The Material and Energy Flow Through the Abrasive Waterjet Machining and Recycling Processes

By

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Submitted to the Department of Mechanical Engineering in Partial Fulfillment of the Requirements for the Degree of

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Abstract

The purpose of this thesis was to investigate the material and energy flow through the abrasive waterjet machine and the WARD recycling machine. The goal was to track all of the material, water, abrasive, energy, air, and tooling through the different components of the machining and recycling processes. The material removal was found to be a function of length and part geometry, while all of the other variables were simply a function of time. The cutting speed determines the abrasive use, water use, and power use, and is varied based on the material, geometry, thickness and cut quality. The cutting speed was found to be linear with machineability – a measure of the material, almost linear with hardness – inversely related to thickness, somewhat inversely related to quality, and linear with power. Water was found to be the most abundant consumable, following by abrasive, together making up over 99% of the output waste. In the recycling process, roughly 60% of abrasive can be recycled after a single use, with the only significant consumable being power, used to dry the moist abrasive. Replacement tooling on both the abrasive waterjet and the WARD recycling unit were found to be negligible compared to the large amount of abrasive sludge produced every minute.

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Table of Contents

Table of Figures

Table of Tables

Introduction to the project

In the early 1990's, the Pentagon established the Joint Strike Fighter (JSF) program in an effort to design a versatile fighter aircraft that could be used among the different military groups. Previously, the Navy had preferred the duel engine aircrafts in case one engine was lost while out at sea, and certain applications called for two pilots, however these obstacles were overcome with compromise and strategic design. With design specifications in mind to accommodate the needs of all of the services and replace their current fleets, 15 month design contracts were granted to several companies to present a family of concept aircrafts. The mission was simple: to design a set of aircrafts with primarily common features that could be adapted to the specific needs of each of the services. The challenge however, was to keep the price at less than one-third of the estimated price for the up-and-coming F-22.

In the fighter jet industry, each and every generation of aircraft has been significantly more expensive than the previous one, no doubt increasing functionality, however reducing the number of aircrafts that can be purchased. In fact, if the current trend continues, by the year 2054, all of the services will be sharing a single plane. Although the fighter aircraft business is certainly an extreme, this sort of price inflation is very common in many industries, including machining.

New generations of machining tools are hitting the market at premium prices. A hammer and nail come quite cheaply nowadays, but if you want the versatility and speed of the latest CNC 3-axis milling machine, or the accuracy of a laser cutter, it will come at a price. There is no doubt that the price can pay for itself over time, but just as the JSF program set out to lower the price of fighter aircrafts, there must be a machining solution. In the early 1990's, without that goal in mind, the abrasive waterjet began to gain popularity and would in fact revolutionize the high speed, high precision machining industry. Over the past 15 years, abrasive waterjets have proven to minimize production cost and maximize versatility. With a comparable initial investment to other machine shop accessories, the waterjet's only substantial costs come in the form of power and abrasive consumption. Although these costs certainly exceed the everyday costs of the waterjet's neighbors, the ability to cut 2-inch thick steel with high edge quality in a matter of minutes makes up the difference. So what is the secret behind the waterjet? Or more importantly, what are we missing? Is there a hidden cost that has not yet been identified? Do we really have a thorough understanding of the entire waterjetting process, all of the inputs and outputs, and all of the costs, both monetary and other? This thesis project explores the flow of material through the abrasive waterjet system, from when the power comes on to when the waste from the bottom of the tank is handled in some form. The goal is to understand in depth the entire waterjetting cycle, the material and energy flow, and the effects on the environment in an effort to accurately and completely compare it to other machining tools.

Abrasive water jet (AWJ)

The focus of this investigation is the flow of material and energy during the waterjetting cycle. To understand this, some background on the abrasive waterjet is certainly in order.

History

Dr. Norman Franz, a forestry engineer, first thought to use ultra high pressure (UHP) water to cut trees in the late 1950's. By experimenting with simple methods of accelerating water to extremely high velocities, Franz gave birth to the concept behind all waterjetting technology, removing material with a high velocity stream of water. He was able to cut trees with acceptable precision, faced with only one major challenge: maintaining consistent high pressure for long periods of time. (Wilkins, 2003)

In the early 1970's, the technology had been developed to solve Franz's problem, and the first waterjet machine was constructed. At that time it was pure water, no abrasive, and the applications were limited. Although often a troublesome machine with short part lives, waterjet technology was used in manufacturing applications ranging from food to textiles, versatility that could not be found with most high performance machining tools. The process was young and came with many problems, but alternatives that waterjetting replaced were far more troublesome. Applications such as the cutting of cardboard and rubber were previously done with cutting blades, an even more challenging and expensive process. (Omax) As a result, the waterjet market expanded quickly, finding applications in almost every manufacturing industry one can think of.

In the early 1990's, Dr. John Olsen drastically increased the opportunities for the waterjet. By introducing abrasive into the jet stream, Olsen found that the cutting capability was hundreds, if not thousands, of times more powerful. The abrasive introduced another variable, however, to a fairly simple process, and with that came a lot of work. Olsen, who later founded Omax Corporation, the largest waterjet manufacturer in the world, knew that he would need a much more advanced pump design, as well as a redesigned nozzle and a more automated cutting process. With the presence of abrasive, the stream was no longer solely beam of water, and the wear and tear on the nozzle components was drastically increased by the added cutting capability. But all of this came with a very healthy reward, the ability to cut several inch think steel in a reasonable amount of time with fairly good accuracy and edge quality, as well as repeatability.

With a huge market to tackle, Olsen employed the help of MIT professor Dr. Alex Slocum in the design process. The modeling of both machine components and cutting performance was essential for the success of the abrasive waterjet. Olsen's goal was to take much of the input away from the user, and instead supplement it with an algorithm, simplifying the process so that the average machinist could pick it up quickly. Since then the technology has been improved without major design changes. The abrasive waterjet is by far the most versatile machine in any machine shop, with a fairly reasonable price tag considering its ability to print money.

Current state of market

Today, the waterjet market touches most imaginable industries. The pure waterjet applications, meaning no abrasive in the jet stream, range from cutting diapers to food to thin plastics. With various grades of abrasive, abrasivejets around the world are cutting wood, aluminum, steel, titanium...you name it, and the abrasivejet cuts it. It has found a place in many industries as well as most machine shops. It can be used by artists to cut stained glass, marble and stone, by architects for detail cuts, by schools as an easy-to-use prototyping tool, and by aerospace, manufacturing, automotive and model shops. Jetting technology is also used in many laser and EDM shops as a complimentary tool for high speed rough cutting and preparation. The process no longer requires extensive operator experience as it did before the days of automation. In the majority of the standard purchasable abrasive waterjets, the user simply inputs a design from a drawing program, a number representing the material, a thickness, and edge quality rating; the machine does the rest. Software has been optimized to minimize jetting effects such as taper, piercing and lag, all to be explained in the following pages. Software updates frequently improve the performance of the machine as the cutting process becomes better understood, tolerances are tightened, and standards are heightened.

Abrasive recycling

Compared to most other machining processes, the abrasive waterjet produces a high volume of waste that is a burden to deal with. In milling operations for example, time is invested to design the material removal process so as to minimize the amount of wasted material. These steps are taken because the work piece is often expensive, and when operating on high volumes, the wasted material accumulates very quickly. Even the smallest shavings are often salvaged and recycled or reused because it results in cost savings. When machining platinum, at over $800 an ounce, the specs of dust carry real value. (www.reuters.com)

Prior to the introduction of abrasive to the jetting industry, the waste, termed sludge, was a very determinable composition of water and the material being cut. It is a simple calculation to determine the amount of material removed when making cuts, as will be shown later, and the only other component is water. After the introduction of abrasive waterjetting, the sludge became far more interesting. Instead of water with suspended and dissolved components from the work piece being sent down the drain, the sludge accumulated very quickly to high volumes and high masses. The abrasive, often consumed at 1+ pound(s) each minute while machining, collected at the bottom of machines only to clog drains and require extensive measures to be removed and likely sent to a landfill. This still happens today, in fact in most abrasive jet applications around the world the sludge is removed and directed to a landfill for disposal. The mixture is almost entirely abrasive, with comparably small amounts of work piece material and minimal amounts of water.

WARD history

Because abrasive consumption represents the majority of the waterjet's operating costs, there has naturally been a move to discover a way to recycle it. (Forming and Fabricating February 2003 vol. 10 No. 2) Not only does abrasive require an initial investment cost, but in addition the removal costs can double the effective cost of the abrasive. In the late 1990's, Richard Ward began work on a solution to this problem, developing the first WARD (Waterjet Abrasive Recycling Dispenser) machine to cater to the larger jetting operations. The one major complaint regarding traditional sludge removal systems, as Ward put it himself, was, "If you cannot keep the system operating continuously, including a couple of hours after cutting to prevent abrasive from settling, the abrasive will clog the jets…You will have to remove it by hand, which is quite a challenge."(Forming and Fabricating)

WARD has recently introduced a second machine that has addressed a wider audience, the roughly 96% of waterjet owners who could not justify the cost of the first machine for their applications. The new machine is smaller, with half the footprint of its predecessor, and relies on a special nozzle design and pumps that are best operated once 12 inches of abrasive has settle to the bottom of the tank. "The key to success is regulating the amount of abrasive transported per minute," says Ward. "If it's too much, it overloads. If it's not enough, it won't be efficient." (Forming and Fabricating)

The new machine also features the ability to produce two different grades of recycled abrasive at the same time, adding both precision and volume increases with respect to the recycled abrasive. (A New Abrasive Recycling System, WJTA News, March 2002)

To date, there are roughly 100 WARD recycling systems in operation around the world, with an estimated total maximum recycling capability of over 500,000 pounds of abrasive each month. Ward claims that this level of recycling has the ability to slash the abrasive contribution to cost by as much as 85%, totaling as much as 56% of the total waterjetting cost. (Waterjet Abrasive Recycling Can Slash Operating Costs, Modern Application News, May 2003)

Part I: The Machines

The purpose of this section is to define and explain the machines being studied, both in terms of separate components and the overall process of machining.

Apparatus

The following pages describe the Omax abrasive waterjetting systems, including the 2626 minijet table and the 2652 table, as well as the P2040 pump. Other pump styles are discussed however the P2040 is the only type that will be analyzed in detail. Following the waterjet and pump sections will be a description of the WARD recycling unit.

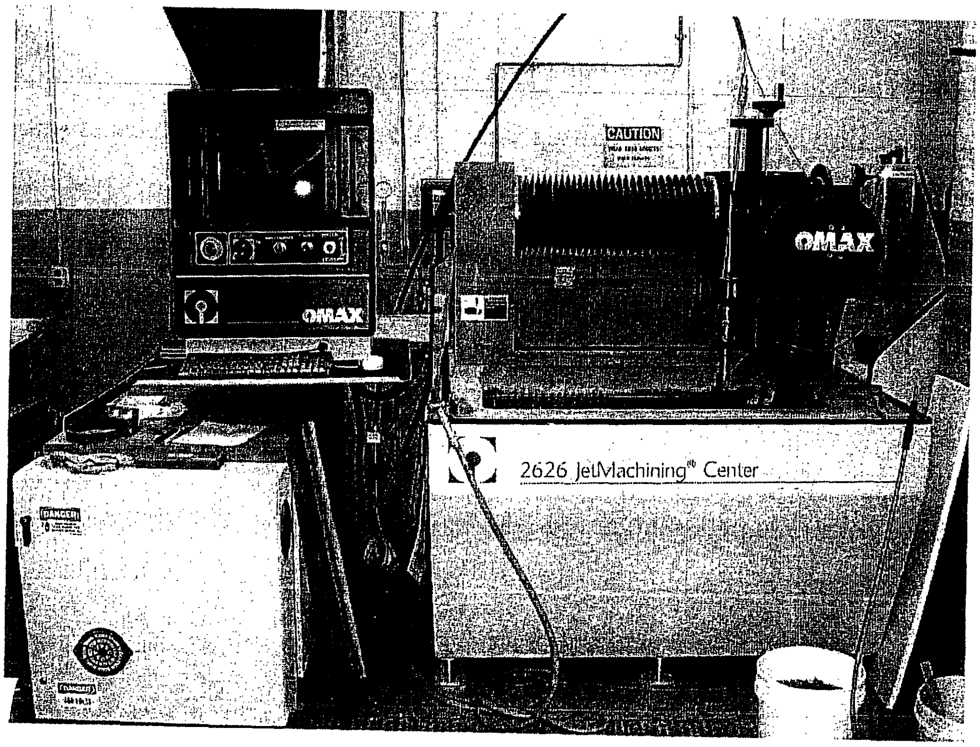

Figure 1: Omax 2626 waterjet system

Detailed description of AWJ

The abrasive waterjet is a high precision tool that requires extremely tight tolerances for successful operation. The slightest deviation of the jet of water can have severe effects on different parts of the nozzle assembly, and will drastically decrease the accuracy and quality of the cut. In the pages that follow, the separate components of the waterjet will be described in detail, followed by how the process of waterjetting works, and the overall performance characteristics. Much of the below information is taken from Omax publications.

Separate components

The most crucial component, perhaps even more important than the pump, is the software of the latest waterjet machines. Recent years have brought extremely high-tech advances in cutting algorithms that have made the waterjetting process as accurate and efficient as it is. The software is designed to recognize design components such as turns and borders and adjust the cutting speed accordingly. The software will not be discussed in further length as it is a thesis project in and of itself, however it will be referred to in cases where it is appropriate.

Pumps

The pumps are really the heart of the waterjet, producing a very steady flow of high pressure water that allows for accurate cutting times. There are two main types of pumps used in the waterjetting industry: intensifier pumps and crankshaft pumps. Intensifier pumps dominated the market for a long time due to an ability to produce higher pressure water reliably. (A Comprehensive Overview of the Abrasivejet Technology, Omax.com) The drawback, however, has been decreased efficiency, which has led to advancement in crankshaft research and technology.

The intensifier pump, often called a hydraulic intensifier pump, uses an engine or electric motor to drive the hydraulic pump creating hydraulic fluids at pressures from 1,000 psi to 4,000 psi.

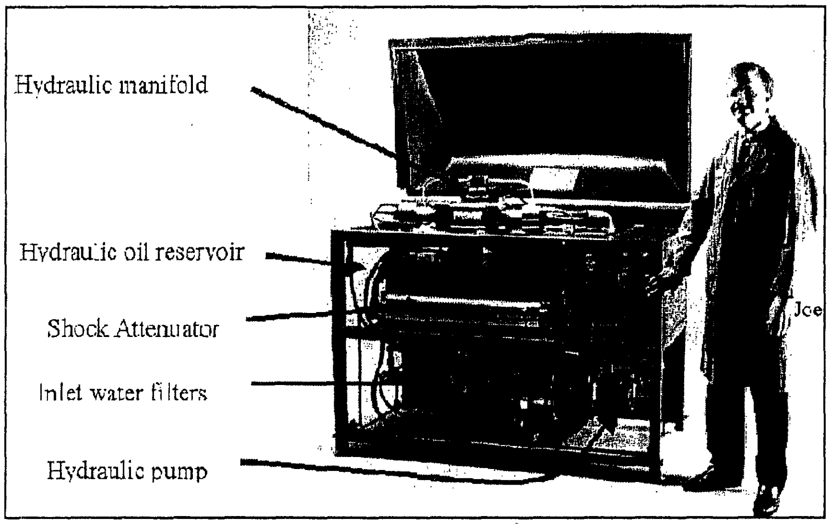

Figure 2: Intensifier pump, courtesy of www.flowcorp.com

The high pressure hydraulic fluid in the intensifier cylinder then exerts a force on a large diameter piston, translating a force to a small-diameter plunger with an increase related to the relative cross-sectional areas of the piston and the plunger.

It is important to note that the back and forth action of the intensifier pump results in pulsating water flow. To compensate for this, the intensifier pump has an attenuator cylinder, which acts as a high pressure reservoir.

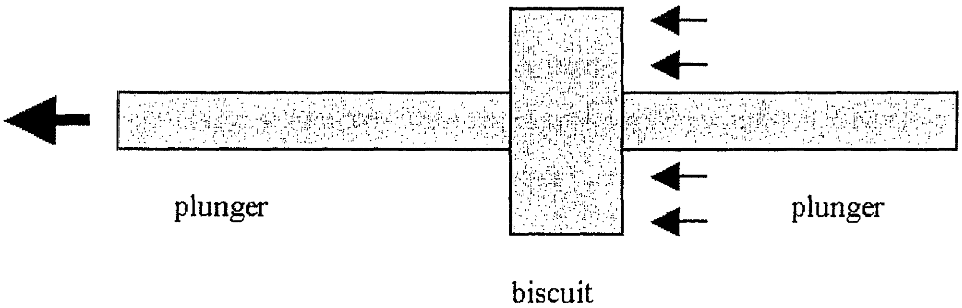

Figure 3: Piston/plunger concept for intensifier pump, courtesy of www.flowcorp.com

There are two 'circuits' in the intensifier pump, the water circuit and the hydraulic circuit. The intensifier and the attenuator cylinder are part of the water circuit, along with inlet water filters and a booster pump. The filtration system for the water typically involves two cartridge filters, a 1 micron filter and a 0.45 micron filter. The filtered water moves to the booster pump, where the inlet water pressure is maintained at approximately 90 psi. The water is then sent to the intensifier and pressurized to ultra-high pressures. The water passes through the attenuator cylinder, and continues on to the high pressure plumbing en route to the cutting head.

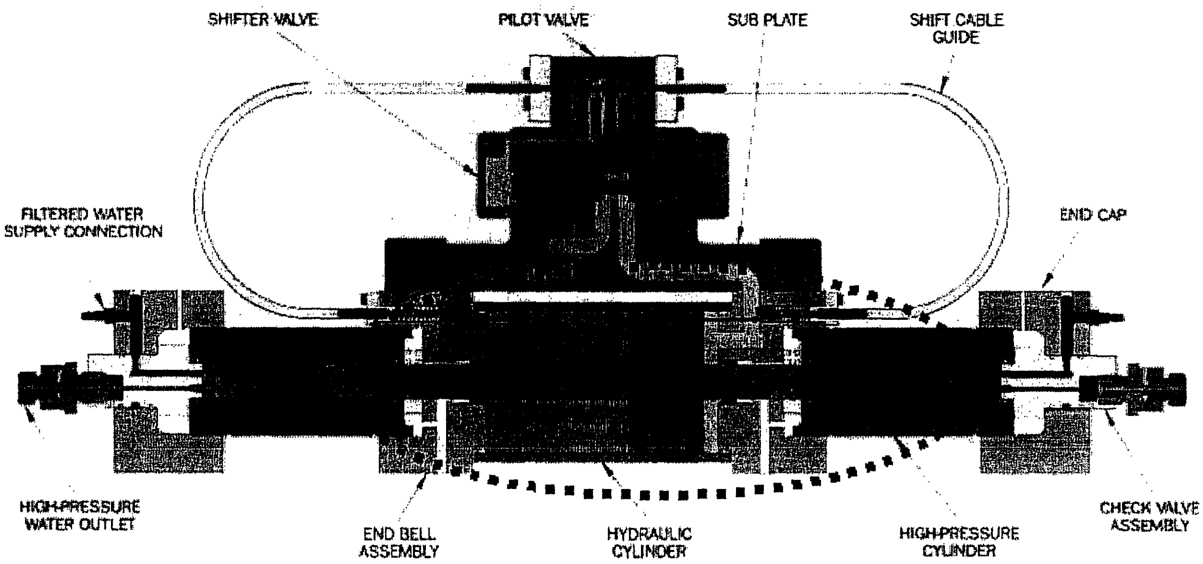

Figure 4: Intensifier pump system diagram, courtesy of www.flowcorp.com

The hydraulic circuit involves an electric motor, typically between 20 and 100 hp, the hydraulic pump, an oil reservoir, manifold and piston plunger. The heart of the intensifier pump relies on the intensification principle, which can be understood with the following example from www.flowcorp.com. Hydraulic oil is pressurized to a pressure of 3,000 psi. The oil pushes against a piston biscuit. A plunger with a surface area of 20 times less than the biscuit pushes against the water. Therefore, the 3,000 psi oil pressure is 'intensified' twenty times, yielding 60,000 psi water pressure. The 'intensification principle' varies the area component of the pressure equation to intensify, or increase, the pressure.

$$\text{Pressure}=\text{Force}/\text{Area}$$

Although capable of higher pressure output, the intensifier pump is far less efficient than the crankshaft pump, as well as more expensive to purchase and maintain. The intensifier pump operates with an efficiency of roughly 70%, where as the crankshaft pump efficiency can exceed 95%.(A comparison between intensifier and crank drive pumps, Dr. John Olsen, www.omax.com) Over the past several years crankshaft pumps, also called direct drive pumps, have increased substantially in their pressure output, becoming competitive with the intensifier pump.

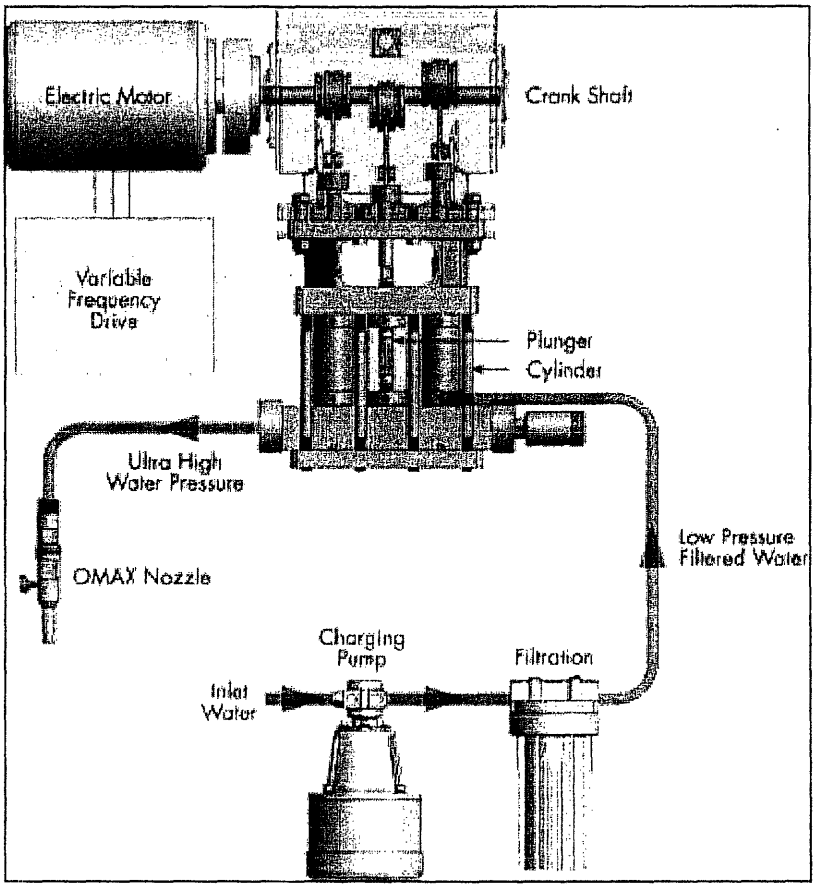

Figure 5: Crankshaft pump diagram. www.omax.com

The concept behind the crankshaft pump involves a mechanical crankshaft to move pistons in a cylinder. Valves in the cylinder allow water to flow in when the piston retracts and then exit when the piston forces the water to the outlet manifold at high pressure. As explained in "A Comprehensive Overview of Abrasivejet Technology" on the Omax website, the crankshaft pump is more efficient because of the absence of the power hungry hydraulic system. Also, because of multiple pistons, the crankshaft pump has the ability to output a very constant pressure flow of water without the need for an attenuator cylinder. Until recently, the seals were the limiting factor of the crankshaft pump, as the high rpm pistons put quite a strain on the seals and check valves. Improved seals, however, have led to crankshaft outputs exceeding 55,000 psi, sufficient for most abrasivejet applications. (www.omax.com)

Figure 6 below presents two photos of the direct drive motor in the Omax P2040 pump. Notice the three plungers, or cylinders, as well as the water filters.

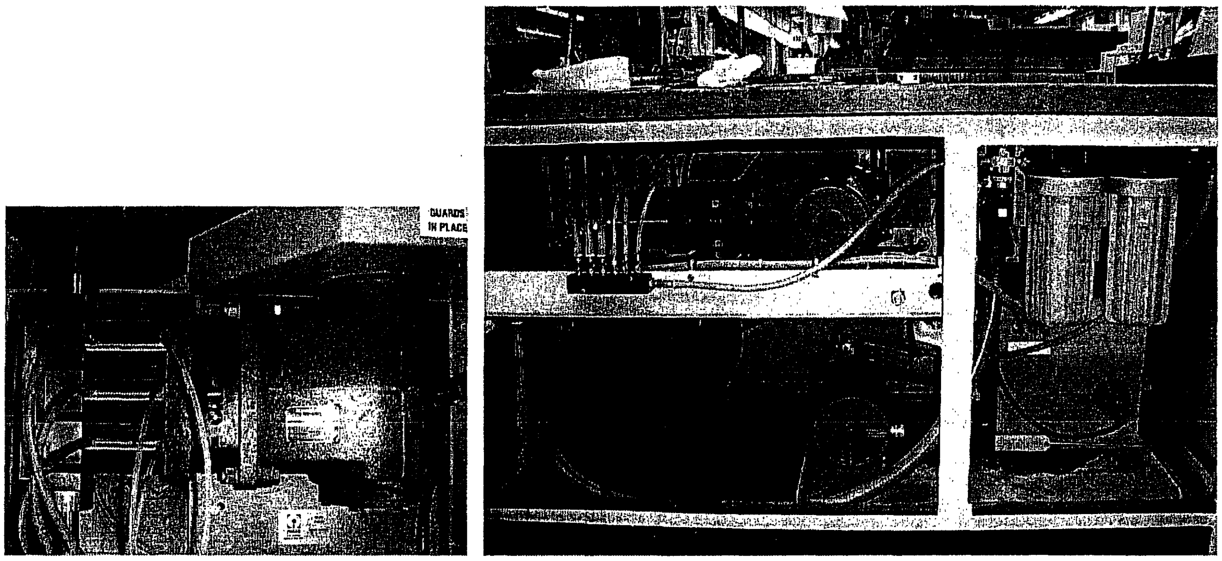

Figure 6: Omax P2040 pump, with a 20 hp direct drive motor and two filters.

Table 1 below details some estimated characteristics of intensifier and direct-drive pumps.

