wear increases. As a result, the jet exhibits increased instability and diminished efficiency. The prolonged use of the focusing tube leads to changes in the exit geometry, particularly an increase in opening eccentricity [24].

The alignment between the orifice and the focusing nozzle significantly impacts wear. Even slight misalignments can result in increased and uneven wear, as the abrasive jet deviates from its intended trajectory, causing localized erosion on the inner surfaces of the nozzle. As time progresses, this uneven wear can intensify the issue, eventually leading to a significant failure referred to as a blowout as shown in the Figure 7 for SiC abrasive section d. A blowout happens when the AWJ wears away the sidewall of the focusing nozzle. Undermining the system's integrity and possibly leading to considerable operational downtime [24].

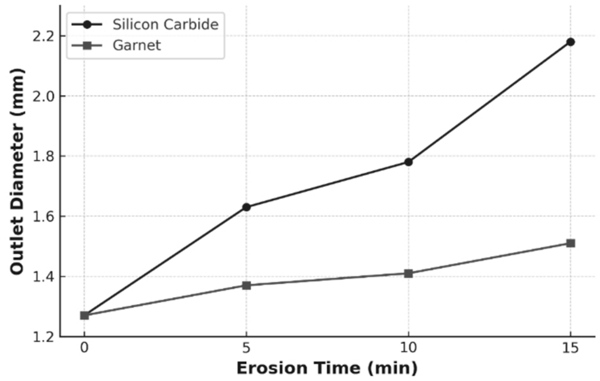


Fig. 6 *Relationship between exit diameter of tested abrasives and erosion duration*

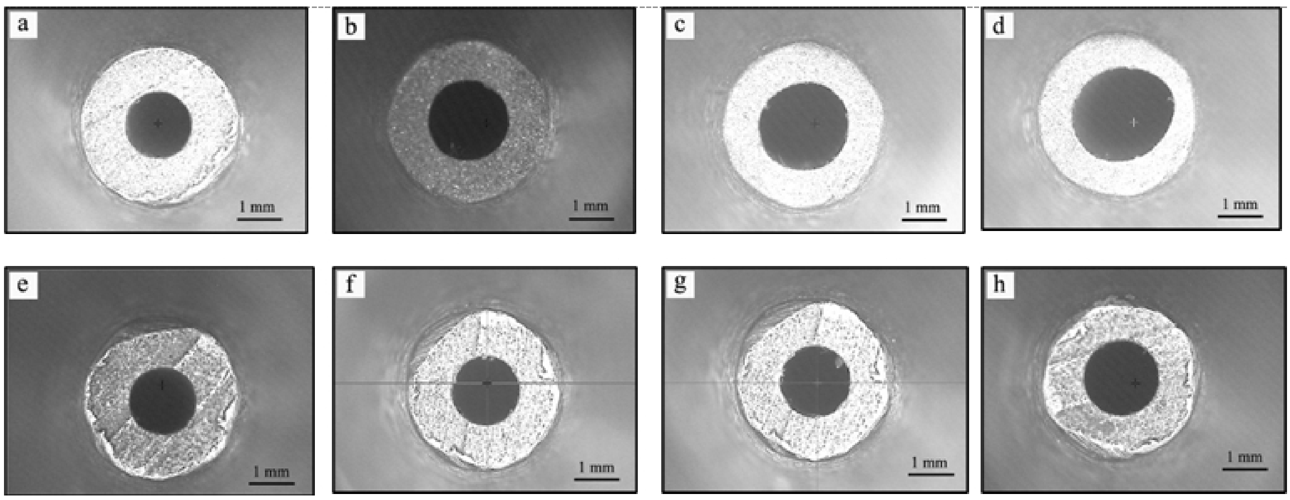


Fig. 7 *Increasing the outlet diameter of the nozzle with SiC abrasive: a) initial diameter, wear test b) 5 minutes, c) 10 minutes, d) 15 minutes of erosion time, and increasing the outlet diameter of the nozzle with garnet abrasive: e) initial diameter, wear test f) 5 minutes, g) 10 minutes, h) 15 minutes of erosion duration*

