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

Paper 4A-2

ABRASIVE WATERJET CUTTING BEYOND 400 MPA

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ABSTRACT

This paper discusses the abrasive waterjet cutting (AWJ) beyond 400 MPa (= 4000 bar), which is the limit pressure for the most of the waterjet cutting systems. The AWJ cutting process is well established up to 400 MPa. Many cutting models were developed based on different principles, and they are validated by the cutting data generated at the current pressure limits. In this study, validity of the previous cutting models was tested up to 700 MPa and the process parameters were adjusted to the higher pressures. The abrasive consumption was discussed in detail. It was figured out that the available cutting models are capable of describing the cutting process beyond 400 MPa. The optimum abrasive flow rate increases as the pressure increases to keep the abrasive load ratio constant. It is also possible to reduce the abrasive usage around 50% while maintaining the cutting speed and the surface roughness.

1. INTRODUCTION

Abrasive waterjet cutting (AWJ) was introduced in 1983 [1] and became popular because of its advantages like its ability to cut wide range of materials with no influence on their microstructure and its flexibility. The operating pressure for abrasive waterjet cutting system remained unchanged at around 400 MPa (= 4000 bar) for many years. In 2004, a high-pressure intensifier company introduced 600 MPa pumps to the market for waterjet cutting.

Nowadays, one of the interesting topics in the abrasive waterjet machining is to explore the possibilities of abrasive waterjet cutting at water pressures higher than 400 MPa, which is the industry standard. Increasing the pressure beyond its current limit may have the following advantages:

- Increased cutting speeds and depths of cut
- Increased efficiency with the pressure increase
- Cutting harder materials
- Reduced abrasive usage, therefore cost reduction in AWJ

This paper focuses on the cutting of metals by abrasive waterjet above 400 MPa. The main concern of the study is presenting the cutting data and providing knowledge about the effect of cutting parameters to the cutting operation at higher pressures where there is not enough information is available in the literature.

Firstly, the theoretical aspects of AWJ machining like abrasive particle acceleration and modelling of cutting process are discussed. Afterwards, the previous researches about the cutting capabilities of AWJ beyond 400 MPa are summarized. Lastly, the cutting tests performed in our laboratory are presented and the results are compared with the models and the previous researches.

2. LITERATURE SURVEY

2.1. Abrasive particle acceleration

The velocity of the abrasives and the energy transferred from the waterjet to abrasive particles can be calculated by using the impulse-balance equations [1]. Inside the cutting head, the kinetic energy of the water is transferred to the abrasive particles. However, due to the interactions between the particles themselves and their surroundings, and the sometimes insufficiently long focusing tube to accelerate the particles, there is a loss of momentum, which is characterized by the velocity efficiency, η.

$$(\dot{m}_{abr} + \dot{m}_w) \cdot v_{awj} = \eta \cdot (\dot{m}_w \cdot v_{wj}) \quad (1)$$

If R is defined as the abrasive load ratio, the velocity of the slurry, v_{awj} can be written as follows:

$$R = \frac{\dot{m}_{abr}}{\dot{m}_w} \qquad (2)$$

$$v_{awj} = \eta \cdot \frac{1}{1+R} \cdot v_{wj} \qquad (3)$$

The energy transfer efficiency, κ, which shows the amount of energy transferred from the water to the abrasive particles, is independent from the pressure. If it is assumed that only the abrasive particles contributes to the cutting process, then;

$$P_{awj} = P_{abr} = \frac{1}{2} \cdot \dot{m}_{abr} \cdot v_{abr}^2 = \frac{1}{2} \cdot \dot{m}_{abr} \cdot v_{awj}^2 \qquad (4)$$

$$P_{wj} = \frac{1}{2} \cdot \dot{m}_w \cdot v_{wj}^2 \qquad (5)$$

$$P_{abr} = \kappa \cdot P_{wj} \qquad (6)$$

$$\kappa = \eta^2 \cdot \frac{R}{(1+R)^2} \qquad (7)$$

The energy efficiency is at its maximum when the abrasive load ratio is 1 (Figure 1) if the velocity efficiency, η is independent from κ. However, in the industrial applications, the abrasive load is generally around 0.15 which means that only 11.3% of the hydraulic energy is transferred to the abrasive particles even when the η is equal to unity. Hoogstrate [1] describes the phenomena as the result of the increase in chance of clogging due to the geometrical constraints of the mixing chamber together with the airborne feeding principle of the abrasives particles, and the increase in friction between the abrasives and the mixing chamber and the focusing tube at higher abrasive load ratios.