	10 Hp Direct Drive*	**20 Hp** Direct Drive**	**50 Hp** Intensifier***	**30 Hp** Direct Drive****	**40 Hp** Direct Drive*****
Hardened Tool Steel	1.26 IPM	3.23	4.43	5.44	7.22
Stainless Steel	1.29	3.29	4.53	5.55	7.38
Aluminum	3.88	9.89	13.59	16.67	22.14
Titanium	1.91	4.87	6.69	8.21	10.90
Copper	1.81	4.62	6.36	7.80	10.36

Table 1: Pump cutting time estimates, www.waterjets.org

The above data highlights the inefficiency of the Intensifier pumps compared to the Direct drive method. The Direct drive pumps are far more efficient and as a result reduce energy cost, or rather loss related to energy, as well as loss related to initial investment. Figure 7 below is a plot of the cutting speed as a function of the five pumps listed above in table 1 for each of the 5 materials.

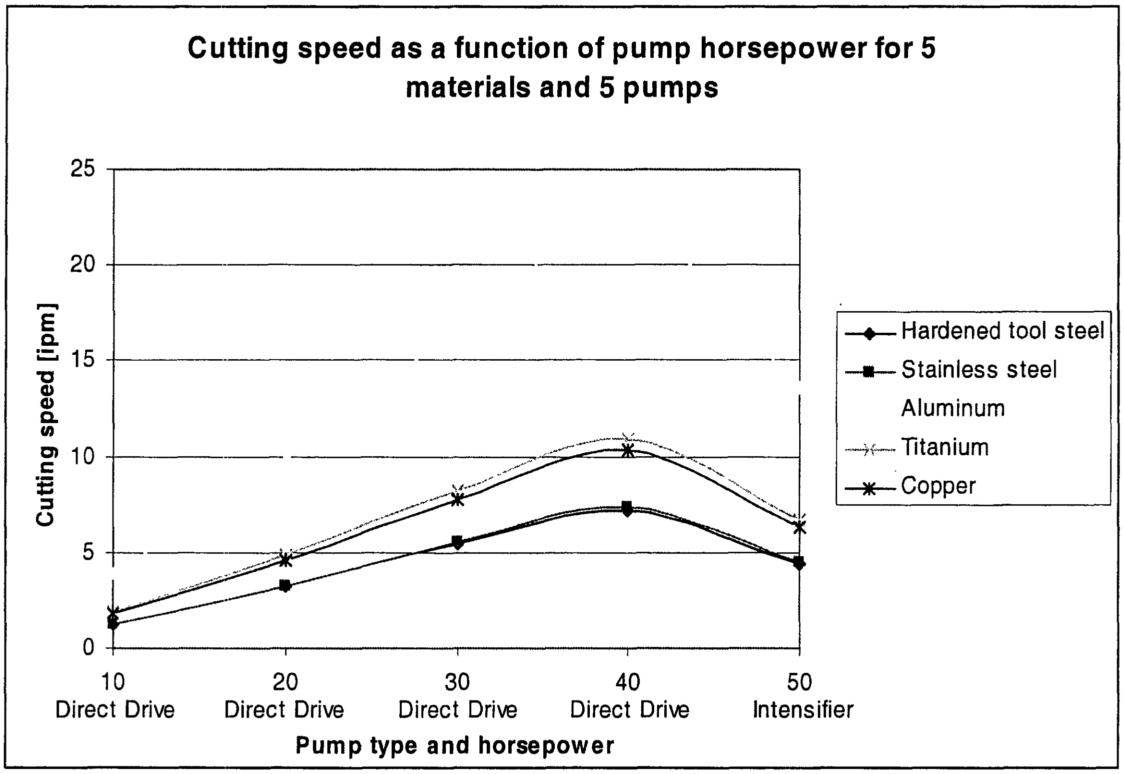

Figure 7: Cutting speed as a function of 5 pumps: 10 Hp Direct Drive, 20 Hp Direct Drive, 30 Hp Direct Drive, 40 Hp Direct Drive, and 50 Hp Intensifier, for five materials: Hardened tool steel, Stainless steel, Aluminum, Titanium and Copper.

Figure 7 above is meant to indicate the inefficiency of the intensifier pump compared to the direct drive pump. The cutting speed with direct drive pumps is more or less linear with horsepower, as seen by the linearity of the 10 Hp, 20 Hp, 30 Hp, and 40 Hp pumps in the figure. The 50 Hp intensifier pump, in terms of cutting speed, is on par with the 30 Hp direct drive pump, and is in fact considerably slower with certain materials.

High pressure plumbing

The high pressure water coming from the pump must be transported efficiently as to maintain as much pressure as possible. In certain instances, the pressurized water must travel long distances over which a substantial amount of pressure could be lost. It is imperative for the efficiency and accuracy of the cutting software that the pressure be maintained at a known level. For this reason, care in the high pressure plumbing installation is crucial. For long distances across shop floors, 9/16 inch stainless steel tubing is used. This tubing is not particularly flexible, and the large internal diameter allows for small pressure losses. In shorter distance applications, 3/8 inch stainless steel tubing can be used, particularly when transporting the high pressure water from the pump to the base of the machine. Lastly, ¼ inch stainless steel tubing will be used in applications where the motion of the cutting head is crucial. The ¼ inch tubing provides freedom for the cutting head, however should not be used over long distances due to the small inner diameter.

Cutting heads

The cutting head for the abrasive waterjet system required the most research and development in adapting the pure waterjet design. Previously, the cutting head, or nozzle, focused a flow of water into a high pressure, small diameter stream of water. With the introduction of abrasive, the nozzle required further design to prevent against significant wear and tear on all of the nozzle components.

Most nozzles used in abrasive jet applications follow the same two stage design shown below in figure 8.

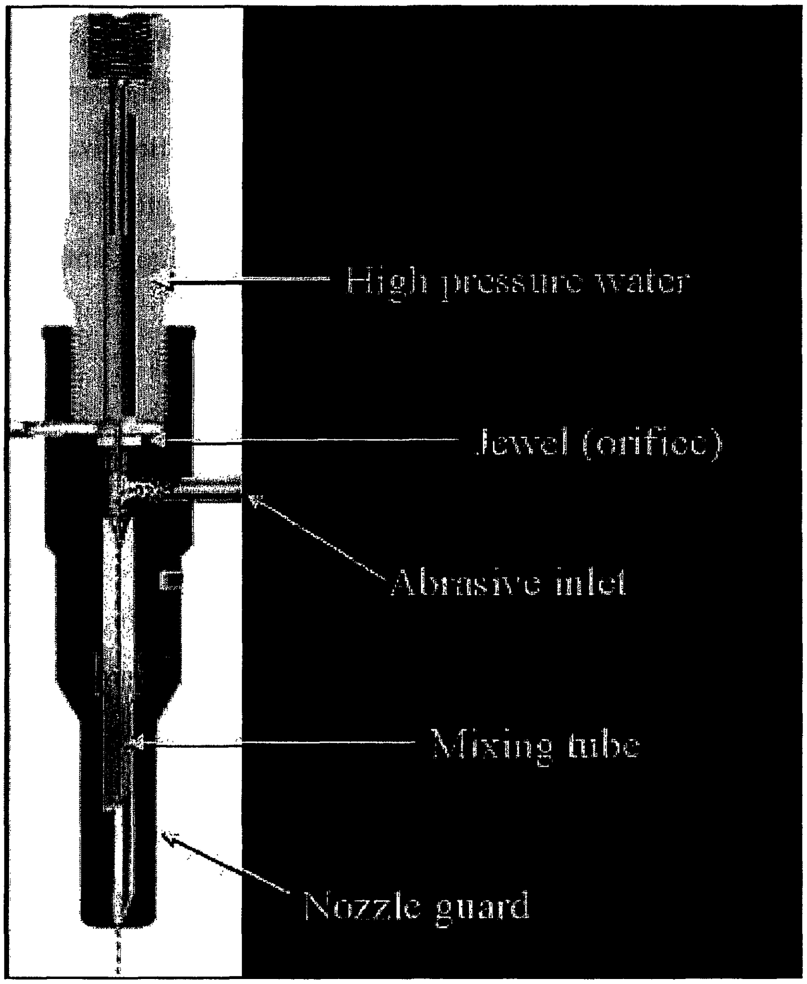

Figure 8: Nozzle, www.omax.com

The water passes through the jewel, typically ruby or sapphire and sometimes diamond, forming a high velocity stream between 0.010 and 0.014 inches in diameter. Larger orifices do exist but are rare in comparison. The high velocity stream of water passes the abrasive inlet, and the Venturi effect draws the abrasive into the jet stream. The mixture continues on to a mixing tube where the water and abrasive are successfully mixed. In the case of Omax, the mixing tube is 4 inches long, resulting in more efficient mixing, more precise cut and less taper, but shorter life span. The precise alignment of the orifice and mixing tube is crucial for the life of the mixing tube, the accuracy of the jet of water, and the quality of the cut. Mixing tubes typically last between 40-100 hours, and the entire nozzle assembly can be replaced for roughly $800. (Omax.com and Barton.com)

Lastly, the nozzle assembly is completed with a nozzle guard to protect the nozzle from unforeseen inconsistencies in the work piece. In the event that a bump or bow is hit, the nozzle guard will protect the mixing tube from significant damage requiring replacement. The orifice and mixing tube diameter determine the abrasive, water, and material scrap consumption through the machining cycle. The Omax 2626 has a 0.010 inch diameter orifice with a 0.021 inch diameter mixing tube. The Omax 2652 has a 0.014 inch diameter with a 0.030 inch diameter mixing tube. These different variables drastically effect the power consumption and material flow.

Abrasive delivery

When the abrasive waterjet first came into use, the abrasive flow rate was a controllable variable. Over time however, designers realized that a fixed flow rate was suitable, and in fact more efficient. Older systems with moving parts got clogged and often failed, resulting in a ruined part due to the absence of abrasive. With the diameter of the abrasive delivery nozzle controlling the flow rate, the user must simply measure the rate during installation and input the value into the control setup. The abrasive hopper is attached to the moving nozzle assembly, and for the smaller, more common abrasive waterjet systems, the hopper lasts for roughly 45 minutes, and can be refilled while cutting.

Tables

There are four types of table designs used for primarily all waterjetting applications. The first is a floor mounted gantry system with a separate cutting table. A frame supporting the X-Y motion system is fixed to the floor and stands over the cutting table. This sort of system requires substantial onsite setup and delivers less accuracy due to a disjoint between the table and the frame. The second common model is the integrated table/gantry system, which eliminates the break between the table and frame, however still produces effort due to relative motion error between X and Y moving components. The third system is the floor mounted cantilever system with a separate cutting table. The relative motion loss is eliminated as the cantilevered Y-axis moves with the X-axis.

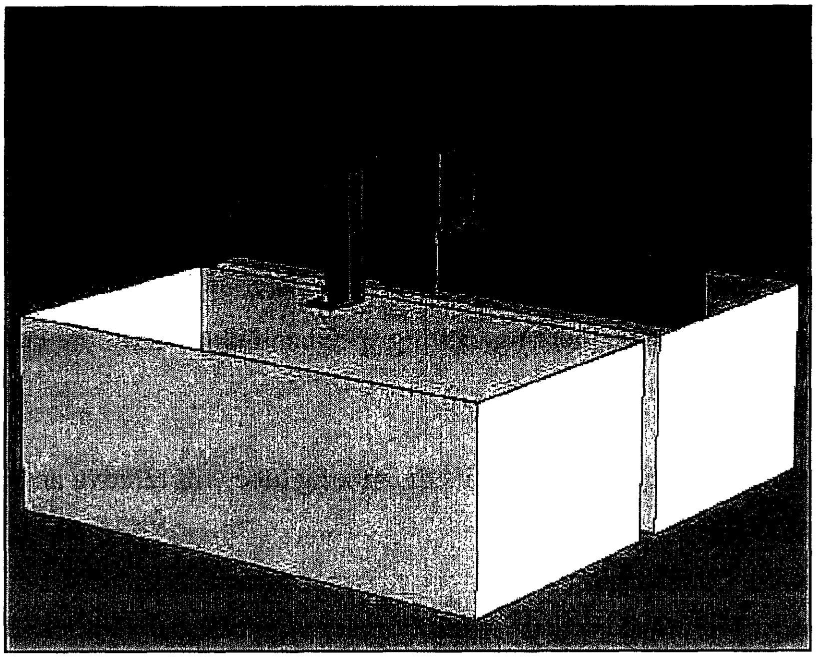

Figure 9: Floor-mounted cantilever system, www.omax.com

This is a common system and is shown in Figure 9 above. The most common application for Omax, and the setup for the 2626 and 2652 systems that will be further analyzed in the text, is termed the integrated table/cantilever system, shown in figure 10.

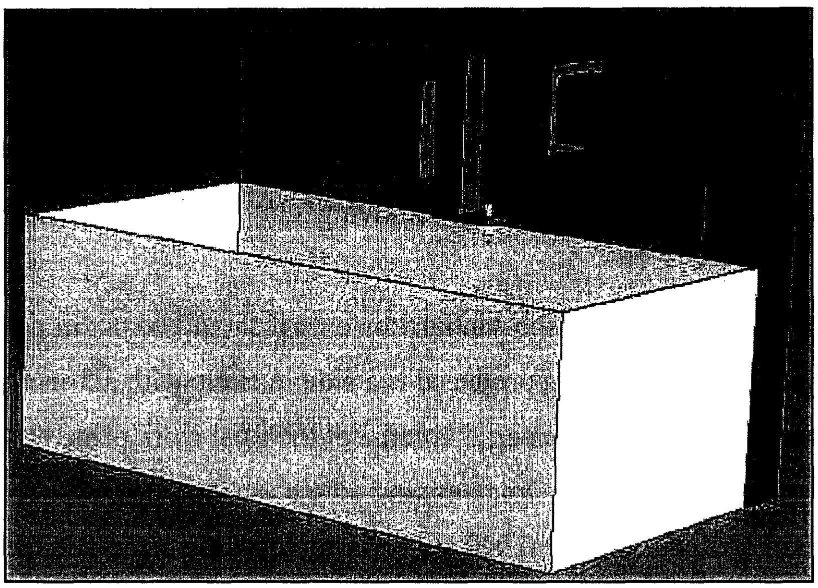

Figure 10: Integrated table/cantilever system, www.omax.com

It involves the cantilevered Y-axis as with the previous example, however in this case the frame is fixed to the cutting table eliminating the separation error. This model provides the greatest amount of accuracy however is limited by production expense and a y-axis travel length of roughly 5 feet.

Performance

It is possible to describe the performance of the abrasive waterjet through quality characteristics of the jet stream and the cut work piece. Taper, the resulting bow from beam lag, precision cutting and positioning, piercing, cutting speed and pump sizes are discussed below.

Kerf

The jet of water and abrasive that exits the mixing tube will remove an amount of material equal to:

Material Removed = (kerf width)*(material thickness)*(cut length),

Where the kerf width is the diameter of the stream of water and abrasive. As discussed above, the stream of water exits the orifice, 0.0140 inches in diameter for the Omax 2652 and 0.010 inches in diameter for the Omax minijet 2626, and enters the mixing tube where the abrasive is introduced into the stream. The mixing tube for the 2652 machine is 0.030 inches in diameter, and 0.021 inches in diameter for the 2626, which is what dictates the kerf width. So, in the machines to be discussed here, the diameter of the stream of abrasive-water is 0.030 inches for the 2652 and 0.021 inches for the 2626. This is one advantage of the Omax design over other products, because the Omax mixing tube is the only type with a diameter of 0.030 inches rather than 0.040 inches, resulting in other machines removing 33% more material than the Omax design.

This percentage figure seems substantial, however it should be put in perspective. Assume for example that the cut being produced is a simple circle with a 5-inch diameter from 0.5 inch thick Aluminum. The total material volume of the final work piece is 9.82in^3. The material removed with the 0.030 inch Omax mixing tube has a volume of 0.24 in^3, resulting in a scrap to product ratio of 2.4%. With a 0.040 inch mixing tube, the scrap volume is 0.31 in^3, with a scrap to product ratio of 3.2%. With a 0.021 inch mixing tube, the scrap volume is 0.16 in^3, with a scrap to product ratio of 1.6%. So for every 100 cubic inches of material produced, the Omax mixing tube saves up to 1.6 cubic inches.

Taper

Taper occurs because as the beam exits the nozzle tip two things happen: first, the beam flares somewhat like a fire hose before entering the work piece, with minimal additional flare while below the surface of the material. The cutting channel tends to hold the beam together, however contact with the sidewalls does occur. Secondly, the beam of water begins to fall behind at the bottom of the work piece. To illustrate this, imagine the jet of water entering the work piece. As the nozzle moves forward, the beam illustrates somewhat of a curved profile as it deflects backwards opposite the direction the nozzle is traveling. This effect results in taper, as well as inside corner errors and sweeping out of arcs. Taper typical results in between 0.0015 and 0.004 inches per side.

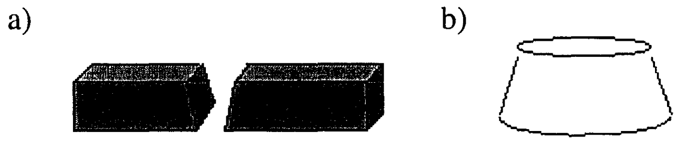

Figure 11: a) V-shaped taper: created when cutting at high speeds. b) Sweeping out of arcs: caused by high speed cutting around an arc resulting in a cone shape

Figure 11 above illustrates taper and sweeping out of arc errors. Both of these effects can be compensated for by increasing the pressure and decreasing the cutting speed. (How Waterjets Work: Accurate Parts, www.flowcorp.com)

As noted, taper can be minimized and even eliminated by increasing the cutting power and decreasing the cutting speed. The advanced software technology recognizes curves and turns, compensating for the lag by decreasing the cutting speed upon approach. This is important to note, because it highlights the fact that the material is not the only determinant for cutting speed. The intricacy of a design can have substantial impacts on the cutting process, and are very hard to estimate. Prior to the days of software control, manual users would have a tremendous amount of difficulty optimizing the cutting speed with intricate shapes. This sort of software results in far more accurate parts, eliminating several negative effects not limited to those discussed.

Precision cutting and positioning

The precision of cutting and position is extremely important for accuracy and repeatability. The integrated table/cantilever system eliminates a lot of the motion that can affect the precision, however factors still remain that can be minimized. Any sort of slop in the gears or screws in the motor can cause vibration that will decrease precision. Also, servo tuning is crucial to the repeatability of the waterjetting process. Positioning is also very important. In the case of small parts, incorrect positioning may go unnoticed. However, in the case of 12 foot tables, the slightest degree of offset will translate to a substantial error.

Pump sizes

Although the horsepower a pump outputs is not necessarily what is used, it is still very important. The nozzle orifice determines the horsepower draw, and in cases where the user is operating a 50hp pump with a 20hp nozzle, power is wasted. When energy is paid for by the current and voltage supply, this means money down the drain. It is very important to choose a pump that is appropriate for the applications for which it will be used.

Omax offers 3 pumps for their standard cutting systems: P2040, P3050 and P4060.

Table 2: Omax pump specifications. This table outlines the maximum pressure output, the output flow rate of water, the necessary water supply and the filtration for the Omax P2040, P3050 and P4060 pumps.

Pump	Horsepower [HP]	Max output pressure [psi]	Output flow rate [gpm]	Water supply [gpm]	Filtration [micron]
P2040	20	40,000	0.4 - 0.9	1	0.2
P3050	30	50,000	0.4 - 0.84	1	0.2
P4060	40	55,000	0.45 - 1.05	1.3	0.2

As the table indicates, the maximum output pressure is not directly correlated with the horsepower. The output pressure for the lower horsepower pump is actually more efficient in terms of energy draw, and is more frequently used in the industry. The pump that will be analyzed in detail therefore is the Omax P2040. The pump is rated at 20hp and requires a 3-phase, 480 V, 60 Hz power supply. It outputs a maximum pressure of 40,000 psi at a flow rate of 0.75 gallons per minute. The P2040 requires 1 gallon per minute of water inflow at 1 psi, the majority of which is used for cutting, with some used for cooling, and provides a 0.2 micron filtration process before pressurizing the water.

Machineability

Each material has a value assigned to it called the *machineability*. The machineability is entered into the machine along with the quality and thickness to determine cutting speed. Machineability is perfectly linear with both linear and arc cutting speed, and can therefore be used instead of material to analyze material and energy flow. Figure 12 below presents the linear and 0.125-inch radius arc cutting speeds as a function of machineability for a quality 3 cut on a 0.5 inch thick work piece.

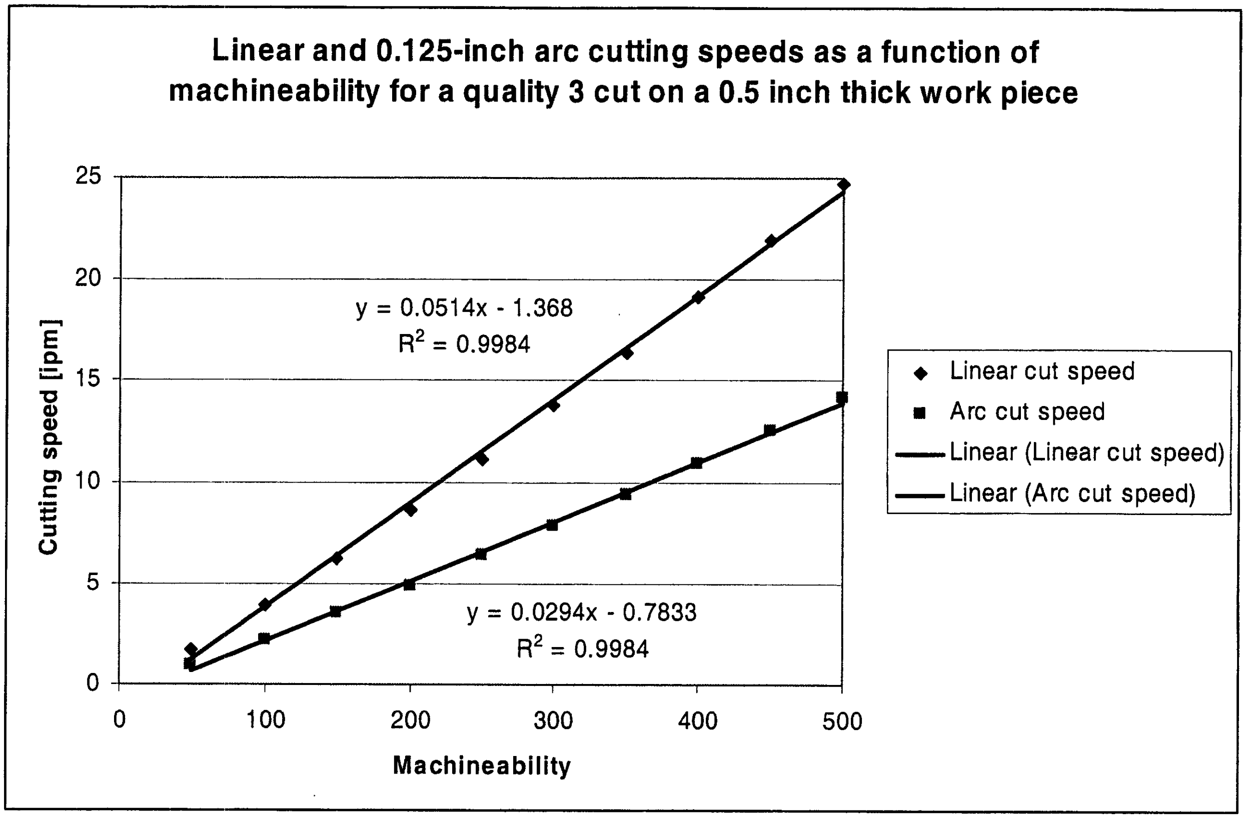

Figure 12: The linear and 0.125-inch radius arc cutting speeds as a function of machineability for a quality 3 cut on a 0.5 inch thick work piece. This plot is designed to illustrate the linearity of machineability with both linear and arc cutting speeds. This allows for an analysis of material and energy flow as a function of machineability, resulting in formulas than can be altered to account for any material.

The trend-line equations above represent the linear and arc cutting speeds as a function of machineability. With R^2 values of 0.9984 for both data series, it is clear that the algorithm is linear. When material and energy flow is determined as a function of cutting speed, it will be possible to calculate the same values for a different material by using the best-fit line equations. The data values used to produce figure 11 can be found in Appendix A.

Table 3 below presents the machineability for several materials.

Table 3: Machineability for several materials

Material	Machineability	Material	Machineability
Hardened tool steel	80.4	White marble	535
Copper	110	Nylon	538
Titanium	115	Glass	596
Brass	184	Plexiglass	690
Aluminum	213	Graphite	879
Granite	322	Polypropylene	985
Lead	490	Pine wood	2637

Cut quality

Aside from the cutting effects discussed above, there is a variable termed quality that must be input for each cut. The quality ranges from 1-5, with 1 corresponding to a rough cut and 5 resulting in a high precision and smooth surface finish. The variance in quality affects nothing other than the cutting speed. For a given material and quality desired, there is a resulting cutting speed. As figure 13 illustrates, the cutting speed increases somewhat exponentially with the decrease in quality settings. Also, the cutting speed varies substantially for different materials as well as thickness.