3.2 Wear Progression of Middle Diameter

The enlargement of the middle diameter during AWJ with various types of abrasives is depicted in Fig. 8. After 5 minutes of testing, the average middle diameter of the worn nozzle reached 0.57 mm with SiC, while it was only 0.36 mm with Garnet abrasive. The worn middle diameter after 15 minutes with SiC abrasives is 2.2 mm, while with garnet abrasives it is 1.75 mm. It is evident that SiC abrasives generated the largest diameter, followed by garnet abrasives. SiC is the hardest abrasive material, thus it maintains its wear resistance as it descends. SiC is acknowledged as the hardest abrasive material, enabling it to maintain its wear resistance while moving through the nozzle during the cutting process. SiC abrasives exhibit superior hardness relative to garnet, allowing them to retain their sharp cutting edges effectively at both the entry and exit points of the jet stream. The retention of sharpness leads to a reduced cut width, as the abrasives sustain their cutting efficiency consistently during the machining process. Conversely, garnet abrasives, due to their softer composition, progressively diminish the sharpness of their cutting edges as they approach the jet exit, resulting in a broader cut and decreased precision [25].

Experimental studies have consistently demonstrated that during machining with various abrasives, the central part of the nozzle undergoes greater wear, resulting in its diameter surpassing that of the outlet. The wear pattern is notably pronounced with SiC, due to its hardness and enduring sharpness, which lead to more intense erosion in the central areas of the nozzle. It was highlighted that the abrasive particles dissipate their kinetic energy as they pass through the jet, resulting in a narrowing of the relative strength zone of the jet. The results of the measurements are interesting and help to justify the nozzle replacement in term of improving nozzle life. Fig. 9 depict a diagram demonstrating the correlation between focusing tube wear and cutting time. The figure illustrates that an extended cutting duration correlates with a wider middle diameter of the focusing tube.

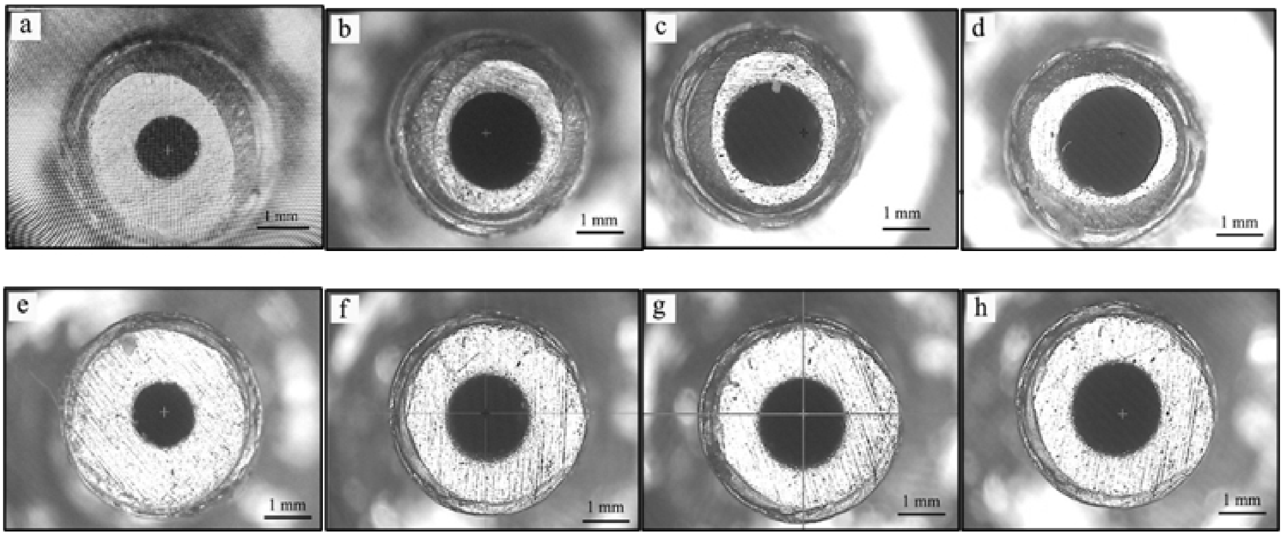


Fig. 8 *Enlargement of the nozzle's middle diameter using SiC abrasive: a) initial diameter, wear test b) 5 minutes, c) 10 minutes, d) 15 minutes of erosion time, and enlargement of the nozzle middle diameter using garnet abrasive: e) initial diameter, wear test f) 5 minutes, g) 10 minutes, h) 15 minutes of erosion duration*

