

Water Jet Cutter: A Tribological Tool for Various Uses in Industry

MANE 6963: Friction and Wear of Materials

Term Research Project

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1. Introduction

The water jet cutter is a tribological tool used in a variety of industries. These industries include: manufacturing (machining, cleaning, and surface preparation), mining and excavation, logging, food preparation, medical, and agriculture. The tool works by providing a high pressure stream of fluid to a material in order to remove particles in the cutting path. Typically the fluid used consists of water with an abrasive agent contained within. This process is very similar to natural erosion, just as a moving river carrying sand particles erodes away at its riverbed. However, the water jet cutting process occurs at a much faster rate at much higher pressures. The versatility of application and speed of the cutting has made this tool very useful for the vast multitude of industries that it is used in. Water jet technology is not only limited to cutting materials but can be used to treat surfaces. The use of this tool can be traced back all the way to the 1800's when this tool was used for hydraulic gold mining in California (Shimizu, 2011).

This paper will specifically discuss the different uses of water jet technology and the tribological phenomena involved with each process.

2. Background

The medium used in the water jet cutter can be categorized into two classifications: Pure water jet and abrasive water jet. A pure water jet consists of a stream of water without an abrasive material passed through a nozzle. Since this type does not contain an abrasive agent, it is primarily used for surface cleaning and cutting of softer materials. Two types of pressures are formed from the contact of the water with the target material during the process. A stagnation pressure, p_s , is created at the impact point from a constantly flowing jet. A water hammer pressure, p_w , is created instantly at the impact point if water droplets are formed in the jet. These pressures are responsible for the work that the water jet does to the target material. Typically, water hammer pressures are higher than stagnation pressures. If the pressures create local stresses high enough to yield the material in the impact location, material removal will occur (Shimizu, 2011). Equations (1) and (2) below can be used to calculate these two pressures (Shimizu, 2011).

$$p_s = \frac{\rho v^2}{2} \quad (1)$$

$$p_w = \rho c v \quad (2)$$

ρ = Density of Water, c = Velocity of Sound in Water, v = Velocity of Water Jet

Abrasive water jets can be further categorized into two classifications: Injection and suspension water jet cutting. The injection water jet cutting process works by creating a high pressure stream of plain water via a pump with pressures ranging from 100 MPa to 400 MPa (Momber & Kovacevic, 1997). A stream of fine grained abrasive material is accelerated toward the cutting head (low pressure). The stream of water and abrasive material enter the cutting head separately. The mixing of the water and abrasive material occurs in a mixing chamber. The abrasive material is "injected" into the high pressure stream of water. The low pressure in the chamber allows for air to mix with the water and abrasive material. This creates an abrasive slurry resulting in roughly 90% air, 6% water, and 4% abrasive that then enters a focusing nozzle (Applied New Technologies AG). This mixture leaves the nozzle at velocities in the order of magnitude of 100 meters per second (Momber, & Kovacevic, 1997; Applied New Technologies AG; Anand, & Katz, 2003).

A suspension water jet differs from the injection water jet in that the mixing of the abrasive agent and water occurs prior to the nozzle, thus resulting in a mixture of roughly 90% water and 10% abrasive (Applied New Technologies AG). The abrasive material is suspended in a storage vessel and is held under pressure which in turn pushes it through the nozzle. Since the abrasive material is held under pressure, the water pressure levels can be significantly lower than that of the injection water jet. In addition, the suspension water jet cuts faster and uses less volume of abrasive material and water when compared to an injection water jet with the cutting depth being held constant between the two types of cutters (Applied New Technologies AG).

The capability of material removal in the abrasive water jet is much higher than that of the pure water jet, thus making this type of water jet capable of cutting hard materials such as rocks or metals (Shimizu, 2011). The process of material removal from a water jet ("erosion by solid particle impingement") can be broken down into 4 mechanisms: Cutting, Fatigue, Brittle Fracture, and Melting (Meng, & Ludema, 1995).

