USING POROUS LUBRICATED NOZZLES TO PREVENT NOZZLE WEAR IN ABRASIVE WATER SUSPENSION JETS (AWSJ)

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ABSTRACT

This paper reports on an on-going research to develop a method for preventing nozzle wear in abrasive water jets used for jet cutting. This method consists of using a nozzle made of a porous material, which is surrounded with a reservoir containing a high viscosity lubricant. The lubricant is forced continuously through the porous medium as a result of the pressure difference between the reservoir and the high-speed flow in the nozzle. The resulting oil film protects the walls of the nozzle from impact and shear caused by the abrasive particles. Previous tests with a two-dimensional, 0.145 mm wide nozzle with windows enabled observations and measurements of the liquid and abrasive particle velocities using PIV (Particle Image Velocimetry). We have established the proper material characteristics and EDM cutting parameters required to maintain the desired porosity. Over the past year we have been experimenting with an axisymmetric nozzle geometry. The effects of varying the lubricant flow rates and viscosities on the wear have been measured. It was found that the presence of oil substantially reduced the wear of the nozzle walls from 111 % to 10.5 % over the same period. The wear increased as the lubricant injection rate decreased. Lowering the viscosity of the oil for the same nozzle increased the lubricant flow rate, however it had little effect on the wear. The oil film also improved the jet coherence.

1. INTRODUCTION

Abrasive water suspension jets, namely water jets containing abrasive particles, have a considerable niche in the material processing industry. The most troublesome difficulty associated with high-speed slurry jets, which presently limits their usefulness, is wear of the nozzle walls (Conn, 1991, Dubensky et al., 1992). Since the jet speed ranges between 100-500 m/sec, and the particle size can be as high as 40% of the nozzle diameter, it does not take long to destroy a nozzle. Consequently in current systems, nozzles must be replaced frequently, requiring constant maintenance, inspection, loss of accuracy and machine down time. Thus, a solution to the wear problem must still be found, which will expand the use and applications of high-speed abrasive jet cutters. It may be possible to increase the jet speed, and reduce its diameter even further (present sizes range between 100-500 μm), allowing much higher precision, deeper cutting, and wider implementation in problematic materials including ceramics.

2. THE LUBRICATED POROUS NOZZLE

The proposed solution to solve the wear problem is sketched in Fig. 1. The nozzle is made of a porous material and is surrounded with a reservoir containing a high viscosity lubricant that is exposed to the same pressure that drives the flow in the nozzle. The lubricant is forced continuously through the porous medium as a result of the pressure difference created due to the high-speed flow in the nozzle.

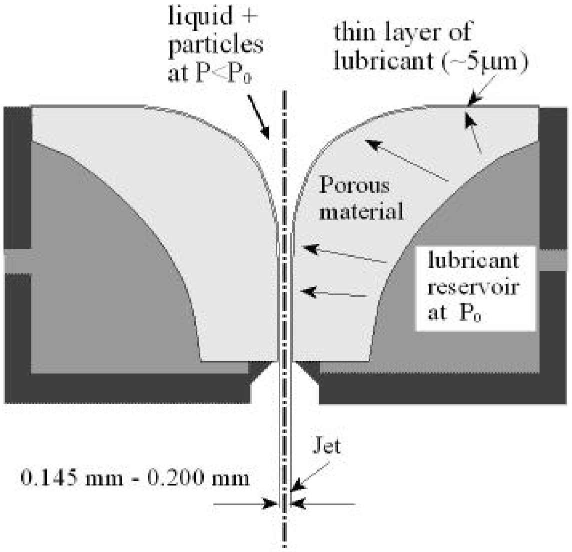

Figure 1. A sketch illustrating the principles of the method for preventing nozzle wear.