2.2. AWJ Cutting Models

In injection type abrasive waterjet, abrasive particles are accelerated through focusing tube (focusing nozzle) by the water sprayed through an orifice. Mixing of water, air and abrasives occurs in the mixing chamber. The high velocity abrasives hit the target material and leads to the erosion of the material. It is very complex process and it is still not well understood. Despite the complexities of the process, there are many abrasive waterjet cutting models trying to predict the cutting results as a function of the cutting parameters. Most of the models can be applied to only one type of materials. The models presented here focuses on the calculation of the depth of the cut for ductile materials (Table 1).

The dependencies of the depth of cut on water pressure, abrasive flow and cutting speed presented in the Table 2. The effect of pressure to the depth of cut is at least linear for all of the models. Some researchers implement a threshold pressure [5, 6]. The influence of abrasive flow rate is modelled with different power exponents varying from 0.211 to 1. However, the experiments show that the depth of cut starts to decrease after a certain value of abrasive flow rate. This behaviour was not presented by any of the models. The cutting speed is inversely proportional to the depth of cut. Except the cutting wear model of Hashish [2], the influence of cutting speed is modelled with power exponents closed to or equal to 1.

2.3. AWJ Cutting Beyond 400 MPa

Because of the very limited availability of waterjet cutting system beyond 400 MPa, there are few researches in this field. Although 1000 MPa water pressures were experimented back in 1972 in plain waterjet cutting [9], first abrasive waterjet experiments beyond 400 MPa were realized in 1996 [10]. However, it only included tests with only small diameter orifices like 0.025 mm and 0.076 mm which are not common in the industry. The following researches [11, 12, 13, 14, 15] contain broader ranges. The results of the studies are presented according to their main concerns in the following paragraphs.

2.3.1. Maximum cutting speed

The highest cutting speed that manages to separate the part into two regardless of the quality of the cut surfaces is the maximum cutting speed. The results of Hashish [10] have shown that for small orifice with 0.025 mm diameter, the cutting speed has been improved 10 times when the pressure is doubled to 690 MPa. However, larger orifices like 0.23 mm in size were not that efficient [11, 12]. It is explained with the fact that threshold pressure is very close to the starting pressure, 345 MPa when 0.025 mm orifices are in charge. The increase in the cutting speed decreases as the material thickness increases. The cutting speed increased 2.5 times when the pressure increased from 350 MPa to 600 MPa for a material of 10 mm thick. It increased 1.8 times when the material thickness is120 mm.

2.3.2. Maximum depth of cut

The depth of cut linearly increases from 2.2 mm to 7.8 mm for austenite and 2.9 mm to 9.7 mm for copper and 5.9 mm to 17.2 mm for aluminium when the pressure increased from 400 MPa to 600 MPa [13]. As it is in the case of maximum cutting speed, the improvement of depth of cut in AWJ is less compared plain waterjet cutting. Lefevre experienced same amount during the comparison of 350 MPa and 600 MPa cutting systems [14].

2.3.3. Abrasive usage

One of the promising outcomes of AWJ cutting beyond 400 MPa is the reduction of the abrasive consumption. The previous researches showed the possibility of using less abrasive while maintaining the same surface quality and the cutting speed when the water pressure increases [15]. It is possible to use half of the abrasive used at 380 MPa to obtain a same quality cut when the pressure is increased to 520 MPa.

Mohamed has shown that the depth of cut increases up to a certain abrasive flow rate then it starts to decrease at 600 MPa as well as 300 MPa [13]. The abrasive flow rate increases the frequency of the impact of the particles. Meanwhile, the velocity of the each particle decreases. Therefore, the loss of particle velocity balances the increase in frequency of the impact. The optimum flow rate is the point where depth of cut reaches its maximum value for the given set of parameters It is 0.8 g/s at 600 MPa and 0.55 g/s at 300 MPa. Although it is not mentioned in this study, further calculations show that the abrasive load ratio is almost equal for both pressures (0.13 for 300 MPa and 0.14 for 600 MPa). It is also in agreement with the results of Chalmers

[16]. Chalmers has found that the optimum abrasive load ratio is constant in the pressure range of 207 MPa to 379 MPa.