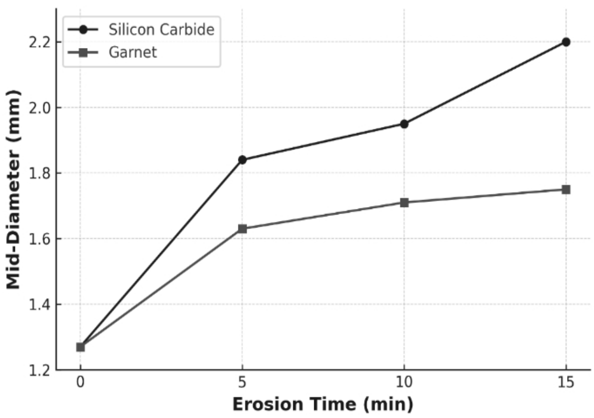


Fig. 9 *Relationship between middle diameter of tested abrasives and erosion duration*

3.3 Mass Loss of Nozzle

Upon completion of each testing phase, measurements were taken and documented for both the inner diameter of the outlet the nozzle mass reduction in. The erosive properties influence not only the parameters of the material being cut, but also impact the durability of the focusing tube [24]. Based on the studies, the ability of erosion abrasive wear rates has been identified through the calculation of the focusing tube. The decrease in the weight of the focusing tube is mainly due to the gradual deterioration of its inner wall, resulting in the formation of noticeable wear patterns on the internal surface. With prolonged use of the focusing tube, the wear patterns become increasingly evident, progressively affecting the structural integrity of the tube. The extended use of the tube ultimately influences its exit geometry, frequently leading to the development of an eccentric or irregular opening at the nozzle exit. The presence of such eccentricity can greatly influence the efficiency of the water jet, resulting in variable cutting quality and heightened nozzle wear [26]. Fig 10 depicts the correlation between the mass loss of the focusing tube and the operational duration for the different abrasive materials evaluated. Silicon carbide #80 demonstrated the most pronounced wear effect among the abrasives, resulting in the greatest mass loss in the focusing tube. Following a 15-minute testing interval, the mass reduction surpassed 0.99 grams, signifying the pronounced erosive characteristics of silicon carbide in comparison to alternative abrasives. The garnet type has the second most wear. The mass loss was over 0.45 g after 15 minutes of exposure.

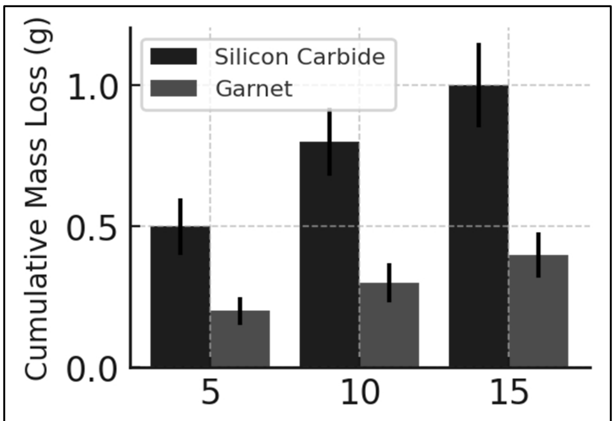


Fig. 10 *Correlation between the nozzle's mass, the abrasive material, and erosion duration*

3.4 Factor of Mass Loss

The mass loss factor was determined using the methodology described by Perec et al. [13], employing the relevant mathematical expression to quantify the wear of the focusing tube. In this equation, Mt signifies the initial mass of the focusing tube and ΔMt denotes the mass loss factor.

$$\Delta \mathrm{Mt} = \frac{\mathrm{mt}}{ma} = \frac{g.\mathrm{min}^{-1}}{\mathrm{kg.min}^{-1}} = \left[g \cdot kg^{-1} \right] \quad (1)$$

Where:

mt…Time of mass loss[$g.min^{-1}$],

ma…Abrasive flow rate [$kg.min^{-1}$].

The outcomes derived from this calculation are illustrated in Fig. 11. The maximum mass loss factor, Mf, observed was 9.98 g kg^{-1}, attributed to the utilization of silicon carbide abrasive, indicating its pronounced erosive properties. The mass loss factor for garnet abrasives was considerably lower, attaining a maximum value of 3.2 g kg^{-1}. As the bore expanded to its maximum size at 15 minutes, the confinement of the high-velocity flow weakened, reducing the impact momentum of the abrasive particles as they exited the nozzle. Consequently, the mass loss factor was lowest at 3 $g.kg^{-1}$ for garnet and 6.9 $g.kg^{-1}$ for SiC, which suggests that the nozzle needs to be replaced. Due to a lower mass loss factor than at 10 minutes, the injected particles were not fully utilized for erosion or service at either 5 or 15 minutes. Therefore, rapid nozzle wear serves as an indicator that the jet is operating at its optimum condition, ensuring effective performance in cutting, peening, or cleaning applications.

