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Paper

OPTIMIZATION OF UHP WATERJET CUTTING HEADS, THE ORIFICE

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ABSTRACT

Selecting the correct jewels, geometry and orifice mount design are critical factors in optimizing the performance of a waterjet cutting head in various UHP shapecutting applications. Synthetic sapphire, synthetic ruby and diamond are three common materials that orifice jewels are composed of.

This paper focuses on a critical component of all waterjet cutting heads, the orifice. A review of the jewel types, geometry considerations and a discussion of practical orifice mount design are presented. A review of a typical state of the art, high-performance cutting head illustrates these considerations and how this affects the optimization of the cutting head in practical applications.

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1. INTRODUCTION

Operators of fabrication shops know the importance of an optimized cutting head in both water only and abrasive waterjet shapecutting applications. Alignment of the waterjet cutting beam, rate of cutting, garnet consumption, and quality of cut all affect costs of operation and profitability. The cutting head is at the heart of the waterjet machine and the orifice is at the heart of the cutting head. Selection of orifice and orifice mount material and design is critical to the success of the cutting head.

2. THE CUTTING HEAD

The cutting head, also referred to as waterjet nozzle, serves to create and align the cutting beam of high pressure water. The effectiveness of the cutting beam requires the efficient and maximum delivery of power at the point of cutting. Ultra High Pressure (UHP) pumps deliver water pressure to the cutting head at sustained pressures from 40,000 psi (276 MPa) to 87,000 psi (600 MPa) through an on/off control valve. The high pressure water is forced through an orifice to create a high velocity waterjet, the cutting beam.

Typical abrasive waterjet (AWJ) cutting heads consist of these components; nozzle body (upstream UHP water tube), orifice, orifice mount, abrasive mixing chamber and mixing tube. Hashish [1] examines the design considerations of the components of an AWJ nozzle/cutting head and the effect on quality of the delivered abrasive waterjet. For example, Hashish found the nozzle body length should be at least 20 times the nozzle body tube diameter to produce good coherent jets.

In water only applications, the orifice creates a focused, aligned, coherent water cutting beam that delivers the energy of the high pressure water, eroding the material being cut. Figure 1 shows a typical high-performance water only cutting head.

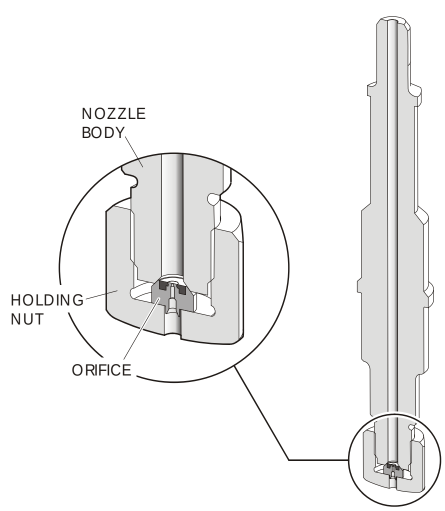

Figure 1. Diagram of high-performance water only waterjet cutting head

In abrasive cutting applications, the high pressure waterjet stream exiting the orifice creates a Venturi effect vacuum in the mixing chamber. This pulls abrasive material, typically fine mesh garnet, into the mixing area, entraining the abrasive into the water stream. Figure 2 shows a typical high-performance abrasive cutting head. The water stream is directed through a mixing tube, promoting a uniform mix, and exits as a powerful water cutting beam with the energy necessary to cut a variety of materials.

Vacuum assist can be added to ensure the immediate entrainment of abrasives into the waterjet stream. Vacuum assist can be accomplished by adding a port to the mixing chamber and attaching a vacuum source to the port. Controlling the on/off of this additional suction aids the low level suction produced by the waterjet Venturi vacuum. The sudden impact of a waterjet on some materials (composites, glass, etc.) may cause chipping, delamination or fracture. The lag time between the start of the waterjet and the arrival of abrasives to the mixing chamber may be long enough to cause this damage. Reducing the water pressure to reduce pressure impact on the material may also result in weak air and abrasive entrainment [1]. Vacuum assist can be used to improve the effect the lower pressure or small diameter waterjets and thus improve the reliability of the lower pressure operation.

