Efficiency Drives Cutting Performance

Axel Henning, Peter Miles
OMAX Corporation, 21409 72nd Ave South, Kent, WA 98032, USA
Telephone: 253-872-2300, Fax: 253-872-6190
Email: axel.henning@omax.com

Abstract

Over the past 40 years, abrasive waterjet technology has been developed from a research tool into a high precision machining tool. Due to its inherent advantages of virtually force and thermal free cutting operation it has found many applications in various sectors of the industry. Machine shop operation is probably among the most prominent applications, because it can operate on many different materials with incredible flexibility. In this context the abrasive waterjet stands in competition with other machining tools. And most importantly each user of abrasive waterjet machines also stands in competition with other companies that offer also abrasive waterjet cutting. In order to provide a competitive offering, every operator has to decide how to best utilize his resources and generate the optimal revenue. In this paper the effect of three of the most prominent factors, pressure, efficiency and software, on cutting performance and revenue of operation are evaluated.

1. INTRODUCTION

The cutting of virtually any known material with abrasive waterjets has led to becoming a widely accepted manufacturing technology since its introduction in the 1980s. Today, applications of abrasive waterjet cutting can be found in many different industries and range from producing very small high precision parts to making rough separation cuts of 6+" steel plates, from singulating tiny electronic components to medical surgery research. Advancements in understanding the physics of the abrasive waterjet cutting process continues to still further advance the state of the art in predictive modeling and motion control software of the abrasive waterjet cutting process [1, 2].

Currently, the most common parameter that is used to evaluate abrasive waterjet cutting performance is the operating pressure of the pump because it is the easiest parameter to adjust by simply varying either the pump speed or adjusting pressure regulators. This is a fallacy, as jet pressure is only a partial and indirect measure of the overall hydraulic power being delivered to the workpiece for removing material. Hydraulic power incorporates the product of two variables, not just one: pressure and flow rate. For a constant input power rating, any increase in pressure requires a proportional decrease in flow rates. The resultant actual change in delivered hydraulic power, may be minimal at best. Higher pressures may be desirable because it drives the velocity of the abrasive particles higher which increases the kinetic energy of each particle. But the resultant decrease in flow rates, at a constant input power, decrease the ability to carry and accelerate more abrasive particles which increases the abrasive kinetic power [3, 4].

Single parameter comparisons may therefore be misleading, if one has ignored that the input power has remained constant. For example, in some studies of pressure effects, the orifice diameter is held constant, and the jet pressure is increased to study its effects. But this also results in an increase in flow rates, and in order to maintain the flow rate at the desired pressure, the pump is required consume more power. Input power selection cannot be so obscured, when the required power input, for the change in pressure at constant flow rate, has demanded in increase from, for example 37 kW to 75kW. Hence two parameters are actually being increased and when one parameter isn't being observed, the results are often attributed to the parameter that was observed.

The purpose of this paper is to study the cutting performance and effects on revenue pressure of cutting operation while maintaining a constant power consumption from a standard 37kW (50 HP) pump.

2. PUMPING TECHNOLOGIES

Currently there are three main pumping technologies available to the waterjet industry. Hydraulic intensifiers and direct drive crank shaft style pumps have been the main workhorses for the ultra-high pressure waterjet cutting and cleaning industries since the 1970s. Direct drive crank shaft style pumps generating pressures upwards to 420 MPa (60 kpsi), and hydraulic intensifiers upwards to 620 MPa (90 kpsi). Since 2008 electric servo pumps entered the market that are capable of generating pressures upwards to 450 MPa (66 kpsi). Though they are all capable of generating high pressures at a wide range of flow rates, they are all not the same in delivering required power to the cutting nozzle.

The overall pump power ratings are driven by international electrical codes (CE) that are based on the pump's maximum electrical power draw from the electrical grid supply, and all pump manufacturers comply with these international codes. Industrial electric motors are designed to be at their peak efficiency near their peak output power rating. Modern high powered DC motors have efficiencies upwards around 90%.

Pumping Technology	Efficiency
Direct Drive [5]	83-87%
Electric Servo [6]	71-77%
Hydraulic Intensifier [7]	60-70%

Table 1: Pump technology efficiency

Table 1 shows various ranges of overall efficiencies of different pumping technologies. Mechanical efficiencies for crank shaft pumps are in the 83 to 87% range as they recover the stored energy due to compression of the water on the down stroke of the plunger [5]. Mechanically electric servo pumps are also fairly efficient since they are using precision ball screws, linear anti-rotation bearings, and roller/thrust bearings, which results in an overall mechanical efficiency of around 75% [6]. Hydraulic intensifiers have two sources of efficiency losses, hydraulic pump and the double acting intensifier. Herbig [7] showed that, theoretically, axial hydraulic pumps combined with double acting intensifiers can have efficiencies up to 72%. Since the hydraulic pump is constantly dumping excess flow of oil to the reservoir, the overall efficiency can range from 60 to 70% for operating in the 350 MPa to 400 MPa range. But that is not practical. Peak efficiency occurs at maximum flow and maximum pressure for hydraulic systems.

