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Tribology in Water Jet Processes

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1. Introduction

In water jetting technology, a high-velocity stream of water is used for cleaning and cutting purposes. Modern water jetting technology has a history of more than forty years and has been used in a wide range of practical applications. These include machining and manufacturing, stone cutting, demolition work, surface preparation, rock and soil excavation, mining, agriculture, food treatment, and medical applications. In ordinary cutting processes using a water jet, water is usually pressurized up to 300 to 400 MPa by a high-pressure pump. Friction and wear between the cylinder and the piston are important problems that have significant influence on the efficiency, reliability, and lifetime of the high-pressure pump. Corrosion and erosion in valves and nozzles are serious problems that affect the reliability of the water jetting system. The primary material removal mechanism of pure water jets is erosion generated by water droplet impingement. Erosion by solid particle impingement is the material removal mechanism of abrasive water jet machining. Equipment for water jet processes and the mechanisms of cleaning and cutting by water jets are directly related to tribology. In this chapter, a brief review of water jetting technology related to tribology is presented. The review describes the history of water jetting technology, high-pressure pumps and water jet machining systems, various water jets used in water jet processes, and the material removal mechanisms of water jets.

2. History of water jetting technology

Water jetting technology has its origin in hydraulic mining, in which a high-speed water stream is used to break up soil and rock, and can be traced back to the end of the nineteenth century. Hydraulic mining was used in gold production in California from 1853 to 1886 (Summers, 1984). However, modern water jetting technology may be traced directly to the development of the high-pressure pump in the 1960s. According to Summers (1984), Franz et al. developed a prototype system for cutting material at pressures of up to 400 MPa and found that high-speed water jets could be used to cut through wood products at relatively high cutting speeds. Imanaka et al. (1972) developed a high-pressure pump in the early 1960s and conducted cutting tests on various materials at jetting pressures of up to 1,000 MPa. On the other hand, studies on the material removal mechanism of the impingement of water droplets began in the 1950s with studies on rain erosion of aircraft components. Springer (1976) published a comprehensive survey on erosion associated with liquid impact. The development of the high-pressure pump and the clarification of the material removal mechanism of water droplets has attracted growing interest in high-speed water jet

applications. In 1972, the British Hydromechanics Research Association (BHRA), currently BHR Group Ltd., held the 1st International Symposium on Jet Cutting Technology, and this symposium has been held biannually since its inception.
The main areas of research in water jetting technology during the 1970s were cutting by pure water jets and excavation of rock and soil connected with mining and civil engineering. In 1982, four papers on abrasive water jet cutting were presented at the 6th International Symposium on Jet Cutting Technology. In a conventional abrasive water jet system, an abrasive water jet is formed by entraining abrasive particles into a high-speed water jet stream in a tubular abrasive nozzle. This abrasive water jet is referred to as the abrasive water injection jet, the abrasive injection jet (AIJ), or simply the abrasive water jet. Since abrasive water jets can cut hard materials such as metals, ceramics, concrete, and rocks at practical cutting speeds, applications of water jetting technology in manufacturing, civil engineering, and construction have expanded rapidly. In 1986, Fairhurst et al. (1986) reported an abrasive water jet system of a different type, which is now referred to as the abrasive water suspension jet, the abrasive suspension jet (ASJ), or the abrasive slurry jet. The abrasive suspension jet has been shown to have a greater capacity for drilling and cutting than the conventional abrasive water jet (Brandt et al., 1994). However, there are a number of problems that remain to be solved before widespread application of the abrasive suspension jet system can be realized. For instance, the development of a reliable and long-life high-pressure slurry valve is necessary. Abrasive suspension jet systems are used in fire fighting and rescue operations (Holmstedt, 1999; Inoue et al., 2008) as well as semiconductor manufacturing (Jiang et al., 2005). Recently, a number of innovative water jetting technologies have been proposed, e.g., liquefied gas jets, ultra-high-pressure pumps that realize pressures exceeding 600 MPa, and a five-axis water jet machining system. Water jetting technology has made steady progress, and applications of water jetting technology continue to expand in various industries.