3. TEST SET-UP AND PROCEDURE

An AWJ cutting system, supplied by Resato Int., was used during the experiments. The design pressure of the high-pressure intensifier is 800 MPa [17]. The test set-up is explained in [18]. Three major parameters are investigated to judge the abilities of the abrasive waterjet at pressures higher than the industry standard 400 MPa; maximum cutting speed, maximum depth of cut and cutting surface quality. For determination of the maximum cutting speed, the test pieces were cut with different cutting speeds. The highest cutting speed that managed to separate the part into two is taken as the maximum cutting speed. The maximum depth of cut is determined by using wedge-shaped aluminium test pieces. The depth of cut is measured by a calliper where the continuous cutting operation is stopped.

Cutting surface quality is characterized by the average roughness value, Ra. It was measured by a stylus-based texture measuring system, Form Talysurf PGI 1240 from Taylor Hobson. The roughness is measured along 25 mm with a cut-off of 2.5 mm and a bandwidth of 1:300 in accordance with ISO standards. The measurements were started 35 mm away from the exit-end of the cut surface. The test pieces are made up of 10 mm thick stainless steel, having a length of 95 mm.

Aluminium and stainless steel, both with thicknesses of 10 mm were used at the maximum cutting speed and roughness experiments. The maximum depths of cut experiments were carried by using aluminium and AISI 304 steel.

The standoff distance was kept constant at 2 mm and the Barton garnet abrasives of 150 mesh were used during all of the experiments.

4. RESULTS AND DISCUSSION

4.1. Abrasive Usage

The amount of abrasive used during the cutting process has a crucial importance not only it is the largest cost factor after the capital and labour costs but also it has a great effect to the cutting performance. As discussed earlier, while the increase in abrasive flow rate increases the number of impacts to the workpiece, the velocities of the particles decrease, hence there is an optimum abrasive flow rate for a given set of parameters (Figure 2). It is also interesting to see that the larger focusing tube increases the depths of cut. The reason can be the higher particle velocities due to the less interaction between the particles and the walls of the focusing tube when the tube diameter is larger.

The velocity of the abrasive particles and the power transfer efficiency are a function of abrasive load ratio. If the figure 2 is redrawn as a function of abrasive load ratio, it can be seen that the maximum depths of cut occurs at the same abrasive load ratio, 0.3 when the focusing tube diameter is kept constant (Figure 3). Increasing the size of the focusing tube shifts the optimum abrasive load ratio slightly.

According to the work of Chalmers [16], the optimum abrasive load ratio is independent of pressure. He conducted test at a pressure range of 207 MPa to 379 MPa. Mohamed [5] also obtained identical optimum abrasive load ratios at pressures 300 MPa and 600 MPa. However, the optimum abrasive flow rate found in this study is two times higher as compared to the one that was reported at the work of Mohamed (Table 3). There may have been several reasons. First is the effect of larger focusing tube used in this study. Second, Mohamed has used smaller abrasives. It is known that smaller particles have a reduced cutting capability [19] and the high pressures may lead to fragmentations and further decrease the size of the abrasives. Finally, the mixing efficiency is dependent on the cutting head design.

The roughness measurements were conducted on the parts cut with different abrasive flow rates. The results (Figure 4) show that within the first 30% of the depth of cut, the cutting quality does not alter significantly with the abrasive flow rate. However, at the rough-cut region where the cutting mechanism changes, higher abrasive flow rates up to a certain limit produce finer surfaces. Further increases in the flow rate do not improve the surface quality.

Lastly, to depict the reduction in abrasive consumption with the pressure increase, the cutting speed (in this case, it is 210 mm/min which is the maximum cutting speed for both case) and the surface quality kept constant while abrasive flow rate were varied. 52 % abrasive reduction is possible when the pressure is increased to 600 MPa from 400 MPa (Figure 5). Xu [16] figured out a similar reduction when the pressure was increased from 380 MPa to 520 MPa.

4.2. Maximum cutting speed

One of the expected advantages of increasing the pressure is the increase in the cutting speed while the other parameters are kept constant. The results (Figure 6) show that the relation between the cutting speed and the pressure is linear for the set of parameter used, i.e. the cutting speed increases around 1.5 times as the pressure increases with the same amount.

The results show (Figure 7) that the increase in the cutting speed in AWJ, i.e. cutting efficiency is less than the increase in the cutting speed in plain waterjet and also less than the increase in hydraulic power. It can be explained by the threshold pressure phenomena (the threshold pressure is close to the starting pressure 350 MPa for plain waterjet) and low efficiency of the abrasive cutting head due to the low abrasive load ratios and the limitations of the energy transfer phenomena during the mixing process.