3. EXPERIMENTAL CUTTING RESULTS

In order to analyze the effect of pressure two series of separation test cuts were performed wherein for each the hydraulic power at the nozzle was necessarily kept constant by adjusting the water flowrate by using different orifice diameters, so as to maintain a single constant power input requirement. The two chosen hydraulic power levels represent each the typical output for a 37kW pump. One for a direct drive pump with 85% efficiency and the other for an intensifier pump with 65% efficiency.

It can be seen in Figure 1 that greater hydraulic power at the nozzle produces higher separation speeds. In this case, each pump maintained at a constant 37kW power input, the higher efficient pump, 31kW delivered more hydraulic power to the nozzle than the lower efficient pump, 24kW. These figures also show that there appears to be an optimal operating pressure at around 300 MPa where the separation speed is maximized and that separation speed begins to decrease as the operating pressure continued to increase. This optimal cutting pressure appeared at the same pressure for both the 31kW and 24kW tests.

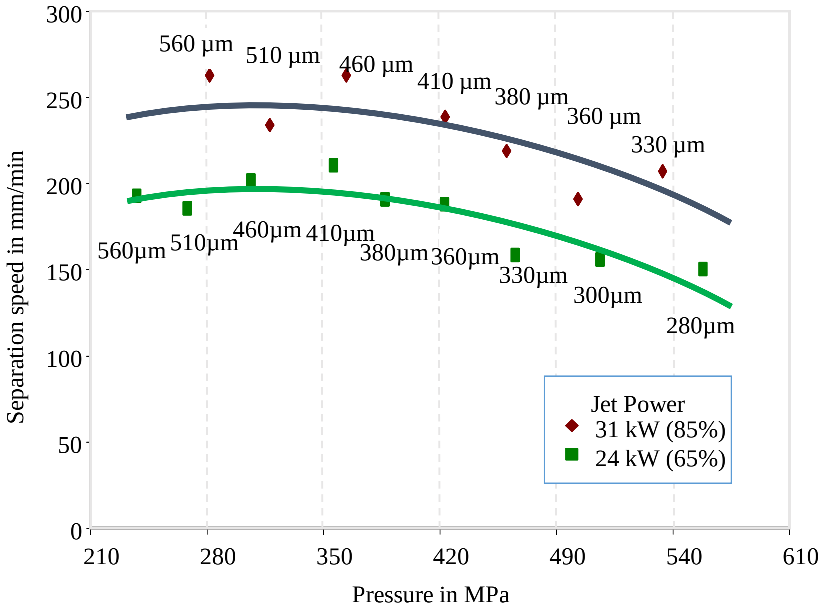

Figure 1: Separation speed for 25.4mm mild steel (A36) with fixed abrasive load (14%) with 37kW pump systems [8]

The critical observation to note with these cutting results is that the proportional change in the cutting separation speed test for the 31kW and 24kW follows the proportional changes in the cutting efficiency, which agrees well with the abrasive kinetic power being a function of the pumping efficiency for fixed abrasive mass loadings [8].

An explanation for the slightly decreasing cutting performance as the operating pressure continued to increase may be due to a greater amount of particle fragmentation within the mixing tube. The kinetic energy of individual particles decreases with fragmentation, and thus less energy to remove material when it impacts the workpiece.

The results of separation test have great implications on how to design the optimal system for industrial use. While it is certainly possible to increase hydraulic power at the nozzle by the power rating of the pump, e.g. by increasing pressure with the same orifice, it appears to be the smarter choice to better utilize the existing input power through the optimum mechanical pump selection focusing on the highest efficiency in operation. Then the performance can still be increased by applying more power.

4. EFFECT OF EFFICIENCY AND PRESSURE ON CUTTING PERFORMACE

In industrial applications the separation speed is not used for cutting; it rather gives a good indication of the performance of a system. In the following section the effect of pressure and efficiency is analyzed by creating an order to carry out a certain length of cut at a good cutting quality. The closest industrial representation of that task would be cutting of large format sheets. There the effect of software optimization is limited, since the time spent on cutting corners and for piercing is relatively small. This analysis delivers therefore a good comparison of the performance of specific operation scenarios that each represent a certain hardware configuration.

But they also have material implications on real life applications and the decisions that all industrial users of abrasive waterjet cutting technologies have to make on a daily basis when choosing the optimal parameters of a specific job and in deciding on the optimal equipment when faced with a purchasing decision.

All scenarios are using a pump with 37kW power consumption. Scenarios A and B are operating at 24kW hydraulic pressure, which would ascertain a 65% efficiency rating that is typical for intensifier pumps. Scenarios C and D are using 31kW, which would be an 85% efficiency as seen by direct drive pumps. Scenarios A and C are using 420MPa pressure, whereas scenarios B and D are using 540MPa pressure. The detailed parameter list can be found in Table 2 Just like in section 3, the orifice diameter was adjusted to obtain the correct pressure at the demanded hydraulic power. The abrasive feedrate was adjusted relative to 12% of the mass of the water flowrate. This resulted in very typical abrasive flowrates that can be found in common abrasive waterjet cutting machines. The separation speed of each was derived from the experimental data in section 3.

