2005 WJTA American Waterjet Conference
August 21-23, 2005 • Houston, Texas

Paper 7B-2

STRATEGIES FOR COST- AND TIME-EFFECTIVE USE OF ABRASIVE WATERJET CUTTING

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ABSTRACT

Abrasive waterjet (AWJ) cutting is today an important industrial cutting technology. With an AWJ almost any material can be cut, and the method is also considered as environmentally friendly. However, there is no easy and practical way of optimising a cutting operation for either maximised production rate or minimised manufacturing cost. This paper will present the cost structure for a typical machine set up, and discuss the economical considerations that have to be taken into account to be able to optimize the cutting operation for cost- and/or time-effective use.

An ongoing project together with the Nordic waterjet industry is focussing on reducing cost and machining time for the project members within their operation of their abrasive waterjet cutting machines. The project members today rely on their own experience when deciding how to use their equipment in the best possible way. The reason for this is of course that the issue of optimizing the process is relatively complex.

The objective for this paper is to present a strategy for how to work with the abrasive waterjet cutting to get the most out of the process, with focus on economical considerations. The discussions will be illustrated by economical calculations focusing on how machine settings and cutting parameters affect the total process economy.

1. INTRODUCTION

Within an ongoing Nordic project called CUT- Competetive Use of waterjet Technology, the fundamental economical issues in the matter of abrasive waterjet cutting have been studied. The network project today has 12 members from industry, developing or using abrasive waterjet equipment. The main issue within this network is to reduce costs for producing parts, and through a more effective use of waterjet cutting machines improve the competitiveness of the companies. This paper will present some important observations made during the first phase of this project.

As a part of the project an optimization model is being developed. The objective is not just to develop a mathematical model but most important to incorporate typical industrial setups and issues such as limitations in pressure, flow rate and number of cutting heads. Also the project has focussed on determining models for instance for how the pressure level influences maintenance cost. Further the output result must be in a form so that they can be directly applied in the practical case.

2. COST- AND TIME-OPTIMIZATION MODEL

As a part of the project, a model for determining optimized parameter settings is being developed. In table 1 can be seen all the parameters used in the economical calculations. The model suggests two separate optimization parameter settings for:

- shortest cutting time and
- lowest cost per cut meter.

The optimization for lowest cost can be of relevance in many cases where a longer cutting time can be accepted. On the other hand, the case of shortest cutting time is of interest when a higher cost can be accepted.

The model has three parts:

I. Input section:
- Cost situation for the job shop (includes all major costs associated with the cutting operations).
- Limitations and possible set-ups (maximum pressure, maximum number of cutting heads, utilization).
- The specific cutting case (material, thickness and quality requirements).

II. Database:
- Contains 500 different parameter combinations along with the costs and cutting times for each combination.
- The database is updated outgoing from the input section data.
- A function for finding minimum points.

III. Output section:
- Parameter settings for the two different optimization cases
- Cost structure

The use of a database has the advantage of yielding discrete values, which have been chosen at industrially relevant levels. The model is still under the course of development, but an example of the use of the model is given in table 2 (input) and table 3 (results). The cost structures presented later in this paper are results from the model.

3. COST ANALYSIS

Economical optimization of the abrasive waterjet process is relatively complex. If it is supposed to be done realistically, there are a lot of parameters that have to be considered. This paper deals with the parameters presented in table 1. To be able to perform a correct analysis of the total costs for a specific machine set up it is essential to consider the conditions under which the machine is to be run. Different machines of course also have their limitations in capacity (pressure, flow rate etc.). The cost analysis made in this paper is based on the expenses for producing a 1 meter cut. The most important economic factors are derived and later discussed focussing on cost and/or time effective use.

3.1 Cost Split-Up

To find out the cost distribution for typical machine settings, cost split up analyses were carried out for tree different machine settings. These settings are listed in table 4. One machine powered with a 37 kW pump and two machines with a 73,5 kW pump. The corresponding cutting speed is calculated basically according to Zeng and Kim (1993) but the model is adapted for higher pressures, in this case 380 and 410 MPa.