- Cutting: Removal of material caused by the contact of high pressure water and abrasive particles with the target material in way of the cutting path. Includes penetration of the water jet and plastic deformation.

- Fatigue: Cracking caused by cyclic loading of water jet pressure causing stress higher than the materials fatigue strength (Cyclic).

- Brittle Fracture: Crack initiation and fast propagation without an increase in stress from applied forces to brittle materials. This is caused by low amounts of plastic deformation and energy absorption prior to the crack initiation and propagation (Non-Cyclic) (Kopeliovich, 2012; Meng, & Ludema, 1995).

- Melting: "Loss of fluid State" (Meng, & Ludema, 1995).

Each of these mechanisms work together in the particle erosion process of the target material in way of the cutting path. (Shimizu, 2011).

Abrasive mass flow rate plays an important role to the performance of the water jet cutter. Higher pressures typically result in higher erosion rates for material removal capability. Higher abrasive mass flow rates result in a higher percentage of abrasive particles sent through the stream. This results in higher cutting rates. However, if the particle density of the jet is too large, the energy of each individual particle decreases as the energy of the jet stays constant. (Shimizu, 2011).

A useful parameter in evaluating the effectiveness of water jet operations is the kerf profile. A kerf profile refers to the profile of the cut, slit, or notch created by the water jet. Parameters include the kerf width, waviness, and roughness. Kerf width is the measure of the width of the cut (i.e. the width of the material removal path). Kerf width is directly affected by the cut depth and tends to decrease as cutting speed increases. Kerf roughness is a measure of the variation in surface height within the cut. Typically kerf roughness increases with increasing cut depth. Kerf waviness is the variation of the cut centerline. This also includes the average width of the cut. Other attributes affect the kerf profile such as cutting speed and target material properties. It has also been determined that kerf waviness or roughness contributes less than 5% to the kerf width, thus making kerf width the governing factor. These parameters that make up kerf profile are especially important because they determine the quality of the cut (MA, & Deam, 2005).

3. Rock Cutting

The water jet has proved a useful tool in the excavation and mining industry. A collimated abrasive water jet can be used for rock cutting and tunneling. In a collimated abrasive water jet, a high pressure jet of water enters a large diameter collimating pipe and diffuses along the pipe wall. This produces suction which in turn draws the abrasive material into a mixing chamber to mix with the high pressure water. The acceleration of the abrasive is very high as it enters the pipe. This creates a high velocity mixture of water, air, and abrasive material, similar to the injection water jet. The collimating pipe contains a reflecting board (or deflectors) at the end to direct the jet of water, therefore setting the a width and depth that the water jet cuts into the rock. (Xiaohonga, Jianshenga, Yiyua, Lina, Huiminga, & Jiajunb, 2000). In addition, these deflectors allow the water jet to produce an enlarged opening in the rock allowing the pipe to be further inserted into the continually deepening hole to further continue the cutting process (Swanson, 1989).