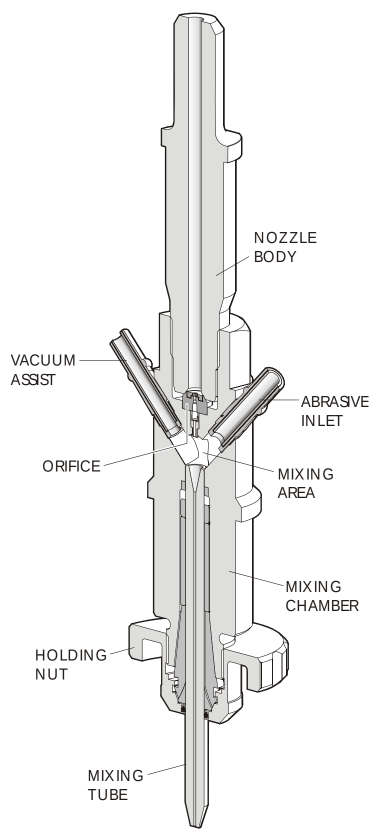

Figure 2. Diagram of high-performance abrasive waterjet cutting head

2.1 Flow Characteristics

The quality of the waterjet stream (flow) is critical to efficient, optimal and repeatable precision cutting. The quality of the stream can be described by the parameters of alignment and coherency. Alignment is a measure of how true the stream is to the designed direction of travel. Typically for AWJ applications, this is coaxial to the inside diameter of the mixing tube.

Coherency can be defined as a measure of the distance traveled by the water stream before the diameter grows larger than a defined threshold value. For example, the coherent length could be the distance traveled by the stream at which point the diameter has increased 200% compared to the diameter of the stream at the point of exit from the orifice. Figure 3 shows two examples of waterjets exiting from an orifice at 60 ksi (414 MPa). Figure 4 shows two examples of waterjets exiting the mixing tube to check alignment. Alignment evaluation tests are typically performed at low pressure, approximately 2000 - 3000 psi.

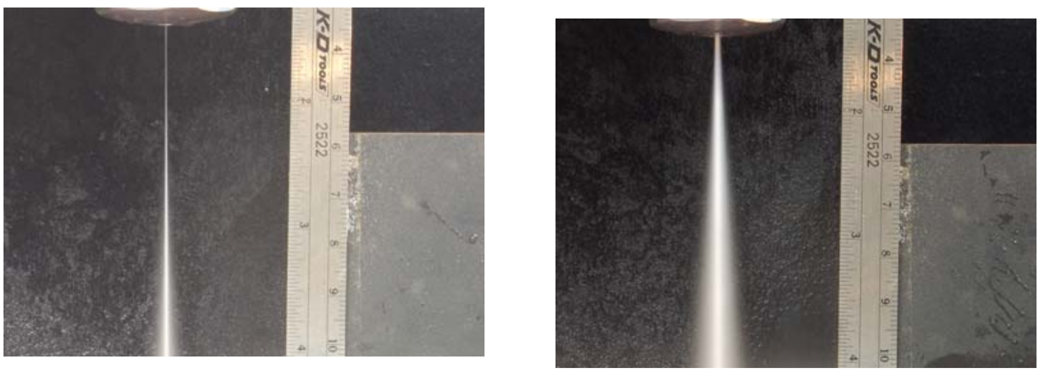

Figure 3. Comparison of coherency length of stream exiting from orifice (60 ksi/414 MPa)

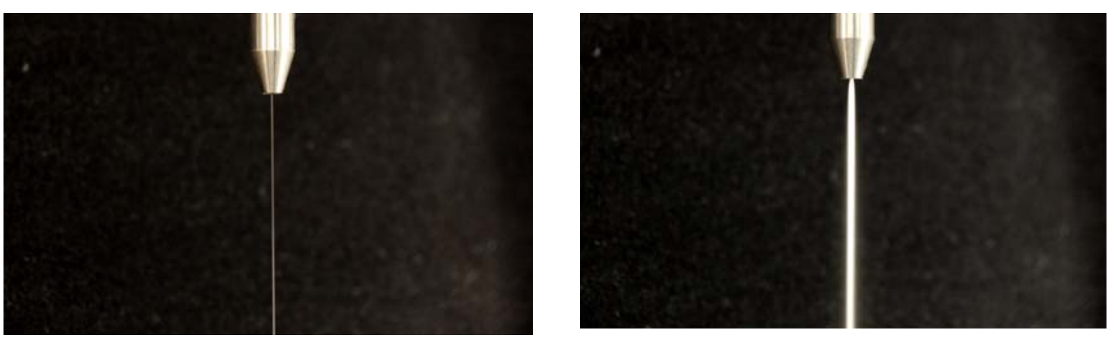

Figure 4. Comparison of a well aligned, coherent stream and not well aligned, less coherent stream exiting from a mixing tube (3 ksi).