3.1.1 Fixed costs

The cost split up makes it clear that the percentage of the fixed costs decreases with an increased number of cutting heads as seen in figure 1, 3 and 5. This is also easy to understand if the fixed cost is split on more than one cutting head that this part will decrease. Notice that in the calculations no extra costs were added for extra setup time, availability and material utilization when more than one cutting head is used. In practice this would make this difference not as significant as calculated. If it would be possible to use the machine more hours annually, this would also in the end generate lower fixed costs per cut meter.

To be able to produce parts with reduced fixed costs per unit the following factors has to be considered:

- Multiple nozzle machine configuration
- Increased annual machine hours (increase number of shifts, workload, availability etc.)

3.1.2 Running costs

Approximately 90% of the running costs is represented by the following cost factors as can be seen in figure 2, 4 and 6:

- Abrasives (~65%)
- Consumables for the cutting head (orifice, focussing tube, valve etc.) (~15%)
- Pump maintenance (~10 %)

Noticeable here are the costs for the machine with four cutting heads and pump pressure 380MPa (#3, figure 6). In this case the lower pump maintenance cost derives from the lower pressure.

To be able to produce parts with reduced running costs per unit the following factors have to be considered:

- Optimized abrasive feeding
- Optimized life length versus cost of cutting head consumables
- Optimized pressure

4. PARAMETER ANALYSIS

In the analysis below every parameter is discussed separately, it is important to point out that they interact, so that for example a higher pressure changes the saturation level for the abrasive feeding.

4.1 Abrasive Feeding

The issue to minimize and optimize the cost for abrasives has been addressed previously by for instance Henning (2004) and Ranney (1995) and the result from the cost split up also indicates that this is a very important area while the abrasive costs represents approximately 60-70 % of the running costs and 22-35% of the total costs.

To be able to optimize the abrasive feeding in a model that describes the total cost for an abrasive waterjet machine, there has to be information in the model about the abrasive feeding saturation curve for the specific cutting head and cutting conditions. It is an extensive work to test every cutting head for every cutting condition to produce such saturations curves. Henning et al (2004) presents a mathematical model such as it would be possible to describe this saturation curve with a minimum of two experiments for a specific cutting condition.

The economic model used in this paper calculates cutting speeds with a modified version of a model presented by Zeng and Kim (1993). This model always predicts a higher cutting speed for an increased abrasive feeding.

To be able to optimize this part of the cost it may result in a lot of tests that have to be performed to evaluate exactly which abrasive feeding is the most cost effective for a specific machine setup.

Figure 7 and 8 shows maximum cutting depth in stainless steel for two different nozzle configurations 0,25/0,76 and 0,35/1,1. The result from the tests shows that the maximum cutting depth in these cases is reached for approximately 400 and 625 g/min respectively. The cutting depths are measured for new nozzles. In practice the maximal cutting depth will decrease as the orifice and focussing tube is worn. Both the quality of the pure waterjet when it leaves the orifice and the focussing tube and its condition affects the jet. The policy at every company how many hours a nozzle should run between replacement is therefore also affecting the total economy.

In practice however every company has its own policy for abrasive feeding, and even if an optimization model generates a specific abrasive feeding, it would not be very likely that a company will change their machine settings between almost every job.

To get a more optimized cut for every specific case a solution like a programmable abrasive metering unit would be interesting to use, but the problem is still that information about abrasive saturation curves for every specific parameter combination has to be generated.