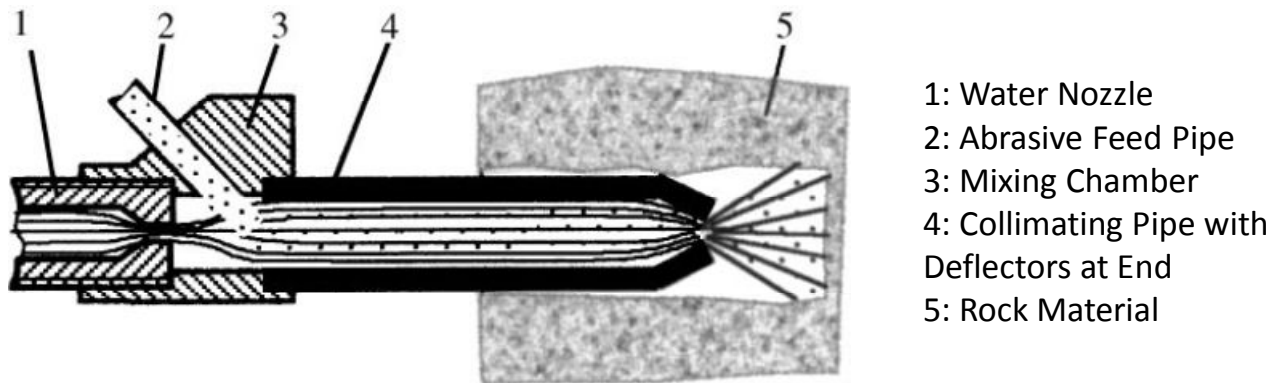


Figure 1 - Schematic of Rock Cutting Water Jet (Xiaohonga, et al., 2000)

Typically, the pressures in the collimating pipe are lower than that of the nozzle, and therefore the material of the pipe does not require high tensile strength as the nozzle does (Swanson, 1989).

The smaller the diameter of the collimating pipe, the greater the flow resistance. Therefore, as the pipe length increases, the diameter of the pipe must be increased. Shorter pipes result in a deeper cutting depth and are used when a deeper cut is desired. However, longer pipes result in a larger volume of rock breakage (Xiaohonga, et al., 2000).

The use of this tool has a multitude of benefits as opposed to conventional methods such as blasting or drilling. It results in a higher quality of rock wall surface and increased cutting precision (Xiaohonga, et al., 2000). In addition, mechanical tools are limited as to how much power is transferred to the rock by the amount of heat energy they create. An increase in heat decreases the tools resistance to wear by decreasing the tool's hardness. Therefore, mechanical tools are limited in power transfer to a magnitude that will not raise the temperature so much that the wear rate exceeds an acceptable value. The water jet creates heat just as the mechanical tools do, however this heat is disseminated into the rock harmlessly without increasing the rate of wear of the water jet cutting equipment. Therefore, the limitations of power transfer are much less (KMT Waterjet, 2012). Additionally, the water jet cutter results in the elimination of bits, and therefore the need for replacing them. Further advantages of the tool are its weight and portability. In addition, this cutting technique reduces the amount of dust and particles emitted to the surrounding air (Swanson, 1989).

4. Manufacturing

Water jet cutters have become a widely used tool for cutting in manufacturing. They can be used to cut a variety of materials, including but not limited to steel and aluminum alloys, iron, glass, rubber, wood, and composites. These water jet cutters typically use abrasives. The most commonly used abrasive is garnet. Garnet is environmentally safe and provides effective wear to the target material. Harder materials, such as aluminum oxide, are rarely used; Although they provide effective wear to the target material being cut, they also accelerate the wear of the water jet equipment (such as the nozzle) thus reducing the tool's or individual component's life (AccuStream Waterjet Systems).

Water jet cutters offer many clear advantages over conventional tool cutting methods such as a band saw, milling machine, or flame torch. These advantages include:

- A variety of materials and material thicknesses can be cut
- No cutter induced warping or distortion
- High accuracy ($\pm 0.003''$ to $\pm 0.015''$) and multitude of cutting geometry (FLOW, 2012)
- Speed of cutting process
- Small kerf for minimal material loss
- No heat affected zone or thermal cracking
- Minimal to no burs produced from cutting
- No dust or sparks produced

Figure 2 provides a micro water jet cutting example that demonstrates the capability of the water jet cutter to cut precise shapes on a very small order of magnitude compared to conventional cutting methods.



Figure 2 - Example of micro water jet cutting (Parette)

Water jet technology is combined with Computer Numerically Controlled (CNC) technology to become an automated cutting process capable of producing a multitude of complex shapes of very high accuracy. They consist of a cutting head that is controlled by a computer. Water jet cutters can produce 1,2, or 3-Dimensional cutting paths.

1-D cutters typically consist of the cutting head positioned statically and the material moved on a conveyor in one direction to produce a straight line cutting path. There may be multiple cutting heads used simultaneously.