The lubricant injection rate, which is controlled by the pressure difference, the nozzle geometry (thickness), permeability and viscosity, is designed to create a thin layer (film), with a typical thickness of 5 μm, on the walls of the nozzle. This film of high viscosity fluid protects the walls of the nozzle from shear and impact of the particles. Since the lubricant is constantly replenished, sites where particles "gouge" the film are repaired, preventing damage to the solid walls. Provided that the proper lubricant (viscosity), film thickness and nozzle geometry (flow rate through the porous medium) are selected, this approach provides a reliable but yet very simple method to prevent nozzle wear. Due to the differences in viscosity between the water and the lubricant (can be as high as 1500:1), the oil consumption is minimal. Further details can be found in Anand & Katz (2000 a, b) and Katz (1999). The idea of using a porous nozzle but with water injected through the porous nozzle has been introduced before by Tan and Davidson (1990) and Tan (1995, 1998). Their experiments were performed at low pressures of 1.3 MPa, i.e. very low particle velocities.

Initially we studied the flow in a 2-D nozzle with windows on both sides (Anand & Katz, 2000 a, b). This setup allowed us to make direct observations of the flow inside the nozzle. The experiments enabled us to confirm the existence of oil layers on the walls of the nozzle. The oil used in these experiments had a viscosity of 1800 mm^2/s (at 25°C). Even though the oil had such a high viscosity, the high shear rates in the nozzle caused considerable entrainment. However, the typical flow rate of lubricant was still very low. Velocity measurements were also performed using Particle Image Velocimetry (PIV). Details on the measurement and analysis method can be found in Dong et. al. (1992) and Roth et. al. (2001). Double-exposure images of tracer nylon particles (4 µm diameter, density = 1.14 g/cc) were recorded. The images were then enhanced and auto-correlation analysis was used to measure the liquid velocity. Sample images of the large slurry particles and tracer particles in the nozzle are shown in Fig. 2 (a) - (c).

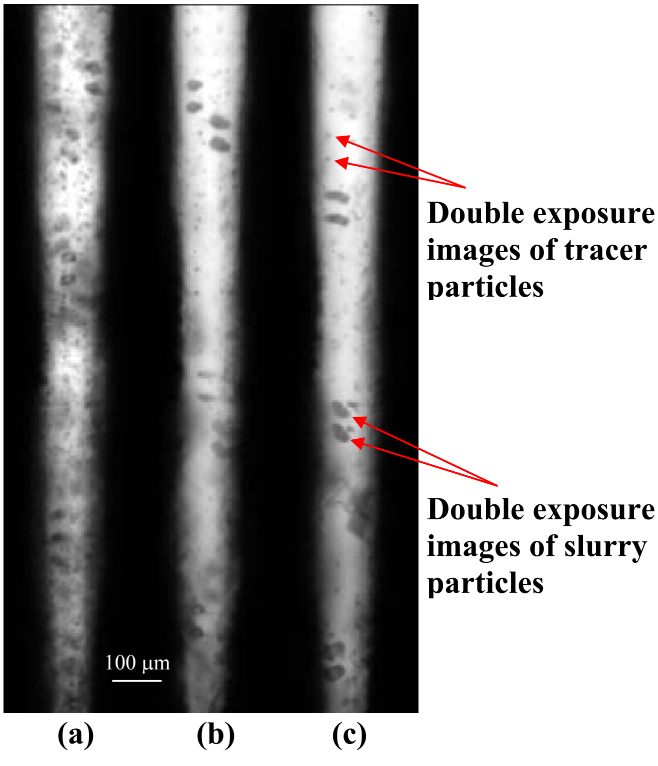

Figure 2. (a), (b), (c) Three samples of double exposure images of the nozzle with water and oil along with slurry (large dark objects) and tracer particles (small dark objects). The flow was from top to bottom.

In order to protect the sapphire windows from being damaged due to the impact from particles during the visualization experiments, we used Celestite (Mohs Hardness 3-3.5, sp.gr. = 3.95) as slurry particles instead of the typical industry standard of Garnet (Mohs Hardness 7-7.5, sp.gr. = 4.0). The velocity of the large slurry particles was measured separately using auto-correlation analysis and subtraction on the enhanced edges of the particles.

We found that there was virtually no change in the centerline velocity when the oil was forced into the nozzle. The slip velocity, which was calculated by subtracting the slurry particle velocity from the average tracer particle velocity in the same region, decreased along the straight section of the nozzle. In fact, near the exit, the slip velocity decreased to negligible levels.