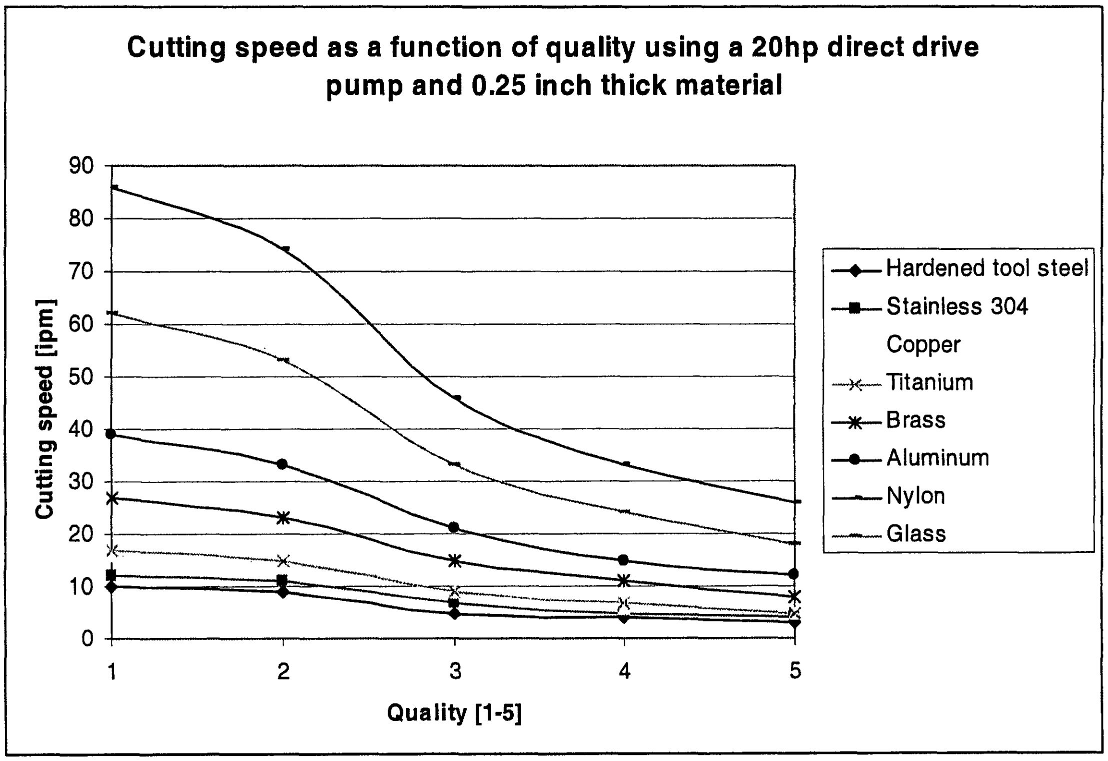

Figure 13: Cutting speed as a function of cut quality using a 20 hp direct drive pump. The materials shown were all 0.25 inches thick and the cuts were straight line cuts. All speeds are in inches per minute and are valid for straight line cuts only. The 20hp pump was operated at 40,000 psi with a 0.014 inch diameter nozzle orifice, 0.030 inch diameter mixing tube and 0.75 lb/min abrasive flow

The cutting speed appears to increase almost exponentially with the linear decrease of material thickness, regardless of the material itself. This is important to note when thinking about optimizing the design and cutting process. Complete data for material, thickness, quality and cutting speed can be found in Appendix B.

Because there are 5 quality settings, the analysis of cutting speed as a function of quality is somewhat difficult to apply. Throughout most of this thesis, the quality will be assumed to equal 3. Figure 14 below is a plot normalizing the cutting speed as a function of quality around the quality 3 values. Therefore, what is shown is: (cutting speed)/(cutting speed of quality 3) vs. quality.

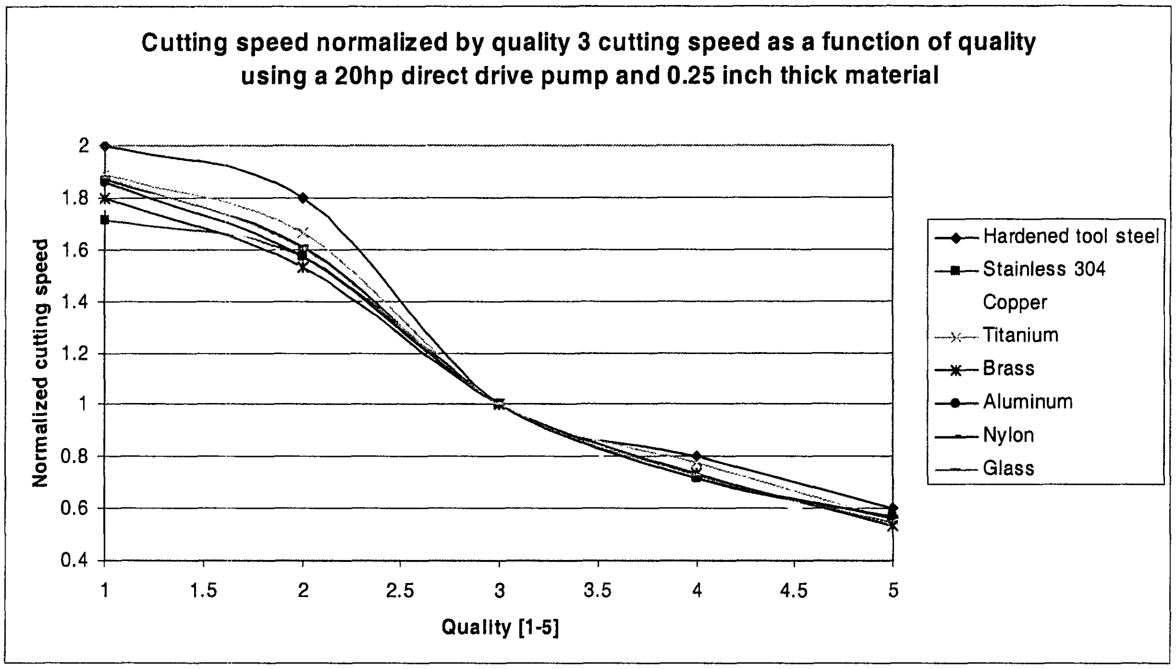

Figure 14: Cutting speed normalized around quality 3 cutting speed, plotted as a function of quality for Hardened tool steel, Stainless steel 304, Copper, Titanium, Brass, Aluminum, Nylon and Glass. This data was for a 20 hp direct drive pump and 0.25 inch thick material, considering only linear cuts.

Figure 14 above illustrates the normalized cutting speed as a function of quality. This sort of relationship is helpful in scaling cutting speed when the known values are for quality 3 cuts, however the desired values are for a different quality cut. What this plot indicates is that for a given cutting speed for a quality three cut, the speed must be multiplied by a factor of between 1.7 and 2, depending on the material, to obtain the appropriate speed for a quality 1 cut, and by a factor of 0.5-0.6, again depending on material, to go from quality 3 to quality 5.

Cutting speed

Cutting speed is crucial in the abrasive waterjetting industry. With the abrasive flow at a constant rate, and the motor resulting in a semi-constant power draw, the only real variable other than the work piece is the cutting speed. Optimizing cutting speed means optimizing abrasive and energy use, and thus has been the focus for improving waterjet software technology over the past several years. Figure 13 above illustrates the cutting speed as a function of the quality desired. Naturally, the superior surface quality of the cut requires a much slower cutting speed and thus a lengthier process. Figure 15 illustrates the cutting speed as a function of thickness with a quality of 3, the average for the abrasive waterjet.

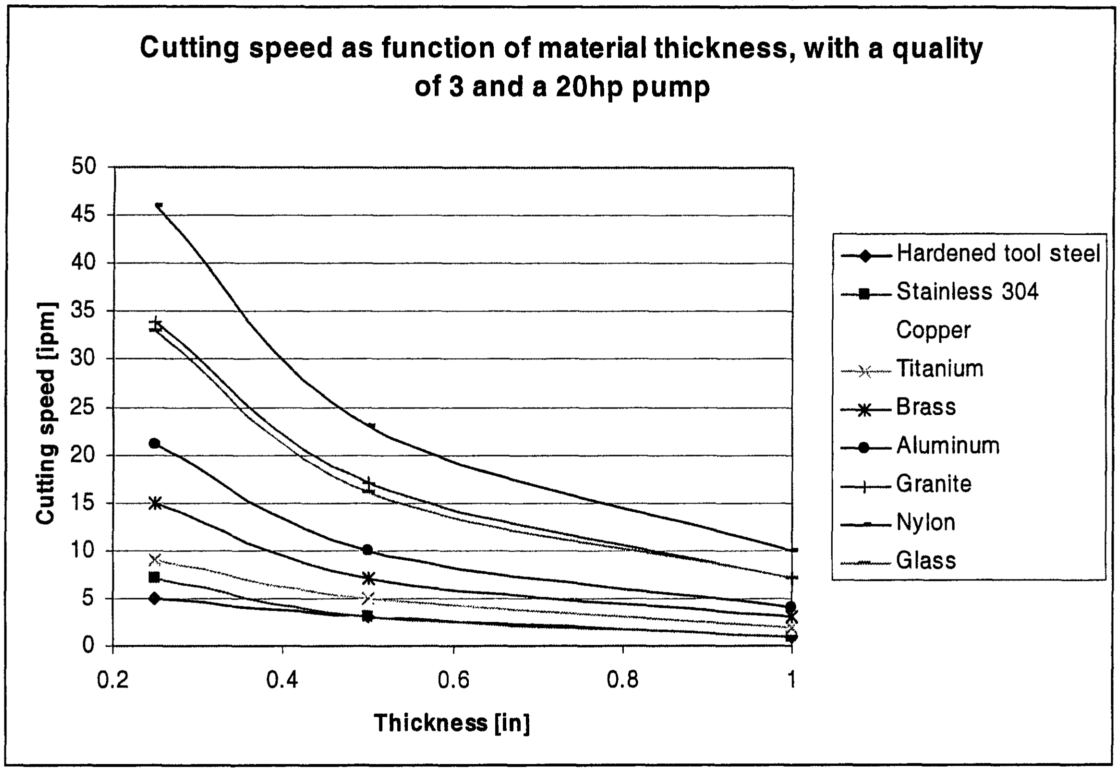

Figure 15: Cutting speed as a function of material thickness using a 20 hp direct drive pump. The values shown were for straight line cuts with a quality of 3. All speeds are in inches per minute and are valid for straight line cuts only. The 20 hp pump was operated at 40,000 psi with a 0.014 inch diameter nozzle orifice, 0.030 inch diameter mixing tube and 0.75 lb/min abrasive flow

The plot indicates that cutting speed is very much a function of thickness, and increases almost exponentially with the linear decrease of thickness. Figures 13 and 15 above are for straight line cuts only, and thus miss a very significant aspect of the waterjet cutting speed. As mentioned above, software controls the speed of the nozzle as it approaches turns in the geometry of the work piece. This compensation helps to minimize the effects of stream lag, however also increases overall cutting time. This reality makes it somewhat hard to quantify cutting speed, as it is very much a function of the geometry of the part being cut. It is still important, however, to present general cases to at the very least explain the effects of curves in the geometry on cutting speed.

There are many cases, particularly when the material is thin and has high cutting speeds, where an arc in the geometry has little effect on the cutting speed. In fact, along with the Omax software is an abrasive waterjet feed rate calculator, which allows the user to estimate the time it will take to cut a certain piece. The feed rate calculator is somewhat inconsistent with the above data provided by an Omax representative, however this discrepancy is likely due to the fact that they are related to different versions of the software. Nonetheless, using the feed rate calculator to predict both the straight line speeds and the arc speeds will illustrate the relationship between the two. Figure 16 below illustrates the cutting speed for aluminum 6061 for straight line cuts as well as arc cuts of different radii as a function of cut quality with a material thickness of 0.5 inches. Figure 17 following is similar, however instead a function of material thickness with a cut quality of 3. The data tables representing both plots can be found in Appendix C.

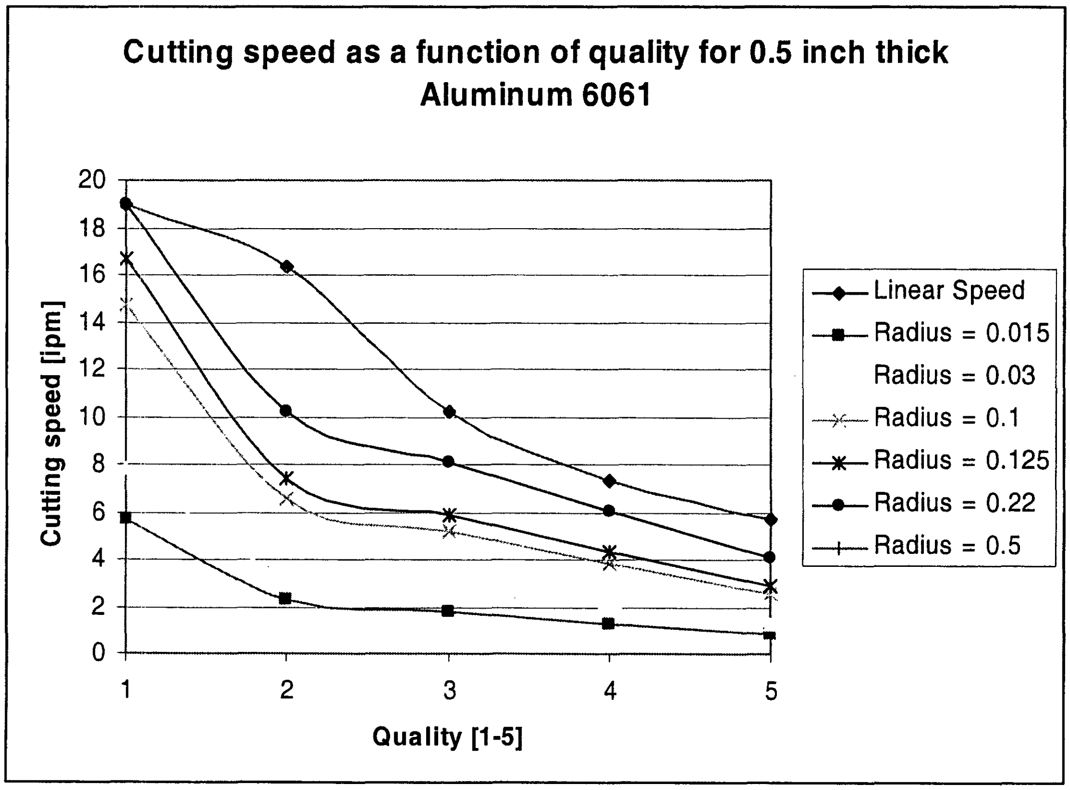

Figure 16: Cutting speed as a function of quality for 0.5 inch thick Aluminum 6061. This plot illustrates the cutting speed for straight cuts as well as arc cuts of different radii.

Although it is not clear from the plot, the 0.5 inch radius arc follows the same cutting speed path as linear cuts. In the case of Aluminum 6061, the critical radius for a quality 5 cut at which point the nozzle will travel at the same speed as with a linear cut is 0.398 inches. There is no set formula to calculate this value, or any of the values plotted above.

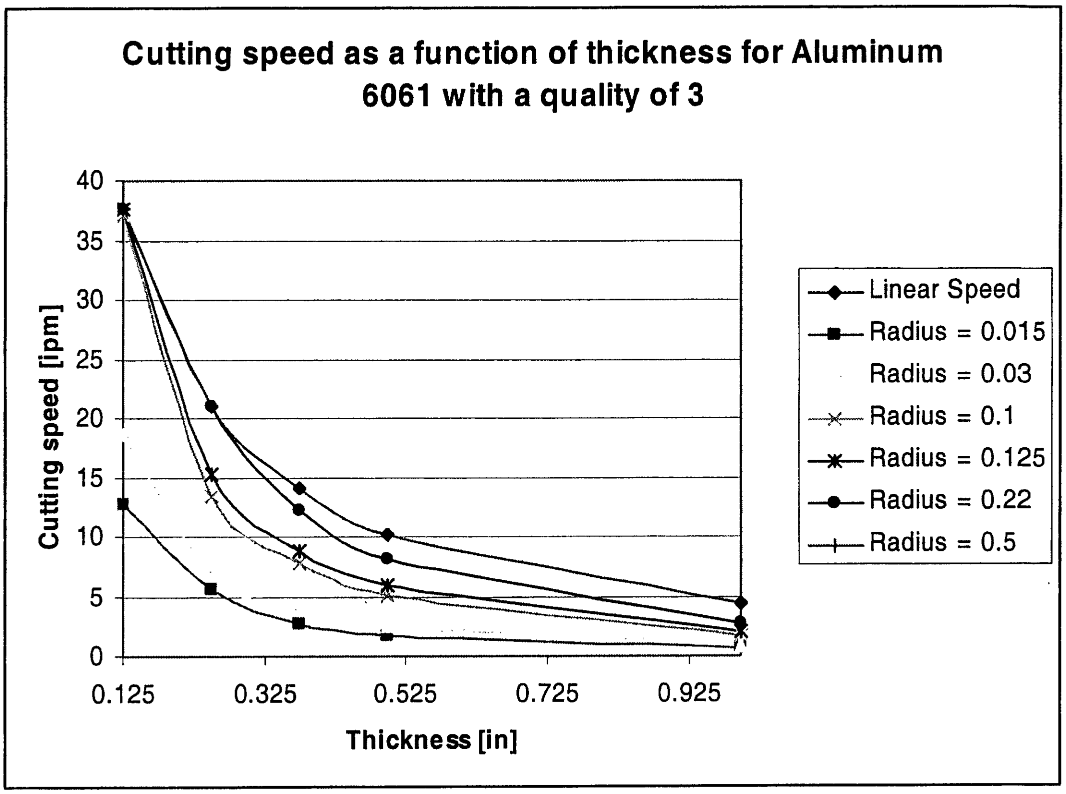

Figure 17: Cutting speed as a function of thickness for Aluminum 6061 with a cut quality of 3. This plot illustrates the cutting speed for straight cuts as well as arc cuts of different radii.

Again, it is clear from the plot that cutting speed is considerably slower for small radius arcs, however as the radius increases the cutting speed begins to approach that of a linear cut. These plots can be made for every material under varied parameters. What is really important is to understand that cutting speed is affected by material, thickness, quality and geometry. A unique part geometry will have a unique cutting time that can be determined either by manual calculation or by the software's estimate of the cutting time. Cutting time is important because it is the sole variable for abrasive use, water use, and energy use for a given part production. With material, thickness, quality and geometry held constant, it is possible to determine abrasive, water and energy consumption as a function of length, however that is somewhat impractical. It seems more ideal to measure these variables as a function of time. The material removal rate, however, can only be measured as a function of time if material, thickness, quality and geometry are held constant, which leads to the fact that it seems more practical to measure material removal rate as a function of length, not time.

This discrepancy will be compensated for by fixing certain variables for the remainder of the investigation. There are an infinite amount of combinations of material, thickness, quality and geometry used in industry, and it is therefore impractical to cover all of it. However, the machineability represents a particular material, and therefore material and energy flow can be determined as a function of machineability, assuming a known thickness and quality. The remaining sections present more specific information about material and energy flow. The following assumptions will apply to all calculations of water, energy, abrasive and material use:

1. The part thickness will equal 0.5 inches, unless otherwise specified
2. The cut quality will be 3 unless otherwise specified
3. The geometry of the cuts will include a square with sides of 1 inch and a circle with a 0.25 inch diameter

These assumptions will allow for all of the important variables – water consumption, abrasive consumption, material removal, and energy consumption – to be documented as a function of length and machineability.

In an effort to understand where exactly machineability comes from, it is important to investigate relationships between the machineability values and known material properties. For example, intuition first suggests that machineability likely has some correlation with hardness. Figure 18 below represents the machineability as a function of HB500 hardness for various materials. A table of the materials and values can be found in Appendix D.

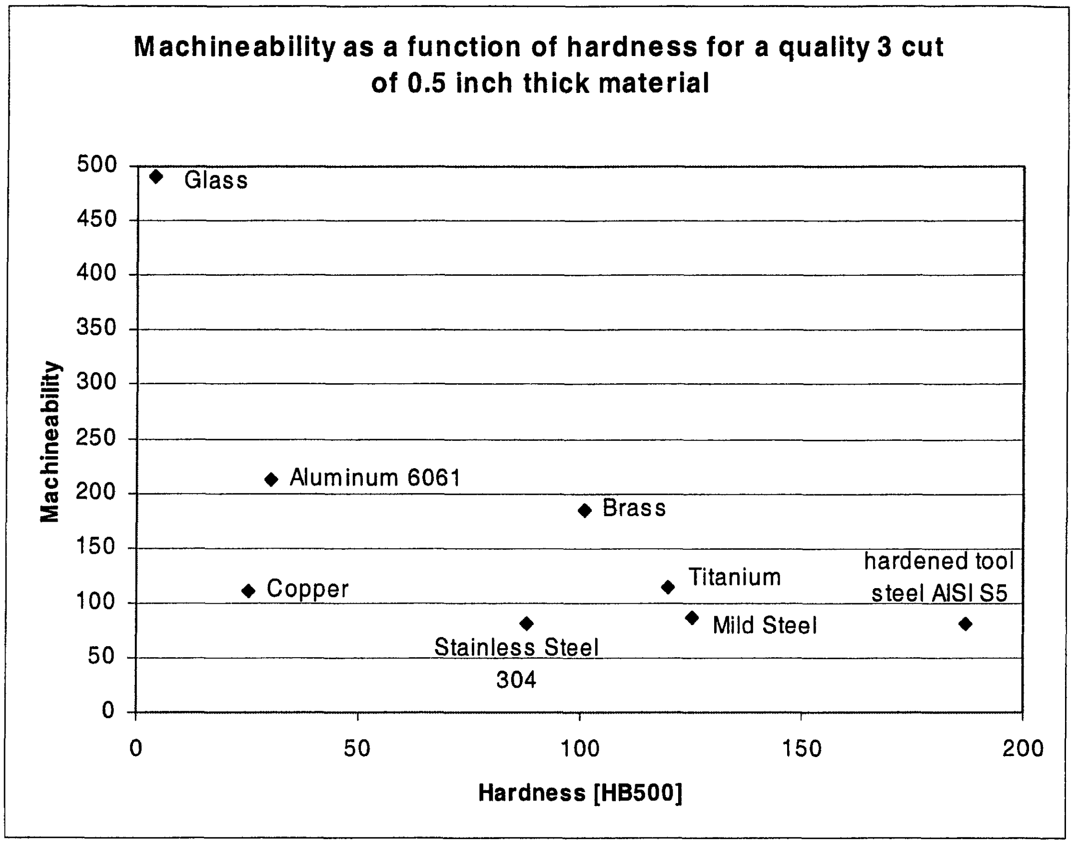

Figure 18: Machineability as a function of hardness for a quality 3 cut of 0.5 inch thick material. Materials include Aluminum 6061, Stainless steel 304, Copper, Titanium, Hardened tool steel AISI S5, Mild steel, Brass, Lead and Glass. See Appendix D for specific data points.

The above plot suggests that although there does seem to be a slightly inverse relationship, the data is not sufficient to prove a dependence of machineability on hardness. The apparent outlier, with a machineability of nearly 500, is glass. The typically brittle materials behave very differently while abrasive jet machining. Often times, the best thing to do is to lower the pressure while cutting brittle materials, despite their extreme hardness, in an effort to avoid chipping of the work piece.

To illustrate the inverse relationship between cutting speed and thickness, figure 19 below illustrates (cutting speed)(thickness) vs. thickness. If the cutting speed is in fact inversely related to thickness, the lines should be linear.

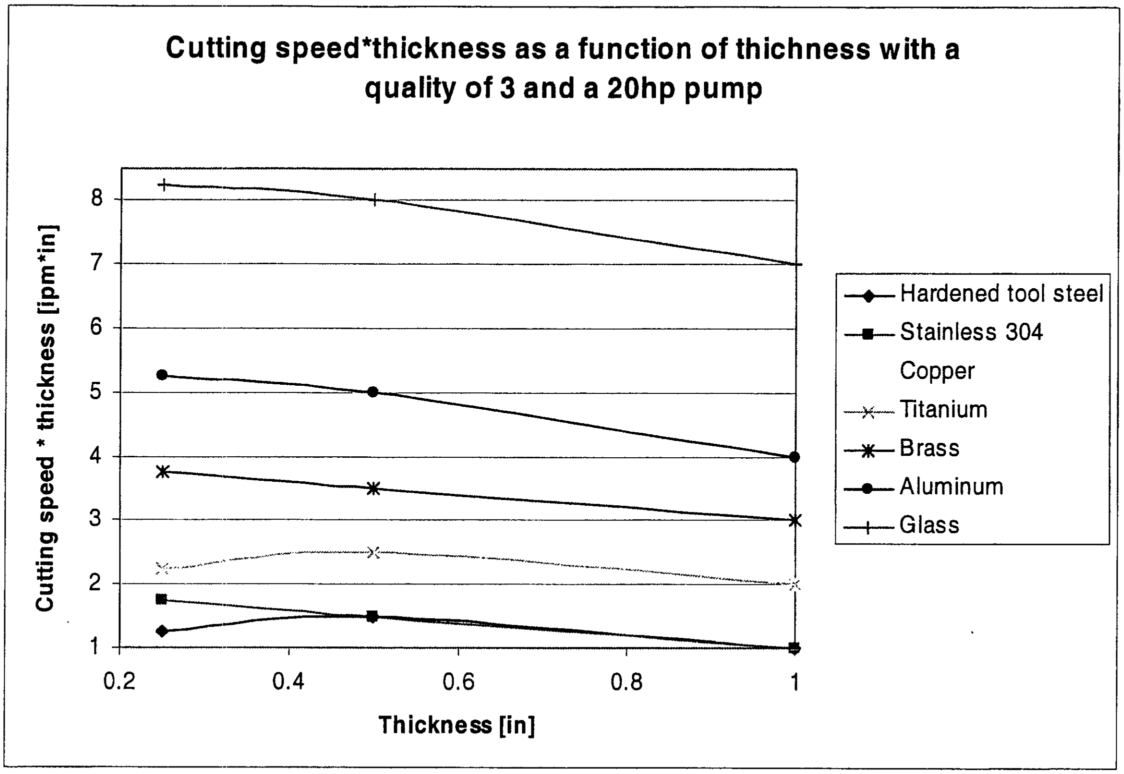

Figure 19: Cutting speed*thickness as a function of material thickness using a 20 hp direct drive pump. The values shown were for straight line cuts with a quality of 3. All speeds are in inches per minute and are valid for straight line cuts only. The 20 hp pump was operated at 40,000 psi with a 0.014 inch diameter nozzle orifice, 0.030 inch diameter mixing tube and 0.75 lb/min abrasive flow

The above relationships indicate that cutting speed is more or less inversely related to thickness. The plot of cutting speed * thickness as a function of thickness linearizes cutting speed with respect to thickness, and therefore when plotted against thickness, should show a linear relationship.

Another potential relationship involves the density of the material being cut. Figure 20 below illustrates the machineability as a function of density for the same materials as Figure 18. The data points can again be found in Appendix D.