Scenario	**A**	**B**	**C**	**D**
Pump power consumption	37 kW	37 kW	37 kW	37 kW
Pump Style	Intensifier	Intensifier	Direct Drive	Direct Drive
Efficiency	65%	65%	85%	85%
Pressure	420MPa	560 MPa	420MPa	560MPa
Orifice Diameter	356 µm	279 µm	406 µm	330µm
Abrasive Feedrate [g/s]	8.19	5.99	10.77	8.11
Separation Speed [mm/min]	190.5	154.2	239.8	209.0

Table 2: Parameters for different scenarios for straight line cutting

To compare a real life scenario in the following section the cutting cost and performance are evaluated against business benchmarks. For this a theoretical order was designed that involved only straight line cutting. Table 3 shows the parameters of the order.

Material	Mild Steel A36
Thickness	25.4mm
Length	100m
Quality	Q3 / 40%

Table 3: Parameters of order

In Figure 2 the consumption of resources and the cutting time required to fulfill the order are displayed. Significant differences in cutting time can be observed. With both pump types, note that the time needed to cut this order increases with higher pressure due to the decreased separation speed. Also, it can be observed that the cutting time for the 65% efficient pumps is significantly higher that the cutting time for the 85% efficient pumps. This effect is attributable to the differences in available hydraulic pressure. Whereas the 65% efficient pump delivers 24kW hydraulic power to the nozzle the 85% efficient pump can deliver 31kW. The difference of almost 30% in hydraulic power has a resultant dramatic effect on cutting speed and therefore on cutting time. The consumed electric power shows a similar picture, since all pumps are consuming 37kW during cutting time. To maintain the same hydraulic power at different pressures, the water flowrate was adjusted by using different orifices[1], as must actually occur to maintain the input power at a constant 37kW. The resultant the 540MP pressure scenarios B and D use less water than the scenarios A and C at 420MPa. Similarly the abrasive feedrate had been adjusted by up to 75% to maintain a 12% abrasive load ratio. This proved to be a necessity as under scenarios B and D, the resultant lowered water flow rates became otherwise oversaturated with garnet, still further deteriorating cutting effectiveness. The total abrasive consumption for the order only varied by up to 16% due to the differences in cutting time, though, with the higher pressure scenarios showing a slightly lower abrasive consumption.

Overall, it can be said that the cutting speed had the greatest effect on consumption of resources. Scenarios with higher pressure and lower efficiency tend to consume more power. Scenarios with higher pressure tend to use slightly less water and the large differences in abrasive feedrate were almost leveled out through longer cutting times for higher pressure scenarios.

[1] For simplicity this analysis only accounts for the water that is used for cutting. Additional potentially necessary water e.g. for cooling of the pump is not accounted for.

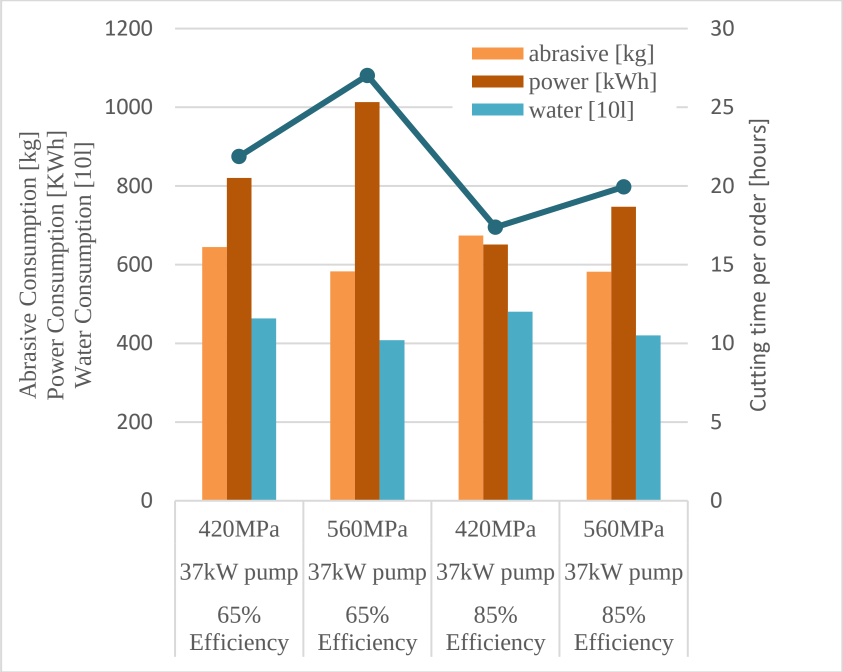

Figure 2: Consumption of resources and cutting time

As the next step the cost of resources and operation are compared for all four scenarios. In Table 4 the assumptions for cost are stated. Operational 'machine' costs consist of labor, depreciation, maintenance, and overhead cost. While those numbers do vary largely between different areas of the country/world and there are many different business models to calculate the operating cost, a simple linear approach is used in this analysis. Also, operating cost can vary largely depending on machine size and style, as well as increased maintenance costs can be assumed when operating at higher pressures. For simplicity for all four scenarios the same cost is assumed.