2.2 Effect of Orifice Mount On Alignment

The key to overall good alignment of the waterjet stream is the positioning of the jewel in the orifice mount and then the positioning of the orifice mount in the cutting head. This requires the careful design of alignment registers between the mount and the corresponding surfaces of the cutting head. This is very important in the abrasive waterjet cutting head, as the stream travels through the mixing tube. A poorly aligned stream will not only rapidly wear through the walls of the mixing tube, producing short life, but also result in an inefficient or ineffective abrasive waterjet.

2.3 Effect of Mixing Tube on Coherency and Alignment

Mixing tube length influences the capability of the mixing tube to focus the jet stream. Longer mixing tubes provide a longer influence on the abrasive entrained water stream and therefore focus better than shorter mixing tubes, leading to incremental improvements in precision. The inside diameter of the mixing tube relative to the orifice determines how fast the mixing tube will wear out, the precision of the cut to be made and the cutting speed. When comparing smaller inner diameter to larger inner diameter mixing tubes, these characteristics are affected;

1. Incremental increase in cutting speed
2. Incremental decrease in mixing tube life
3. Improved precision
4. Smaller kerf width

2.4 Energy Delivered

Power density is defined as the jet hydraulic power per unit area. The greater the power density, the more "powerful" and effective is the water cutting beam. From the study of flow characteristic and power density equations, the energy content E can be seen to be proportional to A_n (orifice cross-sectional area), P (pressure of water above the orifice), and C_d (orifice coefficient of discharge).

$$E \ \alpha \ (A_n)(P^{1.5})(C_d) \qquad (1)$$

From this relationship, we find that doubling the pressure from 50 ksi (345 Mpa) to 100 ksi (690 Mpa) results in an increase in power density of 182 %, or 2.82 times. The increase in water flow rate is only 41%, or 1.41 times, for a given orifice size. [2]

In the case of abrasive waterjet, the kinetic energy and momentum are transferred from the high pressure water beam to the abrasive particles. The kinetic energy of the abrasive particles is applied along the sharp edges of the particles, resulting in the cutting process and material removal of the work piece. The efficiency of the kinetic energy transfer has been found to not exceed 25% [1].

3. THE ORIFICE

The orifice in a cutting head typically consists of a jewel (sapphire, ruby or diamond) with a hole, mounted or placed into a holder or mount. The mount material typically is a high grade of steel. The jewel may be either sintered or mounted using a retaining ring seal. Design of the orifice assembly must consider factors such as repeatability, precision costs and length of serviceable life. Serviceable life can be defined as the point at which the resultant cutting quality exceeds acceptable limits for a given application. The serviceable life of the orifice assembly is affected by observable parameters such as alignment, coherency, fatigue of the jewel and mount, jewel chipping resistance, mount erosion and repeatability.

3.1 The Jewel

Today's cutting heads typically use sapphire, ruby or diamond as the jewel, depending upon the application, type and thickness of material, and the economics of the cutting process.

Sapphire and ruby -
Precision synthetic sapphire or ruby jewels offer a less costly alternative to diamond. Sapphire and ruby are made of the same chemical composition, Al_2O_3, known as Aluminum Oxide or Corundum. Corundum can be naturally found and in this case synthetically manufactured. Corundum (normally white or clear) can be doped to produce sapphire of various colors. If corundum is doped with chromium to a reddish color (e.g. 0.05%), then it is referred to as ruby. Synthetic corundum has the advantage of a hardness of 9 on the Moh's hardness scale. Diamond has a hardness of 10. Studies at Flow have shown that when the shape and geometry of a sapphire orifice and a ruby orifice are the same, the performance of the two materials is very similar.

Diamond -
Diamond provides the most durable material for the jewel today. Natural diamonds can be positioned in the mount through a sintering process. Synthetic diamonds can be positioned in the mount through the use of retainer rings. In both cases, the bore is typically cylindrical, sometimes widening towards the exit side, with a sharp entry edge.

3.2 Geometry

3.2.1 Jewel

A great deal of research has gone into the geometry and finishing of the jewel. The shape of the entry edge of the bore has a great influence over the nature of the flow through the orifice. See figures 5 and 6. The hole diameter, the hole entrance geometry and the pressure differential across the entrance to exit influence both the volume and the resultant exit quality of the flow.