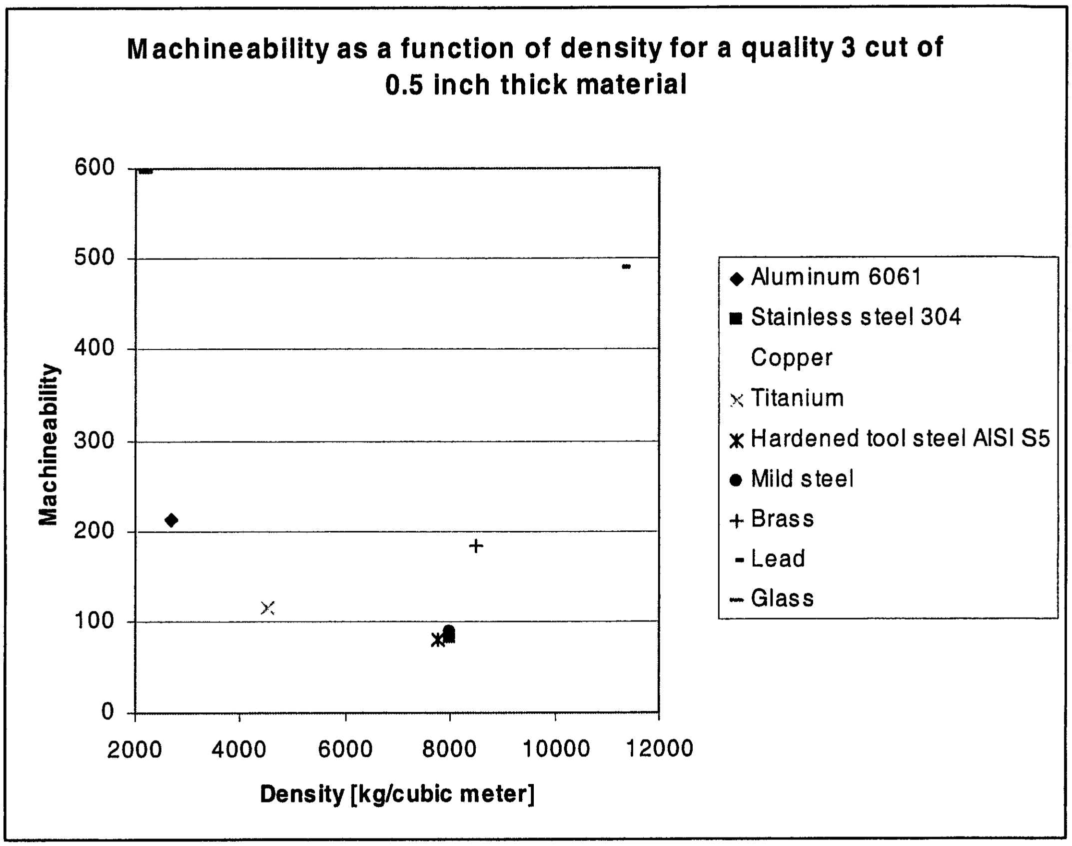

Figure 20: Machineability as a function of density for a quality 3 cut of 0.5 inch thick material. Materials include Aluminum 6061, Stainless steel 304, Copper, Titanium, Hardened tool steel AISI S5, Mild steel, Brass, Lead and Glass. See Appendix D for specific data points.

Again, the plot does not suggest any determinable correlation between machineability and density. A trend line excluding Titanium (4510, 115), Aluminum 6061 (2700, 213) and glass (2200, 596) does show somewhat of a direct relationship. However, the significant outliers combined with a low correlation even when omitted result in the determination that there is no quantifiably significant correlation between machineability and density.

The above plots were made relating machineability to all of the other variables presented in Appendix D, including Poisson's ratio, elastic modulus, tensile strength, yield strength, elongation, reduction in area, shear strength and fatigue strength. No correlations were found of much significance. These plots can be found in Appendix D.

Detailed description of WARD 2 recycling unit

The WARD 2 recycling unit is a new-to-the-market solution to the excessive waste of used garnet in the abrasive waterjet industry. Manufactured by WARDJet Incorporated, the WARD 2 is a second generation model that removes the abrasive sludge from the bottom of the waterjet tank, sorts and dries only the good abrasive, and deposits the reusable abrasive and the waste into separate bins.

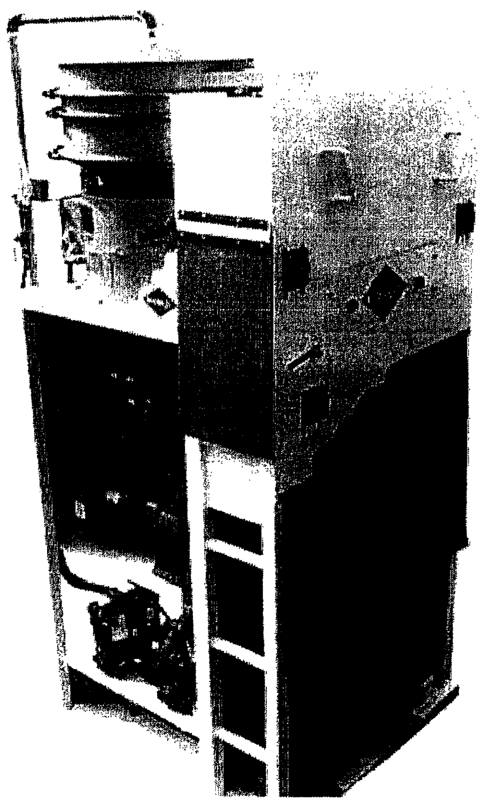

Figure 21: WARD 2 Recycling unit. This product removes abrasive sludge from the bottom of the waterjet tank and sorts and dries only the good abrasive, depositing the waste material into a drum and the reusable abrasive into a removable container. Photo courtesy of WARDJet Inc.

The unit and all of its amenities fit in a 42 inch by 42 inch footprint, and require either a 110 V or 220 V power supply, depending on user preferences. As an additional option, a second sorting phase can take place, resulting in two different grades of recycled abrasive, as well as increased recycleability and savings.

Separate components

The WARD 2 recycling unit is fairly simple in design and construction, with few moving parts and therefore low maintenance costs. The major components are the PLC controller, the nozzle, dryer elements and plate, hoppers, chain including electric motors and gear box, diaphragm pumps, screens and a fan. Each component will be described in detail below.

PLC Controller

The user interface is a PLC controller that is easy to use and provides sufficient control of the machine.

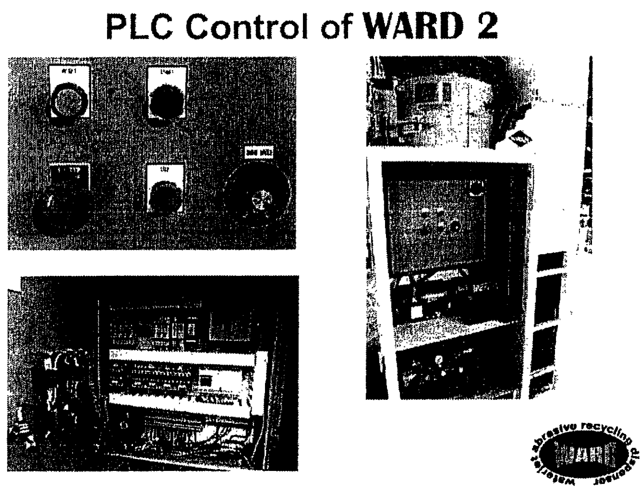

Figure 22: The PLC control unit for the WARD 2. Photo courtesy of WARDJet Inc.

The control system is an upgrade from the first generation WARD unit, and is located on the machine with easy to use features including an emergency stop button, start and stop buttons, and a dial controlling the chain speed.

Nozzle

The patented nozzle design rests in the bottom of the waterjet tank, and operates best with at least 12 inches of abrasive sludge above it. Figure 23 below depicts the nozzle and installation.

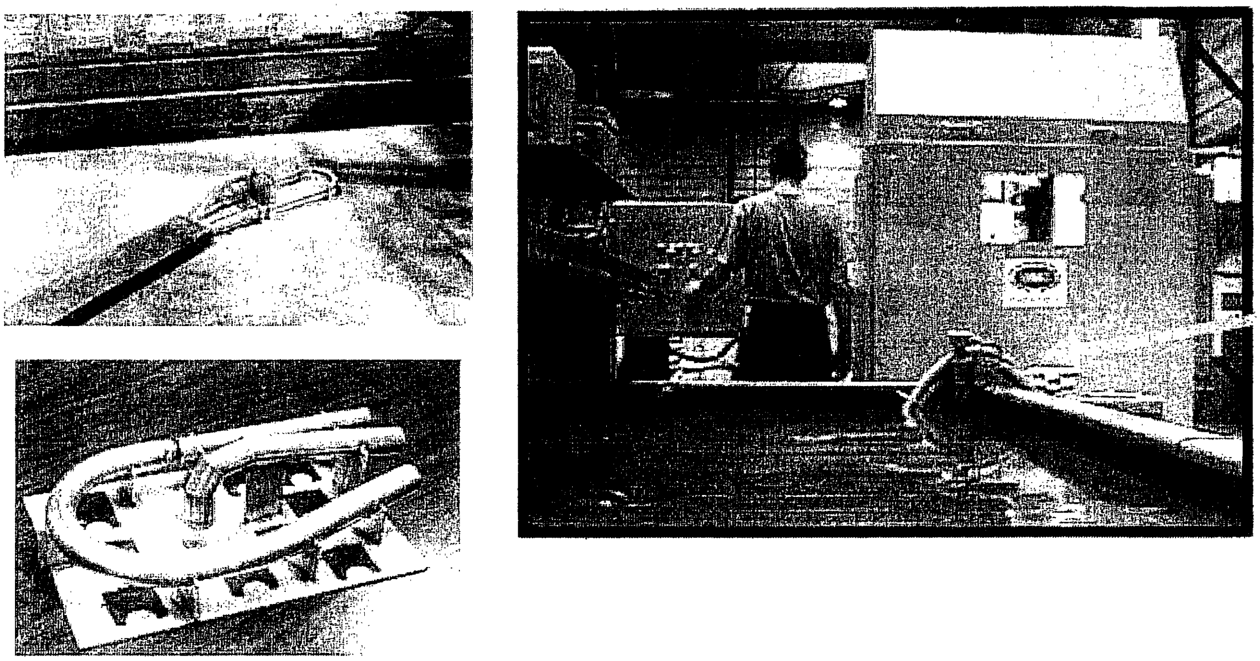

Figure 23: Patented WARD 2 nozzle and installation. The nozzle rests on the bottom of the waterjet tank and is covered for protection. The tubes extend up the side of the waterjet tank wall, requiring no holes in the tank. Photos courtesy of WARDJet Inc.

The patented nozzle design has no moving parts, minimizing the chances of jamming and clogging. The nozzle is installed in the bottom of the waterjet tank and is covered by a 2" x 4" channel for protection. The hoses run along the bottom of the tank and up the side wall, with no need for holes to be drilled in the side of the tank.

Diaphragm pumps

There are four connections to the WARD 2 machine, including a water supply, air supply and two diaphragm pumps that are used to remove the abrasive sludge from the bottom of the waterjet tank.

Upper and Lower hopper

The abrasive sludge is first deposited in the upper hopper where the undersized abrasive and the kerf material fall through to the waste drum, leaving the usable abrasive to be dried. Figure 24 below illustrates the upper and lower hoppers. The usable abrasive seen in the picture on the left is packed into a chain assembly that will be discussed below.

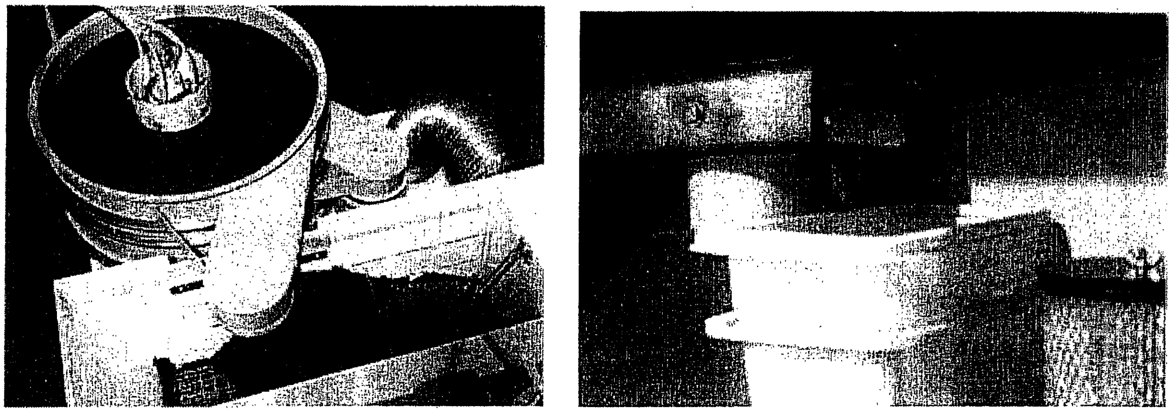

Figure 24: Upper and lower hoppers of the WARD 2 machine. In the upper hopper, the undersized abrasive and kerf material fall through to a waste bin, leaving the usable abrasive to be packed into the chain and dried. The lower hopper includes a final screen. Photos courtesy of WARDJet Inc.

The lower hopper involves a final screening after the abrasive has been dried to remove any large objects, before being deposited into the recycled abrasive storage container.

Chain, electric motor and gear box

The chain used in the abrasive recycling system is a Manganese impregnated stainless chain that travels through the upper hopper and is packed with moist abrasive sludge. The chain then travels over the heating units, and finally deposits the dried abrasive in the lower hopper, returning to the upper hopper empty. In the WARD 2 unit, there is an electric motor as well as a gear box to control the speed of the chain, ensuring sufficient but not wasteful drying.

Dryer and plate

The WARD 2 comes with 2 drying options. With a 110 V power supply, the WARD 2 includes four 1000 Watt elements that heat a metal plate. The 1000 Watt elements can be swapped out for 2000 Watt elements, requiring a 220 V power supply.

Screens

The screens that the WARD 2 unit comes with can be designated by the user to retain a particular abrasive mesh size. The top screen used for separation can be of any mesh size, and is made of stainless steel and mesh. After drying, the usable abrasive drops onto a second screen to remove large pieces, before being deposited into the lower hopper.

Fan

The WARD 2 also comes with a fan to remove steam and dust from the drying compartment. This has become a standard accessory.

How the WARD 2 works

Figure 25 below illustrates the abrasive sludge removal from the bottom of the waterjet tank.

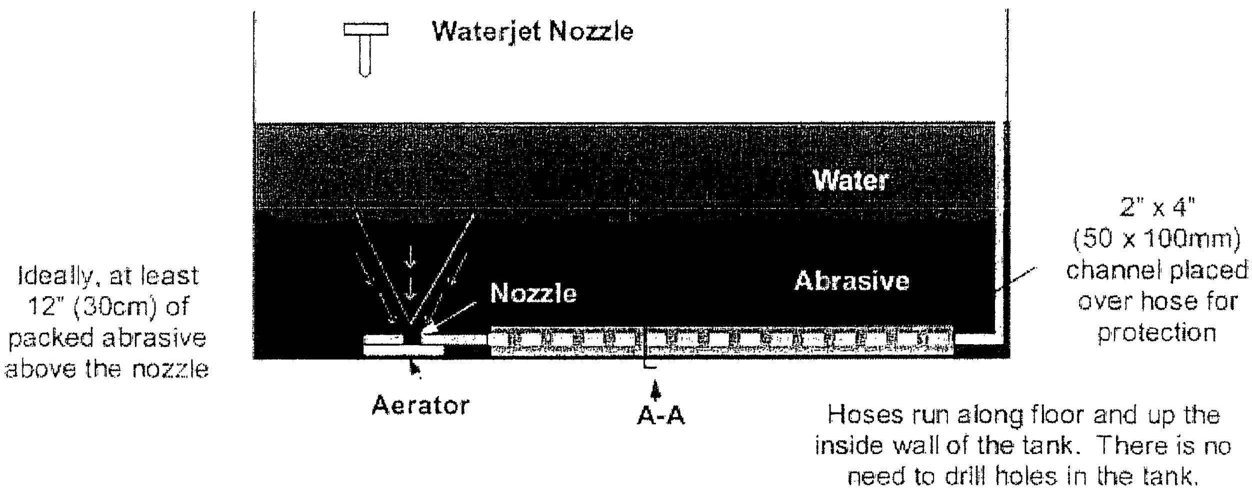

Figure 25: Illustration of abrasive sludge removal from the bottom of the tank using the patented nozzle. Diagram courtesy of WARDJet Inc.

Two tubes transport the abrasive sludge from the patented nozzle at the bottom of the waterjet tank to the WARD 2 machine. The nozzle works best when submerged under at least 12 inches of abrasive sludge. Figure 26 below illustrates the recycling process of the WARD 2.

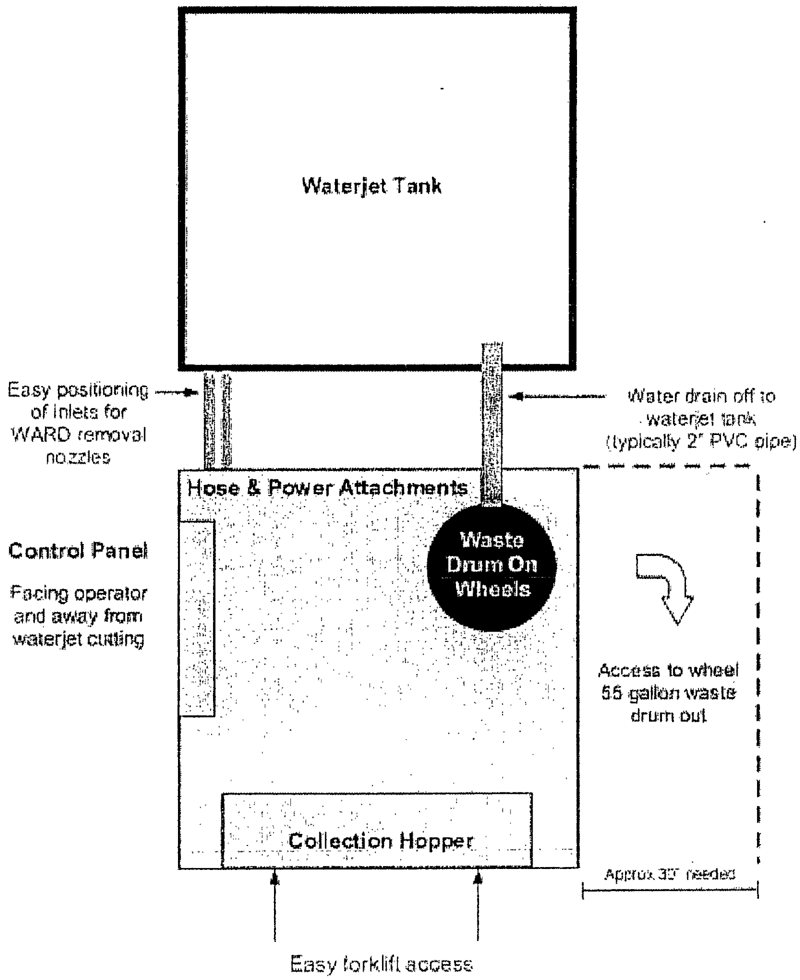

Figure 26: WARD 2 recycling process and setup diagram. Diagram courtesy of WARDJet Inc.

The abrasive sludge is first deposited in the upper hopper where undersized abrasive and all kerf material (except perhaps glass if it has been chipped) fall through to the waste container. The abrasive remaining is packed into the Manganese impregnated chain that travels along the bottom of the hopper. The chain then transports the moist abrasive sludge over the heater plate where the abrasive is dried using four 1000 Watt (or 2000 Watt) elements. The dried abrasive falls from the chain onto the second screen were large pieces are kept from falling into the lower hopper. The speed of the chain can be controlled to ensure that the abrasive is sufficiently dry. As seen in figure 26, the unusable abrasive sludge is deposited into a 55 gallon waste drum that can be removed and replaced or emptied. The dry abrasive is stored in a collection hopper that can be removed with a forklift. Lastly, there is a water drain-off pipe that runs a closed loop connection with the waterjet tank, depositing excess water directly into the tank.

Performance

Extensive testing in and out of industry applications have shown that 50-70% of abrasive can be recovered in a single recycle. Depending on the machine that the WARD 2 is attached to, recovered abrasive can substantially reduce operating costs. If the 110 V WARD 2 machine is used, between 20 and 35 pounds of abrasive can be recovered each hour. The user has control of the abrasive recovery rate solely in the form of the chain speed, however is somewhat limited by the dry time. With the 220 V setup, the recovery rate is more than doubled, producing 80-90 pounds of abrasive each hour.

The recycled abrasive is depicted below in figure 27, along with other brands for comparison.

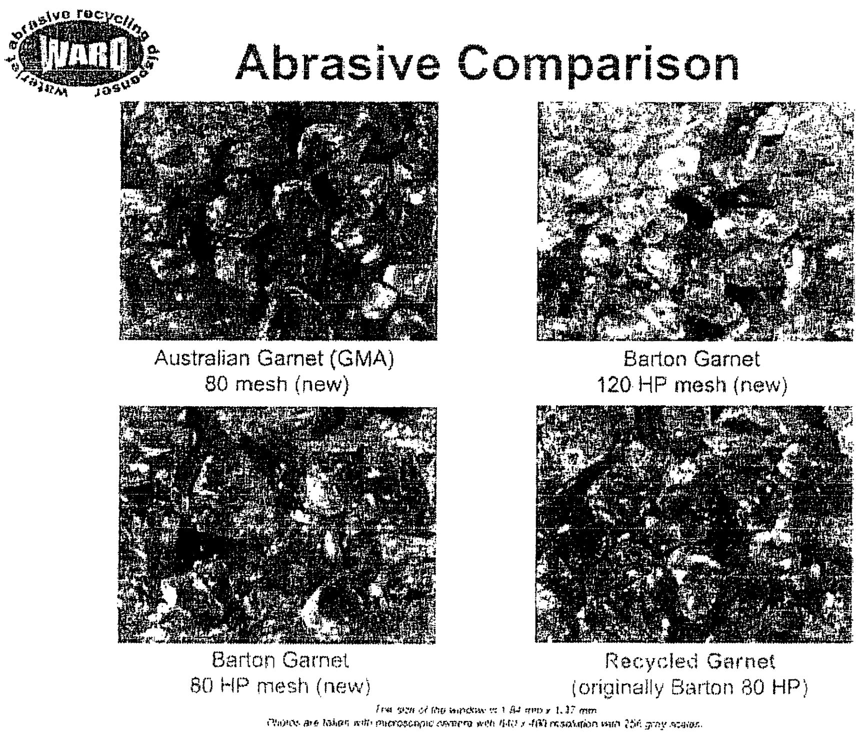

Figure 27: Recycled garnet using WARD 2, originally Barton 80 HP. Also shown are new 80 mesh Australian garnet, new 120 HP Barton garnet, and new 80 HP Barton garnet. Photos courtesy of WARDJet Inc.

Figure 27 illustrates the abrasive grains viewed with a microscopic camera with 640 x 480 resolution and 256 grey scales. The size of each image window is 1.84 mm x 1.37 mm. It is obvious from these photos that there is no distinguishable physical difference between recycled and new abrasive. In fact, although analysis shows a flatter, wider bell curve distribution of grain sizes compared to new abrasive of the same mesh size, tests have shown that there is no difference in cutting speed, surface finish, tolerances or surface quality when recycled abrasive is used rather than new abrasive. Additionally, cutting parameters such as speeds, feeds and pressures need not be altered for the use of recycled abrasive. Lastly, the recycled abrasive can be mixed in any ratio with new abrasive of the same grain size. (Richard Ward, WARDJet Inc. promotional video)

Material flow

The WARD 2 recycling unit has few inputs and outputs in terms of material flow. Figure 28 below illustrates the flow through the machine.

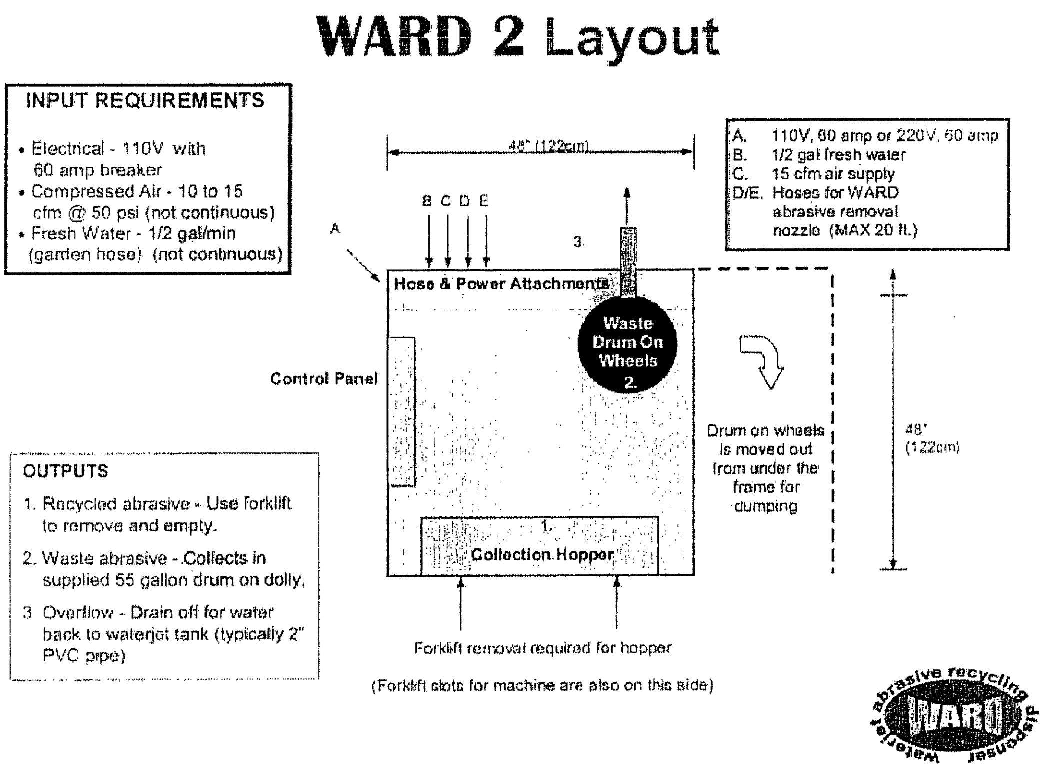

Figure 28: Material and energy flow through the WARD 2 recycling unit. Courtesy of WARDJet Inc.

The WARD 2 requires a 0.5 gpm water supply (a water hose is sufficient) that does not run continuously. The machine also requires 10 to 15 cfm of compressed air at 50 psi, also a supply that is not constant. The part replacement, with the exception of the sifting grates, is negligible in terms of material flow.

The WARD 2 outputs all of the same material, including recycled abrasive, waste abrasive, water and heat. The water is in a closed loop system with the waterjet tank, and the recycled and the waste abrasive are contained in separate tanks.