4.2 Pump Pressure

The pump pressure (P) is an important factor for calculation of the cutting speed. Zeng and Kim (1993) suggests that the cutting speed is proportional to $P^{1,25}$ in the interval 138 to 276 MPa. This is however not the same as it is economically beneficial to run at a higher pressure. To be able to investigate which pressure to run at for a specific case the following example is computed:

Increasing pressure from 350 MPa to 410 MPa would generate an increase in cutting speed with approximately 27% according to performed tests. If one machine is running one shift (ca 1750 hours / year) with a workload of 70%, that will result in 1225 hours of machining. Increasing the pressure from 350 to 410 MPa will free some 260 hours (or 46 days with a workload of 70%). One should have in mind that a higher pressure level increases the flow rate.

This would also generate more downtime and a higher maintenance cost. According to calculations made within the project, a pressure rise from 350 MPa to 410 MPa for a pump would almost treble the cost for spare parts (for the first 10.000 pump hours), and the pressure rise would still be profitable. So if a company has a relatively new pump and a lot of work to do, they ought to consider running at a high pressure. This will then also generate more downtime and a higher maintenance cost.

In the end the question still remains for every company using waterjet equipment if it is profitable or not to turn up the water pressure. The answer has to do with a lot of aspects such as:

- The waterjet equipment itself (available pressure, flow rate, type, age, etc.)
- Downtime
- Maintenance cost
- Workload

4.3 Number of Cutting Heads

The option to use more than one cutting head with a smaller orifice and focussing tube diameter is widely used today. The question then arises how many cutting heads should be used, and what savings are possible. To be able to compare the costs for different number of cutting heads two pump sizes are compared; one 37 kW pump and one 73,5 kW pump, the machine configurations are listed in table 5. The costs are based on realistic investment costs for such pumps. The results are presented in table 5 and figure 9 and 10. If the costs per cut meter are compared it is noticeable how big the difference is between one and two cutting heads.

The basis for the calculation is one 37 kW pump equipped with one 0,35/1,1 mm nozzle. The cost per cut meter with this type of machine is set to 1,00. Four combinations are compared and it is obvious that it is profitable to split the fixed costs on more then one cutting head. If the number of cutting heads is increased to two 0,25/0,76 mm on a 37 kW pump the cost per cut meter is reduced to 0,83. The difference between one 0,35 /1,1 mm nozzle on a 37 kW pump and four 0,25 /0,76 mm nozzles on a 73,5 kW pump is a 42 % reduction in costs per cut meter. Notice that in the calculations no extra costs were added for extra setup time, availability and waste of material.

Generally one should always consider running with at least two cutting heads. This would in most cases be profitable. On the other hand companies should always have in mind that a multiple nozzle configuration implies:

- Increased programming and setup time
- A lower availability on the machine
- Generally more scrap material
- Overall a decreased flexibility

5. CONCLUSIONS

- If an abrasive waterjet cutting operation is to be optimized it is essential to focus on the costs that generates the greatest part in a cost split up.
- The fixed cost is often half or up to two thirds of the total costs for producing a 1 meter cut.
- Using two cutting heads instead of one gives a significant drop in the total cost for producing a 1 meter cut.
- The pump pressure is interesting to study especially if it is important to free machine time. Notice that the flow rate can be a limitation for maximum pump pressure.
- Abrasive feeding is the major part of the running costs, and is relatively complex to optimize. It takes an extensive testing to find saturation curves for every combination of parameters that are to be used.

6. REFERENCES

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7. TABLES

Table 1. Parameters Used in the Economical Calculations

General Costs	Investment cutting table including tubing, software etc.
	Investment pump
	Economic life
	Interest
	Rental charges
	Electricity
	Water
Maintenance Costs	Pump
	Cutting table
Consumables	Abrasives including handling and disposal
	Cutting head (orifice, focussing tube, valves etc.)
Limitations	Max pump pressure
	Max pump flow rate
	Working hours per year
	Availability
Machine settings	Nozzle configuration
	Abrasive feeding
	# of cutting heads
Target material	Type
	Thickness
	Quality of cut