Electric consumption	[USD per kWh]	0.1
Abrasive	[USD per kg]	0.55
Water	[USD per m^3]	3
Machine[2]	[USD per hour]	100

Table 4: Assumptions of cost for resources

Even with those simplified assumptions, in Figure 3 significant differences in cost to fulfill this order can be seen. Scenarios A and D are almost even at $2328 and $2558, whereas

[2] For simplicity of the calculation the same machine cost is used for all scenarios, whereas higher pressure operation is typically associated with significantly higher cost of equipment, higher cost of components, and shorter lifetime of all high pressure carrying components as well as mixing tubes.

scenario B shows the highest cost at $3038 and scenario C shows the lowest total cost at $2124. In all four scenarios the machine cost makes up the largest part of the cost to fulfill the order. To better understand the significant of those numbers, in Figure 4 a scenario is established where all four scenarios are competing against each other to win this order. By comparing the cost of the four competitors, we can establish a 'fair market price' of $2500 for the order of 100m cutting. In Figure 4 the number of meters are displayed that each of the competitors can cut within a month (160 hours of cutting). The outcome varies significantly between under 600 meters and over 900 meters. To make matters worse, scenario B, which only cuts 592m is also operating at a significant operating loss of 22% of operating cost, while scenario C makes 15% profit. Scenario A almost breaks even and scenario D makes a profit of 7%.

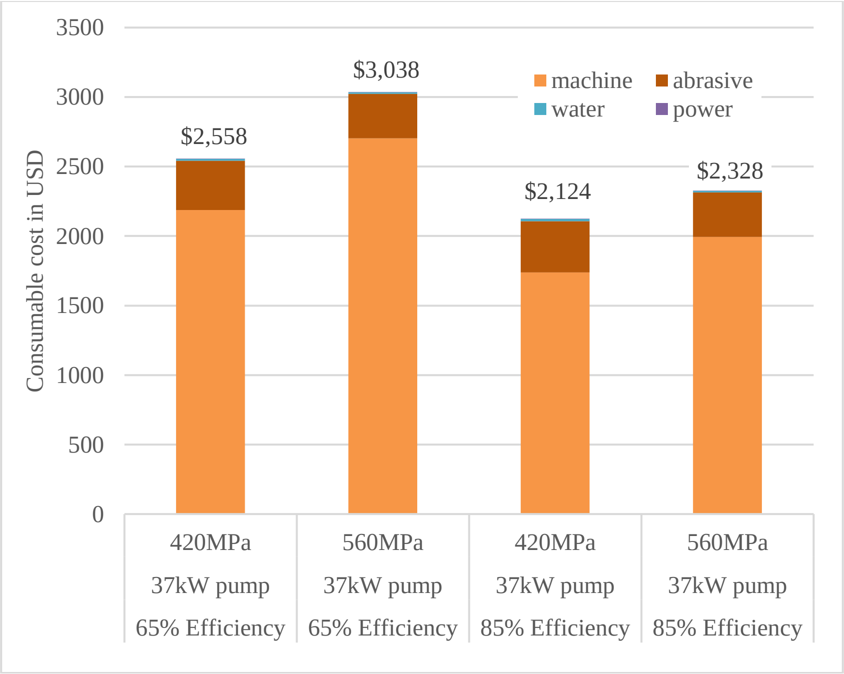

Figure 3: Cost of consumed resources

In a real world scenario a customer would probably not ask for the maximum length that could be cut in a month, but rather have a need for a service to cut a certain length (1000m), which needs to be delivered at a certain time (1 month). Figure 5 shows clearly the dilemma for scenario B. While scenario C can perform this task in about 160 hours and make a profit of $3760, scenario B not only needs to run two shift operation to cover the necessary 275 hours of cutting, but furthermore will lose $5377 while performing the task. Depending on the costing model there might be some savings in two shift operation, because overhead and similar positions will be reduced, but it is still a dire proposition for scenario B.