4.3. Maximum depth of cut

The relations of pressure and the cutting speed with depth of cut were investigated. The depth of cut is related with the pressure with a power exponent of 1.5 for steel and 1.7 for aluminium (Figure 8). The depth of cut is inversely proportional with the cutting velocity with a power exponent of 0.86 (Figure 9).

The relation of abrasive flow rate with the depth of cut discussed earlier. The depth of cut increases first, then it decreases with the increase in the abrasive flow rate, which is not predicted by any of the cutting models. If only the increasing parts of the depth of cut vs. abrasive flow rate graphs are taken into account, the power exponent varies between 0.19 and 0.24 depending on the orifice and focusing tube diameter.

As these power exponents are compared with the ones of the models generated to predict the depth of cut, it is seen that they are very close to each other (Table 4) although the models were generated by using cutting data up to 400 MPa.

4.4. Surface quality

The cutting surface quality is a function of the pressure is observed. As in the case of abrasive flow rate, the depth of fine cut marginally changes with the change of pressure. Up to 30% of the total depth of cut, the surface roughness remains same both for cutting at 300 MPa and 600 MPa (Figure 10). As the distance from the top surface increases the differences between the roughness of the surfaces becomes more distinctive. The particles looses same amount of energy during the cutting operation, however the initial energy the particles at 600 MPa are higher, which results in a smoother surface. The relation of the roughness at different cutting depths with the pressure increase is clear in Figure 11. At 10% of the depth of cut, the surface quality is constant over the pressure range; the improvement in the surface quality is 27% when the cut is at the half way, and 42% when the depth is 80% of the depth of.

5. CONCLUSION

Investigations of cutting with abrasive waterjet beyond 400 MPa have started recently, and there are many gaps in the knowledge database at this pressure range. The possibilities of the higher pressures, selection of the correct cutting parameters, and the understanding the physics of the abrasive mixing process regarding the design of the cutting head are of interest.

For a certain set of parameters, there is an optimum abrasive flow rate and the slope of the curve around the optimum is not so high, which makes it logical to use less abrasive than the optimum value and save abrasives instead of running at the optimum value. The increase in pressure shifts the optimum flow rate to a higher value to maintain the abrasive load ratio constant.

The increase in water pressure makes it possible to cut thicker materials and to increase the cutting speed. The depth of cut and cutting speed increase 2 to 1.5 times respectively when the water pressure increases from 400 MPa to 660 MPa. However, the amount of increase is less as compared to plain waterjet cutting. The possible reasons can be the threshold phenomena and the particle mixing efficiency.

The study of cutting models based on the comparison of power exponents shows that the available models can predict the depth of cut with pressure above 400 MPa, although they are generated by using data up to 400 MPa. The power exponents found in this study are especially close to the ones of Kovacevic [4] whose model is based on a regression study using Hashish [2] volume displacement model as a starting point.

Finally, it can be stated that the roughness of the part improves especially at the far side of the cut when the water pressure increases. The smooth cut region deepens but its quality stays constant, which means that the abrasive size, abrasive flow rate and the cutting speed determine the quality of that region, not the pressure.

6. ACKNOWLEDGEMENT

This project is a co-operation between the Delft University of Technology (TU Delft), Precision Manufacturing and Assembly (PMA) group and Resato International b.v. and supported by the Dutch Ministry of Economic Affairs under the Senter Novem BTS program.

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8. NOMENCLATURE

b	Width of cut	p_{thr}	Threshold pressure
c	Constant	P_{wj}	Power of waterjet
C_k	Characterictic velocity	R	Abrasive load ratio
d_f	Diameter of jet	R_{opt}	Optimum abrasive load ratio
d_o	Orifice diameter	S	Stand-off distance

e_c	Specific cutting energy	v_{abr}	Velocity of the abrasives
h	Depth of cut	v_{awj}	Velocity of waterjet and abrasive
H	Hardness of the material	v_f	Cutting speed
l_f	Length of focusing tube	v_{wj}	Velocity of waterjet
$\dot{m}_{abr}$	Abrasive mass flow rate	ε	Specific energy
$\dot{m}_{abropt}$	Optimum abrasive flow rate	ε_s	Strain
$\dot{m}_w$	Water mass flow rate	η	Velocity efficiency
N_m	Machinability number	κ	Energy transfer efficiency
p	Pressure	λ	Regression parameter
P_{abr}	Power of abrasive mixture	ρ_{abr}	Density of abrasive
P_{awj}	Power of waterjet and abrasive		