Energy

The WARD 2 system has a maximum power draw of 60 A at 110 V, equaling 6.6 kW. The WARD 2 Enhanced model, with the 2000 W elements draws a maximum of 60 A at 220 V, equaling 13.2 kW. Actual data for the power consumption for both the WARD 2 and the WARD 2 Enhanced models would be less than these maximum values, and due to the large dependence on the heating elements, is almost linear with the mass of abrasive dried.

The maintenance and operating costs – including electricity, consumables etc. – for the WARD 2 are minimal, at less than $3.50 each hour. With the ability to produce 35 pounds of abrasive in an hour, worth $10.50, the unit is already worth the investment. Additionally, the WARD 2 takes care of removing the abrasive sludge from the bottom of the tank, and eliminates the cost of disposing of the garnet that has now been recycled, quite an expensive process at the rate used abrasive accumulates. The 220 V model, capable of drying over 80 pounds of abrasive an hour, substantially reduces the cost. Assuming the same abrasive cost, the savings on abrasive alone would total $24 each hour, certainly worth considering at any level of production.

Analysis tools

To record the power consumption of the machines during different parts of the cycle, the Amprobe RS-3 Super clamp-on volt-amp-ohmmeter was used. The Amprobe is capable of measuring voltage and current simply by clamping the jaws around the wire to be measured. Figure 29 below depicts the Amprobe device that was used.

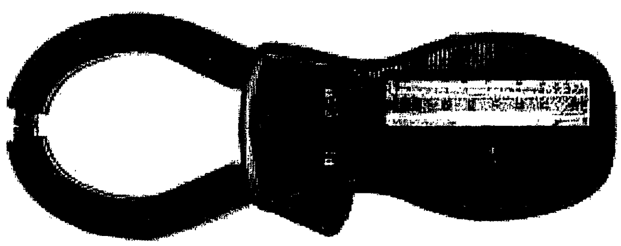

Figure 29: Amprobe RS-3 Super. This was the clamp-on volt-amp-ohmmeter tool used to measure the voltage and current through a wire in order to determine the power consumption during different parts of the machining cycle.

The RS-3 Super is a top of the line multimeter product. The display offers 3 voltage settings, 150V, 300V and 600V maximum to provide precision whenever possible. The AC current scales include 6A, 15A, 40A, 100A and 300A maximums. This tool was extremely convenient and simple to use, providing accurate voltage and current readings during different parts of the machining cycle. Further information regarding this product can be found at www.Amprobe.com.

Part II – Machining Analysis

This section covers the steps taken to analyze the machining process including the system definition, the material and energy flow, and the testing procedure. Also, the system parameters and material flow are discussed in detail for specific example cuts.

System definition

To analyze the flow of material and energy through the machining and recycling process, it is of course necessary to define a cycle. Because the waterjetting process has different components, it is important to encompass every aspect that contributes to the production of a part.

Inputs/outputs of different parts of cycle

The cycle for this project is defined as everything that happens during material processing and recycling/waste disposal. This means essentially that from when the system is turned on to when the sludge is handled will be considered. The material inflows and outflows are of particular interest, and the goal is to follow the path of each input until it exits the cycle. Figure 30 below depicts the cycle and flows.

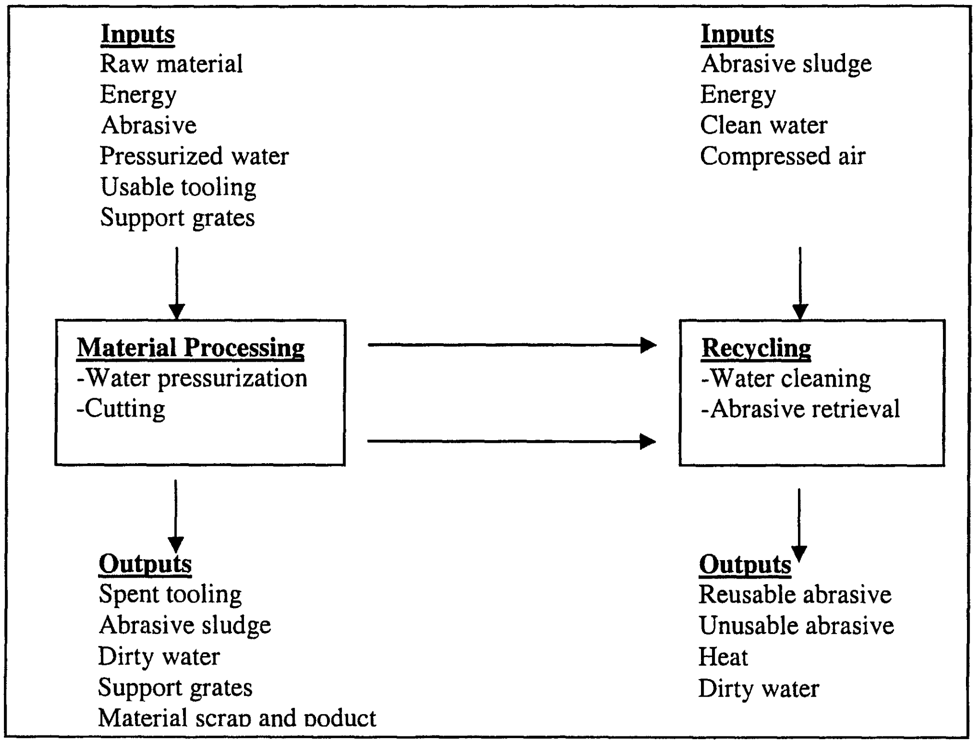

Figure 30: Inputs and outputs of energy and material during the waterjetting cycle.

Material processing involves pressurizing the water, cutting the material and cleaning the work piece. The pump will be described in detail below, but the inflows are water, energy, and replacement parts. The outputs of the pressurization component are spent valves and filters, rings, plungers and pressurized water. Cutting requires inputs of energy, material, pressurized water, and abrasive, while the process outputs finished material and sludge made up of abrasive, removed material and water. The material processing cycle as a whole also requires tooling and grate inputs, while outputting used tooling, waste parts and spent grates.

In most applications, the waste outputs of the material processing cycle – spent tooling, grates, material scrap and sludge – are sent to a landfill for disposal. Some instances, however, involve a recycling process for the sludge. Dirty water still exits the waterjet system and flows down the drain, however the sludge that accumulates at the bottom of the tank can be recycled and reused. The result is unusable abrasive, dirty water and reusable abrasive.

Abrasive

The abrasive industry has been around since long before the abrasive waterjetting machines. The supplier to the MIT machine shops, Barton Mines Company, has been in existence since 1878, producing garnet for the sand paper industry. With the introduction of the abrasive waterjet, Barton Mines was able to provide the same garnet they were already producing for a second market. The abrasive used in waterjetting applications comes primarily from a unique crystalline hard rock deposit in the Adirondack mountains. They offer many grades of abrasive, in fact too many to discuss, covering a range of suggested applications. There are three main categories of abrasive offered by Barton: High performance crystalline waterjet abrasives (HPX); High performance alluvial waterjet abrasives (HPA); and Construction grade abrasives (CG). The HPX is by far the most common, and thus will be discussed in the following pages. The HPA, available in a variety of grain sizes, is produced in Western Australia and "provides excellent performance and cost control in less demanding precision cutting applications." (www.Barton.com) Construction grade abrasives are coarse, resulting in aggressive cutting. It is available in three grades and minimizes consumption while maximizing performance. The drawback, of course, is inferior cut quality and precision, as well as more material scrap, because the grain sizes are larger and therefore remove more material.

HPX garnet comes in many sizes, and represents the standard in the abrasive waterjetting industry. HPX provides a high quality surface finish with an impressive cutting speed. Due to a unique structure, the abrasive grains fracture along crystal cleavage lines resulting in very sharp edges. (www.Barton.com) The sharp, angular edges of the grains result in the superior cutting speed. Also, HPX abrasives have high garnet purity, and therefore low dust levels. Dust often causes clogs and inconsistent cutting power, and therefore should be minimized. Lastly, "a cleaner abrasive results in a cleaner waste product that is easier to move and recycle." (www.Barton.com)

Table 4 below outlines the 6 grades of HPX waterjet abrasive. The information, not the table, was taken from www.Barton.com.

Table 4: HPX abrasive grades and characteristics, www.Barton.com.

50 HPX	• Largest grain size • Most powerful cutting performance and speed • Used when speed is more important than edge quality • Materials: thick stainless steel, titanium, stone
65 HPX	• Combined cutting power of 50 HPX with edge quality of 80 HPX • Materials: thick materials where surface finish is important
80 HPX	• Greatest versatility in applications • Fast cutting speed and good edge quality • Most common on market • Materials: wide variety including all metals, composites, ceramics and stone
85 HPX	• Cutting power of 80 HPX with superior edge quality • Used when thickness is medium or lower, high speed is superior edge quality is important • Materials: same as 80 HPX
120 HPX	• Superior edge quality • Eliminates secondary finishing • Materials: steel, aluminum, glass, ceramics, laminates, composites and other brittle materials
150 HPX and 220 HPX	• Extremely high edge quality • Limited applications • Small kerf width • Industries: electronics, communications and precious metals • Materials: composites, printed circuit boards and fiber optic cables

The wide variety of abrasive options often makes it hard to choose. In this report, 80 HPX and 120 HPX will be of interest as those are what are used in the MIT abrasive waterjetting applications.

Because abrasive is the most abundant component of the sludge waste, the following detailed analysis seems appropriate. To avoid constant referencing, all of the information related to abrasives has been taken from www.Barton.com unless otherwise specified.

The HPX abrasive is characterized as a combination of Almandite and Pyrope varieties of garnet. It is a homogeneous mineral containing no free chemicals. All oxides and dioxides are combined chemically as follows: $Fe_2O_3Al_2(SiO_4)_3$. Table 5 below represents the chemical breakdown of the garnet.

Table 5: Chemical breakdown of Barton garnet abrasive grains, www.Barton.com.

Silicon Dioxide	(SiO_2)	41.34%
Ferrous Oxide	(FeO)	9.72%
Ferric Oxide	(Fe_2O_3)	12.55%
Aluminum Oxide	(Al_2O_3)	20.36%
Calcium Oxide	(CaO)	2.97%
Magnesium Oxide	(MgO)	12.35%
Manganese Oxide	(MnO)	0.85%
		100.14%

The abrasive garnet is a reddish pink color, with a melting point of 1,315 C. It contains no Quartz, is not reactive, and has a specific gravity of 3.9 to 4.1. The dust content does not exceed 10 mg/m^3. Garnet is not soluble in water, has no odor, is not flammable, is stable, cannot polymerize and has no chemical incompatibilities or hazardous decomposition products. Table 6 below presents the grain size breakdown of the two garnets to be discussed, 80 and 120 HPX. The remaining Barton product grain size breakdowns can be found in Appendix E.

Table 6: Barton abrasive grain size breakdown for 80 HPX and 120 HPX, www.Barton.com.

Grain size [microns]	80 HPX [%]	120 HPX [%]
500		
425		
355	3.0%	
300	15.0%	
250	31.0%	
212	24.0%	2.0%
180	17.0%	11.0%
150	7.0%	30.0%
125	3.0%	28.0%
106		16.0%
90		7.0%
75		6.0%

In both cases, the grain size exhibits somewhat of a bell curve, which is to be expected. The range of grain size is however somewhat surprising, and certainly brings into question the importance of consistency. It seems however, considering Barton could produce very consistent grain sizes if that was desired, that the range is known and accepted.

Cycle breakdown

The following pages will explore in more depth the different parts of the cycle for the two cut types outlined above – a square with sides of 1 inch and a circle with a 0.25 inch diameter. The inflows and outflows of the pump and cutting components of the machining cycle will be discussed. The assumptions regarding cut quality, material and thickness presented above are applicable.

Procedure for doing cuts

There are two cuts that will be analyzed in detail regarding the material, abrasive, water, replacement parts and energy flow through the pump and cutting components of the machining cycle. Two machines will be considered on a theoretical and actual basis: Omax 2626 minijet with P2040 pump and Omax 2652 with P2040 pump.

<u>Cut 1</u>

Theoretical inflows and outflows

The first cut to be analyzed is a simple square with 1-inch sides. The material thickness is 0.5 inches, and any calculations will be done using machineability, however will be discussed in the case of Aluminum 6061, machineability 213. Figure 31 below illustrates the cut geometry and tool path.

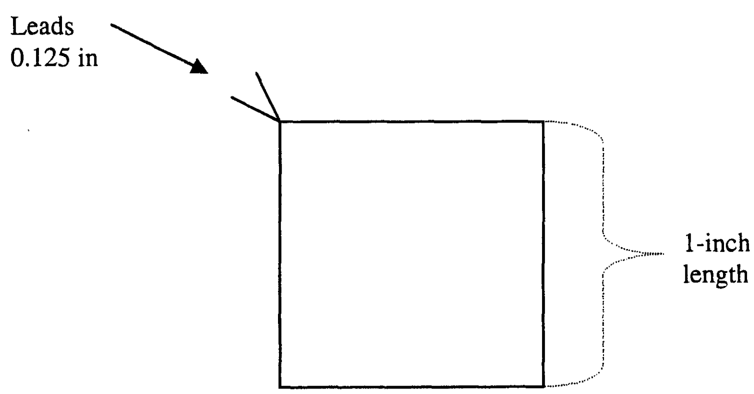

Figure 31: Cut 1 shape. Square with 1-inch side length, 0.125 inch lead-in, 0.125 inch lead-out.

The overall cut length of 4.25 inches because of the 0.125 inch lead-in and lead-out.

Material

The material inflow for cut 1 is simply the work piece in the cutting operation, as there is no material inflow to the pumping process. The work piece must be slightly larger than the square being cut. Because the size of the work piece is unknown, the scrap material, excluding the kerf material, will be disregarded in the material flow analysis. This is because there is no way of knowing if this material is in fact scrap, or if it will be used for further part production. The kerf material, however, is known to be scrap and thus contributes to the waste output.

Therefore, the input material is the 1 in x 1 in square plus 0.030 inches added to each side for removed material. (this value would be 0.021 inches for the 2626 machine) The total volume is 0.5618 in^3, assuming a thickness of 0.5 inches. The output is a product of 0.5 in^3 in volume, as well as 0.0618 in^3 if scrap material from the kerf width. (0.043 in^3 for the 2626 machine) The output waste volume is independent of material, and is purely a function of cut length, kerf width and material thickness.

Abrasive

Abrasive is used only in the cutting process. The amount of abrasive consumed during a cut is a function of cut time, as the flow of abrasive is constant. 2652 machines can be setup to use either 0.75 lb/min or 1.0 lb/min of abrasive, while the 2626 uses 0.3 lb/min. In the case of standard materials of normal thickness, 0.75 lb/min is sufficient. From the cutting times discussed above, the time of this linear cut,

$$t = (0.0514 * \text{machineability} - 1.368) * \text{length}/100,$$

in units of fraction of a minute. With a cut length of 4.25 inches and an Aluminum machineability of 213, the cut time is equal to 25.05 seconds, or 0.418 minutes. (0.734 minutes for the 2626) To determine the abrasive use, simply multiply the time in minutes by 0.75. In the case of this first cut, 0.3135 pounds of abrasive is used by the 2652 machine, while only 0.2202 pounds is used for the 2626.

Water – quality and pressure

The quality of the water has a significant effect on the life of the nozzle and the pump components, as well as on the quality of the cut. Because of the high precision, high speed nature of the machining process, any dissolved or suspended solids in the water become very important to part life. Particles that are suspended in the water can impact the edge of the orifice and in fact chip it, resulting in poor jet quality, poor cutting capability and a shortened mixing tube life. Dissolved solids, over time, will precipitate out of the solution and create a ring around the orifice, leading to further chipping as with suspended solids. Water that is too pure, on the other hand, can be very detrimental to components of the pumping system because of a high potential to dissolve materials that it comes in contact with. (www.Omax.com)

The crankshaft pump offered by Omax requires roughly 1 gallon per minute of water flow at 1 psi. There is some filtration that takes place, removing 0.2 micron and greater solids from the solution. Unlike the intensifier pump that requires 3 gallons per minute to cool the system as well as 1 gallon per minute to cut, the crankshaft pump in the 2652 has an output water flow rate of 0.75 gallons per minute, 0.39 gpm for the 2626. Therefore, to calculate the volume of water used for the square cut, simply multiply 0.75 gpm (0.39 gpm for 2626) by the time for the cut, in minutes. In the case of the square cut, the volume of water used equals 0.313 gallons. The 2626 minijet would require 0.39 gpm, roughly half of the 2652.

Replacement parts

Although part life does vary significantly as a result of difficult to quantify variables, a typical mixing tube and orifice assembly will last between 40 and 60 hours. The pump maintenance depends substantially on the quality of the water supplied to the pump. Appendix F contains the periodic maintenance for the Omax P2040 pump. Every 300 hours, the seals and back-up rings must be replaced; every 600 hours, the check valves and retainer must be replaced; every 1200 hours the pump requires an overhaul, changing the seals and back-up rings, the plungers, check valve body and check valve retainer. In order to account for the flow of parts through the cycle as a function of a given cut, it is appropriate to use a concept known as straight-line depreciation. Assuming the nozzle lasts for 50 hours on average, straight-line depreciation suggests that 1/50 of the nozzle is consumed every hour, or 1/3,000 every minute. Accordingly, 1/300 of the seal life and back-up ring life is used every hour, 1/600 of the check valve life is used every hour, and 1/1,200 of the plunger, check valve body and check valve retainer lives are used every hour..

Therefore, with a cut such as cut one, lasting 0.418 minutes, for the sake of accountability, roughly 1/7,100, or 0.014%, of the mixing tube and orifice were consumed, roughly 1/43,000, or 0.00232%, of the seals and back-up rings were consumed, roughly 1/86,000, or 0.0012% of the check valves was consumed, and roughly 1/172,000, or 0.0006% of the plunger, check valve body and check valve retainer were consumed.

Lastly, the support slats are typically replaced every 6 months to 1 year. This is entirely at the discretion of the operator, and can be replaced as often as every 3 months, or as infrequently as every few years.

Energy

The abrasive waterjet and pump are quite simple from the energy standpoint. With the exception of the computer console, there are no components that are constantly running regardless of whether or not a part is being produced. It is of interest to know the energy profile while cutting, and to identify which machining parameters, if any, have a quantifiable effect on the power consumed. It should first be noted that power in this case can be determined by using the equation,

$$P = V*I,$$

Where *V* represents the voltage, and *I* represents the current. Tests have shown that the direct drive P2040 pump contributes most of the overall power consumption during cutting. The two machines of interest, the Omax 2652 and the Omax 2626 minijet have very different power consumption profiles, due to different nozzle and mixing tube diameters as well as different voltage supplies. In the case of both machines, the computer draws 110 V at 2 A while idle. This is constant for any amount of time that the machine is on. When cutting, the draw from both the 2652 and the 2626 computer and motors increases to 2.2 A, implying that the motors require 0.2 A with 110V. The current increased to 2.4 A at full speed rapid traverse, 200 ipm for the 2652 and 190 ipm for the 2626. There is no significant energy profile as a function of speed for the motors, and the existence of one would provide negligible values compared to the pump energy consumption.

In the case of the 2652, the P2040 pump receives 480 V 3-phase power. The pump is either off or on, and turns on 3 seconds before the cut begins. There is a spike in current as the pump ramps up, however the current levels to a constant 25 A for the remainder of the cutting process. So for a given cut, the pump runs for 3 additional seconds before the cut begins. At the end of the cut, the machine stops the flow of abrasive while the pump and water run for an additional 1.5 seconds to clear the lines, before they are both shut down. For any cut on the 2652 machine, the pump and water flow occur for 4.5 seconds longer than the cut time.

For the 2626, the wall supplies 220 V 3-phase power to a step-up transformer, rated to produce 480 V. The current while cutting for the P2040 pump attached to the 2626 machine is only 11 A, and the same idle currents and voltages apply to this machine as did the 2652. Basically, the energy is very constant. There is always a 2.0 A – 2.4 A current on 110 V, resulting in an average of 0.242 kW for both machines, and the 2652 adds an additional 12 kW for the pump, while the 2626 only adds an additional 4.62 kW. Energy therefore is significantly dominated by the pump, and thus whether the pump is on or off drives the energy consumption.

The energy profile for the first cut can be determined both theoretically and actually. To determine the theoretical maximum energy use, the power equation above can be applied, substituting the appropriate voltage and current profile. The calculation would be an estimate of the maximum power draw, and would not capture an average value for cutting operations. In table 10 below, from an Omax publication, the average hourly power consumption for the P2040V system is roughly 16 kWh. This estimate takes into account the pump, servo motors, on/off valves, garnet distribution and water supply. This value is a more appropriate estimate with which to compare the theoretical energy profile for each cut, because it represents an average, not a maximum.

Actual inflows and outflows

The actual inflows and outflows are quite different from the theoretical predictions. Table 7 below presents the theoretical and actual values for the variables in question, including abrasive, water, energy, material, and replacement part consumption.

Table 7: Theoretical and actual material and energy flow for cut 1. This table presents data for the Omax 2652 with a 0.014 inch diameter orifice and 0.030 inch diameter mixing tube, as well as the Omax 2626 with a 0.010 inch diameter orifice and 0.021 inch diameter mixing tube. Both machines use the P2040 20 hp Omax pump.

Cut 1				
Item	Machine 1 - 2652		Machine 2 - 2626	
	Theoretical	Actual	Theoretical	Actual
Machineability	213	213	213	213
Thickness [in]	0.5	0.5	0.5	0.5
Quality	3	3	3	3
Cutting time [min]	0.418	1.21	0.734	1.416
Abrasive use [lb]	0.3135	0.79	0.2202	0.38
Energy use [kWh]	0.085	0.247	0.085	0.115
Water use [gallons]	0.3135	0.9075	0.28626	0.55224
Volume of material removed [cubic inches]	0.06	0.06	0.042	0.048

The table indicates that the theoretical predictions are often quite inaccurate. The cutting time is drastically underestimated, which results in fairly inaccurate values for the abrasive, water, material and energy consumption.

Material

The actual material removed is the same for the 2652 as the theoretical prediction, however in the case of the 2626, 14% more material is removed due to a kerf width larger than the mixing tube diameter.

Abrasive

Both machines consume more abrasive than the theoretical predictions. The 2652 consumes 0.79 pounds for cut 1, compared to the predicted value of 0.31 pounds. This is entirely due to the fact that the estimated theoretical cutting time is inaccurate because abrasive flow is purely a function of time. In the case of the 2626 machine, the abrasive consumed was 0.38 pounds, compared to the predicted value of 0.22 pounds.

Water

The actual amount of water used for cut 1 on the 2652 machine was 0.91 gallons, compared to the 0.31 gallons estimate, and 0.55 gallons compared to the 0.29 gallon estimate for the 2626 machine. This is also due to the inaccurate prediction for cutting time.

Energy

To test the actual power use for the pump and waterjet during cut 1, the Amprobe RS-3 Super clamp-on volt-amp-ohmmeter was used to measure the actual voltage and current during the cut. The leads were placed across the power supply to determine voltage, and the device was clamped around the power supply wires of the pump and computer unit to record current. Figure 32 is a photo of the Amprobe clamped around one of the wires to the computer console and x-y table, in order to determine the current.

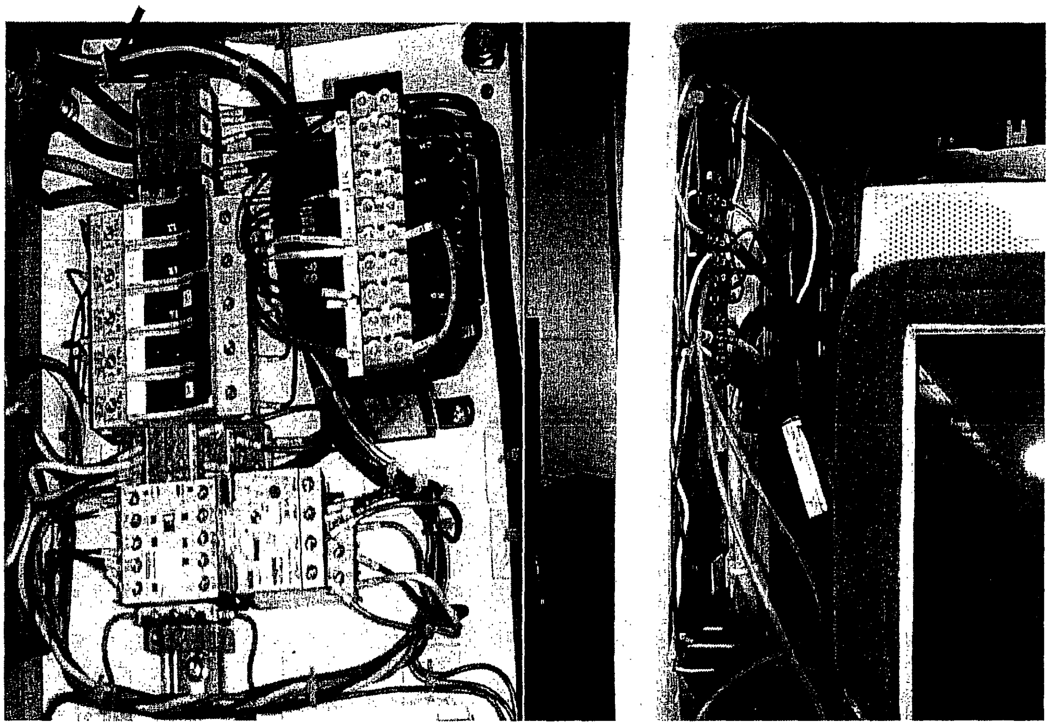

Figure 32: Amprobe RS-3 Super clamped around the electricity line feeding the computer and waterjet table. The picture on the left is of the control box for the 2652 pump, with the arrow pointing to the power input lines.

In reality, the Omax feed rate software is fairly inaccurate. The software fails to take into account ramp-up and ramp-down times, as we as other important variables. In the case of the 2652 machine for the first cut, the actual cutting time is 1.21 minutes. From tests on the machines, with a machineability of 213, the actual energy consumption is 0.247 kWh. 0.242 kWh of that total energy consumption is related to the pump, roughly 98%.

In the case of the 2626 machine, the power draw for the computer and motors was the same as the 2652, at an average of 2.2 A and 110 V. The pump was theoretically estimated to consume the same amount of power as with the 2652 test, however in actuality, to total power consumed was less than half the 2652 model, at 0.115 kWh. This is much closer to the prediction than with machine 1. 95% of this energy draw is due to the pump operating.