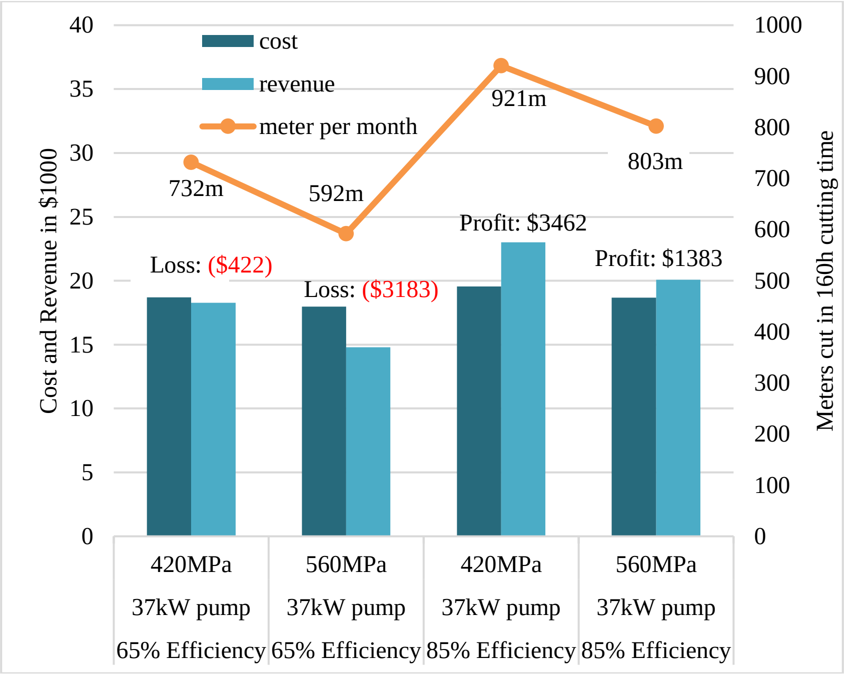

Figure 4: cost, profitability, and length of cut in 160 hours cutting time

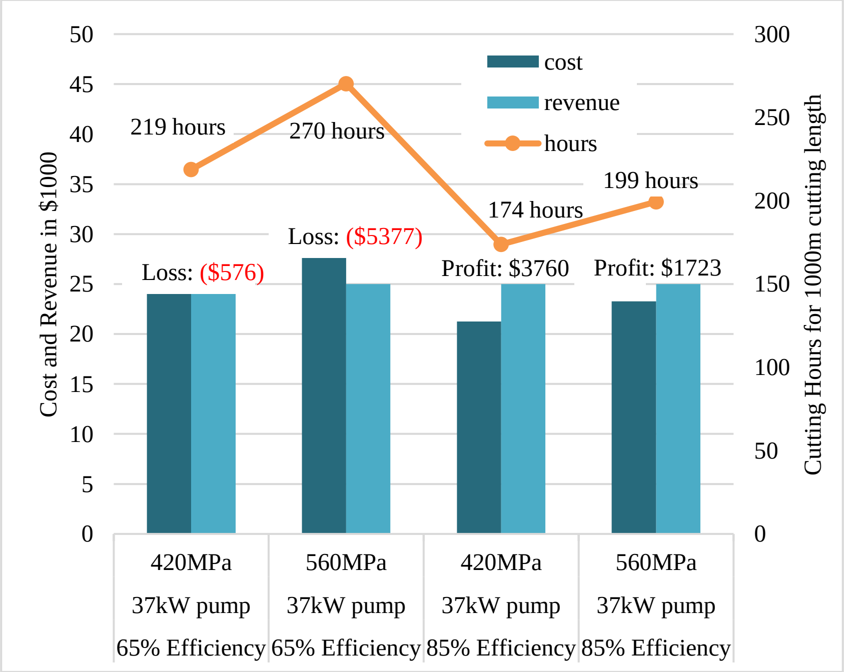

Figure 5: Cost, profit, and cutting hours needed for cutting 1000m

5. EFFECT OF SOFTWARE ON CUTTING PERFORMANCE

Creating scenarios for straight line cutting speed is a useful tool to compare different pump parameter configurations and their effect on the business performance because it separates any effects of software, serving to remove this variable from the picture. In real life applications an commercial order would rarely solely be a straight line, but mostly consist of pierces, straight lines, corners, and arcs. This is where software comes into play in choosing the correct speed to obtain the demanded precision.

5.1. Same cutting part

To separately extract the effect of software on cutting performance, the same part was cut with the same abrasive waterjet parameters was cut with three different versions of path interpolation. In this analysis a typical configuration for a 37kW direct drive pump was used. The configuration parameters can be seen in Table 5. Only the type of path interpolation software was varied between three different versions. The first one in scenario A is the IntelliMAX® Generation 2 software as it had been introduced in 1998. Scenario B features IntelliMAX® Generation 3 with tilting capabilities as it had been introduced in 2008. And scenario C shows the effect of the most currently, in 2014 introduced IntelliMAX® Generation 4 that facilitates tilt forward options. All three versions of path interpolation software are available in the OMAX IntelliMAX® suite.

Scenario	**A**	**B**	**C**
Pump power [kW]	37	37	37
Efficiency [%]	85	85	85
Pressure [MPa]	420	420	420
Orifice Diameter [µm]	406	406	406
Abrasive Feedrate [g/s]	10.77	10.77	10.77
Software	IntelliMAX® Gen2	IntelliMAX® Gen3	IntelliMAX® Gen4
Software [year]	1998	2008	2014
Part	22 teeth gear, Modulus 2	22 teeth gear, Modulus 2	22 teeth gear, Modulus 2
Material	Stainless Steel 316	Stainless Steel 316	Stainless Steel 316
Thickness [mm]	25.4	25.4	25.4
Part time [min]	84.252	55.85	27.78

Table 5: Parameters for different scenarios

The part that was chosen for this analysis, a 22 tooth gear in 25.4mm thick stainless steel (Figure 6) represents a typical example of abrasive waterjet cutting. To obtain the required quality for a gear application a cutting quality of Q3 (40%) was maintained. The resulting tolerances as they were measured on a portable CMM (MasterCAM gage) were on the order of +/- 50µm as shown in Figure 7.