9. TABLES

Table 1. AWJ models for depth of cut for cutting ductile materials

Author	Equation	Notes
Hashish – 1 [2]	$h=\frac{c\cdot d_f\cdot v_{abr}}{2.5\cdot C_k}\cdot\left(\frac{14\cdot\dot{m}_{abr}}{\pi\cdot v_f\cdot d_f^{\,2}\cdot\rho_{abr}}\right)^{0.4}$	Cutting wear, C_k is the characteristic velocity
Hashish – 2 [2]	$h=\frac{2\cdot(v_{abr}-v_c)^2\cdot\dot{m}_{abr}}{\pi\cdot d_f\cdot v_f\cdot\sigma_f}$	Deformation wear, σ_f is the material flow stress
Matsui [3]	$h=\frac{10^{4.74}}{v_f\cdot(H\cdot\varepsilon_s)^{0.67}}$	Regression H hardness of the material, ε_s is the strain.
Kovacevic [4]	$h=0.00139\cdot\frac{d_f^{\,0.765}\cdot\dot{m}_{abr}^{\,0.211}\cdot p^{1.47}}{S^{0.139}\cdot v_f^{\,0.74}}$	Regression, for mild steel Based on the model of Hashish
Chung [5]	$h=\frac{(p-p_{thr})\cdot\dot{m}_{abr}^{\,0.6}}{v_f\cdot b}$	Energy conservation and regression p_{thr} is the threshold pressure, b is the width of the cut
Blickwedel [6]	$h=\frac{(p-p_{thr})\cdot C_0}{v_f^{\,0.86+\frac{2.09}{v_f}}}$	Energy conservation and regression C_0 is the material constant
Oweinah [7]	$h=\frac{v_{abr}^{\,2}\cdot\lambda\cdot\dot{m}_{abr}}{2\cdot v_f\cdot b\cdot\varepsilon}$	Energy conservation and regression
Hoogstrate [8]	$h=(0.9113\cdot v_f^{\,0.134})\cdot\frac{P_{abr}}{e_c\cdot d_f\cdot v_f}$	Energy conservation P_{abr} is the power of the abrasive particles (6), e_c is the specific cutting energy of the material

Table 2. Power exponents of the AWJ models of depth of cut

Author	Power exponents		
	P	**m_{abr}**	**v_f**
Hashish – 1 [2]	1	0.4	0.4
Hashish – 2 [2]	2	1	1
Kovacevic [4]	1.47	0.211	0.74
Chung [5]	1	0.6	1
Blickwedel [6]	1	-	$0.86+2.09/v_f$
Oweinah [7]	2	1	1
Hoogstrate [1]	1.5	1	1

Table 3. Optimum abrasive flow rate

	Mohamed [5]	**This study**	**Chalmers [16]**	
m_{abropt} (g/min)	54	100	-	-
R_{opt}	0.14	0.3	0.3	0.19
p (MPa)	600	650	207 - 379	207 – 379
d_o (mm)	0.1	0.1	0.25	0.38
d_f (mm)	0.4	0.5	0.76	1.14
l_f (mm)	70	76	51	76
Abrasive size	Barton 220	Barton 150	AU 80	AU 80
v_f (mm/s)	100	400	150	150
S (mm)	2	2	-	-
Material	Al	Al	1018 Steel	1018 Steel

Table 4. Comparison of power exponents of the AWJ models and this study

Author	Power exponents		
	P	**m_{abr}**	**v_f**
This study	1.5 – 1.7	0.19 – 0.24	0.86
Kovacevic [4]	1.47	0.211	0.74
Chung [5]	1	0.6	1