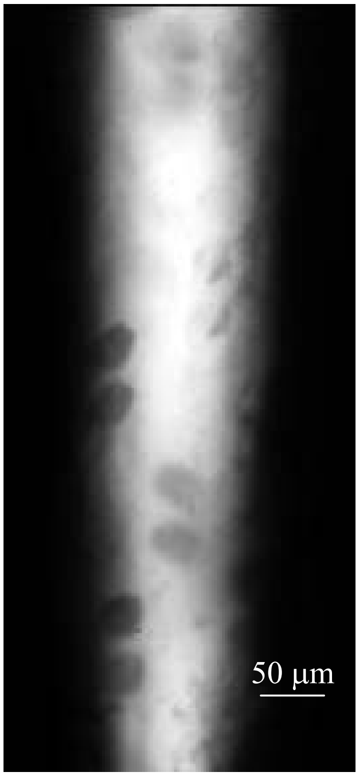

Figure 3. Slurry particles impinging the nozzle walls. The flow was from top to bottom.

Most of the slurry particles appeared to be moving in the center of the nozzle as the sample images in Fig. 2 show. However, as shown at the left side of Fig. 3, in some cases the slurry particles gouged the oil layer. The images recorded shortly before and after the one in Fig. 3 demonstrated that the oil layer immediately replenished itself. Consequently, the integrity of the lubricant layer was not damaged. In order to study the performance of the approach and test the extent of nozzle wear we have also constructed an axisymmetric nozzle facility. The results are discussed in the following section.

3. EXPERIMENTAL OBSERVATIONS AND RESULTS

3.1 Axisymmetric Setup

Figure 4 illustrates the supply system of lubricant and abrasive particles. The water was supplied by a 7.46 kW positive displacement pump whose maximum operating pressure was 68.95 MPa and maximum flow rate was 9.46 x10 $^{-5}$ m^3/s. We typically operated at pressures up to 34.5 MPa.

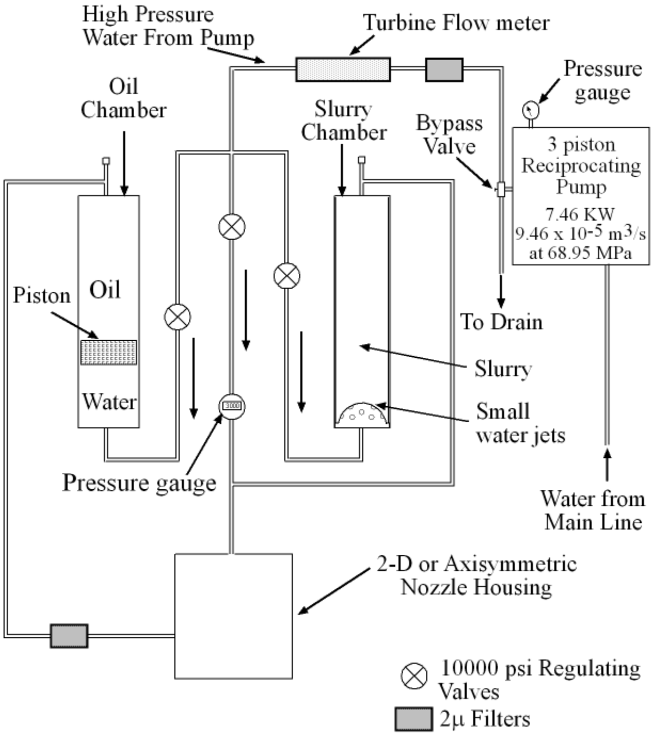

Figure 4. Schematic of the system supplying slurry particles and lubricant to the test chamber.

Using high pressure regulating valves, the pressurized water was used to pressurize both the oil and abrasive slurry chambers. The slurry chamber contained highly concentrated slurry of particles. During an experiment some water was directed towards this chamber from below, entrained some of the particles, and exited from the top of the chamber. Injection into the slurry chamber was from below since the particles were heavier than water and tend to settle. The second reservoir was filled with lubricant and a small loosely fitted piston separated the water from the lubricant. A high pressure gauge and a turbine flow meter were used to record the experimental conditions. Fig. 5 (a) shows the components of the axisymmetric nozzle setup and Fig. 5 (b) shows a cross-section of the porous nozzle. The nozzle consisted of a short converging section followed by a straight section. The length of the straight section was chosen so that the slurry particles attained nearly the liquid velocity as they exited the nozzle. The abrasive slurry and oil supply tubing are shown in Fig. 4. The oil entered through the oil port and collected in the reservoir surrounding the porous nozzle. It then flowed through the porous medium due to the pressure difference to create a thin film on the nozzle walls. The abrasive slurry entered through the upper port.