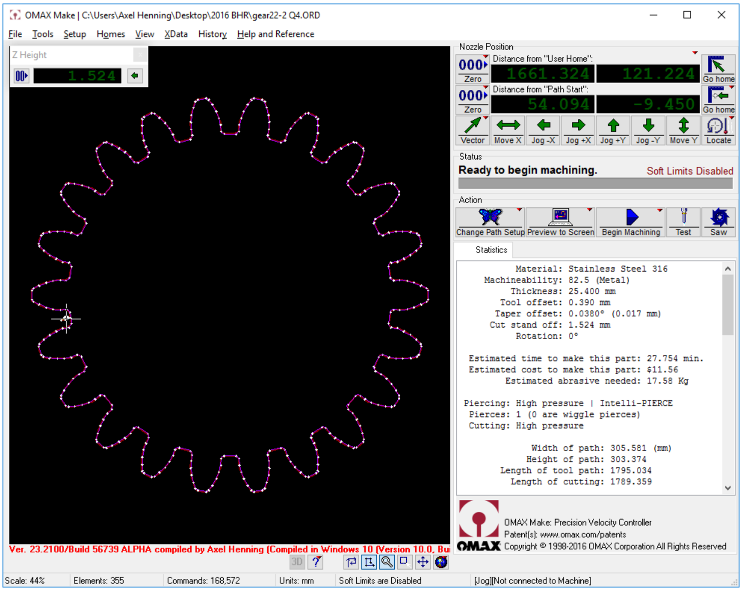

Figure 6: Screenshot cutting path in OMAX IntelliMAX® software

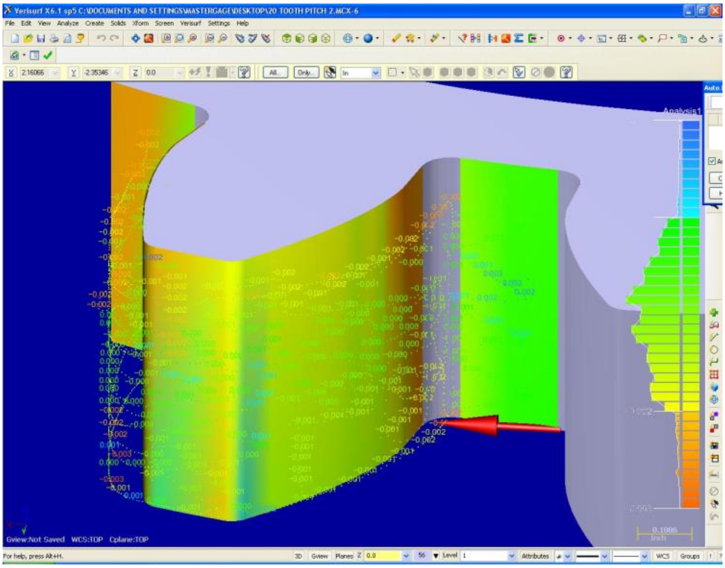

Figure 7: 3D Measurement of tooth

In accordance with the procedure to compare straight line cutting orders, an exemplary order of 10 gears was generated. Already in the first analysis of cutting time and consumption, significant differences can be observed. The order of 10 gears that was cut with software that had been introduced in 1998 took 14 hours to complete. The underlying cutting model and toolpath generation based on experimentally derived equations and patented cutting strategies. The equations had been developed to derive cutting speed from a set of parameters. This approach was very novel in the 1990's and is still used in various commercial software suites for abrasive waterjet cutting today. As abrasive waterjet cutting converted from a rough cutting tool to industrial machining it became evident that the capabilities of the cutting model had to be extended to a much wider range of cutting conditions. The result of scenario B represents the evolution of cutting strategies and cutting model, which now allowed for a wider range of conditions and also fully supported tilting operation to reduce taper without sacrificing cutting speed. With the IntelliMAX® Generation 3 software that was introduced in 2008, the cutting time for 10 gears was reduced significantly from 14 hours down to 9.3 hours. As scenario C shows the cutting model and cutting strategies could be further improved with release of OMAX IntelliMAX® Generation 4 in 2014, that now comprises full 3D compensation of the cutting operation to obtain the optimal geometry (see Figure 7) while maintaining the highest possible cutting speed. The reduction of cutting time for 10 pieces from 14 hours to 4.6 hours while maintaining and actually improving the geometrical tolerances bears additional weight, since this was accomplished without changing the operational parameters pressure, water flowrate, or abrasive feedrate. As seen in Figure 8 the consumption of resources changes naturally proportional with cutting time. The consumption of abrasive for this order can be reduced from over 537kg to 177kg; the power consumption was reduced from 527kWh to 174kWh; and the water consumption from 3880 liter to 1240 liter.