Table 2. Example of input to the optimization model

Investment	272 000	€
Abrasives, total cost	0,43	€/kg
Operator	32,6	€/h
Working hours per year	3750	h
Max pump power	73,5	kW
Max pump pressure	400	MPa
Available cutting heads	3	
Utilization	70	%

Table 3. Output from optimization model, for cutting of 20 mm steel in a medium quality

	Shortest cutting time	Lowest cost
Pressure	360 MPa	400 MPa
Abrasive feed rate	500 g/min	400 g/min
Orifice diameter	0,304 mm	0,356 mm
Nozzle diameter	0,9 mm	1,0 mm
Number of cutting heads	3	2
Cutting speed	53 mm/min	68 mm/min

Table 4. Machine Settings used for Cost Split Up

	#1	#2	#3
Pump power (hp / kW)	50 / 37	100 / 73,5	100 / 73,5
Max pressure (MPa)	410	410	380
$d_{orifice}$ / $d_{focussing\ tube}$ (mm)	0,35 / 1,1	0,35 / 1,1	0,25 / 0,76
Abrasive feeding (g/min)	625	625	400
# cutting heads	1	2	4
Cutting speed 18 mm stainless steel (mm/min)	88	176 (88*2)	200 (50*4)
Total cost €/h	96,1	131,2	141,4
Total cost (€/m)	18,1	12,4	11,7

Table 5. Multiple nozzle configurations

	#4	#5	#6	#7
Pump power (hp / kW)	50 / 37	50 / 37	100 / 73,5	100 / 73,5
Pressure (MPa)	380	380	380	380
$d_{orifice}$ / $d_{focussing\ tube}$(mm)	0,35 / 1,1	0,25 / 0,76	0,35 / 1,1	0,25 / 0,76
Abrasive feeding (g/min)	625	400	625	400
# cutting heads	1	2	2	4
Normalized cost per meter	**1,00**	**0,83**	**0,68**	**0,58**
Normalized cost per meter	**1,47**	**1,22**	**1,00**	**0,85**