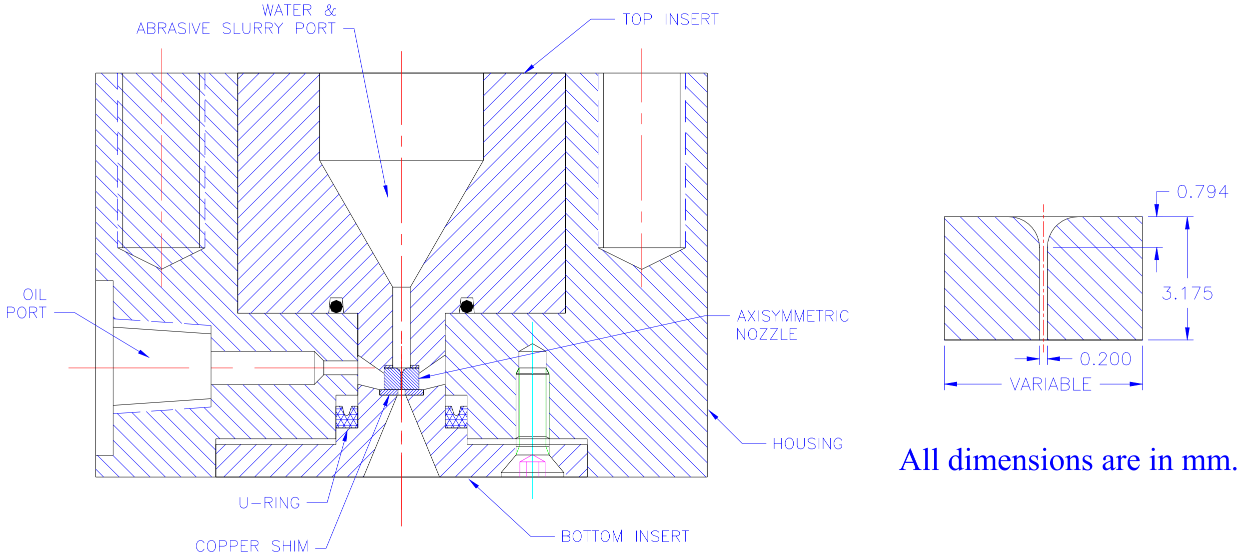

Figure 5. (a) Components of the axisymmetric nozzle housing; (b) Cross-section of the porous nozzle.

The nozzles were made of porous 316-stainless steel and machined using Electric Discharge Machining (EDM). The proper material characteristics and EDM cutting parameters required to maintain the desired porosity have been established and verified by observations using Scanning Electron Microscopy (SEM). Figure 6 (a) and (b) show SEM images of the top and cut section of the porous nozzle.

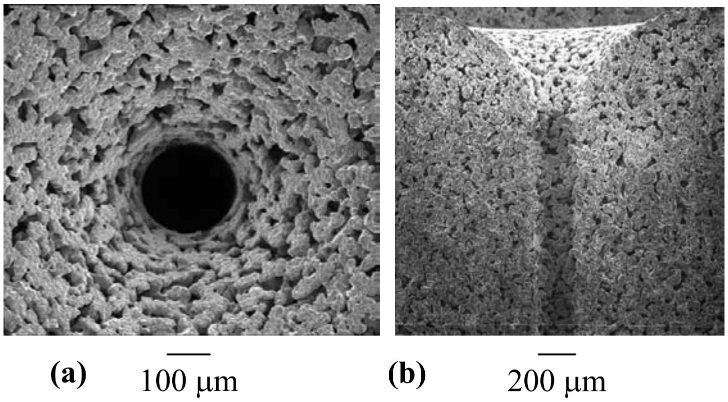

Figure 6. SEM images of the (a) top and (b) cut section of the porous nozzle.