3. High-pressure pump and water jet machining system

Two types of pump are commonly used in the water jet industry, namely, the direct drive plunger pump and the intensifier pump. At pressures lower than 150 MPa, the direct drive plunger pump is the most commonly used type. In a typical triplex pump, three plungers are equally arranged about a crankshaft at 120-degree increments, and the plungers move backward and forward in the cylinders. At pressures higher than 150 MPa, the intensifier pump is used as a pumping unit. A typical circuit of an intensifier pump system is shown in Figure 1 (Ibuki et al., 1993). The intensifier is a reciprocating pump in which the piston assembly consists of a large-diameter piston and small-diameter plungers at both ends. Hydraulic oil pushes against the larger-diameter piston, and the smaller plunger generates higher pressure on the water contained in the cylinder. Since the typical area ratio of the plunger and the piston is 1:20, the intensification ratio of pressure is 20:1. When the oil pressure is 20 MPa, the resultant water pressure becomes 400 MPa. In the water jet machining industry, pressures of 300 to 400 MPa are commonly used. In order to obtain higher cutting speeds and reduce abrasive consumption, ultra-high-pressure water jet machining systems at working pressures of 400 to 700 MPa have been used in practical applications. A two-stage intensifier pump system is proposed in order to reduce dynamic loading and obtain longer system lifetimes for ultra-high-pressure water jet machining systems (Koerner et al., 2002).

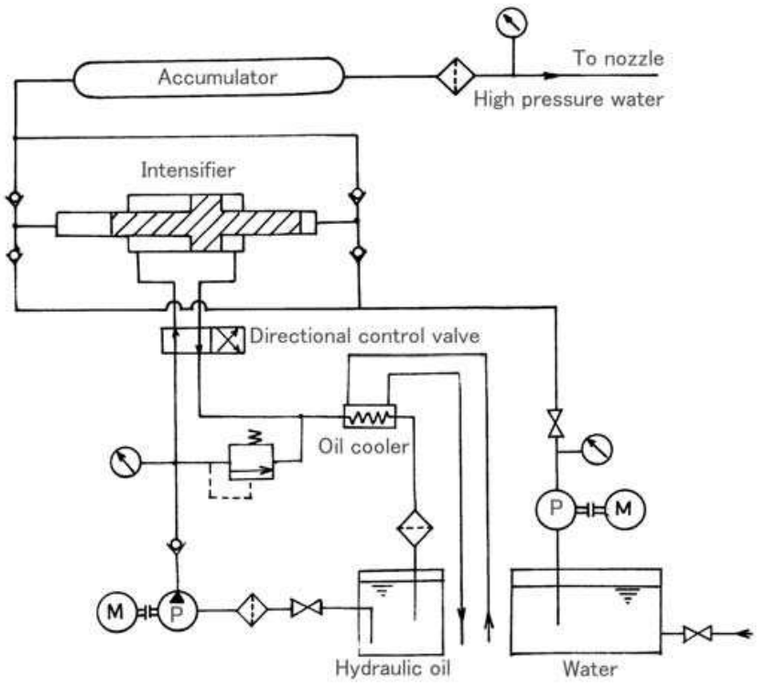


Fig. 1. Circuit of the intensifier pump (Ibuki et al., 1993)

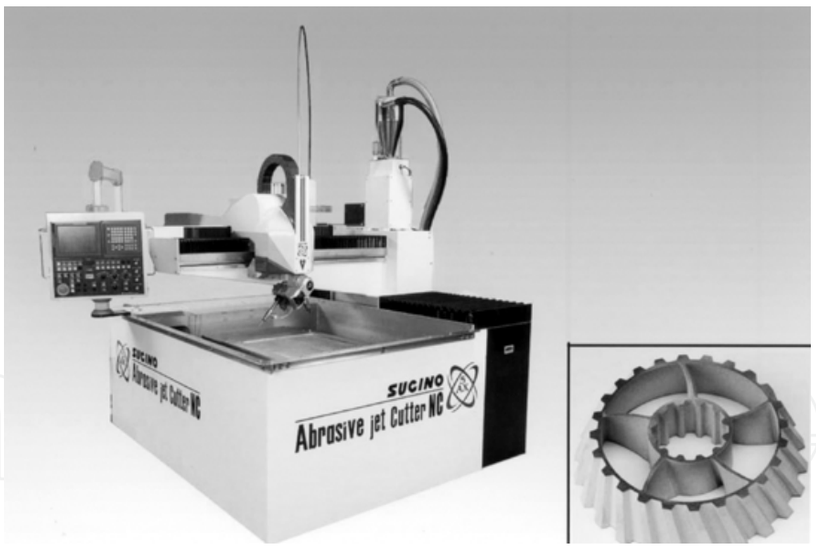


Fig. 2. Modern five-axis water jet machining system and sample part manufactured by the system (Sugino Machine Ltd., 2007)

XY tables are the most common forms of water jet machining motion equipments. These machines are used for two-dimensional cutting. With recent advances in control and motion technology, five-axis water jet machining systems have been used practically. An example of the latest five-axis water jet machining system and a sample part manufactured using this system are shown in Figure 2 (Sugino Machine Ltd., 2007). In addition to the *X* (back/forth), *Y* (left/right), and *Z* (up/down) axes, two degrees of freedom are added to the nozzle

movement, namely, the angle from the perpendicular and rotation around the *Z*-axis. In the case of two-dimensional cutting, more accurately manufactured parts can be produced at higher cutting speeds by the five-axis machine. Three-dimensional complex shapes can be produced by the five-axis machine in single-pass operation.