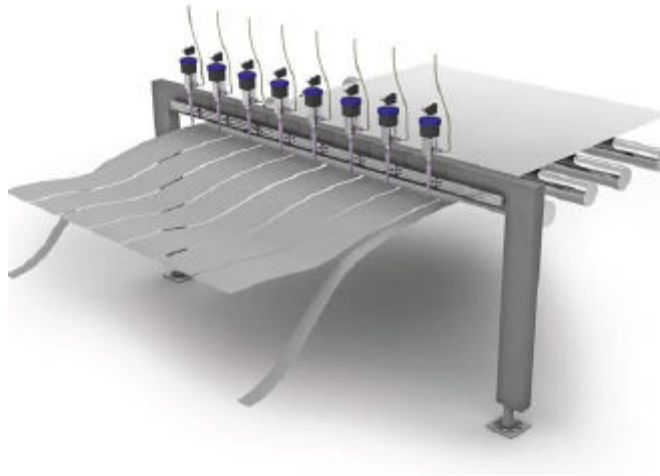


Figure 3 - 1-Dimensional Water Jet Cutter (KMT Waterjet Systems, 2011).

2-D cutters consist of the target material being secured to a table. The cutting head can move in 2 directions (X-axis and Y-axis). The movement of the cutting head is controlled by the computer. The desired shape is entered into the computer which then uses an algorithm to determine the cutting path. Micro-movements in the X and Y direction produce smooth curves. 5-axis machines allow the cutting head to tilt to produce complex edges or cone-shaped cuts (KMT Waterjet Systems, 2011).



Figure 4 - 2-Dimensional Water Jet Cutter (KMT Waterjet Systems, 2011).

3-D cutters consist of the cutting head being placed on a robotic arm which allows for the cutting head to move anywhere in 3 dimensions (KMT Waterjet Systems, 2011).

5. Surface Treatment

Water jet technology can be used on surfaces to remove coatings, paint, deposits, or even rust. It can also be used to treat surfaces. The roughness parameters of the substrate of a metal are especially important for the pull-off strength or delamination of paint or other protective coatings. The water jet is a useful tool for preparing surfaces prior to painting or coating to ensure a proper protection for a longer life (Teimourian, Shabgard, & Momber, 2010). The water jet velocity for a cleaning process is generally between 80 to 200 m/s (Guha, Barron, & Balachandar, 2010). The water jet in air can be subdivided into three regions, each with different characteristics:

- Initial: This is the region located directly after the jet stream leaves the nozzle. The water jet has continuous flow characteristics. The flow has a velocity equal to the velocity at the nozzle exit.
- Main or Droplet: In this region, the continuous water is broken up into droplets as the water interacts with the surrounding air. The size of the droplets decreases as the radial distance of the droplets from the jet centerline increases.
- Diffuse Region: This is a wide region where the droplets are disintegrated into very small droplets and scattered over a large area. The velocity of the droplets in this region

drops significantly and is therefore not useful for any cleaning or working of a surface. (Rajesh, Babu, 2001; Guha, Barron, & Balachandar, 2010).

It is important that the water jet be positioned so that the water jet contacts the surface in the main or droplet region. The impact of a water droplet on a surface can be broken into two stages. In the first stage, the water hits the solid surface and creates a high pressure, thus causing most of the damage resulting from the impact. Once this pressure is released, as there are no boundaries adjacent to the droplet, the second stage begins consisting of outward flow tangential to the surface. This outward flow can be as much as 5 times the velocity of the droplet at impact (Foldyna, Sitek, Scucka, Martinec, Valicek, Palenikova, & 2009). This tangential flow can create very large shear forces and stress on the surface. The more asperities and/or the higher the roughness parameters of the surface, the higher the shear forces will be. They can even be high enough to cause shear fractures (Foldyna, et al., 2009). This phenomenon can be used to treat or clean a surface.