There were several processes for manufacturing the porous material, even for the same porosity (permeability), depending on the particle size, pre-compaction and whether the sintering was based on gravity or on pressure compaction. The quality of the machined surface varied substantially, depending on the method used for manufacturing the porous material. We have experimented with different materials and found an optimum. Using this material, machining by EDM did not “smear” the pores on the surface of the nozzle and uniform pore distribution was maintained. Samples of successful and unsuccessful attempts are shown in Fig. 7.

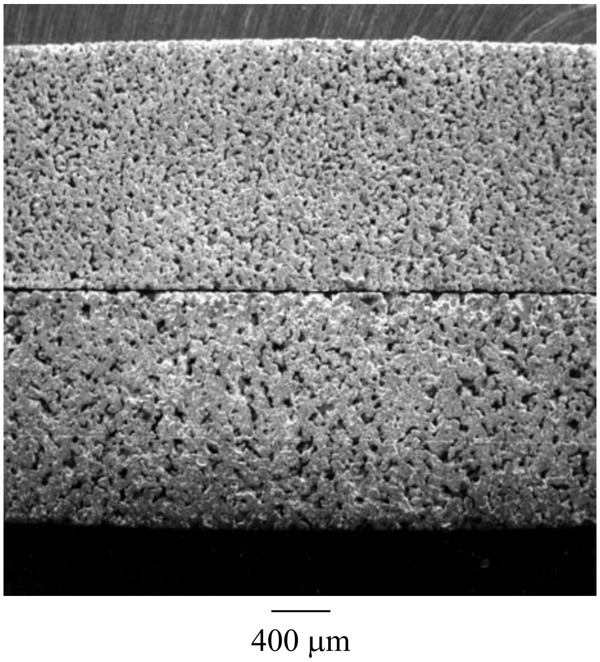

Figure 7. SEM image of EDM'ed surfaces of porous materials manufactured using different processes. (Top)– uniform porosity was maintained. (Bottom)–uneven pore distribution.

The EDM cutting parameters, such as energy levels, spark frequencies, cutting speeds, etc., also affected the quality of the surface, as illustrated in Figure 8 (a) and (b). The parameters were optimized to ensure uniform pore distribution on surfaces in the critical regions of the nozzle. The parameters were also adjusted for preventing oil flow in undesired regions of the nozzle.

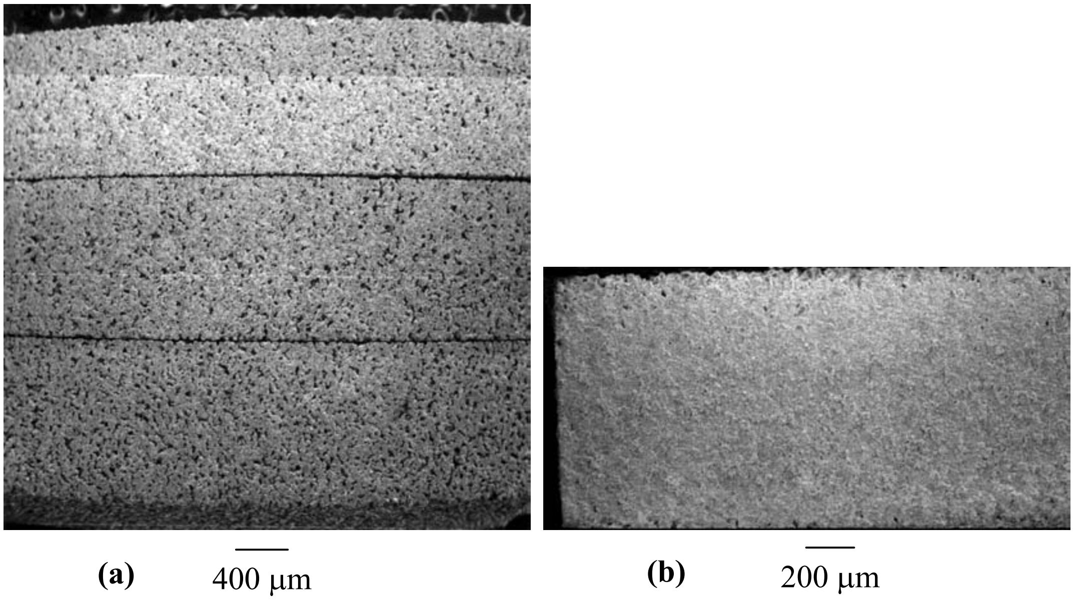

Figure 8. Effects of EDM cutting parameters on the porous surface. SEM images of: (a) Top to bottom – improvements by decreasing the cutting speed and energy level; (b) the result of non-optimized machining – a completely "smeared" surface.