10. FIGURES

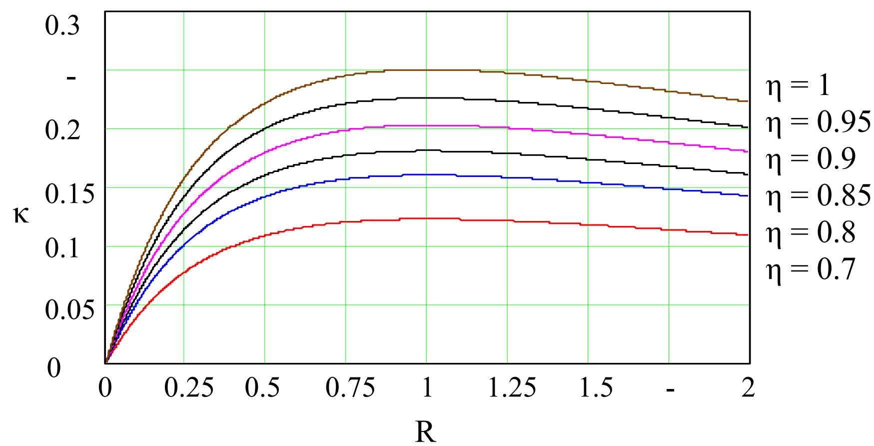

Figure 1. Energy transfer efficiency as a function of abrasive mass load

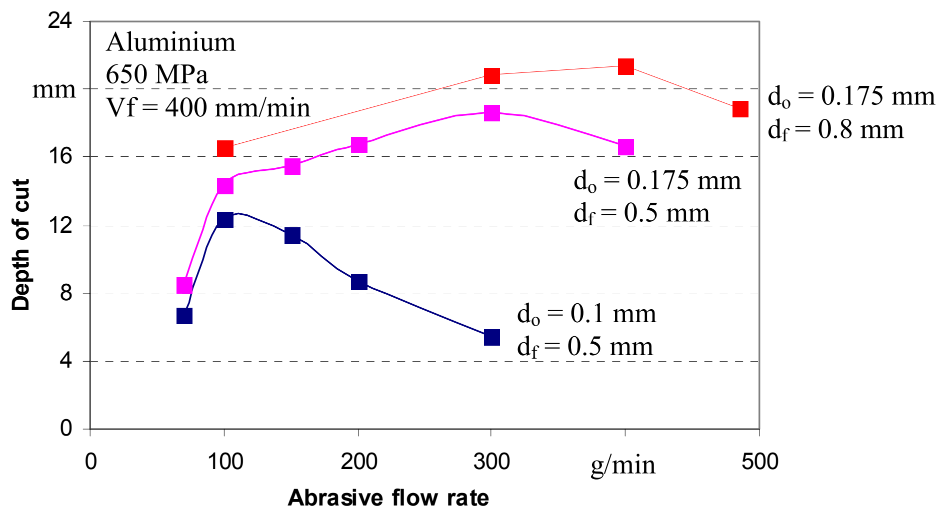

Figure 2. Effect of abrasive flow rate on depth of cut

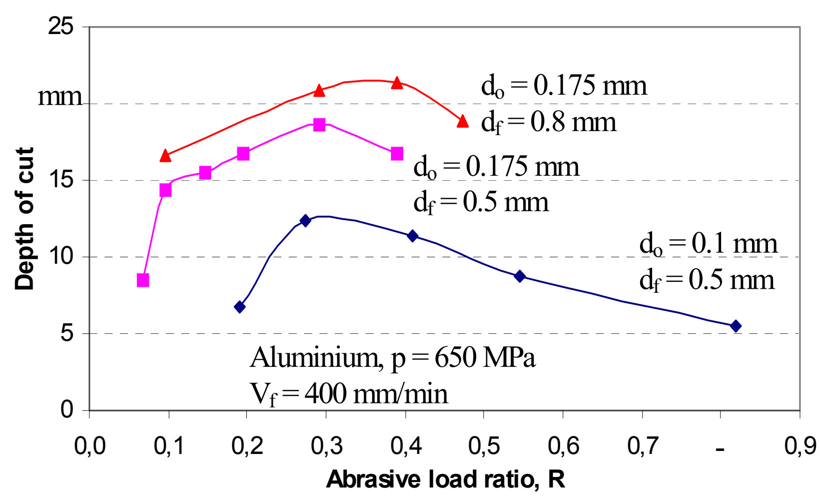

Figure 3. Effect of abrasive load ratio on depth of cut