Discussion of cut 1

Table 7 above presents the theoretical and actual results for both machines executing cut 1, a 1 inch square cut of 0.5 inch thick Aluminum. The theoretical values are quite different from the actual values, and require discussion. Figure 33 below depicts the theoretical and actual results for the material and energy flow of machine 1, cut 1.

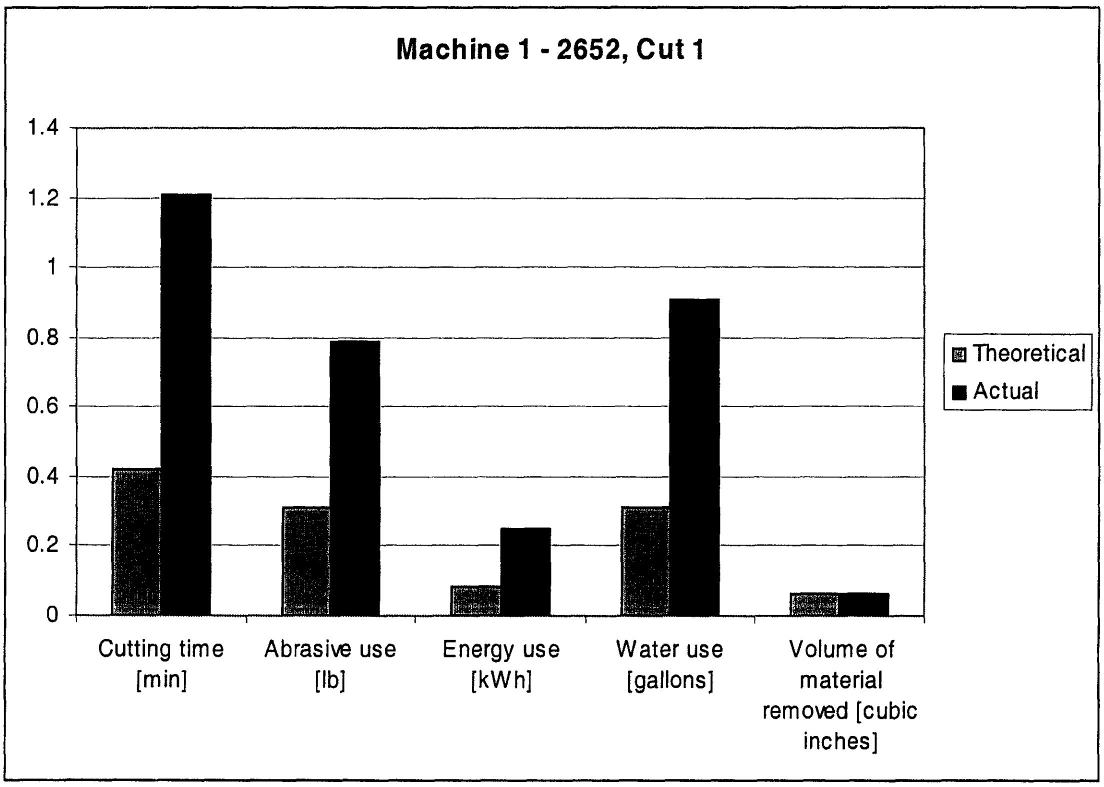

Figure 33: Theoretical and actual results for cutting time, abrasive use, energy use, water use and material removed for the Omax 2652 machine with a P2040 pump. This graph is of cut 1.

In each case, the actual consumption is either equal to or greater than the theoretical predictions. With the feed rate calculator supplied by Omax, the cycle time does not include delays that increase the overall cutting time. In the case of the above variables, the difference is almost entirely due to an incorrect cutting time for the theoretical predictions. What is important is not the theoretical, but instead what the Omax software determines the values to be, as those values represent exactly what will take place while cutting, and are depicted above as the actual results.

In the case of the second machine, the discrepancies are not quite as significant, however still exist. Figure 34 below is similar to figure 33, however in this case representing the second machine, the 2626.

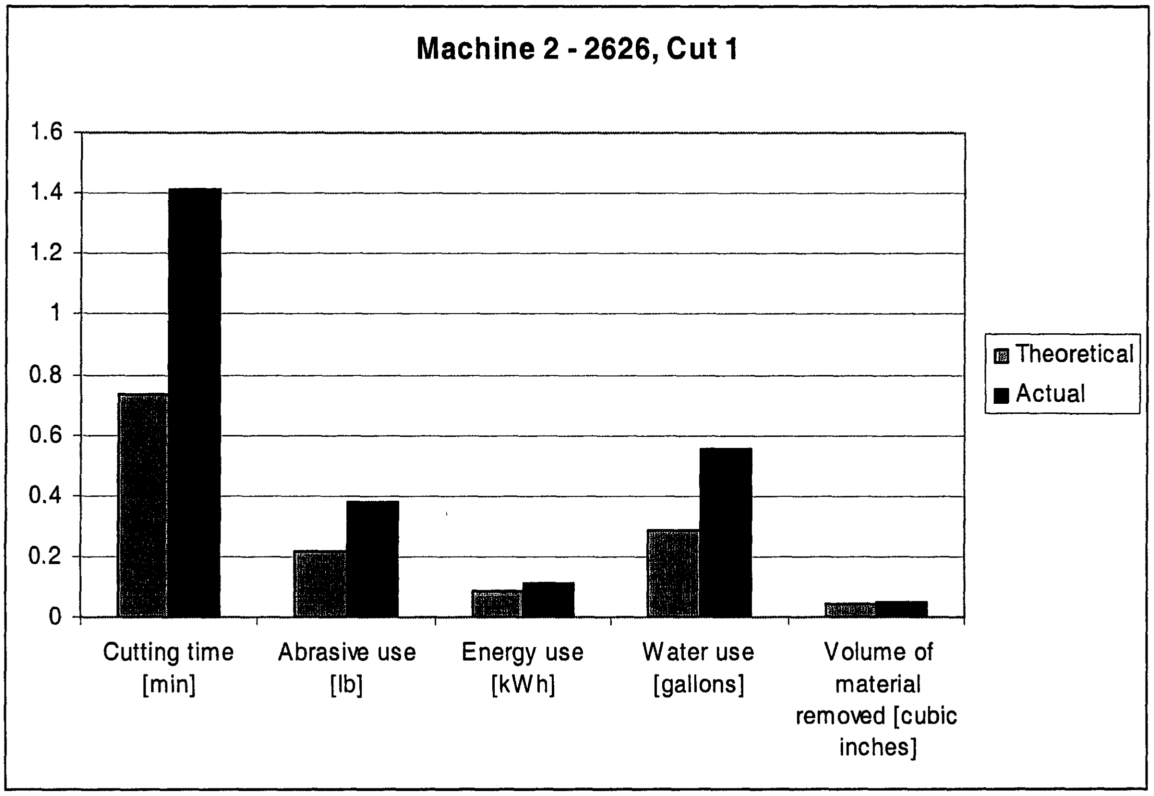

Figure 34: Theoretical and actual results for cutting time, abrasive use, energy use, water use and material removed for the Omax 2626 machine with a P2040 pump. This graph is of cut 1.

Overall, the 2626 machine consumes less in every category than the 2652 machine. As a result, considering very similar theoretical predictions to the 2652 process, the actual results in the case of the 2626 are closer to the theoretical ones. The energy used is roughly 0.1 kWh, and the material consumed is 0.048 in^3 compared to the 0.060 in^3 for the 2652 machine.

In the case of Aluminum 6061, the density is 2700 kg/m^3, with a chemical composition outlined in table 8 below.

Table 8: Chemical composition of Aluminum 6061.

Element	Weight %
Al	97.9
Si	0.60
Cu	0.28
Mg	1.0
Cr	0.20

With the density and volume known, the mass of the Aluminum 6061 scrap material produced can be calculated. Because the mass simply equals the density times the volume, the Aluminum mass consumed for the first cut is equal to 2700*9.83E-7 for the 2652, and 2700*7.86E-7 for the 2626, which equals 0.001207 pounds of Aluminum 6061 for the 2652 and 0.00096 pounds for the 2626.

In the case of water, the density is 1000 kg/m^3. As table 7 indicates, 0.91 gallons of water was consumed using the 2652 machine, and 0.55 gallons with the 2626 machine, resulting in masses of 1.57 pounds and 0.95 pounds, respectively. Table 9 below illustrates the breakdown by percent weight.

Table 9: The composition and amount of the waste produced for cut 1.

Machine 1			Machine 2		
Element	**Mass [lb]**	**% Total weight**	**Element**	**Mass [lb]**	**% Total weight**
Water	1.5627	66.3877%	Water	0.9510	71.3955%
Abrasive	0.79	33.5613%	Abrasive	0.38	28.5294%
Aluminum 6061	0.0012	0.0510%	Aluminum 6061	0.001	0.0751%
Al	0.0011748	0.0499%	*Al*	0.000979	0.0735%
Si	0.0000072	0.0003%	*Si*	0.000006	0.0005%
Cu	3.36E-06	0.0001%	*Cu*	0.0000028	0.0002%
Mg	0.000012	0.0005%	*Mg*	0.00001	0.0008%
Cr	0.0000024	0.0001%	*Cr*	0.000002	0.0002%

It is important to note that in terms of waste produced, water is the most abundant by mass. However, because the water goes down the drain, the abrasive sludge that is removed is almost entirely abrasive, with very little metal scrap material. For cut 1, machines 1 and 2 differ significantly in terms of the ratios of the waste products. For machine 1, the water to abrasive ratio is roughly 2:1, the water to metal ratio is 1300:1, and the abrasive to metal ratio is roughly 658:1. For machine 2, the water to abrasive ratio is 2.5:1, the water to metal is 950:1, and the abrasive to metal ratio is 380:1. From these numbers, it is clear that machine 2 uses significantly less abrasive for each unit of material removed, which is significant considering the large percentage of cost that abrasive is responsible for.

Cost analysis of machining time – Cut 1, Machines 1 and 2

Depending on the costs of certain parameters such as power, abrasive and replacement parts, the cost of machining can vary quite significantly. It would be difficult to determine industry averages, however Omax has published figures for their waterjet systems. Table 10 below represents the cost breakdown for three Omax machining systems. (Bingham, Omax)

Table 10: Estimated hourly costs for 3 Omax waterjet systems: P2040V, P3050V, and P4060V. (20, 30, and 40 hp respectively) This table includes the operating and maintenance costs associated with running the waterjet for the entire hour. www.Omax.com

Estimated Hourly Costs of Omax Waterjet Systems			
Item	**P2040V**	**P3050V**	**P4060V**
X-Y table (includes periodic grate replacement, servo drive belts, on/off valves, high pressure plumbing, etc.)	$3.90	$3.90	$3.90
Abrasive system (includes nozzle components and maintenance, not consumables)	$0.83	$0.83	$0.83
High pressure pump (includes replacement of water filters and all pump maintenance)	$4.08	$5.93	$6.48
Consumables			
Nozzle orifices	$0.92	$0.92	$0.92
Nozzle mixing tubes	$2.50	$2.50	$2.50
Garnet abrasive at $0.3 lb.	$13.50	$13.50	$13.50
Water [gph]	49	55	58
Electric power [kWh/hr]	16	22	28
Total	**$25.73**	**$27.58**	**$28.13**

The P2040V system is of interest as that is the pump for both MIT machines. The periodic replacement or maintenance costs for the x-y table, which includes grate replacement, servo drive belts, on/off valves, high pressure plumbing, etc. totals $3.90 per hour of actual machining. The abrasive system, including nozzle components and maintenance, totals $0.83 per hour of machining. The maintenance of the pump, including filter, seal and ring replacement totals $4.08 per hour of machining. The nozzle orifice and mixing tube together cost $3.42 for an hour of machining, and the garnet, depending on the source, can cost between $10 and $15 an hour. On average, 49 gallons of water are consumed during an hour of machining on the P2040V system, and 16 kWh of power. The Omax estimate of the total hourly cost for the P2040V waterjet system running for the entire hour is $25.73. If this is considered to be true, then the costs of cut 1, with a length of 1.21 minutes for the 2652 machine and 1.416 minutes for the 2626 machine, are roughly $0.51 and $0.61, respectively. These costs exclude costs other than operation and maintenance, such as initial investment, operator expenses, and installation costs. 14% of the cost for cut 1 is related to the x-y motors, 3% related to the abrasive system, 17% related to the pump, 4% related to the nozzle orifice, 10% related to the mixing tube, 50% related to the abrasive consumption, and 5% related to power use. In actuality, the cost of using the 2626 machine is different than the estimate, totaling $1.18. (From the Omax software) It is important to note that abrasive consumption, at a conservative estimate of $0.30 lb., is over 50% of the operating and maintenance cost. This again highlights the applicability of the abrasive recycling process.

Cut 2

Theoretical and actual inflows and outflows

Figure 35 below illustrates the geometry for the second cut.

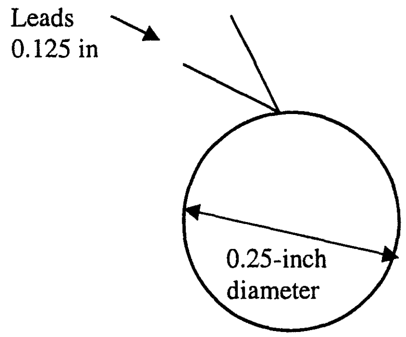

Figure 35: Cut 2 shape. Circle with 0.25-inch diameter, 0.125 inch lead-in, 0.125 inch lead-out.

A detailed discussion as with the first cut is not entirely necessary here, as the explanation of each variable in different parts of the cycle has already taken place. Instead, the results of abrasive, water, material, replacement parts and energy will be presented and discussed for the second cut. The second cut is a circle 0.125 inches in diameter. The kerf width is the same as with the first cut, 0.030 inches for the 2652 and 0.021 inches for the 2626. The theoretical radial feed rate of the nozzle for a machineability of 213 and a part thickness of 0.5 inches is 5.479 ipm. The total length of the cut is 0.785 inches.

Table 11 below presents the theoretical and actual results for the two machines executing cut 2.

Table 11: Theoretical and actual material and energy flow for cut 2. This table presents data for the Omax 2652 with a 0.014 inch diameter orifice and 0.030 inch diameter mixing tube, as well as the Omax 2626 with a 0.010 inch diameter orifice and 0.021 inch diameter mixing tube. Both machines use the P2040 20 hp Omax pump.

Cut 2				
Item	Machine 1 - 2652		Machine 2 - 2626	
	Theoretical	Actual	Theoretical	Actual
Machineability	213	213	213	213
Thickness [in]	0.5	0.5	0.5	0.5
Quality	3	3	3	3
Cutting time [min]	0.143	0.68	0.252	0.448
Abrasive use [lb]	0.10725	0.39	0.0756	0.09
Energy use [kWh]	0.029	0.247	0.02	0.115
Water use [gallons]	0.10725	0.51	0.09828	0.17472
Volume of material removed [cubic inches]	0.012	0.012	0.008	0.009

The material removed is as expected with both machines. Again, the amount removed by the 2626 machine is slightly larger than the estimate due to a kerf width that is greater than the mixing tube, but the difference is small. 0.39 pounds of abrasive was used by the 2652 machine, compared to the 0.107 estimate, and 0.09 pounds were used by the 2626 machine, compared to the 0.08 estimate. Energy use was greater in the actual sense as well, as was water consumption. All of these discrepancies are can be attributed to the incorrect prediction of the cutting time due to the absence of accountability for delay times.

The delay times for every part are the same, some holding significance and some more or less negligible. When the pump is on, any sort of delay time is important because a large amount of power is being consumed. As noted above, a total of 4.5 seconds elapses when a cut is not being made, however the pump is operating. The pump runs for 3 seconds before the cut begins, and an additional 1.5 seconds after the cut has been completed to drain the lines of abrasive. No additional abrasive is used during delay times, so the extra consumption is 4.5 seconds worth of power and 1.5 seconds worth of water for every cut, no matter the material, geometry, quality or thickness.

Discussion of cut 2

As table 11 indicates, theoretical and actual values for the material and energy flow are quite different. Figures 36 and 37 below illustrate the theoretical and actual values for the second cut for both machines.

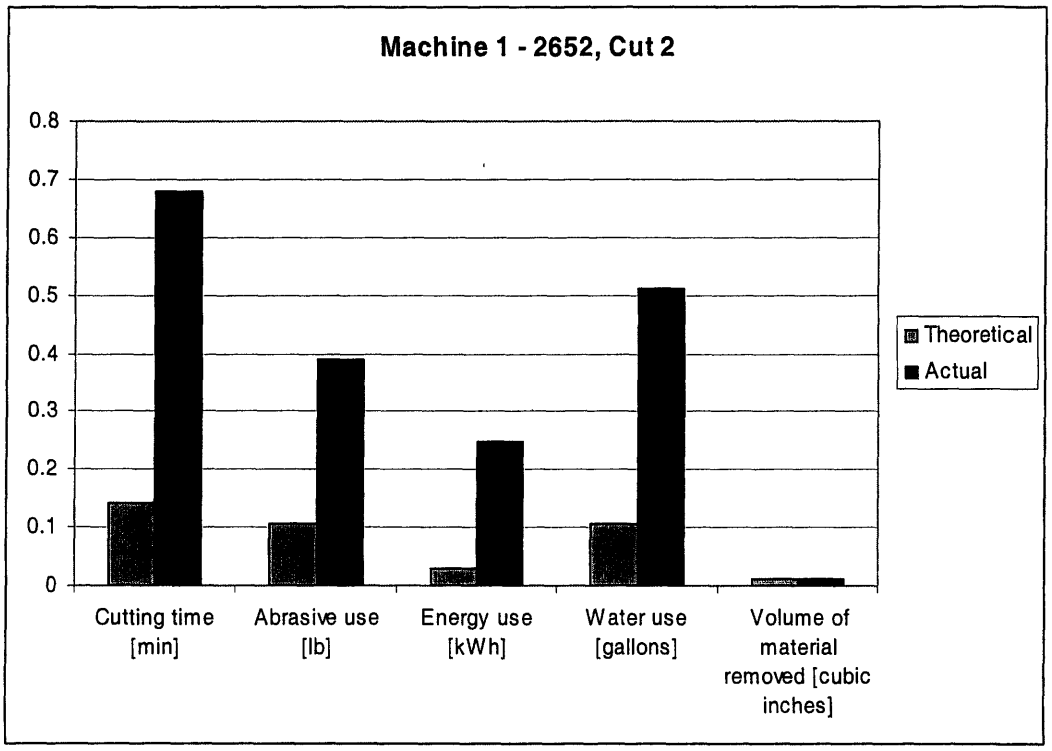

Figure 36: Theoretical and actual results for cutting time, abrasive use, energy use, water use and material removed for the Omax 2652 machine with a P2040 pump. This graph is of cut 2.

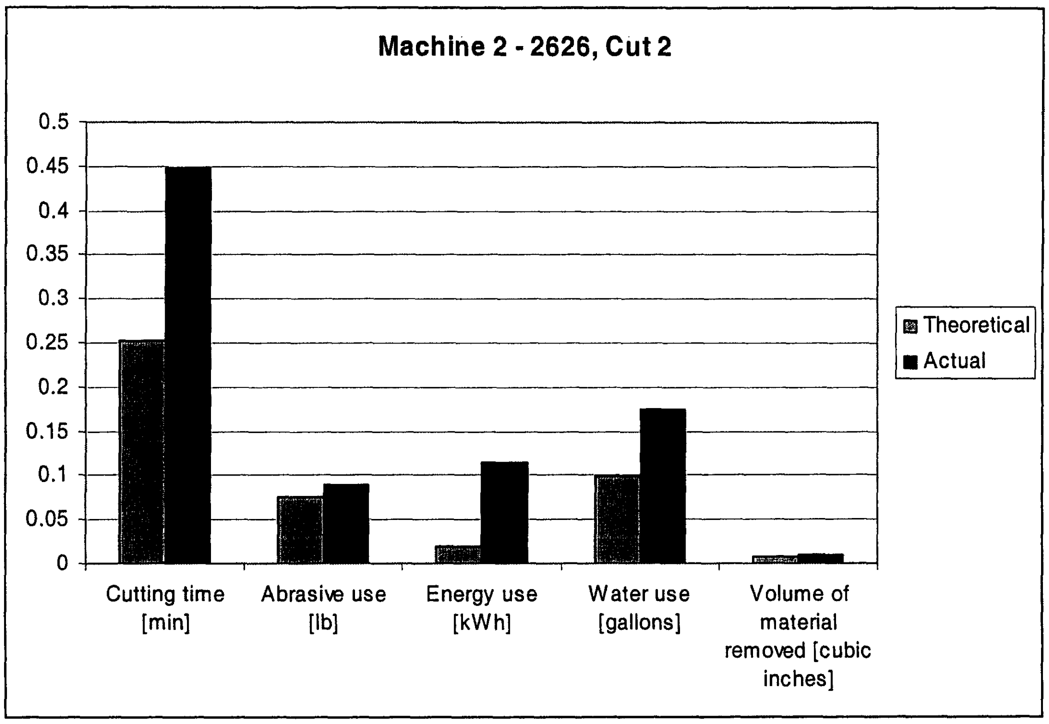

Figure 37: Theoretical and actual results for cutting time, abrasive use, energy use, water use and material removed for the Omax 2626 machine with a P2040 pump. This graph is of cut 2.

Again, although the theoretical predictions are typically low, the 2626 machine performs much closer to expectations than the 2652 machine. Most of this can be attributed to the smaller orifice and mixing tube, and therefore smaller need for power, as well as less material to be removed. This does come at a cost, which is in the form of a shorter life span for the orifice and mixing tube.

With the density and volume known, the mass of the Aluminum 6061 scrap material produced is calculated. Because the mass simply equals the density times the volume, the Aluminum mass consumed for the second cut is equal to 0.00024 pounds by the 2652 machine, and 0.00018 pounds for the 2626 machine. Table 11 above presents the data for abrasive, aluminum and water consumption. Table 12 below presents the composition and amount of the waste produced for cut 2.

Table 12: The composition and amount of the waste produced for cut 2.

Machine 1			Machine 2		
Element	**Mass [lb]**	**% Total weight**	**Element**	**Mass [lb]**	**% Total weight**
Water	0.878	69.2298%	Water	0.3009	76.9408%
Abrasive	0.39	30.7513%	Abrasive	0.09	23.0132%
Aluminum 6061	0.00024	0.0189%	Aluminum 6061	0.00018	0.0460%
Al	0.000235	0.0185%	*Al*	0.0001762	0.0451%
Si	1.44E-06	0.0001%	*Si*	0.000006	0.0015%
Cu	6.72E-07	0.0001%	*Cu*	0.0000028	0.0007%
Mg	0.0000024	0.0002%	*Mg*	0.00001	0.0026%
Cr	4.8E-07	0.0000%	*Cr*	0.000002	0.0005%

Again, the most abundant waste product is water, which is sent directly down the drain assuming a non- toxic material work piece. In the case of the abrasive sludge, again, less than 0.1% is material scrap. Again, for cut 2, machines 1 and 2 differ significantly in terms of the ratios of the waste products. For machine 1, the water to abrasive ratio is roughly 2.25:1, the water to metal ratio is 3650:1, and the abrasive to metal ratio is roughly 1625:1. For machine 2, the water to abrasive ratio is 3.34:1, the water to metal is 1670:1, and the abrasive to metal ratio is 500:1. From these numbers, it is clear that, again, machine 2 uses significantly less abrasive for each unit of material removed, in fact less than 1/3 the amount of machine 1, which is significant considering the large percentage of cost that abrasive is responsible for.

Cost analysis of machining time – Cut 2, Machines 1 and 2

As with the first cut, outlined in table 10 above, the overall cost per hour to operate the 2626 or 2652 is $25.73. If this is considered to be true, then the cost for cut 1, with a length of 0.68 minutes for the 2652 and 0.448 minutes for the 2626, is $0.29 and $0.19, respectively. In actuality, the cost for cut 2 using the 2652 machine was $0.28, where as the cost for the 2626 machine was $0.37. The 2652 estimate is almost exactly on, however the 2626 estimate was quite low. This makes sense, because the software calculations, in this case the actual results, takes into account more than the outlined cost in table 10.

Discussion of the two machines

The 2626 machine, although much more conservative in terms of material consumption, is still more expensive to operate than the 2652 for a given part. The costs estimated by the Omax software for both the first cut and the second cut were at least 30% greater for the 2626 machine. This does overlook some noteworthy costs, such as the additional cost to dispose of the abrasive used in the 2652 cut, which is much larger than the amount used for the 2626 cut.

The following pages contain several figures that represent the actual material and energy flow through the two machines for each cut.

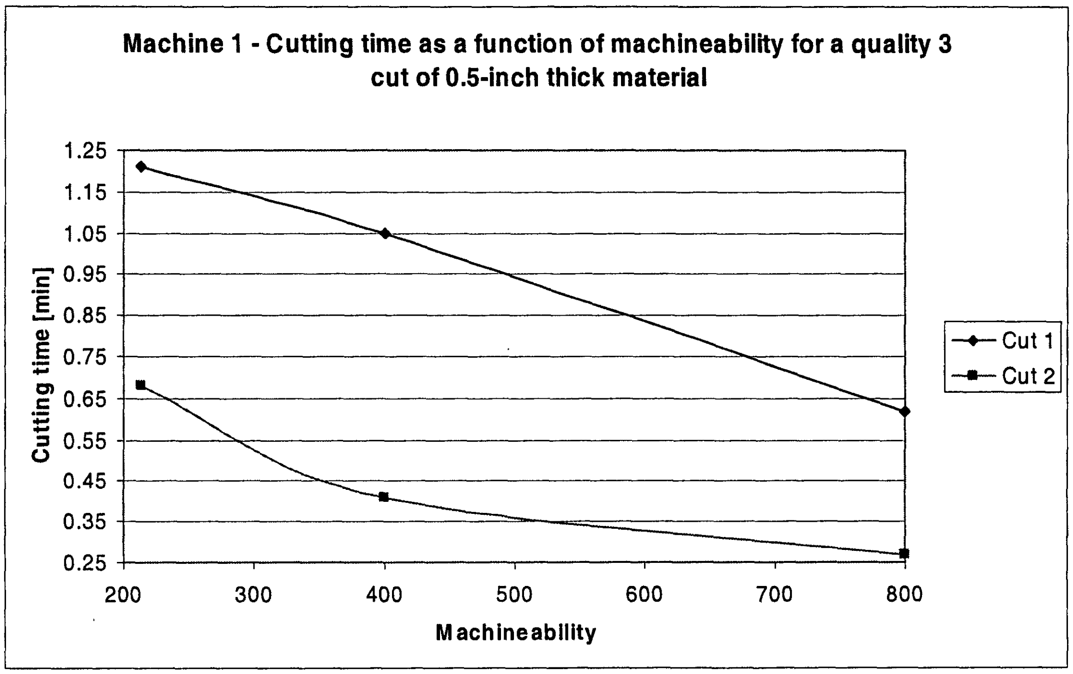

Figure 38: Cutting time as a function of machineability for the 2652 Omax machine cutting 0.5 inch thick material with a quality of 3. This plot illustrates the cutting time for both cuts.