As shown in Fig. 4, a 2-micron porous filter was inserted upstream of the nozzle housing. The presence of this element was critical. Experiments performed without this filter resulted in the clogging of the porous medium. Fig. 9 (a) and (b) show SEM images of the clogged nozzle surface resulting from experiments with no filter. Fig. 9 (a) shows dirt coating the porous surface and Fig 9 (b) shows the same surface with embedded dirt after the surface coating was removed by pressurized air. Fig. 10 (a) and (b) show SEM images of the nozzle surface recorded before and after experiments with the in-line filter installed. As is evident, the nozzle surfaces remained unchanged, free from blockage.

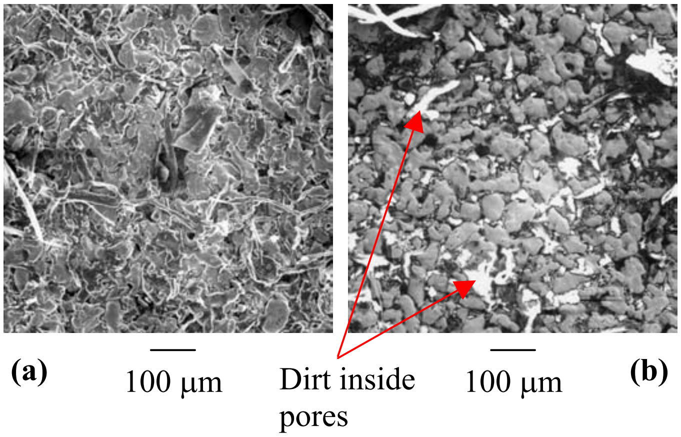

Figure 9. SEM images of the clogged nozzle surface when a filter was not used. (a) Coating of dirt on the surface. (b) Dirt inside the pores.

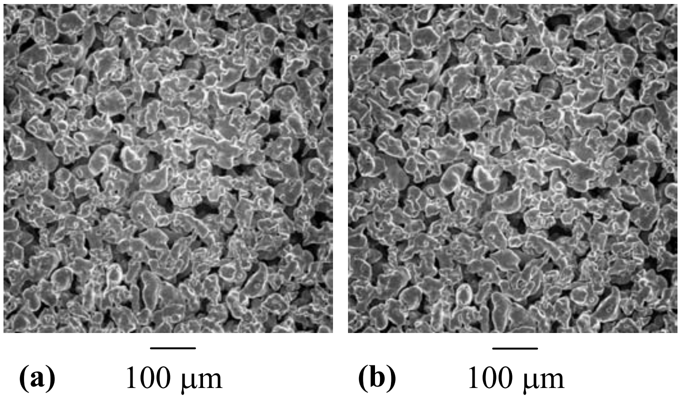

Figure 10. (a), (b). SEM images of the nozzle surface recorded before and after experiments with a filter installed.

3.2 Results

Figure 11 shows the time required to empty the 125 cm^3 oil reservoir as a function of viscosity at an upstream pressure of 14.48 MPa. Also shown is the flow rate of oil relative to that of water. As is evident, the time required to empty the chamber varied linearly with viscosity, in agreement with the Darcy's Law. Accordingly, the relative oil flow rate curve exhibits a hyperbolic behavior.