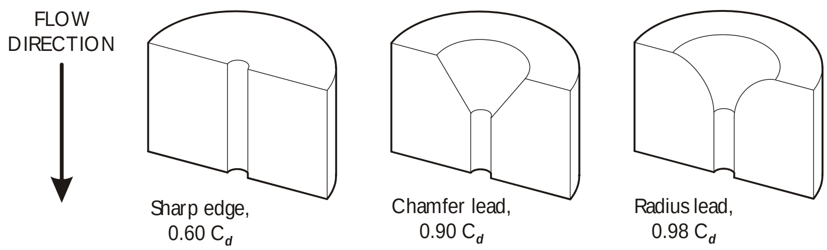

Figure 5. Comparison of jewel leading edge geometry. [3]

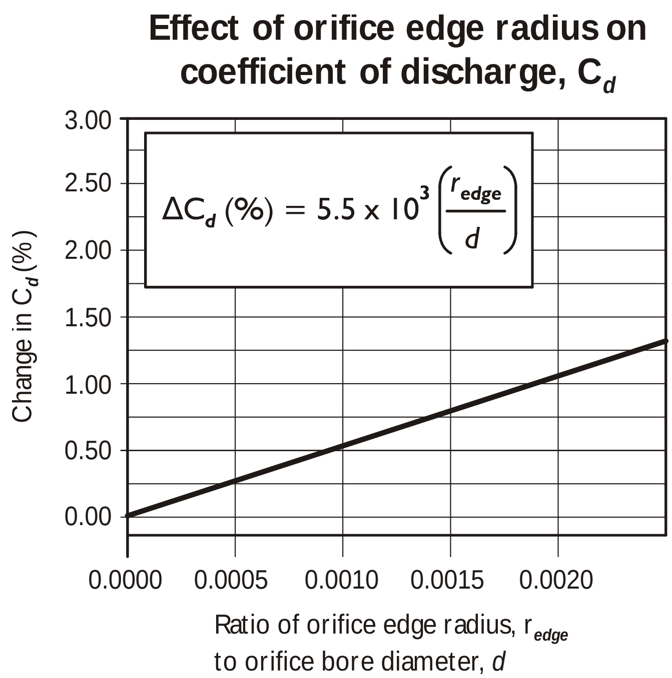

Figure 6. Relationship of radius edge to C_d, Coefficient of Discharge. [3]

A useful metric in understanding the behavior of the stream flow through an orifice is the coefficient of discharge, C_d As can be seen in fig 5 the coefficient increases as the leading edge of the orifice changes from sharp to radius [3]. The larger is the coefficient, the greater the volume of water flowing and the higher the rate of flow. Fig 6 shows a relationship derived experimentally, where the coefficient increases as the ratio of radius to bore diameter increases. This relationship is important to understand when comparing the flow behavior of a radius orifice of a certain bore size to a sharp edged orifice of the same bore size. In addition, Hashish [1] observes that for a given waterjet power, it is more efficient (higher C_d) to increase the pressure than to increase the orifice diameter to convert the pressure's potential energy to kinetic energy. This can also be noted from equation (1).

3.2.2 Jewel Mount Method

The geometry of the bore of the mount also influences the nature and quality of the waterjet flow [4, 5]. Three possible bore configurations can be labeled as cylindrical, cone-up and cone-down as shown in figure 7.

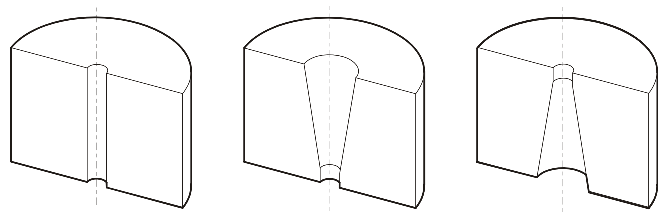

Figure 7. Orifice mount styles; cylindrical, cone-up, and cone-down [4, 5]

Studies [4, 5] have shown that cone-down mount geometry has the following advantages.

1. Lower discharge coefficient and higher velocity coefficient.
2. The resultant constricted jet greatly reduces cavitation, reduces turbulence and disturbances in the jet leading to higher stability and longer break up length/coherency.
3. Reducing the cone angle has no effect on the constricted waterjet.
4. Increasing nozzle aspect (hole length/hole diameter) ratio has no effect on the constricted waterjet.

Figure 8 shows an example of fluid flow field for a cone-down mounting method.