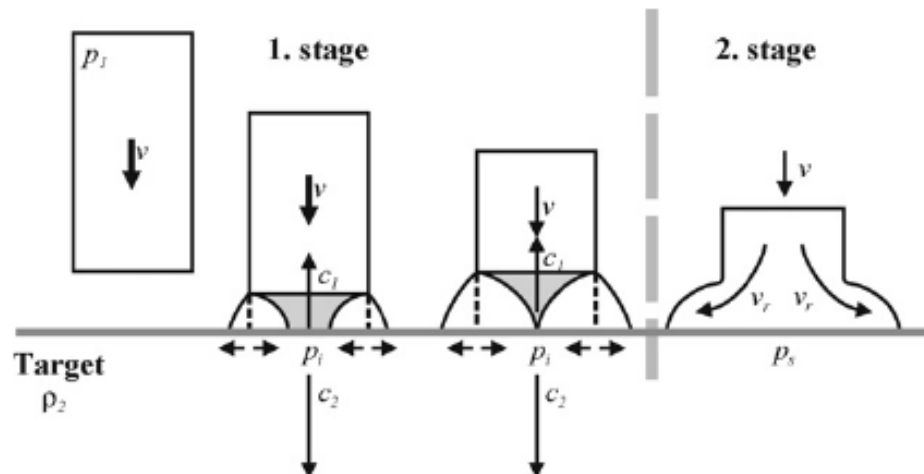


Figure 5 - Structure of Water Jet in Air (Foldyna, et al., 2009).

Another useful surface treatment is water jet shot peening. The benefit of this process is that it offers improved fatigue strength of the material by increasing the materials resistance to crack initiation and propagation. Water jet shot peening also increases a material's resistance to corrosion. This process especially benefits materials used for strength in underwater applications by preventing stress corrosion cracking (Rajesh & Babu, 2001).

Water jet peening typically utilizes pressures in lower ranges than that used for water jet cutting. Specifically, pressures in the range of 20 MPa to 140 MPa are used for aluminum and steel alloys. The process is similar to the process of cleaning surfaces with water jets discussed above based on the structure of the jet in air. In specific, water jet peening works by creating a pressure distribution on the target material surface. Peak loads create stress above the

materials yield strength causing plastic deformation. However, this area is constrained by the surrounding area thus creating high residual compressive stress. This increase in residual compressive stress creates the material's increase in fatigue strength, or resistance to crack propagation (Rajesh & Babu, 2001).

6. Food Industry

Water jet cutters are now being used in the food processing industry. This tool can be used for cutting meats and fish, frozen foods, vegetables, and even prepared foods such as cakes, pastries, and bread. The water jet cutter offers many clear advantages to cutting food over conventional methods. The most important advantage is that this process is a hygienic method for cutting food. No blades or other tools contacting the food are involved. Instead, only a jet stream of pure water contacts the food and is washed away after removal. This minimizes risk of salmonella contamination. No chemicals, heat, or radiation are involved in the process as well.

This tool results in faster production of food. Decreased downtime from its reliability combined with ease of reconfiguration to accomplish different tasks or cut different foods result in increased production. The absence of a blade makes the setup easier to clean and there is no need to replace or sharpen a cutting tool. The water jet cutter has a typical kerf loss of 0.004" to 0.009" in this application as opposed to a typical kerf loss of 0.25" to 0.35" for a blade. The precise cutting properties results in a clean, accurate cut, without compressing or tearing the surrounding food, which results in a higher yield (KMT Waterjet, 2012; FLOW, 2001).

7. Summary

The water jet tool has many diverse uses and is used in a multitude of industries. It can be used as a practical method for surface finishing or cutting a variety of materials and thicknesses, ranging from hard materials such as rock and steel alloys to an efficient and hygienically practical method for cutting food. The tool can be used as a portable cutting tool or placed on a CNC arm and used to produce highly accurate cutting profiles. The water jet cutter offers many clear advantages over conventional mechanical cutting methods. It works by particle erosion at a very high rate of velocity and pressure. The water jet is useful tribological tool in which further advances in the technology are creating alternate methods of application in an already diverse tool.

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