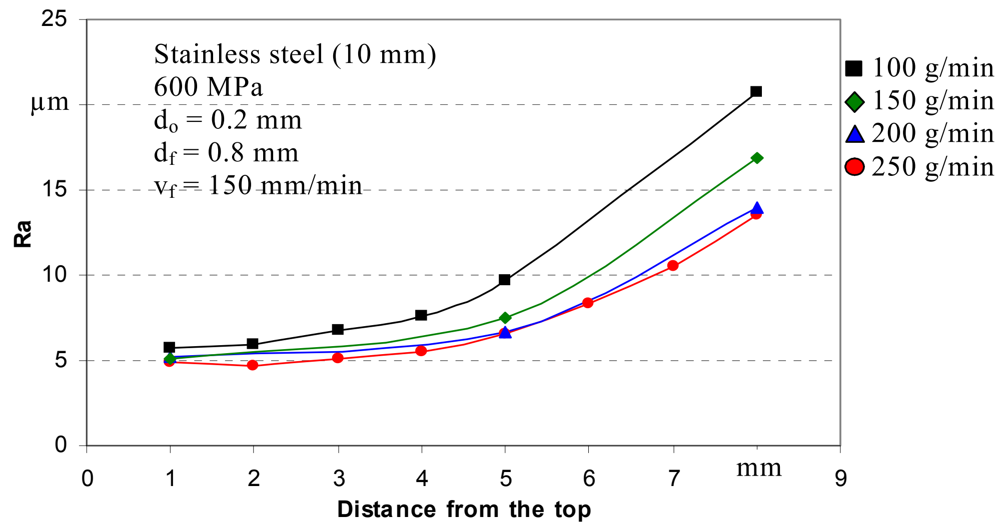

Figure 4. Surface quality along the cut for various abrasive flow rates

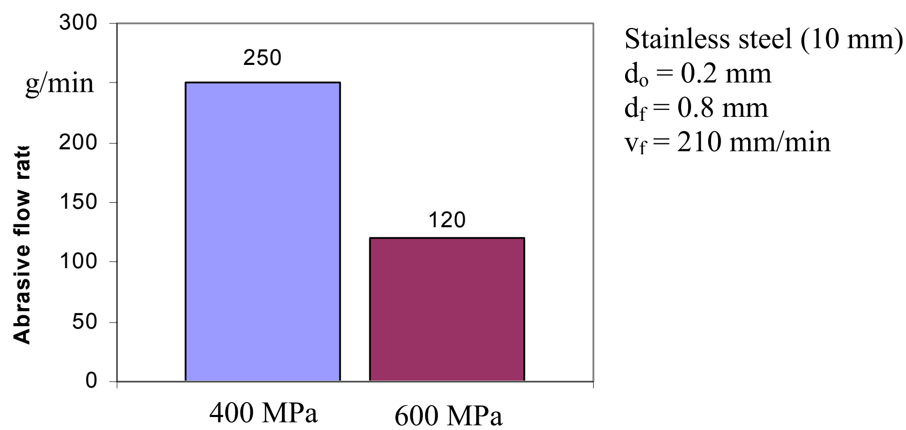

Figure 5. Abrasive reduction with increasing pressure

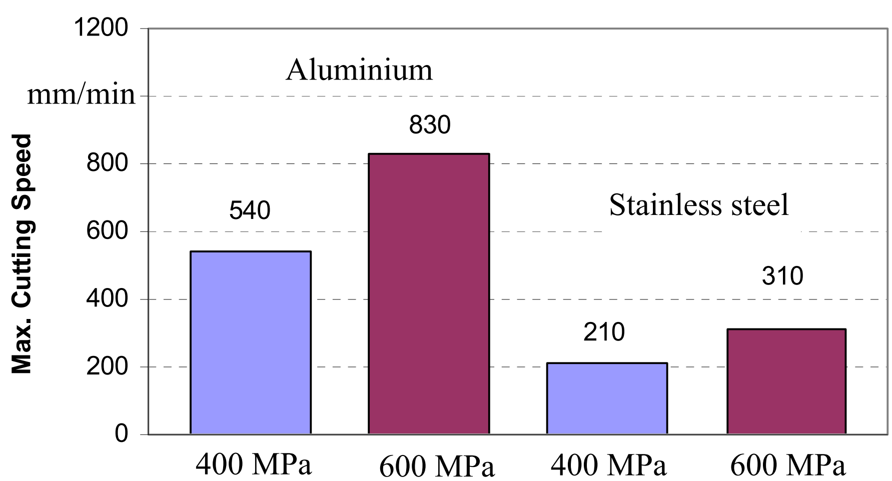

Figure 6. Effect of pressure on maximum cutting speed