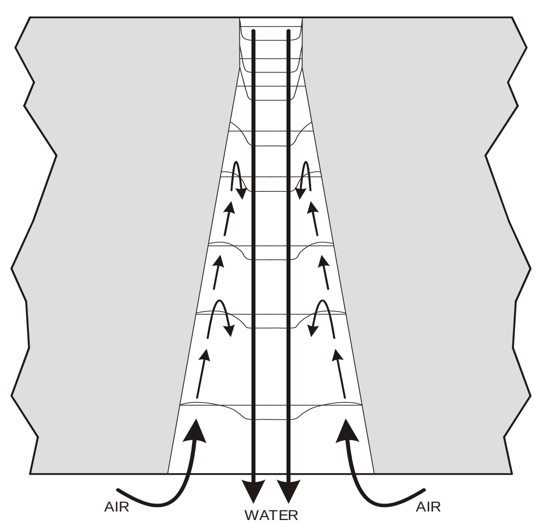

Figure 8. Water and air flow characteristics of a cone-down orifice/mount design. [4, 5]

Due to the properties of the mixing chamber below the orifice mount assembly, abrasive material may be drawn back up against the lower surfaces of the mount, causing erosion of the mount. By increasing the nozzle aspect ratio, the amount of air being drawn back up is decreased and thus reducing the erosion of the underside of the mount. Long term exposure to this erosion may erode sufficient mount material away, leading to failure of support to the jewel orifice. In the case of sapphire and ruby orifices, the serviceable life of the jewels is typically far less than the mount. However, with diamond, the diamond jewel may outlast the mounting material in which it is mounted and thus care must be taken with the design of diamond mounts.

Hashish [1] also observed that increasing the distance between the orifice and abrasive entry port causes the abrasives to first move toward the orifice and impact the bottom of the orifice mount, increasing wear. Conversely, by reducing the distance, wear on the orifice mount may be reduced.

3.3 Chipping Resistance

An important waterjet operational practice is to ensure that the water supplied to the cutting head is of high quality with minimal particulate matter. Sapphire and ruby orifices that have a sharp leading edge are prone to damage, as shown in figure 9, from particulates in the high pressure water stream.

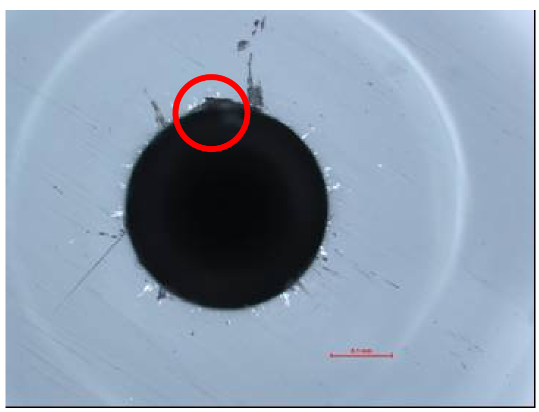

Figure 9. Sapphire orifice, sharp leading edge, chipping due to particulate material.

Studies at Flow have shown that a leading edge with a small radius is much more resistant to chipping or damage due to particulate matter. A ruby orifice with a radiused leading edge can typically last 2-4 times as long as a sapphire with a sharp leading edge. Key to high quality water stream is a uniform radius around the entire circumference of the leading edge. However, chipping failure may still occur as shown in figure 10, leading to a degraded waterjet stream.

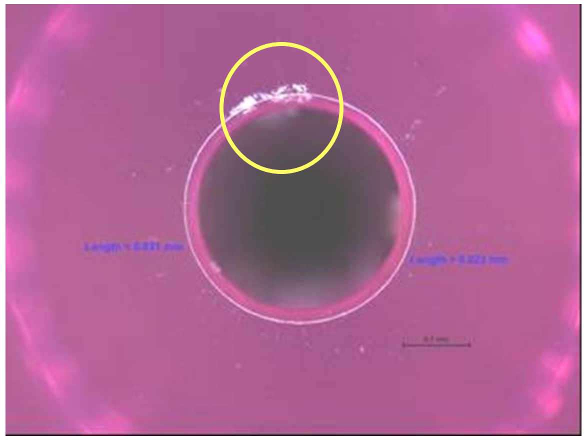

Figure 10. Ruby orifice, radius on the leading edge, chipping present.

Diamond jewels with a sharp edge are extremely resistant to chipping and the serviceable life of the jewel may outlast the orifice mount. Minerals and deposits may build up on the leading edge of the diamond and reduce the quality of the diamond stream. Best practices dictate cleaning of the diamond orifice every 100 to 200 hours in order to ensure optimum performance. Figure 11 shows normal wear on a natural diamond orifice edge during a lifetime study in an abrasive application at 87 ksi (600 MPa).