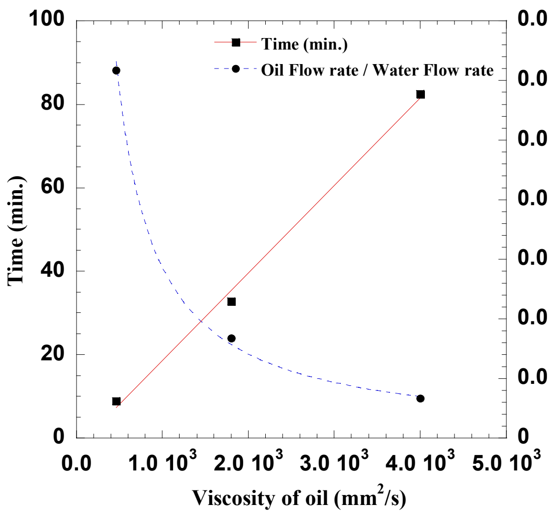

Figure 11. Time taken to use 125 cm^3 of three different oils.

We tested the axisymmetric nozzles for wear, using Garnet particles (Nominal size: 25 µm) as abrasive with a slurry concentration inside the slurry chamber of 4.44 x10^{-3} g/cm^3. The experiments were performed with different flow rates and viscosities of oil. For all the present results, the upstream pressure was 14.48 MPa and run-time was 1 hour 45 min. We started with a non-lubricated nozzle as a reference case. Fig. 12 (a) and (b) show SEM images of the nozzle exit taken before and after the experiments for the non-lubricated nozzle. The exit diameter changed from an initial size of 202 µm to 426 µm based on the diameter of a circle with an equivalent area, i.e. a change of 111 %.

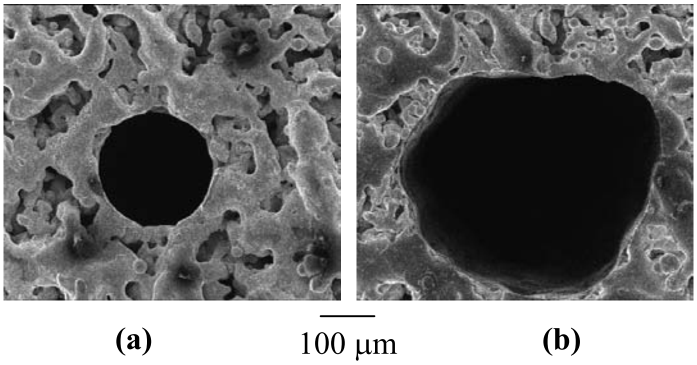

Figure 12. SEM images of the nozzle exit recorded (a) before and (b) after experiments with only abrasive slurry without any oil.

Fig. 13 (a) and (b) – 15 (a) and (b) show SEM images of the nozzle exit taken before and after experiments with different conditions. In Fig. 13 the viscosity of the oil was 1800 mm^2/s (at 25°C) and the ratio of oil flow rate to that of water was 0.0140. The exit diameter changed from an initial size of 210 µm to 232 µm, i.e. an increase of 10.5%. In Fig. 14 all the experimental conditions were the same except that the oil flow rate ratio of 0.0099 was lower than before. In this case the diameter changed from 200 µm to 244 µm, i.e. an increase of 22%. In Fig 15 the viscosity of the oil was 460 mm^2/s (at 25°C) and the oil flow rate ratio was 0.0411. The exit diameter changed from 208 μm to 248 μm, i.e. an increase of 19 %.

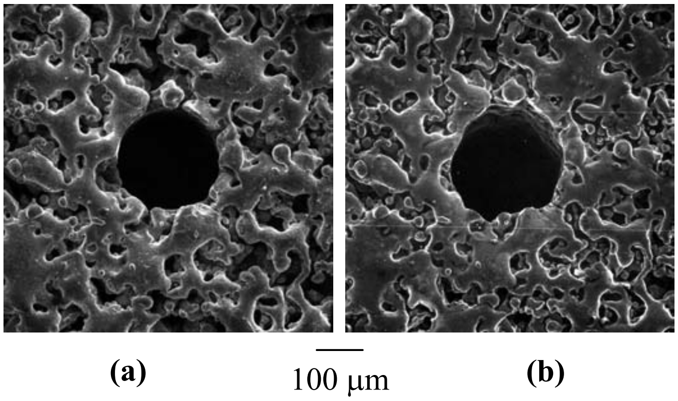

Figure 13: SEM images of the nozzle exit recorded (a) before and (b) after the experiments with oil viscosity of 1800 mm^2/s. The ratio of oil flow rate to that of water was 0.0140.