4. Various water jets and material removal mechanisms

High-velocity-water jets used in water jet processes can be categorized according to the environment around the jet, the fluid medium, and the jetting regime, as shown in Figure 3 (Shimizu, 2003). Depending on the environment around the jet, water jets are classified as either water jets in air or submerged water jets. The submerged water jets are further classified as cavitating jets or non-cavitating jets, depending on the jetting and ambient pressures. In ordinary pressure levels of water jet processes, cavitation occurs in the region of high shear at the boundary between the jet and the surrounding water. Depending on the fluid medium, water jets are categorized as either pure water jets or abrasive water jets. In some cases of pure water jets, water-soluble polymeric additives are added in order to reduce the friction in the plumbing and improve the compactness of the jet issuing from the nozzle. Abrasive water jets are classified as either abrasive injection jets (AIJs) or abrasive suspension jets (ASJs) based on the generation mechanism and the phase composition. Abrasive injection jets are solid-air-liquid three-phase jet flows, and ASJs are solid-liquid two-phase jet flows. With respect to the jetting regime, water jets can be classified as continuous water jets or discontinuous water jets. Although all high-velocity water jets generate a discontinuous phase during impact, continuous water jets are considered to be water jets that are not broken up artificially by external mechanisms. The structures of the jets and the material removal mechanisms are differ according to the combination of these three factors. In addition to these three factors, nozzle shape also affects the flow structure of the jet. The most common nozzles have a circular cross section, and the water jets issued from such nozzles become round jets. Nozzles that can form a fan shaped water jet are often used to clean large areas. This type of nozzle is referred to as a fan jet nozzle. In the following, we consider only round jets.

4.1 Pure water jets

The most common water jets used in water jetting processes are continuous pure water jets in air issued from a nozzle having a circular cross section. This type of water jet is widely used in water jetting industries for cleaning, surface preparation, and cutting of soft materials. A schematic diagram of a high-seed water jet in air is shown in Figure 4 (Yanaida and Ohashi, 1980). The jet consists of three regions, namely, the initial region, the main region, and the final region. In the initial region, the stagnation pressure is considered to be the same as that at the nozzle exit, and the initial region length is determined from extrapolation of the decrease in the stagnation pressure. In the main region, the axial velocity of water is considered to be constant, irrespective of the axial distance from the nozzle exit. The breakup length exists in the main region. The continuous structure of the water jet disintegrates at the breakup length, and the jet becomes a droplet flow composed of water lumps and droplets surrounded by fine droplets. The velocities of the water lumps and relatively large droplets remain unchanged in the main region. In the final region, the decrease in the water droplets velocities becomes noticeable as the droplets break up into finer droplets.

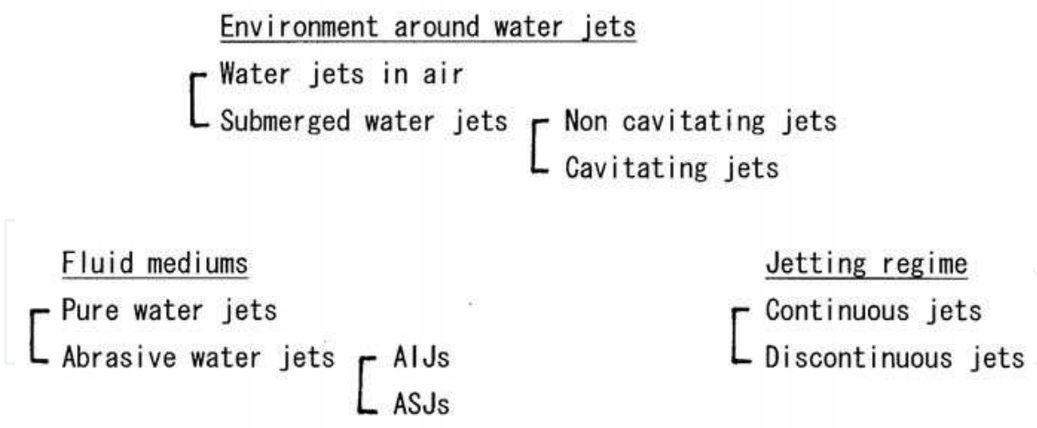


Fig. 3. Division of water jets (Shimizu, 2003)

When we consider a water jet impacting a solid material, two different pressures are considered to occur at the point of impact. If a continuous jet impinges on a solid material, then the jet stagnation pressure p_s is generated at the impact point. If a water lump or droplet impinges on a solid material, then the water hammer pressure p_w is generated at the instant of impact. The stagnation pressure p_s and the water hamper pressure p_w are given by the following equations:

$$p_s = \rho v^2/2 \tag{1}$$

$$p_w = \rho c\, v \tag{2}$$

where ρ is the density of water, c is the velocity of sound in water, and v is the velocity of water. Since the velocity of sound in water at normal temperature and atmospheric pressure is approximately 1,500 m/s, the water hammer pressure p_w is much larger than the stagnation pressure p_s under ordinary impact conditions.