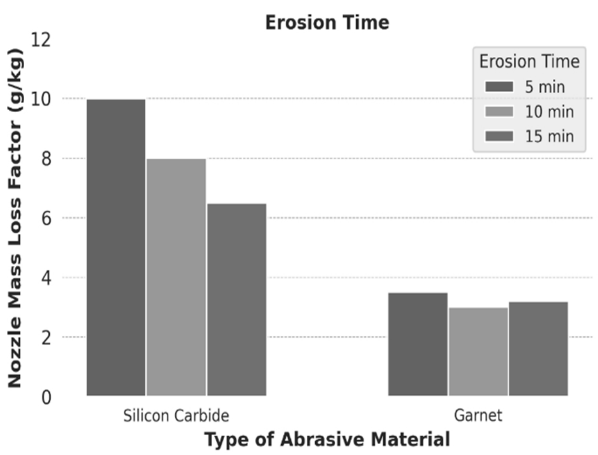
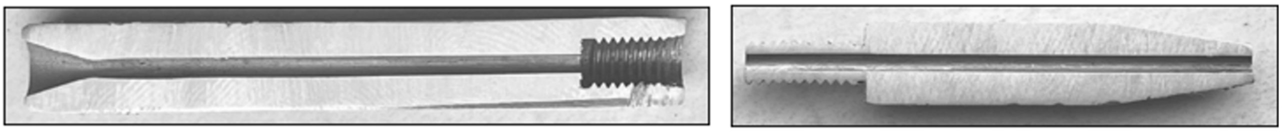


Fig. 11 *Mass loss coefficient of nozzles*

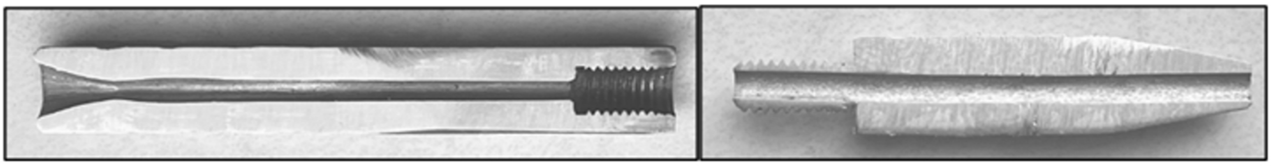
3.5 The configuration of the internal geometry

The interaction of abrasive particles with the inner wall of the focusing tube occurs at multiple angles, leading to material wear and degradation. When the focusing tube is adequately extended, the abrasive particles situated at the distal end of the tube tend to travel parallel to the inner wall. The parallel motion diminishes the impact force applied to the inner surface, which may affect the wear patterns seen in the tube. The fundamental mechanisms of focusing tube degradation are the formation of micro-cuts and microcracks [24,26]. Fig. 12 illustrates the wear on the internal surface of the focusing tubes caused by abrasive flow. After a 15-minute testing period, wear was predominantly noted in the transition zone between the internal cone and the cylindrical section of the nozzle, where the design shifts from conical to cylindrical geometry. Furthermore, indications of deterioration started to appear in the central area of the focusing tube during this period. The wear in these particular zones persisted, with additional increases in degradation recorded. Additionally, wear was observed in the outlet area of the nozzle, suggesting that various sections of the focusing tube are vulnerable to abrasive damage during operational conditions. These results indicate the significance of observing wear in various nozzle regions to gain a deeper insight into wear patterns. The intensity was especially pronounced for SiC #80 abrasives. Air is additionally introduced when abrasive is incorporated into the mixing chamber, resulting in the jet comprising over 90% ambient air [8]. The result is a more rapid disintegration of the jet. The rapid divergence of the water jet upon leaving the focusing nozzle causes immediate interaction with the surrounding fluid, resulting in a turbulent flow regime. The turbulence markedly enhances the disintegration of the jet. The turbulent flow enhances the mixing of abrasive particles with water and increases the shear forces on the nozzle surfaces [9].

The erosion of the nozzle caused by abrasive particles occurs in a random manner, characterized by irregular wear patterns that vary significantly across the surface. Upon closer examination, this chaotic erosion results in the formation of a distinct wave-like pattern along the inner walls of the nozzle. This pattern arises as specific regions undergo greater wear from the continuous impact of abrasive particles, illustrating the intricate relationship between fluid dynamics and abrasive characteristics. These promising results are presented as one of the main achievements of this work. Both the conventional nozzle and the proposed nozzle illustrated similar performance. This pattern of observation has been shown in previous works, According to Nanduri [20], the abrasive particles are active in the formation of the first wave near the top of the nozzle during the early stages of the wear test. There is no wavy wear in the lower/exit region, so the exit bore grows with the same amount of uniformity.