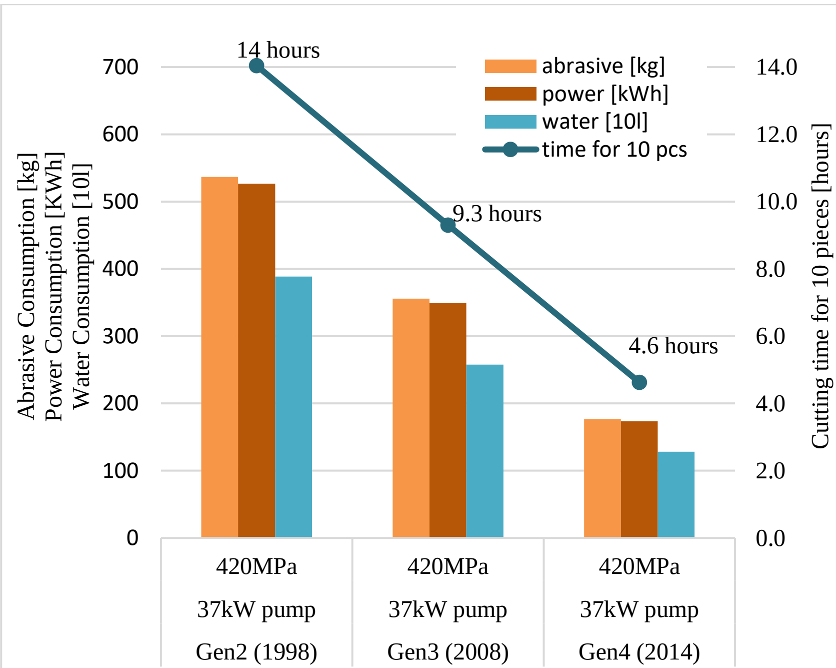

Figure 8: Consumption of resources and cutting time

All this has not only significant environmental implications; it rather has a major effect on cost of operation. Scenario A would have a cost of $1,712, scenario B a cost of $1,135, and scenario C a cost of $565 per order of 10 gears. If the three companies were competing a 'fair market price' at which a customer would be able to purchase the cutting service of 10 gears would probably be around $1200. In Figure 9 the potential cutting performance is demonstrated by how many gears could be cut in 160 hours. The operator in scenario A that uses the software from 1998 can cut only 114 pieces in 160h while scenario B can cut 172 pieces and scenario C with the latest IntelliMAX® software can cut 345 pieces. Having naturally the same operational expenses in those 160 hours of cutting operation the revenue rises linearly with the number of gears that can be produced. As depicted in Figure 9 this has multiplicative effects on the profit of each scenario. Scenario A would operate at a significant loss that would make it impossible to operate at this price. Scenario B would almost break even and scenario C would not only be able to sell his services, but also realize a profit level at about double his operating expenses, he can also satisfy more customer orders and significantly reduce his lead time.