The condition of impact, i.e., whether a stream of water impinges continuously or water lumps and droplets impinge intermittently, affects the pressure generated at the impact point. If the pressure generated at the impact point is larger than the strength of material such as the yield strength, material removal occurs at the impact point. Accordingly, material removal by a pure water jet is significantly affected by the flow structure of the jet. In general, sharp cutting by a pure water jet is conducted in the initial region, and massive material removal over a wide area is realized in and around the region in which jet breakup occurs.

Since the water hammer pressure is much larger than the stagnation pressure, discontinuous water jets generated by some external mechanisms have much larger destructive power than continuous water jets. Vijay and Foldyna (1994) developed a forced pulsed water jet nozzle containing a vibrating tip. The tip is forced to vibrate at high frequency by an ultrasonic piezoelectric or magnetostrictive transducer. Figure 5 (Yan, 2007) shows a photograph of the fully developed forced pulsed water jet taken with a Nd-YAG laser. Mushroom shaped water lumps are generated in the jet. The material removal capability by the forced pulsed water jet at the standoff distance, at which distinct water lumps are formed, is much larger than material removal capability of ordinary continuous water jets.

When a high-velocity water jet is injected in a submerged environment, a free shear layer is established around the jet, and this layer grows in thickness as the jet emerges from the nozzle. The shear layer quickly becomes unstable, breaks down into turbulent motion and

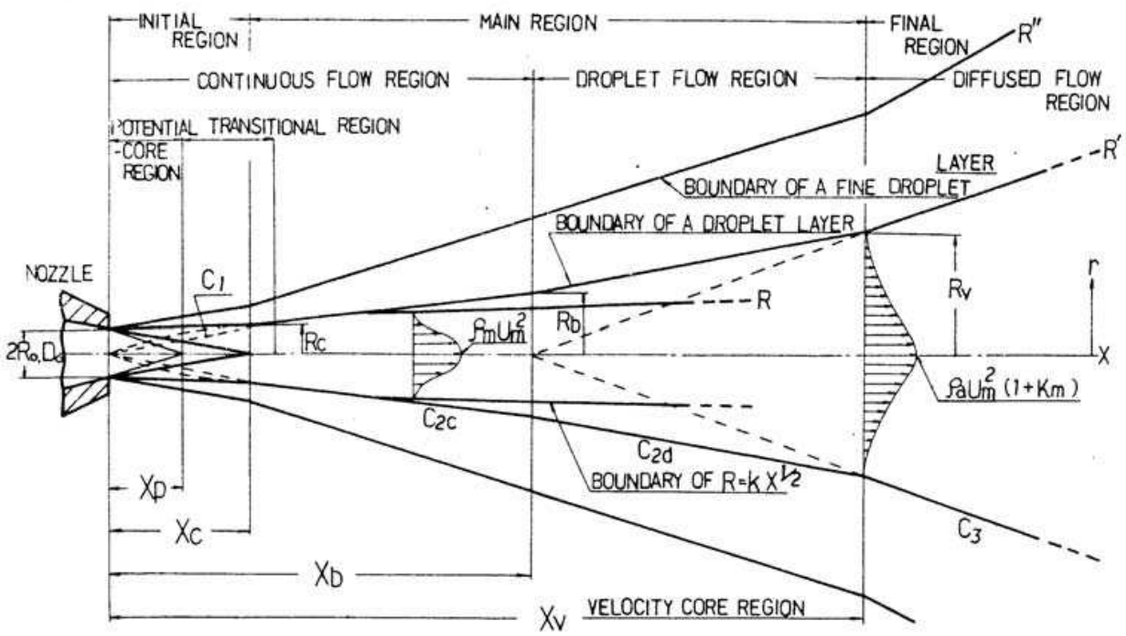


Fig. 4. Structure of a water jet in air (Yanaida and Ohashi, 1980)