(a)



(b)

***Fig. 12** Sectioned nozzle after 15 minutes of testing using (a) Garnet (b) SiC*

4 Conclusions

This work presents an experimental investigation into the effect of abrasive materials on the wear progression of the nozzle (in terms of nozzle diameter, mass loss of loss, and shape internal geometry) through accelerated wear test in AWJ process. The outcomes demonstrated that nozzle wear is influenced by the kind of abrasive particles. The following conclusions can be made in light of the research:

- A linear relationship has been proposed between extended cutting times and the increase in the diameter of the focusing tube outlet, indicating a nearly proportional correlation. However, to establish a more precise understanding of this relationship and to accurately assess the influence of the specified parameters, further investigations are necessary. These additional studies will help clarify the dynamics at play and refine the predictive models associated with nozzle wear under varying cutting conditions.
- Following a 15-minute exposure of the focusing tubes to each abrasive particle type, a significant increase in wear was observed, as indicated by both mass loss and an expansion of the outlet's inner diameter. Among the tested abrasives, silicon carbide exhibited the most significant increase in wear, underscoring its aggressive characteristics and effect on the structural integrity of the focusing tubes. Variations in abrasive types affect abrasive velocities and energy distribution. More abrasive materials are more prone to producing larger diameters. Diverse abrasive materials exhibit distinct trends in the mass loss factor of the nozzle utilized in the tests.
- Comprehensive wear tests conducted using silicon carbide (SiC) abrasive demonstrate that the wear rate of the focusing tube is three times greater than that observed with garnet abrasive. The findings include the ultimate diameter of the focusing tube after the tests, as well as the calculated mass loss factor, which provides a quantitative measure of material degradation for both types of abrasives. These results highlight the significant impact of abrasive selection on the wear characteristics of the focusing tube.
- The changes in the nozzle's internal geometry are due to gradual wear, influenced by the direction of the abrasive water flow. As the flow intensifies, material is progressively eroded from the internal surfaces, resulting in a morphological alteration that directly impacts the nozzle's performance and efficiency over time.

Acknowledgement

The authors express their sincere gratitude for the technical and financial support received from Universiti Malaysia Pahang Al-Sultan Abdullah through PGRS 230327, the vice chancellor scholarship (VCS), and the Ministry of Higher Education Malaysia through PRGS/1/2024/TK10/UMP/02/1 (RDU240802).

References

[1] HREHA P, RADVANSKÁ A, CÁRACH J, LEHOCKÁ D, MONKOVÁ K, KROLCZYK G, et al. Monitoring of focusing tube wear during abrasive waterjet (AWJ) cutting of AISI 309. *Metalurgija*. 2014;53(4):533–6.

[2] WAN L, XIONG J, CAI J, WU S, KANG Y, LI D. Feasible study on the sustainable and clean application of steel slag for abrasive waterjet machining. *J Clean Prod.* 2023;420:138378.

[3] DEKSTER L, KARKALOS NE, MACHNIK R, KARMIRIS-OBRATAŃSKI P, PAPAZOGLOU EL, MARKOPOULOS AP. The Influence of Silicon Carbide Abrasive on Machining of Ti-6Al-4V by AWJ. *Eng Proc.* 2022;24(1):3.

[4] JÓZWIK J, RUGGIERO A, LELEŃ M. Microscopic Analysis of the Surface Morphology of Multilayer Structures of the Aluminum Alloy - Silicon Type after Water Jet Cutting. *Manuf Technol.* 2022;22(6):693–702.

[5] MÜLLER M, VALÁŠEK P, KOLÁŘ V. Research on Application of Technology Using Water Jet on Machining of Polymeric Composite Biological-Reinforced Materials. *Manuf Technol* [Internet]. 2018;18(4):630–4. Available from: https://doi.org/10.21062/ujep/151.2018/a/1213-2489/MT/18/4/630

[6] SHIVAJIRAO M, SATYANARAYANA S. Abrasive water jet drilling of float glass and characterization of hole profile. *Glas Struct Eng.* 2020;5:155–69.