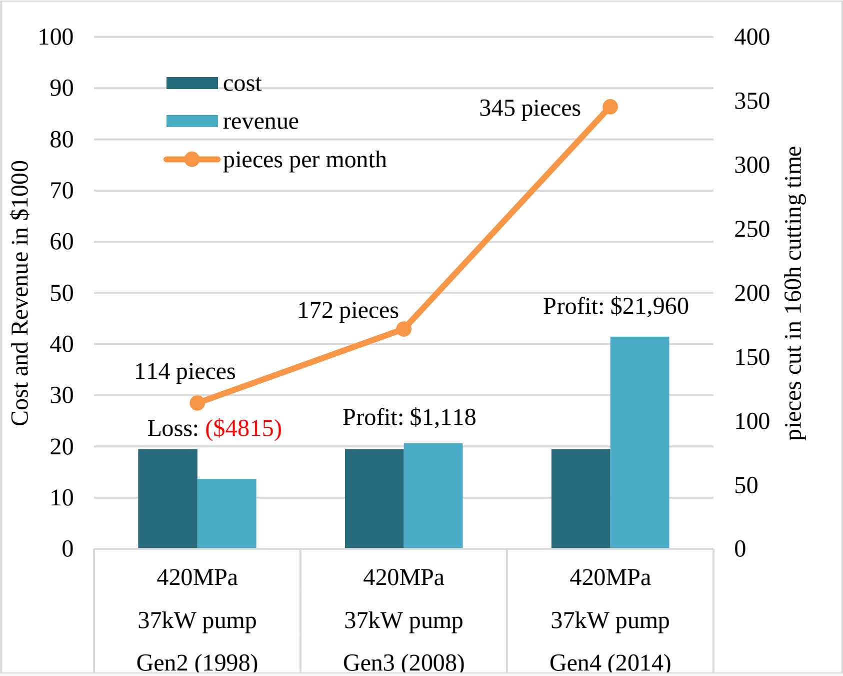

Figure 9: Cost, revenue and gears cut in 160 hours cutting time

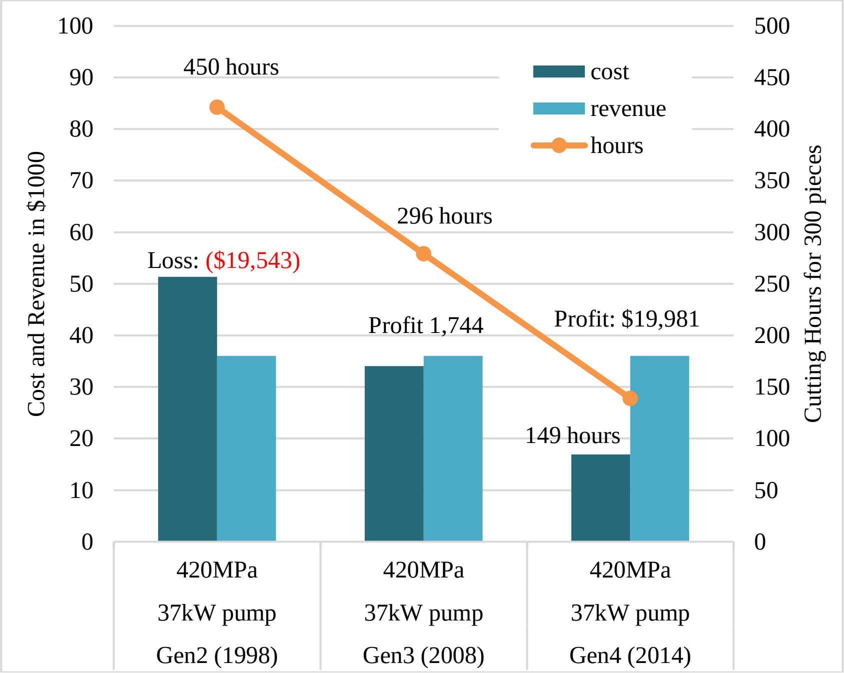

Figure 10: Cost, revenue and hours cutting time for300 gears

Figure 10 gives another example of that. Here the effect of an order of 300 pieces of the same gear is compared in all three scenarios. Since it is a competitive situation, the customer is willing to pay, again, $1200 per gear and expects delivery in 1 month. Scenario C can easily deliver this order within one month at 149 cutting hours- even in single shift operation. Scenario B would need 296 hours which can be accomplished by either two month or operation of two shifts per day, which is still reasonable. Scenario A would need 450 cutting hours, which is more than two shift operation. In addition to the complication of installing and managing additional shifts, Scenario A would operate at a significant loss, which is probably not sustainable. In the long run it would be very difficult for the company with Scenario A to compete against Scenario B or C, which are utilizing the more advanced software. Even Scenario B will most likely have trouble staying afloat, since Scenario C can easily undercut A and B in both, price and lead time.

5.2. Same cutting time

The differences in cutting performance can be easily pictured when comparing three gears that each of the scenarios above would cut in the same cutting time. The gears in Figure 11 were all cut in roughly 30 minutes and only the cutting model and cutting strategy were varied.

Figure 11: Comparison of gears cut with the same resource consumption and same time with different software versions.

6. CONCLUSIONS

In this paper the effect of pressure, pump efficiency and optimized cutting path generation was evaluated. In the first section cutting experiments were carried out to obtain the maximum separation speed at different pressures while necessarily maintaining the same hydraulic power at the nozzle, given a fixed input power level. It was shown that with increased pressure at the same deliverable hydraulic power, the maximum separation speed decreased slightly and that an increase of hydraulic power showed a significant increase in separation speed.

Based on this data, economic analysis were carried out for four different scenarios with a theoretical order of 100m long cutting at a good Q4 quality. Even though the lower pressure scenarios were using a significantly higher abrasive feedrate (up to 75% higher), their higher cutting speed lead to a very similar total abrasive consumption (16% difference). The scenario with 420MPa and 85% pump efficiency showed also significant advantages over the other scenarios with higher pressure and/or lower pump efficiency. For this comparison the operating costs were assumed at a fixed cost per hour for all operating scenarios. This is likely not a real world example, as the cost reduction from garnet usage for higher operating pressures, are typically more than offset by the resultant increases in costs of maintenance from accelerating fatigue cycles for components now stressed at much higher operating pressures. Consequently, in holding constant operating costs, for simplification purposes, the economics of operations at higher operating pressures are also likely optimistically skewed.

In the second section three scenarios from different versions of software were evaluated for cutting a 25mm thick stainless steel gear, while keeping the operational parameters

(420MPa, 37kW) constant. The results showed that the newer versions of software were significantly increasing the average cutting performance by about 300%. The economic analysis showed dramatic differences in the monetary side as well as in operational factors. The newest software was able to cut three times faster (or three times more parts) while significantly reducing the operational costs. Additionally, the newest software also contributed to offering additional business opportunities by allowing a higher volume and shorter lead times.

Overall it can be concluded that more efficient operation as well as increased efficiency through smarter path planning can help optimize the cutting process and will help to make the abrasive waterjet technology more competitive to expand its application to new and growing markets.

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