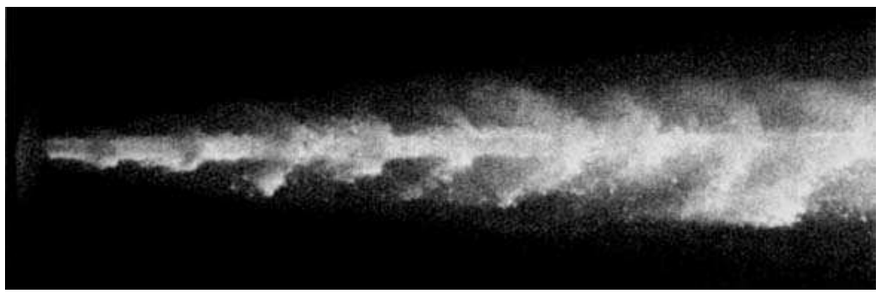


Fig. 5. Photograph of a fully developed forced pulsed water jet (Yan, 2007)

starts to spread, entraining surrounding water. In an ordinary submerged environment, cavitation occurs in the region of high shear at the boundary between the jet and the surrounding water. Cavitation around the jet suppresses the deceleration of the jet and produces cavitation erosion by the collapse of cavitation bubbles. Accordingly, cavitation around the jet significantly affects the material removal characteristics of submerged water jets. The parameter similitude in cavitation is defined by the cavitation number σ as follows:

$$\sigma = (p_a - p_v) / (p_i - p_a) \tag{3}$$

where p_a , p_i, and p_v are the ambient pressure, the injection pressure, and the vapor pressure of water, respectively. The cavitation number σ measures the resistance of the flow to cavitation. The lower the cavitation number, the more likely cavitation is to occur. If cavitation occurs, lowering the cavitation number will increase the extent of cavitation, i.e., the number and size of vapor bubbles will increase. Figure 6 shows an example of an instantaneous photograph of a cavitating jet at p_i = 69 MPa and σ = 0.006. The nozzle diameter is 0.5 mm. Since the jet is illuminated from behind, the cavitation clouds appear to be black. The cavitation clouds are

continuous near the nozzle exit but separate and develop into lumps as they travel with the jet. Shimizu et al. (1998) conducted erosion tests using submerged water jets at injection pressures ranging from 49 to 118 MPa and cavitation numbers ranging from 0.006 to 0.022. Since the jet decelerates faster under a submerged environment, material removal by jet impingement is restricted in the region near the nozzle exit, as compared to jets in air. In addition to high-speed jet impingement, cavitation erosion is an additional material removal mechanism in the submerged environment. Cavitating jets are used for cleaning and shot-less peening (Soyama et al., 2002) in the water jetting industry.

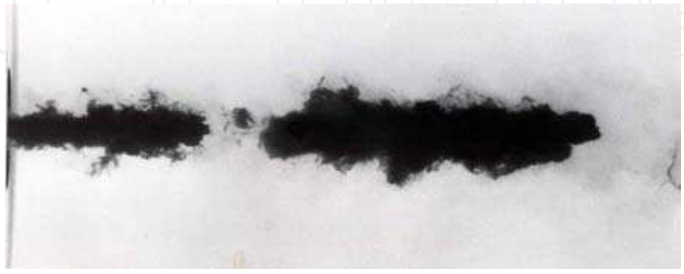


Fig. 6. Cavitating jet at p_i = 69 MPa and σ = 0.006 (flow direction is from left to right)

4.2 Abrasive jets

The material removal capability of abrasive water jets, in which abrasive particles are added to the water stream, is much larger than the material removal capability of the pure water jets. In an abrasive water jet, the stream of the water jet accelerates abrasive particles, which erode the material. The material removal capability of the water is slight in abrasive water jet processes. The impact of single solid particles is the basic material removal mechanism of abrasive water jets. Meng and Ludema (1995) defined four mechanisms by which solid particles separate material from a target surface, as shown in Figure 7 (Momber and Kovacevic, 1998). These mechanisms are cutting, fatigue, brittle facture, and melting, which generally do not work separately, but rather in combination. The importance of these mechanisms for a particular erosion process depends on several factors, such as the impact angle, the particle kinematic energy, the particle shape, the target material properties, and the environmental conditions.

Abrasive water jets can be classified as abrasive injection jets (AIJs) or abrasive suspension jets (ASJs), as stated earlier. Abrasive injection jets are formed using the nozzle head shown in Figure 8. A high-speed water jet is injected through the nozzle head. The diameter of the water jet nozzle is typically 0.2 to 0.4 mm. The high-speed water jet stream creates a vacuum, which draws abrasive particles into the mixing chamber along with air. The water jet stream accelerates the abrasive particles and air in the mixing tube, which is typically 0.5 to 1.5 mm in diameter. The cutting width of the AIJs depends on the diameter of the mixing tube and the standoff distance. For a mixing tube of 1.0 mm in diameter and the standoff distance of 3 to 5 mm, the cutting width is approximately 1.2 mm.