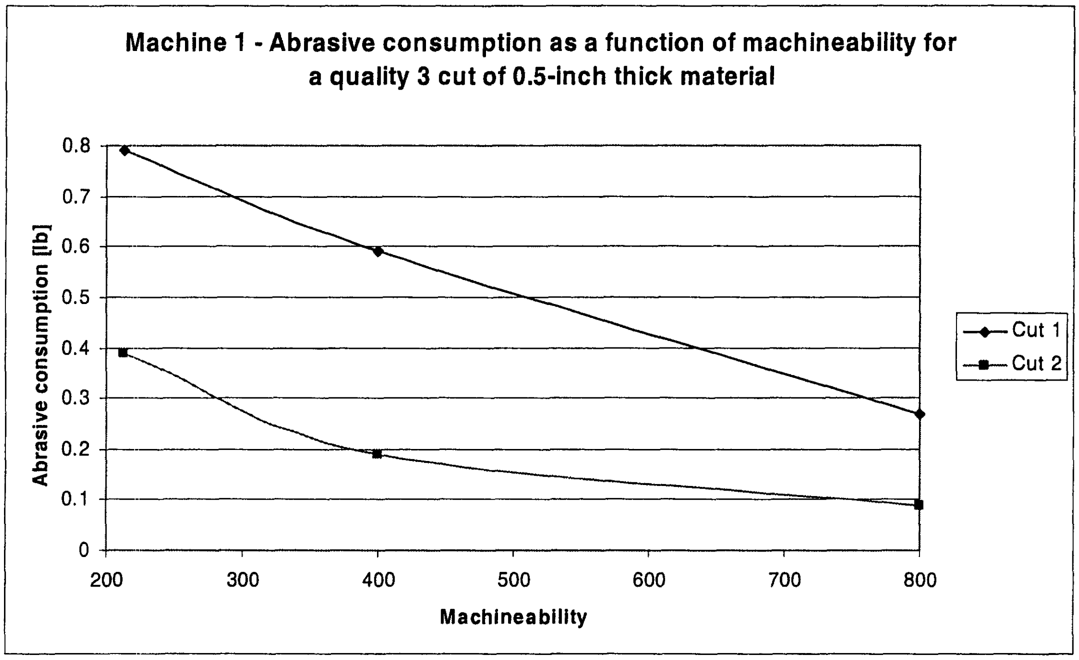

Figure 39: Abrasive consumption at a function of machineability for the 2652 Omax machine cutting 0.5 inch thick material with a quality of 3. This plot illustrates the abrasive consumption for both cuts.

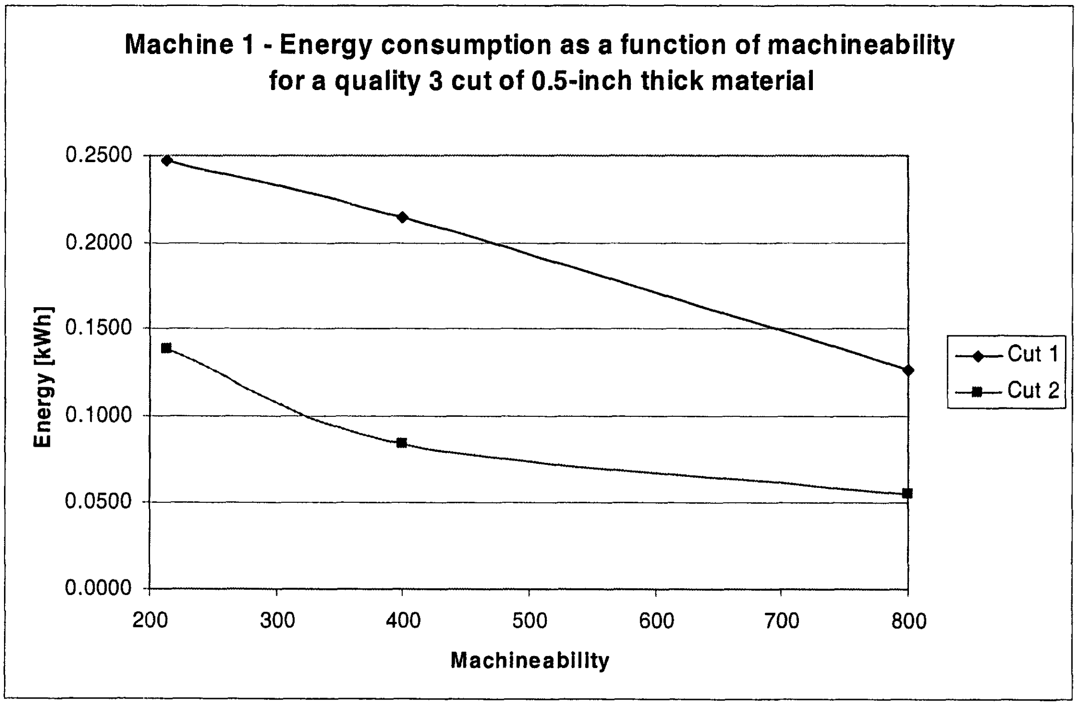

Figure 40: Energy consumption as a function of machineability for the 2652 Omax machine cutting 0.5 inch thick material with a quality of 3. This plot illustrates the energy consumption for both cuts.

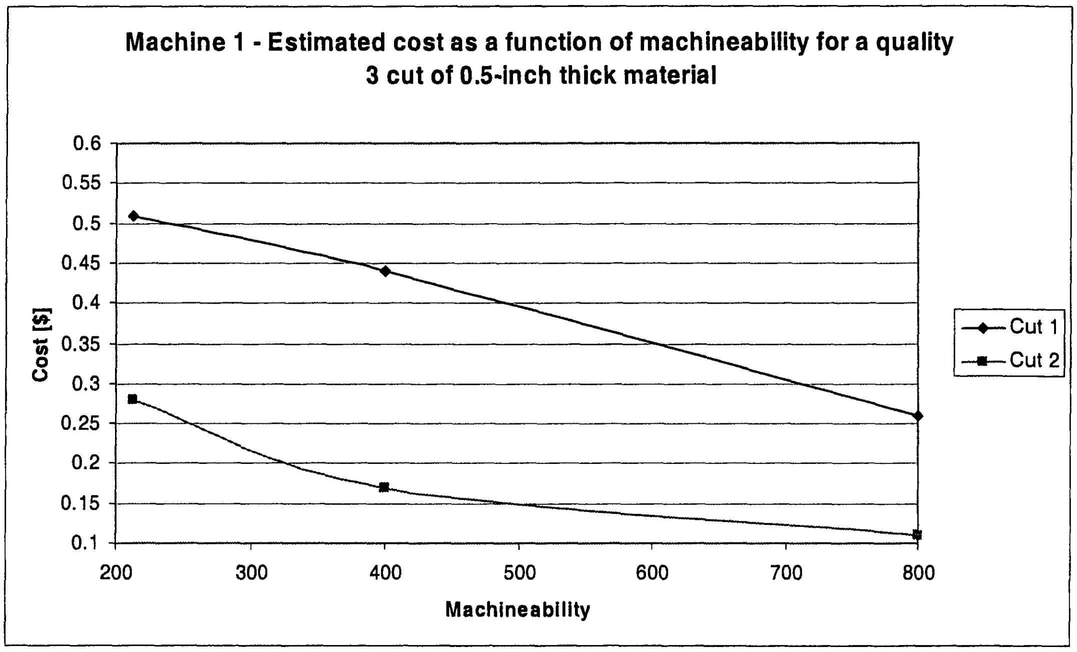

Figure 41: Estimated cost as a function of machineability for the 2652 Omax machine cutting 0.5 inch thick material with a quality of 3. This plot illustrates the estimated cost for both cuts.

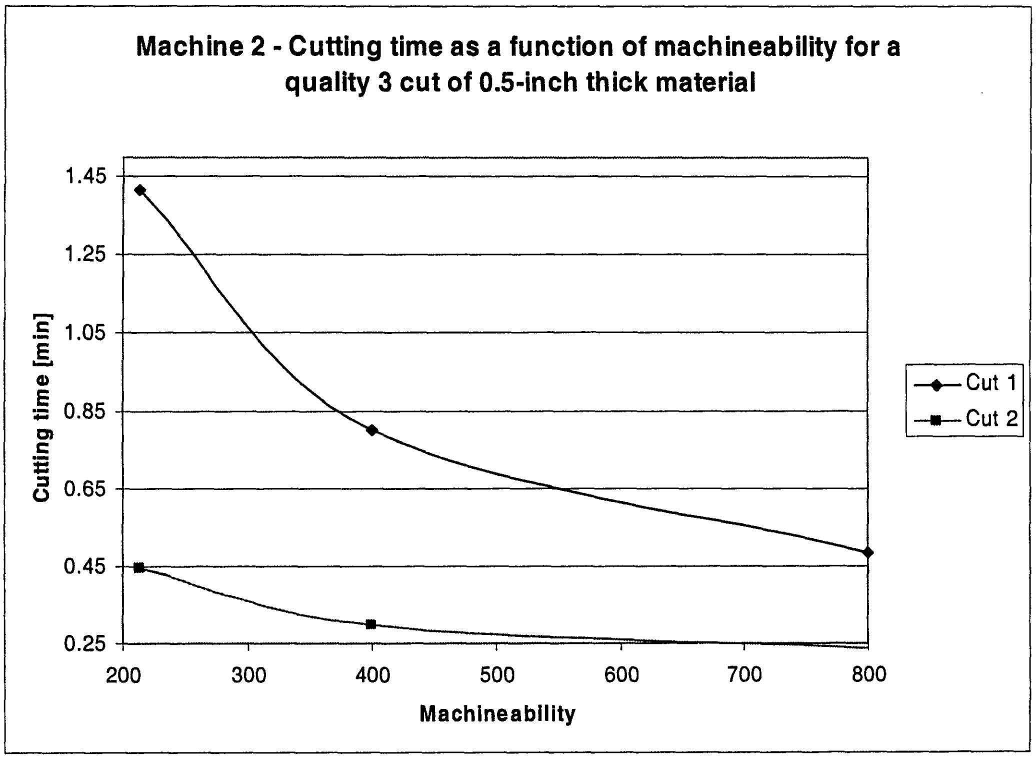

Figure 42: Cutting time as a function of machineability for the 2626 Omax machine cutting 0.5 inch thick material with a quality of 3. This plot illustrates the cutting time for both cuts.

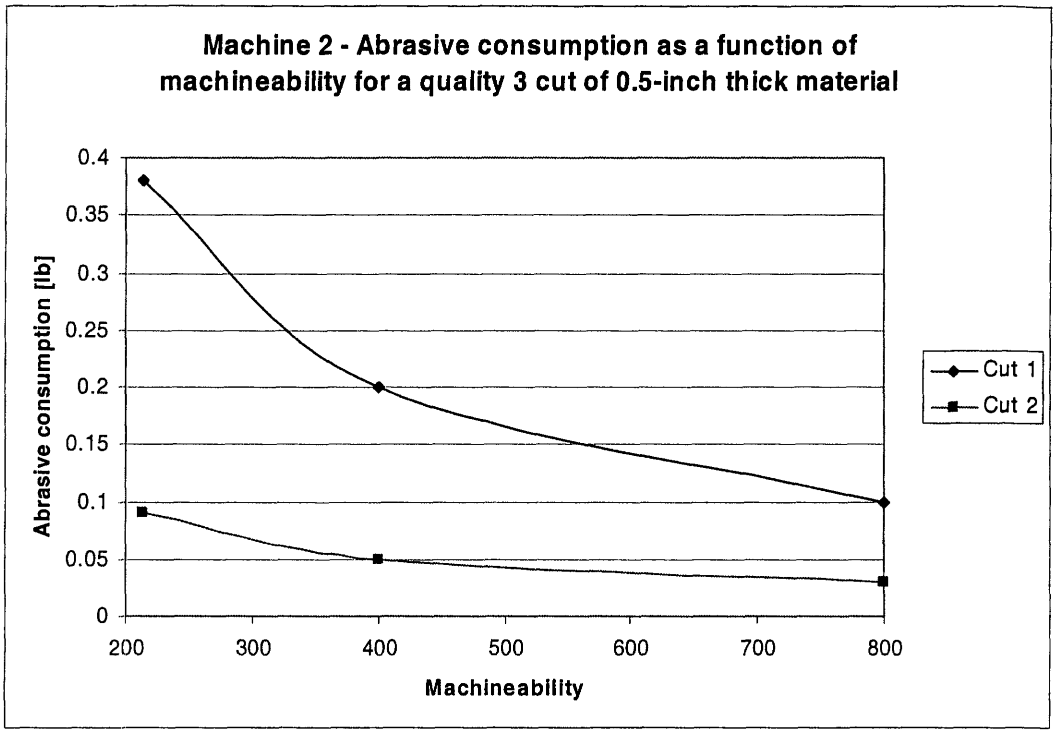

Figure 43: Abrasive consumption as a function of machineability for the 2626 Omax machine cutting 0.5 inch thick material with a quality of 3. This plot illustrates the abrasive consumption for both cuts.

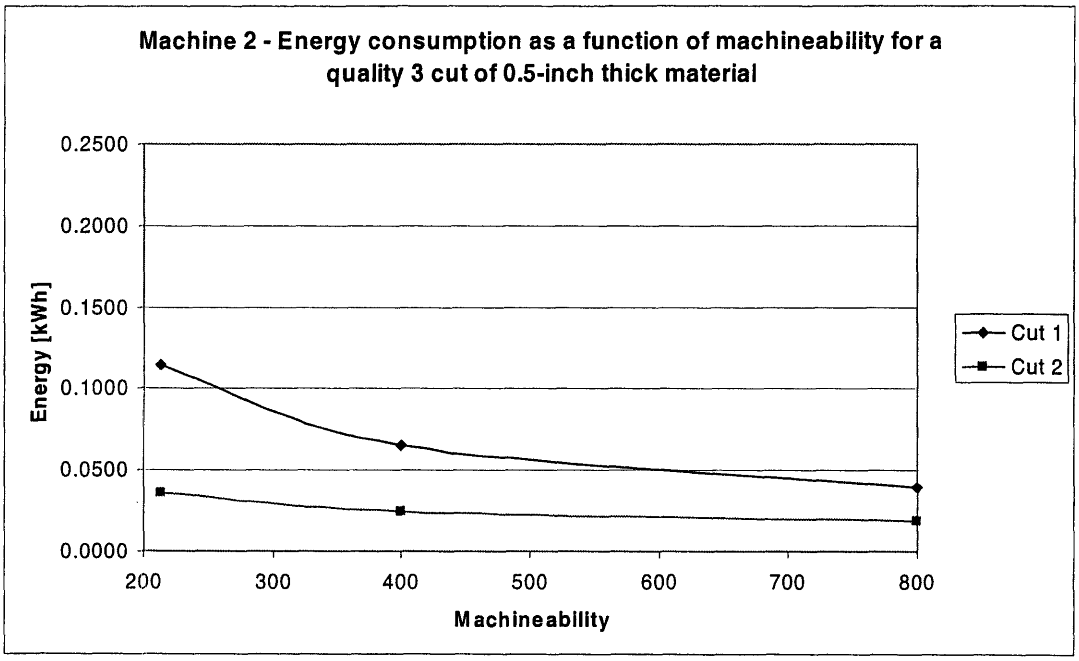

Figure 44: Energy consumption as a function of machineability for the 2626 Omax machine cutting 0.5 inch thick material with a quality of 3. This plot illustrates the energy consumption for both cuts.

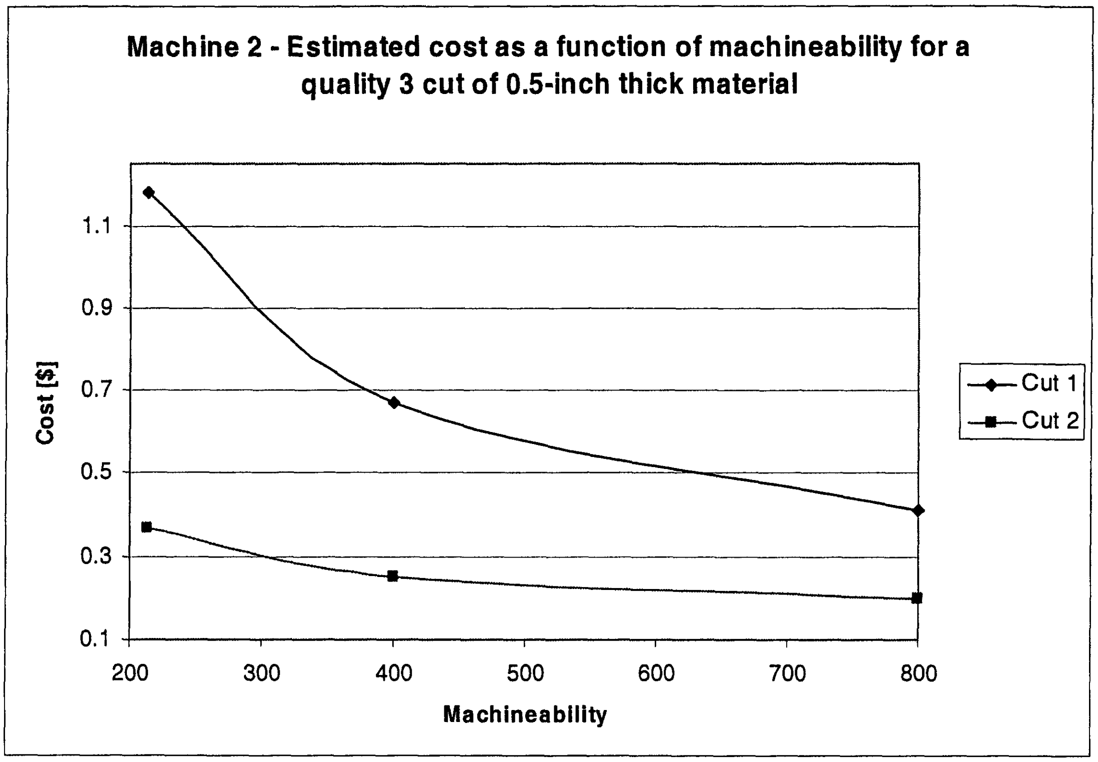

Figure 45: Estimated cost as a function of machineability for the 2626 Omax machine cutting 0.5 inch thick material with a quality of 3. This plot illustrates the estimated cost for both cuts.

Table 13 below is a summary of the inflows and outflows for each machine for both cuts.

Table 13: Abrasive, water, waste material and energy consumption per inch for each machine for both cuts.

Consumption per inch for 0.5 inch think Aluminum 6061, quality 3 cut	Machine 1		Machine 2	
	Cut 1	*Cut 2*	*Cut 1*	*Cut 2*
Abrasive [lb/in]	0.1859	0.0918	0.4841	0.1146
Water [g/in]	0.3677	0.2066	1.2115	0.3833
Waste material [cin/in]	0.0150	0.0150	0.0105	0.0105
kWh [kWh/in]	0.0581	0.0326	0.1461	0.0462

Part III: Waste disposal

In the abrasive waterjetting process, there are two forms of waste that are relatively separate: water and abrasive/material scrap. Assuming non-toxic waste, the water is typically sent down the drain and the abrasive sludge is transported to a landfill. When toxic, the waste must obviously be handled according to regulations.

Industry numbers

Industry numbers representing the abrasive waterjet are very hard to find, and with so many manufactures, determining the number would be quite a challenge. In the November 1989 issue of American Machinist, a survey was published indicating that there were 1,255 waterjets in 48 United States. This is the only figure that could be found, and represents pure waterjets, not abrasive waterjets. Because of the versatile application, one could infer that the number of abrasive waterjets in the United States likely exceeds 1,255, however the only known number is 800 Omax machines in the US. With that many machines, operating an average 5 hours a day, 264 days each year, Omax machines total over a million hours of operation each year in the United States. This is a very rough estimate, and should be taken as such, however will suffice to estimate further figures.

Composition

The water typically flows out of the machine at a rate equal to the water inflow, maintaining a certain water level in the tank. The water exiting the machine is surface water, and therefore does not contain a substantial amount of suspended solids. There are filtration systems in place that are unique to each machine, however it is safe to assume that all of the solid waste is disposed of the same way, whether it came from the water filtration or the bottom of the tank.

The second component of the waste, the abrasive and material scrap composition, is typically removed from the bottom of the tank either manually or with sludge removal systems. Sludge removal systems are optional purchases along with the Omax machine itself, and have been found to work fairly poorly due to clogging issues. The machines discussed above disabled the sludge removal systems due to their problematic nature, and therefore an in depth analysis will not be presented here. What is important is to note that the sludge removed, however it is removed, is a mixture of abrasive, material scrap, and minimal amounts of water. Any water in the sludge is equivalent to the water that went down the drain, and in the case of disposing sludge, will be omitted. Therefore the composition in question is mostly abrasive with a small portion made up of material scrap.

To determine the relative amounts of abrasive and scrap material, the machining processes executed to produce the sludge are needed. The abrasive is used at a rate of 0.75 lb/min for the 2652, and 0.3 lb/min for the 2626, and therefore all that is needed is the total time resulting in the sludge under question to determine the abrasive content.

Determining the material scrap contribution is somewhat more difficult. A time evaluation is insufficient unless you know the weighted average feed rate as well as the weighted average material thickness. (Kerf with is constant, at 0.030 inches for the 2652 and 0.021 inches for the 2626) In this case, the actual cutting executions would be important, and would simplify the calculation significantly. For each cut, knowing the length of the cut and the thickness of the material would lead to a value of the total material scrap in the sludge composition.

If we assume that the material is Aluminum 6061 with a density of 2700 kg/m^3, the average thickness is 0.5 inches, and the typical cut is an even mix of linear and 0.125-inch radius arc, the sludge composition is determinable. In this case, the linear feed rate would be 9.58 ipm, and the radial feed rate would be 5.479 ipm. The cutting time is 0.104 minutes per inch of linear cuts, and 0.183 minutes per inch of radial cuts, resulting in an average cut time of 0.144 minutes per inch cut. With an average cut time of 0.144 minutes per inch, the resulting abrasive content would be 0.108 lb/in, and the resulting material content would be 0.00030 lb/in. Therefore the resulting composition is 99.7% weight abrasive and 0.3% weight Aluminum 6061. Although this is a rough average, it is meant to highlight the fact that no matter the cutting conditions, the abrasive is the dominant component of the sludge.

From a different angle, the sludge production can be calculated on a time basis, instead of length. With the same assumptions as above, the average feed rate would be 7.53 ipm, resulting in a material removal rate of 0.113 cubic inches each minute. 0.113 cubic inches of Aluminum 6061 translates to 0.0023 pounds each minute. With an abrasive consumption of 0.75 lb/min, the total waste production is 0.7523 lb/min, 99.7% abrasive and 0.3% material scrap. Continue the industry assumptions presented above, a machine produces 45.14 lb/hour of waste, which is equivalent to 59,585 pounds each year per machine. Assuming 800 machines operating, the result is 47,667,840 pounds of sludge produced each year in the united states, corresponding to 47,524,836 pounds of abrasive and 143,004 pounds of material scrap. 179 pounds of Aluminum 6061 per machine each year may not seem like much, but a figure like 143,004 pounds deserves significant concern and attention.

Disposal methods

The abrasive sludge pumped out of all MIT machines, as well as most machines in the industry, is treated as non-regulated waste. The metals and plastics cut in the machines are not considered hazardous waste, and therefore can be disposed off without regulation. If the abrasive sludge, or the material work piece cut, was a hazardous material of some sort – such as chromium or cadmium plates – the material would have to be disposed of as hazardous waste. There is no restriction on which facilities can be used for non-regulated materials, and the abrasive sludge simply ends up in a landfill. In the case of hazardous material, depending on the material, certain facilities have the appropriate license. In Boston, Clean Harbors is a licensed hazardous waste hauler and is recommended by the MIT Environmental, Health and Safety Office to handle both the hazardous and non-regulated waste from the abrasive waterjets on campus. (Jeff Bernard, MIT EHS)

Appendix A

Below is the data used to illustrate the linear and 0.125-inch radius arc cutting speeds as a function of machineability for a quality 3 cut of 0.5-inch thick material.

Table A.1: Data used to illustrate the linear and 0.125-inch radius arc cutting speeds as a function of machineability for a quality 3 cut of 0.5-inch thick material.

Machineability	Linear cut speed	Arc cut speed
50	1.75	1
100	3.89	2.22
150	6.2	3.54
200	8.62	4.93
250	11.15	6.37
300	13.75	7.86
350	16.41	9.38
400	19.14	10.94
450	21.91	12.52
500	24.74	14.14

Appendix B

Courtesy of Leslie Bingham of Omax Corporation

Table B.1: Cutting speeds for linear cuts in various materials of various thicknesses, with quality ranging from 1-5 The materials include hardened tool steel, mild steel, stainless 304, stainless 316L, copper, titanium, brass, aluminum, granite, white marble, nylon, glass, acrylic, polypropylene and pine wood of thicknesses 0.125", 0.25", 0.5", 1.0", 1.5" and 2.0".