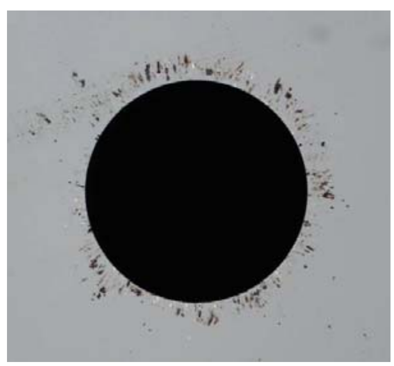

Figure 11. Natural diamond jewel orifice showing signs of wear, maintaining sharp leading edge.

In abrasive cutting heads, fine abrasives may migrate upstream above the orifice when the on/off valve cycles during normal cutting operation. This migration is caused by hydraulic transient phenomena induced by on/off valve cycling [1]. These abrasive particulates significantly reduce the orifice serviceable life. Hashish [1] describes two methods to prevent this; (1) a venting port in the orifice mount to the mixing region directly below the orifice and (2) sequence the waterjet on/off valve cycling and abrasive feed on/off valve cycling so that the abrasives are flushed out of the mixing chamber prior to waterjet off cycle.

3.4 Sharp vs. Radius Leading Edge

A sharp inlet leading edge on the orifice provides a more coherent stream length than an orifice with a radius. For water only applications, a sharp edge is the best choice and assuming the water is high quality, a sapphire orifice should last a long time relative to abrasive waterjet applications. A sharp edge diamond orifice would provide the longest serviceable life, if low water quality is suspect or if the economics justify it. For abrasive applications, a sharp edge diamond orifice is the optimum choice. If a less costly solution is required, then a ruby with a radius provides good serviceable life.

4. CHALLENGES AT 87 ksi (600 MPa)

During the development of the 87 ksi (600 MPa) cutting head, a number of challenges were overcome. The higher water pressure introduced the need for modifications to the bore of the nozzle body, to minimize the wear on the nozzle body as well as ensuring a coherent water stream exiting from the orifice. The increase in water pressure required additional engineering design considerations of material fatigue for both the diamond jewel orifice and the orifice mount. Diamond orifices were selected to be the best material at this time for 87 ksi (600 MPa). There was also an increased rate of erosion of the underside of the orifice mount that was compensated for. New geometry and material considerations were required. In order to minimize the wear on the mixing tubes, the alignment of the waterjet stream from the diamond orifice was carefully positioned with respect to the cutting head.

5. CONCLUSION

The orifice is a critical component of the cutting head. Optimum cutting relies upon the efficient power transfer from the UHP pump to the high pressure water, from the high pressure water to the entrained abrasive material and delivered as a cutting force at the point of cutting. A well aligned and coherent abrasive waterjet stream ensures the most efficient and effective cutting to occur. Increasing the water pressure provided to the cutting head from 60 ksi (414 MPa) to 87 ksi (600 MPa) delivers more effective cutting power. 87 ksi pumps operate at 45% higher pressure, moving abrasive particles faster. As a result, each abrasive particle carries more momentum and cutting power and therefore fewer abrasive particles are required. Studies at Flow have shown that operation at 87 Ksi results in 20 - 30% faster cutting, 30-50% less abrasive consumption, 20 - 30% in lower parts costs and reduced taper.

6. ACKNOWLEDGEMENTS

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7. NOMENCLATURE

E = power
An = orifice cross-sectional area
P = pressure
C_d = coefficient of discharge

8. REFERENCES

1. Hashish, M., "Inside AWJ Nozzles," Proceedings of the 2003 WJTA American Waterjet Conference, paper 1-D, Houston, Texas, Aug. 2003.

2. Hashish, M., "Observations on Cutting With 600MPa Waterjets," *Journal of Pressure Vessel Technology*, Vol. 124, 2002, pp. 229-233.

3. Baillo, P., "Simple orifices have an edge," Machine Design, Vol. 76, Num. 6, 2004, pp. 66-67.

4. Begenir, A., "The Role of Orifice Design in Hydroentanglement", Master Thesis, Textile Management Technology, North Carolina State University, Dec. 2002.

5. Tefreshi, H. V., Pourdeyhimi, B., "The Role of Orifice Design in Hydroentanglement: Simulations," Presentation, Nonwovens Cooperative Research Center, North Carolina State University, http://www.tx.ncsu.edu/ncrc/presentations.html.