The three-phase jet flow discharged from the mixing tube consists of abrasive particles, water, and air. The material removal capability of the AIJ formed by a certain nozzle head (the dimensions and shape of the nozzle head are fixed) is affected by the pump pressure and the type and mass flow rate of abrasive. In general, the higher the pump pressure, the greater the material removal capability. When the abrasive flow rate is relatively small, the material removal capability increases with the abrasive mass flow rate, because the higher

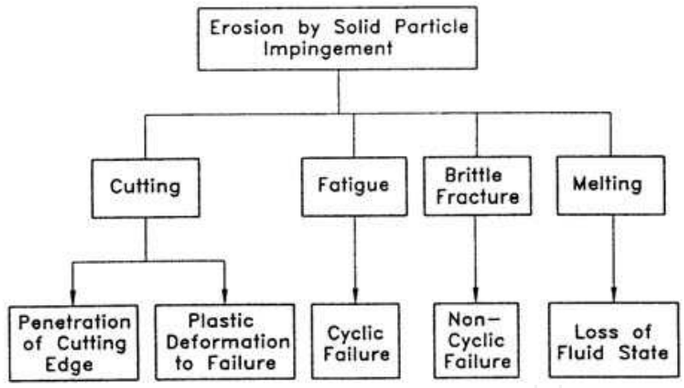


Fig. 7. Mechanisms of material removal by solid particle erosion (Momber and Kovacevic, 1998)

the abrasive mass flow rate, the higher the number of abrasive particles involved in the cutting processes. On the other hand, when too many abrasive particles are supplied to the nozzle head, the kinematic energy of the single abrasive particles tends to decrease because of the limited kinematic energy of the water jet. Thus, there exists an optimum abrasive mass flow rate. In addition, an uneven abrasive supply to the nozzle head can cause violent pulsation in AIJs. Shimizu et al. (2009) conducted high-speed observations of AIJs using high-speed video. Figure 9 shows a series of photographs of an AIJ issuing from the nozzle head at an injection pressure of 300 MPa and a time averaged abrasive mass flow rate of 600 g/min. The time interval between frames is 12.29 μs, and the flow direction is downward. Frame numbers are indicated at the top of each photograph. At frame number 1, the jet spreads radially just downstream of the mixing nozzle exit. As time proceeds, the hump of the jet develops into a large lump and moves downstream while growing in the stream-wise direction. As the lump leaves the mixing nozzle exit at frame number 10, another hump of the jet appears just downstream of the mixing tube exit. Observations of the flow conditions in the abrasive supply tube just upstream of the mixing chamber of the abrasive nozzle head were also conducted. Based on image analysis of the video, Shimizu et al. concluded that the pulsation of an AIJ at a frequency of less than 100 Hz is closely related to the fluctuation of the abrasive supply.

Wearing of the mixing tube is a serious problem in abrasive water jet machining. In the early days of abrasive water jet machining, the lifetime of a mixing tube constructed of standard tungsten carbide was only approximately five hours. However, advances in anti-wear materials technology have extended the lifetime of the mixing tube to 100 to 150 hours.

In contrast to the abrasive injection jets, abrasive suspension jets are solid-liquid two-phase jet flows. As shown in Figure 10, abrasive suspension jets are classified into two systems according to the generation mechanism (Brandt et al., 1994), namely, the bypass system and the direct pumping system. In the bypass system, part of the water flow is used to draw the abrasive material out of the storage vessel and to mix it back into the main water flow line. In the direct pumping system, the pre-mixed slurry charged in a pressure vessel is pressurized by high-pressure water. An isolator is used to prevent mixing of the slurry and the water.

In the case of the AIJ, the addition of abrasive particles increases the jet diameter and decreases the jet velocity. The velocity of the ASJ discharged from the nozzle is 0.90 to 0.95 times the theoretical jet velocity calculated by Bernoulli's equation assuming the loss in the nozzle to be zero (Shimizu, 1996). Moreover, a compact ASJ can be formed if a suitable