[7] LELEŃ M, RUGGIERO A, JÓZWIK J. Geometric Features of a Multilayer Surface After Water Jet Cutting in Variable Cutting Conditions. *Manuf Technol.* 2022;22(6):713–23.

[8] FOWLER G, PASHBY IR, SHIPWAY PH. The effect of particle hardness and shape when abrasive water jet milling titanium alloy Ti6Al4V. *Wear.* 2009;266(7–8):613–20.

[9] LAUAND CT, HENNIES WT, CICCU R. Abrasives in water jet cutting systems. In: *Mine Planning and Equipment Selection 2000*. Routledge; 2018. p. 641–5.

[10] LLANTO JM, TOLOUEI-RAD M, VAFADAR A, AAMIR M. Recent progress trend on abrasive waterjet cutting of metallic materials: A review. *Appl Sci.* 2021;11(8).

[11] NANDURI M, TAGGART DG, KIM TJ. The effects of system and geometric parameters on abrasive water jet nozzle wear. *Int J Mach Tools Manuf.* 2002;42(5):615–23.

[12] BOURGEOIS L, FABBRI E, FASTRE P, KREMER J, KOESTERS R. New tungsten carbide material with nanoscale grain size for focusing tubes. In: *Proceedings of WJTA American Waterjet Conference*, Houston, Texas, USA. 2005. p. 21–3.

[13] PEREC A, PUDE F, GRIGORYEV A, KAUFELD M, WEGENER K. A study of wear on focusing tubes exposed to corundum-based abrasives in the waterjet cutting process. *Int J Adv Manuf Technol.* 2019;104(5–8):2415–27.

[14] MADHU S, BALASUBRAMANIAN M. Influence of nozzle design and process parameters on surface roughness of CFRP machined by abrasive jet. *Mater Manuf Process* [Internet]. 2017;32(9):1011–8. Available from: http://dx.doi.org/10.1080/10426914.2016.1257132

[15] MADHU S, BALASUBRAMANIAN M. Impact of Nozzle Design on Surface Roughness of Abrasive Jet Machined Glass Fibre Reinforced Polymer Composites. *Silicon.* 2018 Nov 1;10(6):2453–62.

[16] SYCHUK V, ZABOLOTNYI O, MCMILLAN A. Developing New Design and Investigating Porous Nozzles for Abrasive Jet Machine. *Powder Metall Met Ceram.* 2015 Jan 1;53(9–10):600–5.

[17] SINGH H, BHOI NK, JAIN PK. Developments in abrasive water jet machining process-from 1980 to 2020 [Internet]. Advanced Machining and Finishing. *Elsevier Inc.*; 2021. 217–252 p. Available from: http://dx.doi.org/10.1016/B978-0-12-817452-4.00011-7.

[18] MARDI KB, DIXIT AR, PRAMANIK A, BASAK AK. Tribology in (abrasive) water jet machining: A review [Internet]. Machining and Tribology: Processes, Surfaces, Coolants, and Modeling. *Elsevier Inc.*; 2021. 113–125 p. Available from: http://dx.doi.org/10.1016/B978-0-12-819889-6.00004-6.

[19] HASHISH M. Observations of Wear of Abrasive-Waterjet Nozzle Materials. *J Tribol.* 1994;116(3):439–44.

[20] NANDURI M, TAGGART DG, KIM TJ. A study of nozzle wear in abrasive entrained water jetting environment. *J Trib.* 2000;122(2):465–71.

[21] ANAND U, KATZ J. Prevention of nozzle wear in abrasive water suspension jets (AWSJ) using porous lubricated nozzles. *J Trib.* 2003;125(1):168–80.

[22] PEREC A. Environmental Aspects of Abrasive Water Jet Cutting. 2018.

[23] MURUGAN M, GEBREMARIAM MA, HAMEDON Z, AZHARI A. Performance analysis of abrasive waterjet machining process at low pressure. In: *IOP Conference Series: Materials Science and Engineering*. IOP Publishing; 2018. p. 12051.

[24] BARALIĆ J, NEDIĆ B, MARUŠIĆ V. Focusing tube wear and quality of the machined surface of the abrasive water jet machining. *Tribol Ind*. 2008;30(3&4):55.

[25] KHAN AA, HAQUE MM. Performance of different abrasive materials during abrasive water jet machining of glass. *J Mater Process Technol*. 2007;191(1–3):404–7.

[26] NEDIĆ B, BARALIĆ J. The wear of the focusing tube and the cut-surface quality. *Tribol Ind*. 2010;32(2):38–48.