8. GRAPHICS

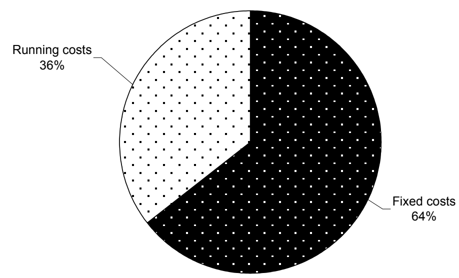

Figure 1. Cost Split Up for configuration #1, Total costs

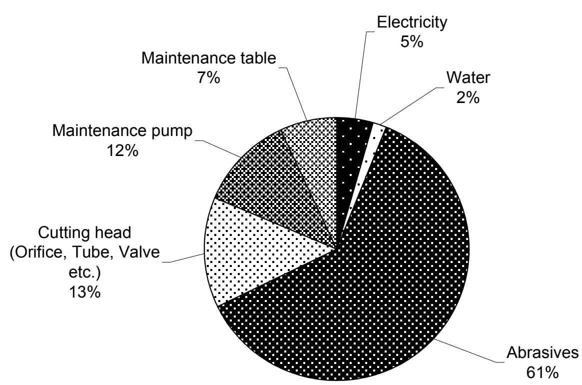

Figure 2. Cost Split Up for configuration #1, Running costs

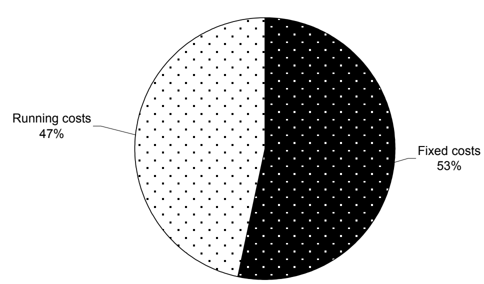

Figure 3. Cost Split Up for configuration #2, Total costs

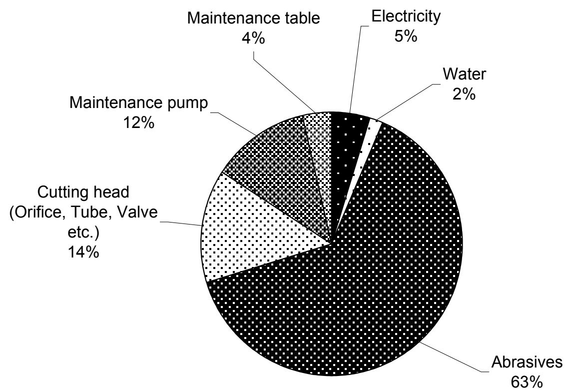

Figure 4. Cost Split Up for configuration #2, Running costs

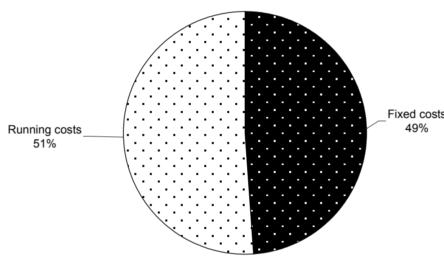

Figure 5. Cost Split Up for configuration #3, Total costs

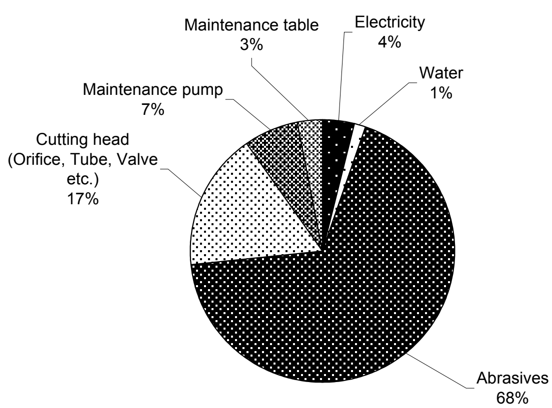

Figure 6. Cost Split Up for configuration #3, Running costs

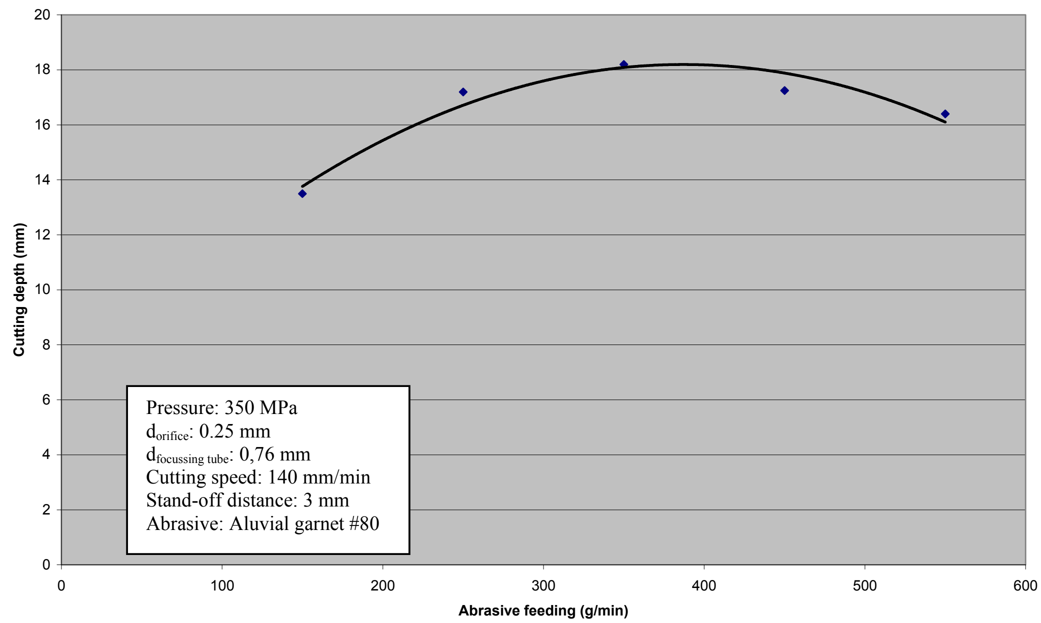

Figure 7. Maximum cutting depth in stainless steel for a 0,25/0,76 nozzle at 350 MPa