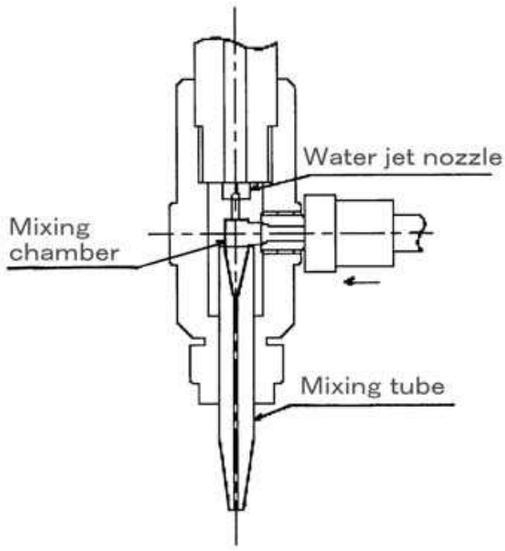


Fig. 8. Abrasive water jet nozzle head

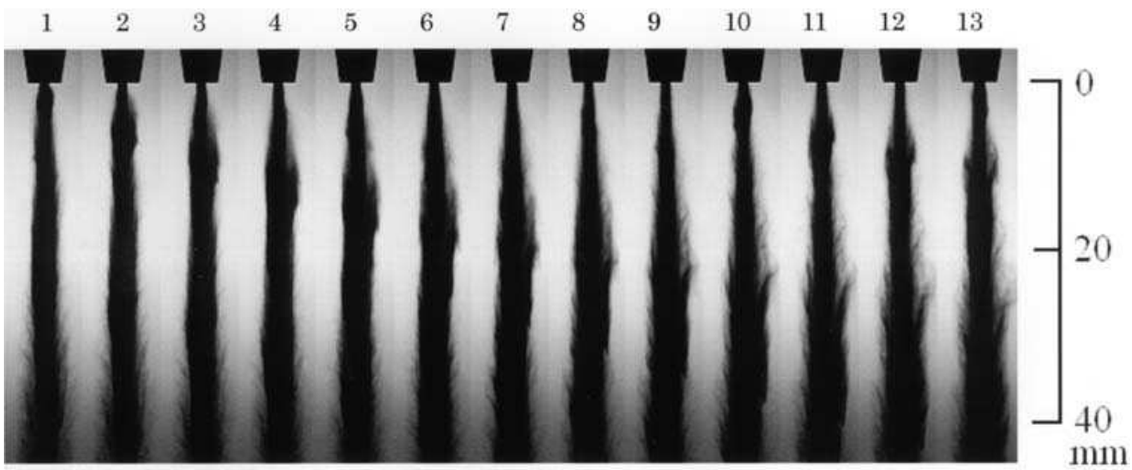


Fig. 9. Sequential photographs of AIJ,injection pressure: 300 MPa, abrasive mass flow rate: 600 g/min, abrasive: #80 garnet (Shimizu et al., 2009)

nozzle shape is adopted. It is also possible to form an ASJ with a very high abrasive concentration, such as 50 wt%. Accordingly, the abrasive suspension jet has a greater capability for drilling and cutting than the abrasive water injection jet. Brandt et al. (1994) compared the cutting performances of the ASJ and the AIJ under the same hydraulic power ranges and the same abrasive mass flow rate. They concluded that the ASJ cuts at least twice as deep as the AIJ at the same hydraulic power. A micro-abrasive suspension system with a nozzle diameter of 50 μm was also developed (Miller, 2002). Since a cutting width of 60 to 70 μm can be realized using such a system, applications in micro-machining and semiconductor industries are expected.

In the ASJ system, a convergent nozzle followed by a constant diameter straight passage (focusing section) of suitable length is generally used. Since abrasive-water slurry flows at high-speed in the nozzle, slurry erosion of the nozzle is a serious problem. Therefore, in

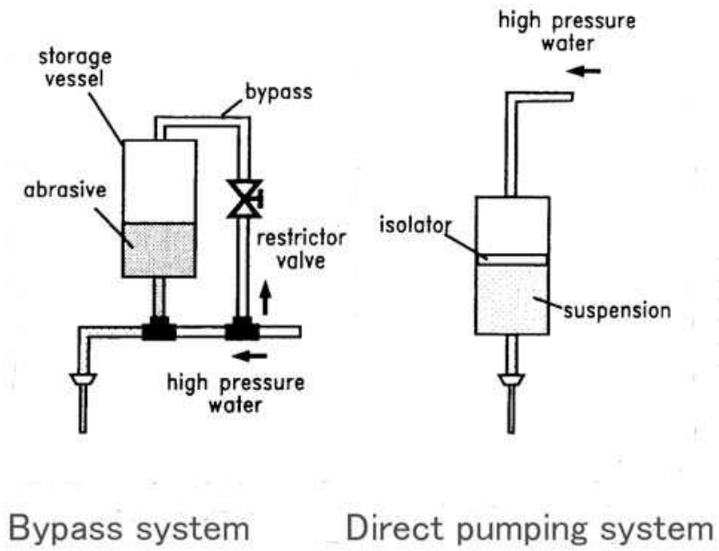


Fig. 10. Abrasive suspension systems (Brandt et al., 1994)