Quality of Cut: 1

Material	.125 in.	.25 in.	.5 in.	1 in.	1.5 in.	2.0 in
Harden Tool Steel	18	10	5	2	1	1
Mild Steel	22	12	6	3	2	1
Stainless 304	22	12	6	3	1	1
Stainless 316L	23	13	6	3	2	1
Copper	29	16	8	3	2	1
Titanium	31	17	8	4	2	1
Brass	49	27	13	6	3	2
Aluminum	70	39	19	8	5	3
Granite	113	63	31	13	8	5
White Marble	150	83	41	17	10	7
Nylon	154	86	42	18	10	7
Glass	111	62	30	13	7	5
Acrylic	217	121	60	25	14	9
Polypropylene	352	196	96	41	23	15
Pine Wood	1319	735	358	153	88	57

Quality of Cut: 2

Material	.125 in.	.25 in.	.5 in.	1 in.	1.5 in.	2.0 in
Harden Tool Steel	16	9	4	2	1	1
Mild Steel	19	11	5	2	1	1
Stainless 304	19	11	5	2	1	1
Stainless 316L	19	7	5	2	1	1
Copper	25	14	7	3	2	1
Titanium	27	15	7	3	2	1
Brass	42	23	11	5	3	2
Aluminum	60	33	16	7	4	3
Granite	97	54	26	11	6	4
White Marble	129	72	35	15	9	6
Nylon	132	74	36	15	9	6
Glass	95	53	26	11	6	4
Acrylic	186	104	51	22	12	8
Polypropylene	302	168	82	35	20	13
Pine Wood	1131	630	307	131	75	49

All speeds are in Inches per Minute & valid only for straight line cuts
Operating Conditions: 40,000 PSI, .014" Orifice, .030" Mixing Tube, 0.75 LB/MIN Abrasive Flow

Revised 2/04

Quality of Cut: 3

Material	.125 in.	.25 in.	.5 in.	1 in.	1.5 in.	2.0 in
Harden Tool Steel	10	5	3	1	1	.4
Mild Steel	12	7	3	1	1	1
Stainless 304	12	7	3	1	1	1
Stainless 316L	12	7	3	1	1	1
Copper	16	9	4	2	1	1
Titanium	17	9	5	2	1	1
Brass	27	15	7	3	2	1
Aluminum	38	21	10	4	2	2
Granite	61	34	17	7	4	3
White Marble	81	45	22	9	5	4
Nylon	83	46	23	10	5	4
Glass	60	33	16	7	4	3
Acrylic	117	65	32	14	8	5
Polypropylene	190	106	51	22	13	8
Pine Wood	710	395	193	82	47	31

Quality of Cut: 4

Material	.125 in.	.25 in.	.5 in.	1 in.	1.5 in.	2.0 in
Harden Tool Steel	7	4	2	1	.5	.3
Mild Steel	9	5	2	1	1	.4
Stainless 304	9	5	2	1	1	.4
Stainless 316L	9	5	2	1	1	.4
Copper	11	6	3	1	1	.5
Titanium	12	7	3	1	1	.5
Brass	18	11	5	2	1	.9
Aluminum	28	15	7	3	2	2
Granite	44	24	12	5	3	2
White Marble	58	32	16	7	4	3
Nylon	59	33	16	7	4	3
Glass	43	24	12	5	3	2
Acrylic	84	47	23	10	6	4
Polypropylene	136	76	37	16	9	6
Pine Wood	510	284	138	59	34	22

All speeds are in Inches per Minute & valid only for straight line cuts
Operating Conditions: 40,000 PSI, .014" Orifice, .030" Mixing Tube, 0.75 LB/MIN Abrasive Flow

Revised 2/04

Quality of Cut: 5

Material	.125 in.	.25 in.	.5 in.	1 in.	1.5 in.	2 in.
Harden Tool Steel	5	3	1	1	.4	.2
Mild Steel	7	4	2	1	.4	.3
Stainless 304	7	4	2	1	.4	.3
Stainless 316L	7	4	2	1	.4	.3
Copper	9	5	2	1	1	.4
Titanium	9	5	3	1	1	.4
Brass	15	8	4	2	1	1
Aluminum	21	12	6	2	1	1
Granite	34	19	9	4	2	1
White Marble	45	25	12	5	3	2
Nylon	46	26	13	5	3	2
Glass	33	18	9	4	2	1
Acrylic	65	36	18	8	4	3
Polypropylene	105	59	29	12	7	5
Pine Wood	394	220	107	46	26	17

All speeds are in Inches per Minute & valid only for straight line cuts
Operating Conditions: 40,000 PSI, .014" Orifice, .030" Mixing Tube, 0.75 LB/MIN Abrasive Flow

Revised 2/04

Appendix C

Below is the data used to illustrate the cutting speed as a function of geometry.

Table C.1: Data used to illustrate cutting speed as a function of quality for 0.5-inch thick Aluminum 6061.

Aluminum 6061

Thickness: 0.5 inches

Quality	Linear Speed [ipm]	Arc Speed [ipm]					
	Linear Speed	Radius = 0.015	Radius = 0.03	Radius = 0.1	Radius = 0.125	Radius = 0.22	Radius = 0.5
1	19.005	5.688	7.849	14.764	16.693	19.005	19.005
2	16.3	2.275	3.314	6.516	7.397	10.214	16.3
3	10.225	1.776	2.605	5.149	5.848	8.081	10.225
4	7.345	1.31	1.933	3.837	4.36	6.029	7.345
5	5.683	0.871	1.292	2.572	2.924	4.045	5.683

Table C.2: Data used to illustrate cutting speed as a function of thickness for Aluminum 6061 with a quality 3 cut.

Aluminum 6061

Quality: 3

Thickness	Linear Speed [ipm]	Arc Speed [ipm]					
	Linear Speed	Radius = 0.015	Radius = 0.03	Radius = 0.1	Radius = 0.125	Radius = 0.22	Radius = 0.5
0.125	37.631	12.667	18.694	37.109	37.631	37.631	37.631
0.25	20.961	5.585	6.761	13.413	15.24	20.961	20.961
0.375	13.998	2.674	3.932	7.785	8.843	12.223	13.998
0.5	10.225	1.776	2.605	5.149	5.848	8.081	10.225
1	4.369	0.605	0.881	1.732	1.967	2.715	4.345

Appendix D

Table D.1 below presents the material properties, machineability and cutting speed for various materials.

Table D.1: Material properties including density, Poisson's ratio, elastic modulus, tensile strength, yield strength, elongation, reduction in area, hardness [HB500], shear strength, fatigue strength, as well as machineability and linear cut speed (quality 3 cut, 0.5 inches thick) for Aluminum 6061, Stainless steel 304, Copper, Titanium, Hardened tool steel AISI S5, Mild steel, Brass, Lead and Glass.

	Aluminum 6061	Stainless steel 304	Copper	Titanium	Hardened tool steel AISI S5	Mild steel	Brass	Lead	Glass
Density [kg/cubic meter]	2700	8000	8870	4510	7760	8000	8500	11300	2200
Poisson's ratio	0.33	0.285	0.34	0.34	0.285				0.245
Elastic modulus [GPa]	75	193	117	102.7	200				
Tensile strength [MPa]	115	515	172	152	725				
Yield strength [MPa]	48	205	62	97	440				
Elongation [%]	25	40	40	32	25				
Reduction in Area [%]		50		80	50				
Hardness [HB500]	30	88	25	120	187	125	101	4	450
Shear strength [MPa]	83								
Fatigue strength [MPa]	62								
Machineability	213	81.9	110	115	80.4	87.6	184	490	596
Linear cutting speed [Q=3, t=0.5, ipm]	9.27	3.09	4.34	4.56	3.02	3.34	7.84	24.17	30.27

The following figures represent the machineability as a function of yield strength, tensile strength, elastic modulus and Poisson's ratio.

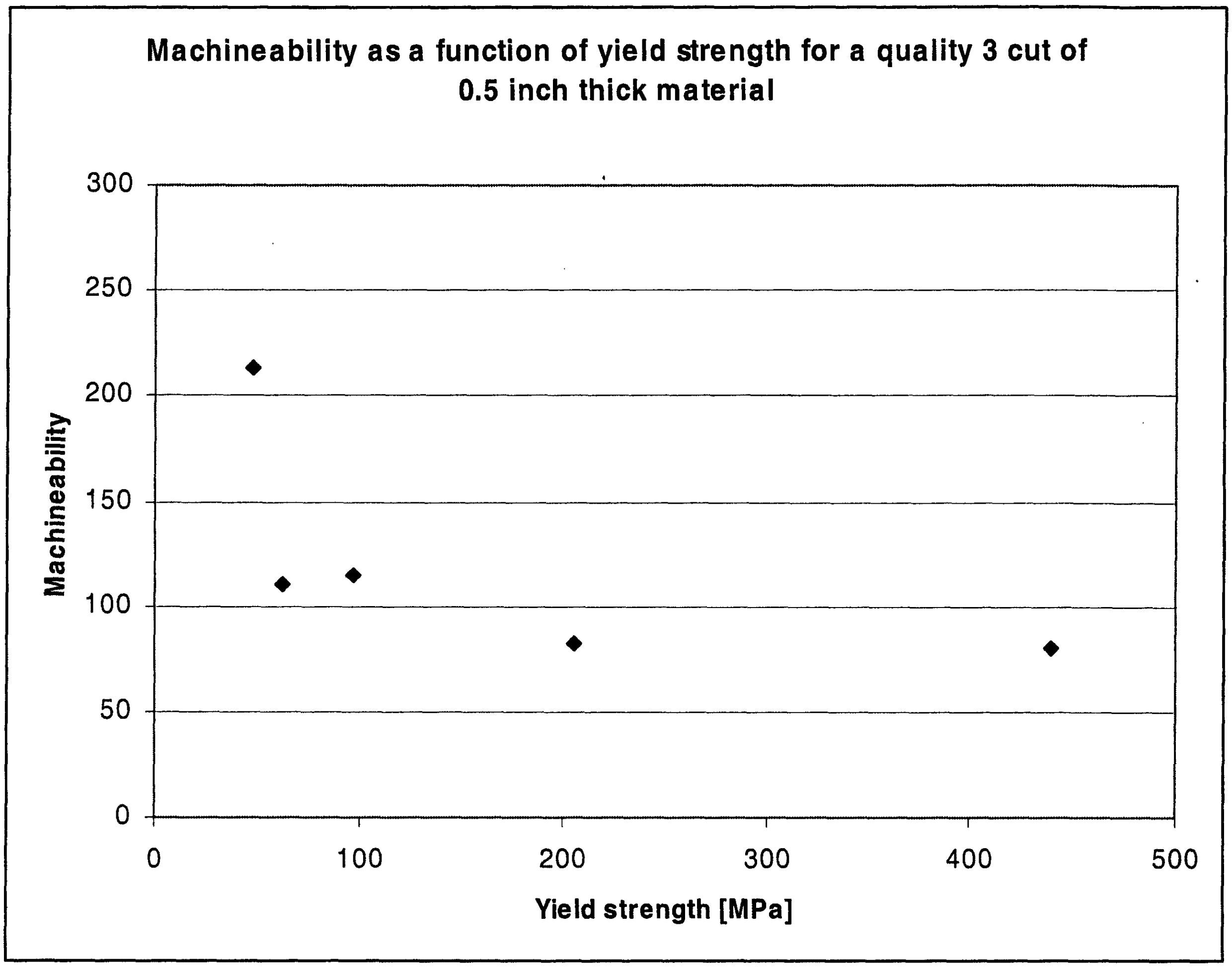

Figure D.1: Machineability as a function of yield strength for a quality 3 cut of 0.5 inch thick material. Materials include Aluminum 6061, Stainless steel 304, Copper, Titanium, Hardened tool steel AISI S5.

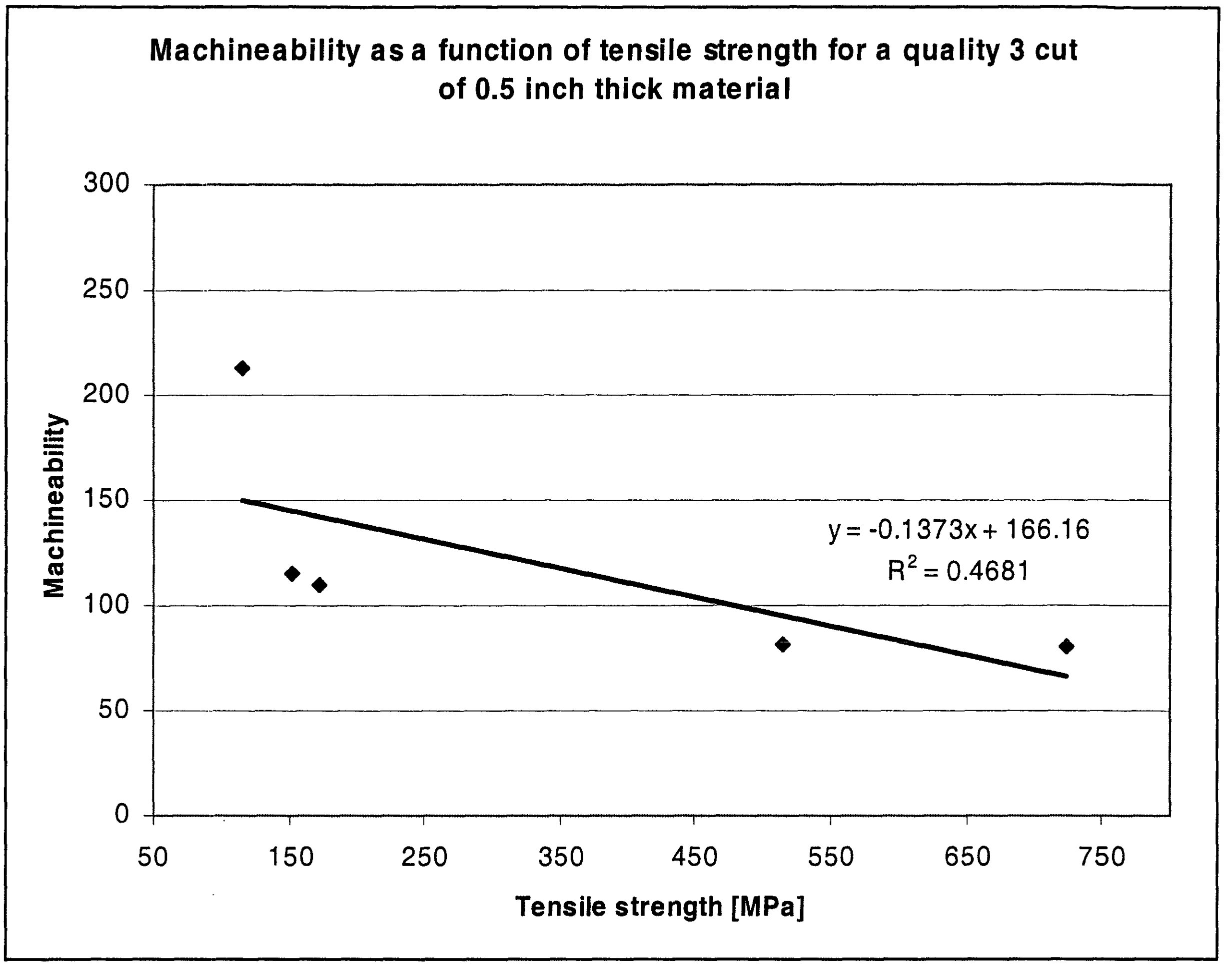

Figure D.2: Machineability as a function of tensile strength for a quality 3 cut of 0.5 inch thick material. Materials include Aluminum 6061, Stainless steel 304, Copper, Titanium, Hardened tool steel AISI S5.

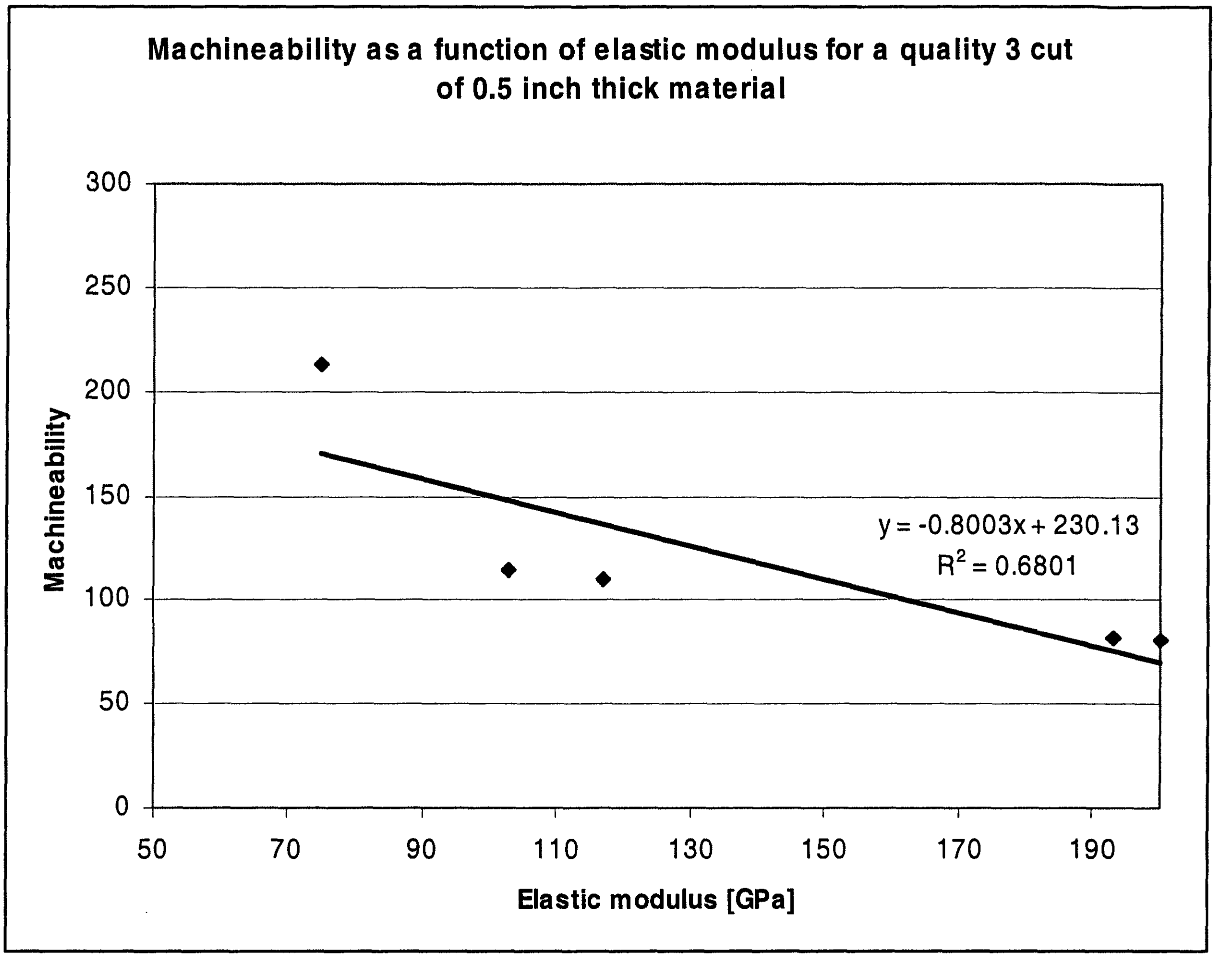

Figure D.3: Machineability as a function of elastic modulus for a quality 3 cut of 0.5 inch thick material. Materials include Aluminum 6061, Stainless steel 304, Copper, Titanium, Hardened tool steel AISI S5.

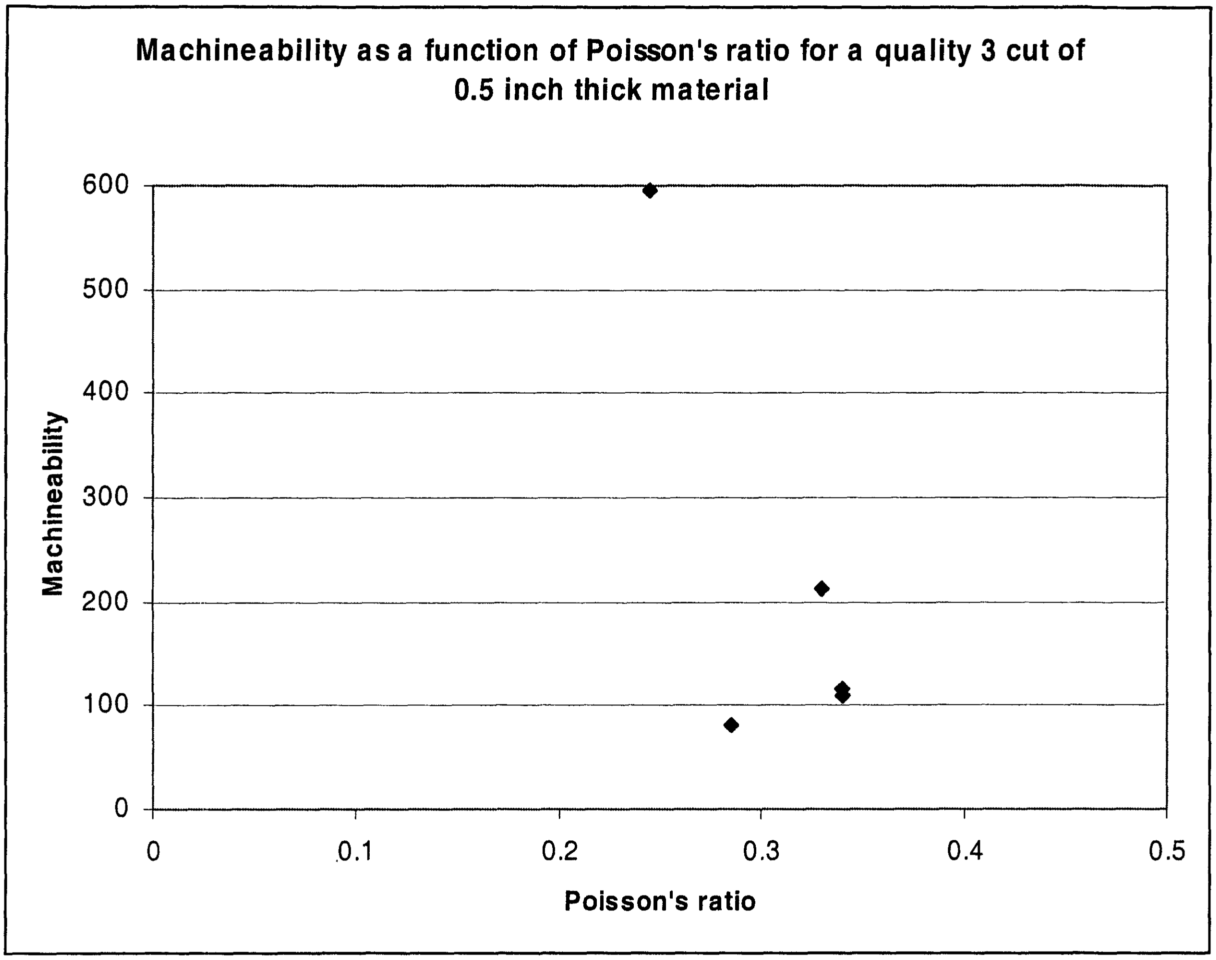

Figure D.4: Machineability as a function of Poisson's ratio for a quality 3 cut of 0.5 inch thick material. Materials include Aluminum 6061, Stainless steel 304, Copper, Titanium, Hardened tool steel AISI S5.

Appendix E

Grain size breakdown for Barton abrasive garnet.

Table E.1: Garnet size breakdown for different Barton abrasive garnets

50 HPX

Tyler Screen (micron)	Percentage Retained
32(500)	1.0
35(425)	16.0
42(355)	37.0
48(300)	29.0
60(250)	15.0
65(212)	2.0
80(180)	
100(150)	
115(125)	
150(106)	
170(90)	
200(75)	
250(63)	
270(53)	
325(45)	

80 HPX

Tyler Screen (micron)	Percentage Retained
32(500)	
35(425)	
42(355)	3.0
48(300)	15.0
60(250)	31.0
65(212)	24.0
80(180)	17.0
100(150)	7.0
115(125)	3.0
150(106)	
170(90)	
200(75)	
250(63)	
270(53)	
325(45)	

80 HPA

Tyler Screen (micron)	Percentage Retained
32(500)	
35(425)	
42(355)	

100 HPA

Tyler Screen (micron)	Percentage Retained
32(500)	
35(425)	
42(355)	

48(300)	7.0	48(300)	
60(250)	38.0	60(250)	
65(212)	30.0	65(212)	5.0
80(180)	20.0	80(180)	50.0
100(150)	5.0	100(150)	35.0
115(125)		115(125)	8.0
150(106)		150(106)	2.0
170(90)		170(90)	
200(75)		200(75)	
250(63)		250(63)	
270(53)		270(53)	
325(45)		325(45)	

120 HPX		**150 HPX**	
Tyler Screen (micron)	Percentage Retained	Tyler Screen (micron)	Percentage Retained
32(500)		32(500)	
35(425)		35(425)	
42(355)		42(355)	
48(300)		48(300)	
60(250)		60(250)	
65(212)	2.0	65(212)	
80(180)	11.0	80(180)	
100(150)	30.0	100(150)	1.0
115(125)	28.0	115(125)	14.0
150(106)	16.0	150(106)	38.0
170(90)	7.0	170(90)	27.0
200(75)	6.0	200(75)	14.0

250(63)	
270(53)	
325(45)	

250(63)	4.0
270(53)	1.0
325(45)	1.0

220 HPX

Tyler Screen (micron)	Percentage Retained
32(500)	
35(425)	
42(355)	
48(300)	
60(250)	
65(212)	
80(180)	
100(150)	
115(125)	5.0
150(106)	18.0
170(90)	24.0
200(75)	25.0
250(63)	18.0
270(53)	7.0
325(45)	3.0

60 HPA

Tyler Screen (micron)	Percentage Retained
32(500)	
35(425)	
42(355)	10.0
48(300)	28.0
60(250)	38.0
65(212)	16.0
80(180)	7.0
100(150)	7.0
115(125)	5.0
150(106)	
170(90)	
200(75)	
250(63)	
270(53)	
325(45)	

85 HPX

Tyler Screen (Micron)	Percentage Retained
32(500)	
35(425)	
42(355)	3
48(300)	9
60(250)	15
65(212)	14
80(180)	15

100(150)	21
115(125)	15
150(106)	6
170(90)	2
200(75)	
250(63)	
270(53)	
325(45)	

Appendix F

OMAX Pump Rebuild Kits

300 Hours

Minor Rebuild Kit, (MTBF 300 hrs) part # 302700, consisting of	$ 430.95

1 Pump Repair Kit
1 Set of Back up rings

600 Hours

Major Rebuild Kit (MTBF 600 hrs) , # 302701, consisting of	$ 770.10

1 Pump Repair Kit
1 Set of Back-Rings
Check valve repair kit
Retainer

900 Hours

Minor Rebuild Kit, (MTBF 300 hrs) part # 302700, consisting of	$ 430.95

1 Pump Repair Kit
1 Set of Back up rings

1200 Hours

Pump overhaul kit, (MTBF 1,200 hrs.) consisting of	$ 4,204.52

1 Pump Repair Kit
1 Back-up ring set
1 Set of Plungers, Extended
1 Set of check valve body
1 Set of check valve retainer

Total - 1200 Hours of operation	$ 5,836.52
Hourly maintenance cost	**$ 4.86**

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