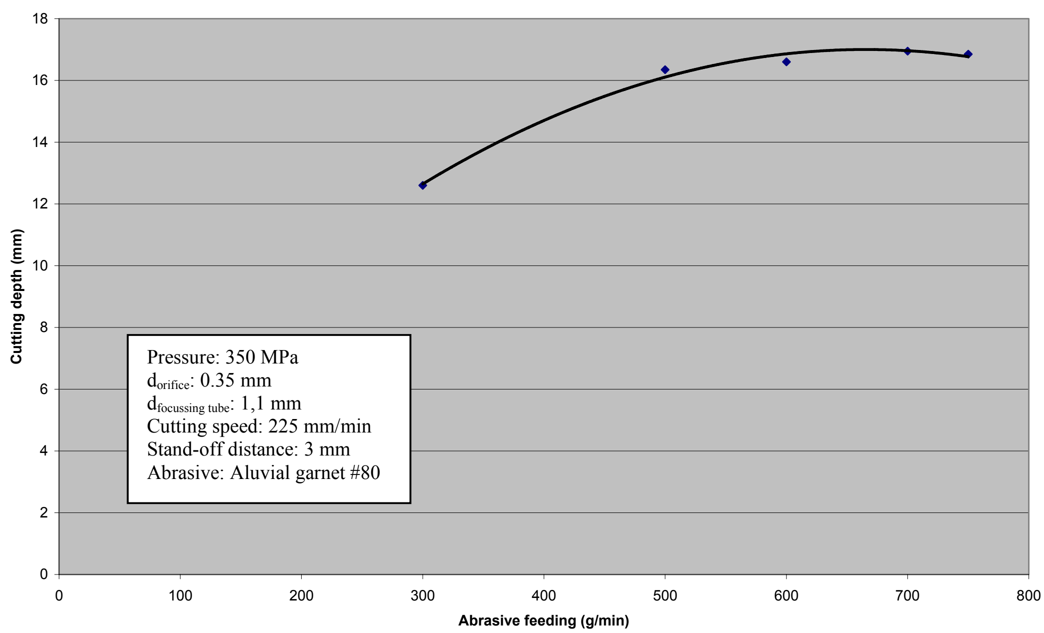

Figure 8. Maximum cutting depth in stainless steel for a 0,35/1,1 nozzle at 350 MPa