order to reduce nozzle wear, the outlet of the convergent section and the focusing section are constructed of wear resistance materials, such as sintered diamond. In order to investigate the effects of the wear of the nozzle focusing section on the material removal capability of the jet, an experimental nozzle was used to perform drilling tests (Shimizu et al., 1998). The outlet of the convergent section was constructed of sintered diamond, and the focusing section was constructed of cemented carbide. The drilling tests were conducted at a jetting pressure of 11.9 MPa with specimens of stainless steel and #220 aluminum oxide abrasive. Figure 11 shows the variation of drilling pit depth with standoff distance for a jetting duration of 60 s. The numbers in the figure are the order of the tests. The cross section of the nozzle after the drilling tests is shown in Figure 12. The total jetting duration was 780 s. The focusing section (indicated by the arrow) is worn, and the wear of the focusing section causes a serious reduction in drilling capability, as shown in Figure 11.

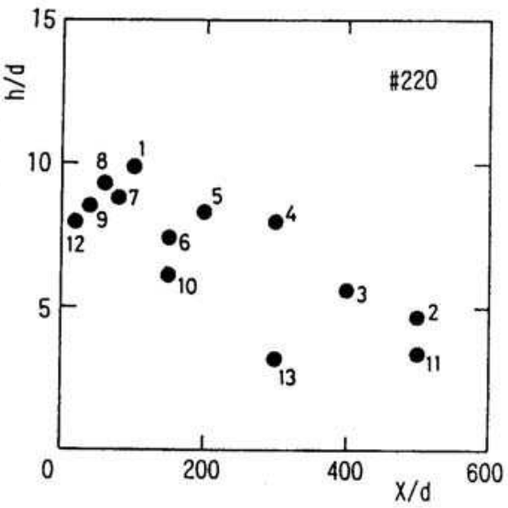


Fig. 11. Effect of nozzle wear on pit depth (Shimizu et al., 1998)

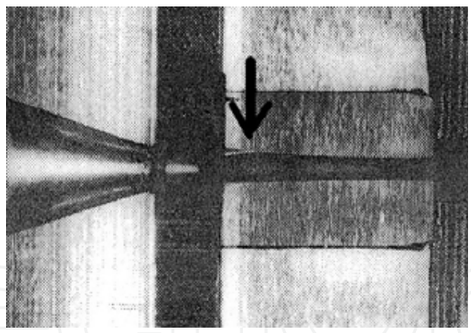


Fig. 12. Nozzle after drilling tests, jetting pressure: 11.9 MPa, abrasive of aluminum oxide mesh designation of #220 (Shimizu et al., 1998)

5. Conclusion

Friction and wear between the cylinder and the piston of high-pressure pumps used in the water jetting processes are important problems greatly influence the efficiency, reliability, and lifetime of the high-pressure pump. Corrosion and erosion in valves and nozzles are serious problems that affect the reliability of water jetting systems. Erosion by water droplet impingement is the material removal mechanism of pure water jets, and erosion by solid particle impingement is the material removal mechanism of abrasive water jet machining. Knowledge of tribology is indispensable in order to realize more reliable and more efficient water jet machining systems.

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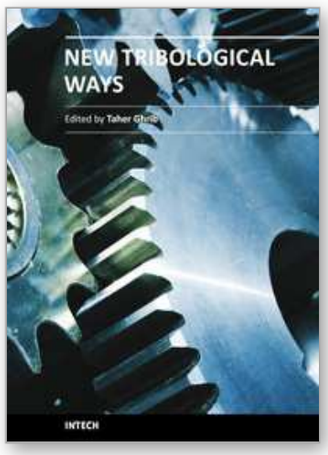
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This book aims to recapitulate old information's available and brings new information's that are with the fashion research on an atomic and nanometric scale in various fields by introducing several mathematical models to measure some parameters characterizing metals like the hydrodynamic elasticity coefficient, hardness, lubricant viscosity, viscosity coefficient, tensile strength .... It uses new measurement techniques very developed and nondestructive. Its principal distinctions of the other books, that it brings practical manners to model and to optimize the cutting process using various parameters and different techniques, namely, using water of high-velocity stream, tool with different form and radius, the cutting temperature effect, that can be measured with sufficient accuracy not only at a research lab and also with a theoretical forecast. This book aspire to minimize and eliminate the losses resulting from surfaces friction and wear which leads to a greater machining efficiency and to a better execution, fewer breakdowns and a significant saving. A great part is devoted to lubrication, of which the goal is to find the famous techniques using solid and liquid lubricant films applied for giving super low friction coefficients and improving the lubricant properties on surfaces.

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