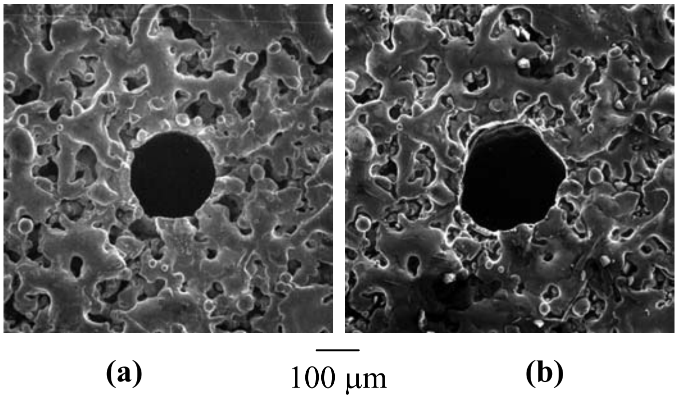

Figure 14. SEM images of the nozzle exit recorded (a) before and (b) after the experiments with oil viscosity of 1800 mm^2/s. The oil flow rate ratio was 0.0099.

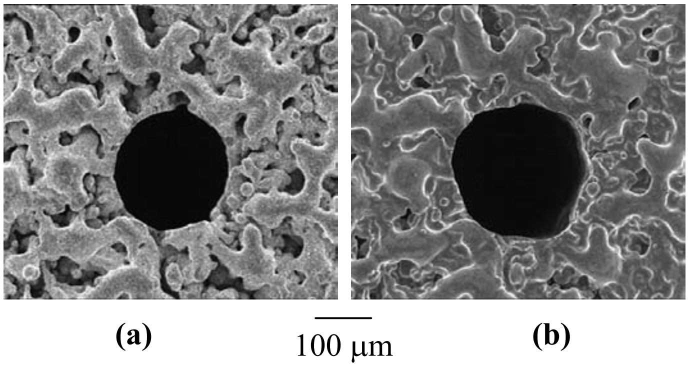

Figure 15. SEM images of the nozzle exit recorded (a) before and (b) after the experiments with oil viscosity of 460 mm^2/s. The oil flow rate ratio was 0.0411.

From these images it was evident that the presence of an oil film on the nozzle walls had a substantial impact on the extent of the nozzle wear. The lubricant flow rate and the viscosity of the oil (for a given pressure difference) were the primary factors affecting the reduction in nozzle wear. From Fig. 13 and 14 it was apparent that for similar experimental conditions the wear increased as the oil injection rate decreased. Comparing Fig. 13 and 15 we saw that lowering the viscosity of the oil led to an increase in the oil injection rate but the wear was still higher. However, we have not yet measured the effect of viscosity separately, i.e. determined the wear at the same oil flow rate for different viscosities. These experiments are currently in progress.

We also observed that as long as the oil injection occurred in the nozzle, the jet exit stream was extremely coherent and well defined. Once the oil injection stopped, the jet spread out. This effect could be attributed to the smoothening of the jet walls by the presence of the oil layer.

4. CONCLUSIONS

This paper describes a novel solution for preventing nozzle wear in high-speed slurry jets used for jet cutting. The nozzle was made of porous material and was surrounded by a jacket of lubricating oil. In our setup the oil reservoir was exposed to the same pressure that drove the flow in the nozzle. The oil was forced through the porous nozzle walls and created a lubricating film that protected the walls from impact and shear caused by the abrasive particles. The proper material characteristics and EDM cutting parameters required to maintain the desired porosity have been established. When the particles gouged the oil layer, it immediately replenished itself. It was found that the presence of oil substantially reduced the wear of the nozzle walls from 111 % to 10.5 % over the same period. The wear increased as the lubricant flow rate decreased for similar experimental parameters. When oil of a lower viscosity was used, there was an increase in the lubricant injection rate but it had little effect on the wear. The presence of oil also improved the coherence of the jet. This ability to accelerate the particles to nearly the liquid velocity with minimal damage to the nozzle, even when the nozzle is made of just plain stainless steel, is a major advantage over other presently used technologies.

5. ACKNOWLEDGEMENTS

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