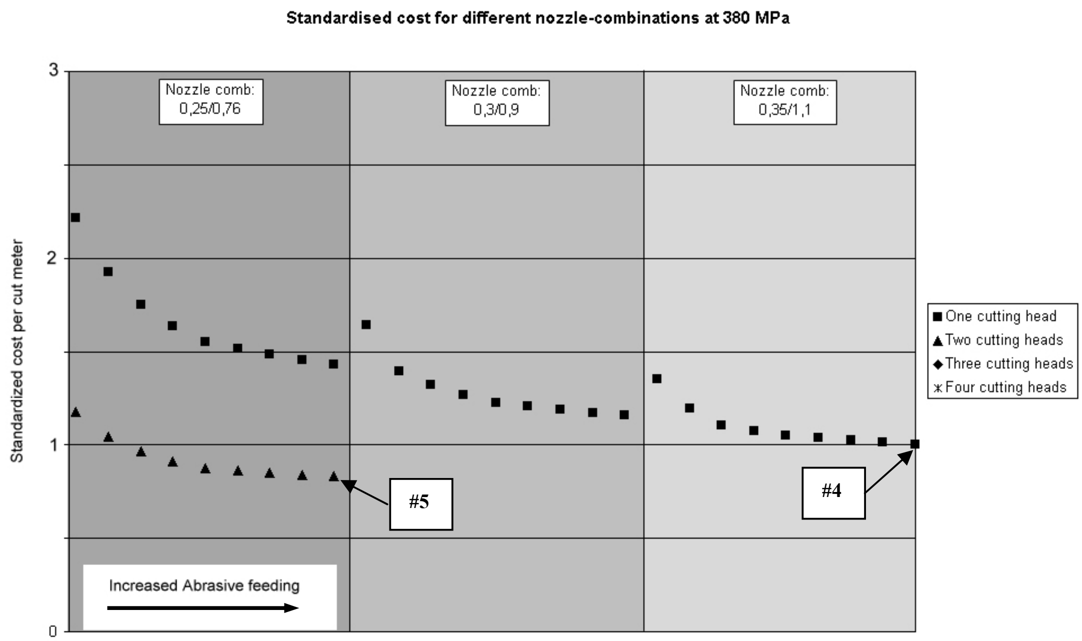

Figure 9. Standardized costs per cut meter for machine setup #4 and #5, compared with three different nozzle configurations and with increasing abrasive feeding for each nozzle configuration.

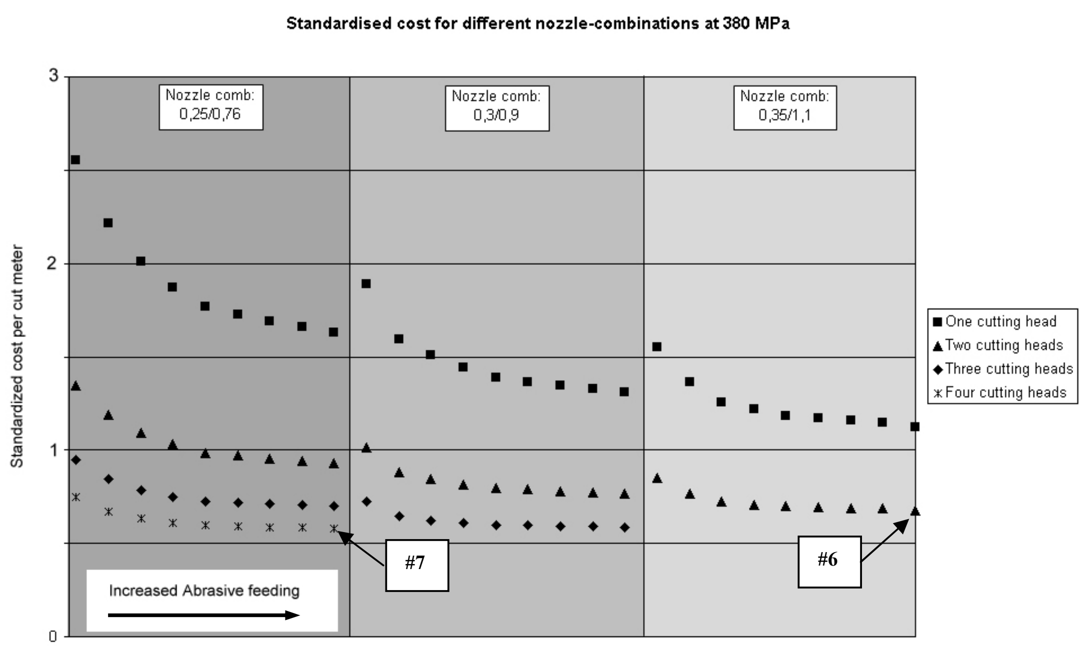

Figure 10. Standardized costs per cut meter for machine setup #6 and #7, compared with three different nozzle configurations and with increasing abrasive feeding for each nozzle configuration.