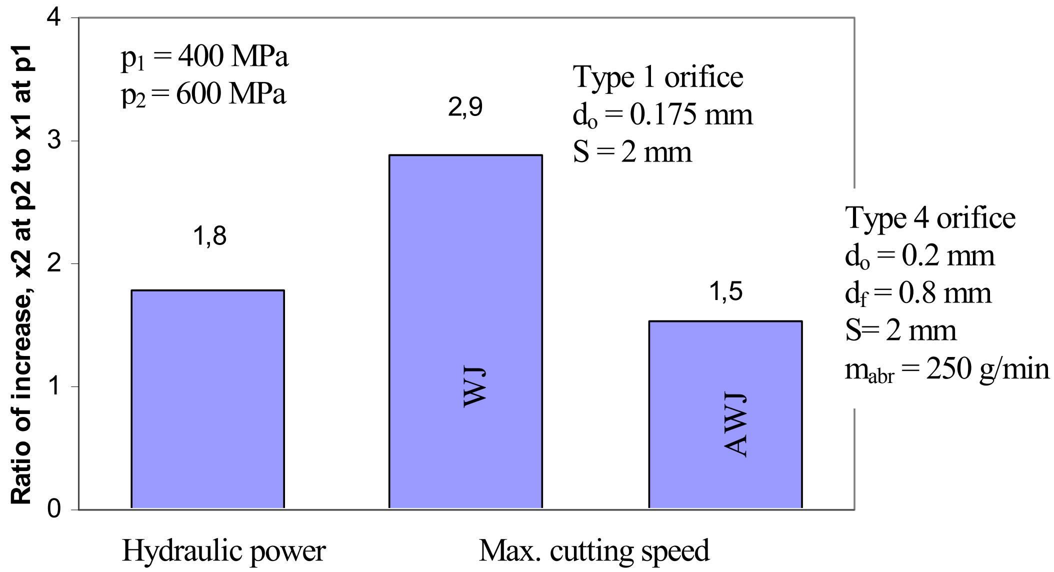

Figure 7. Comparison of increases of hydraulic power and maximum cutting speed

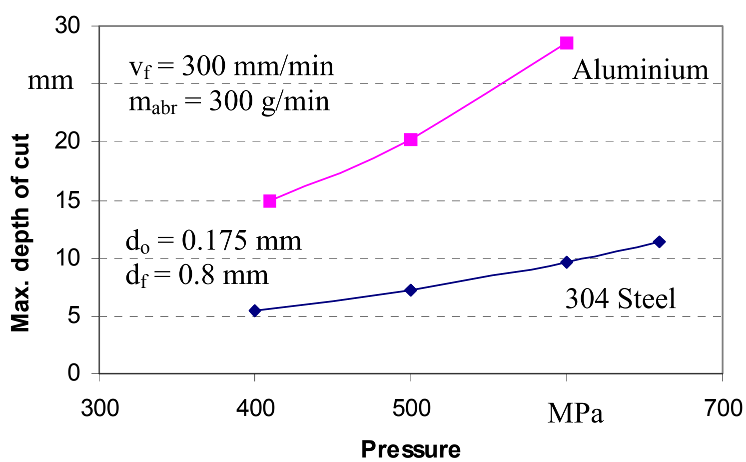

Figure 8. Depth of cut as a function of pressure

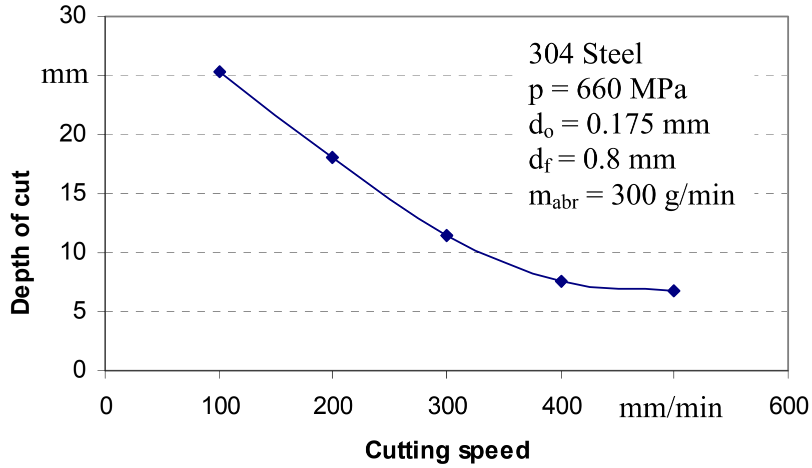

Figure 9. Depth of cut as a function of the cutting velocity

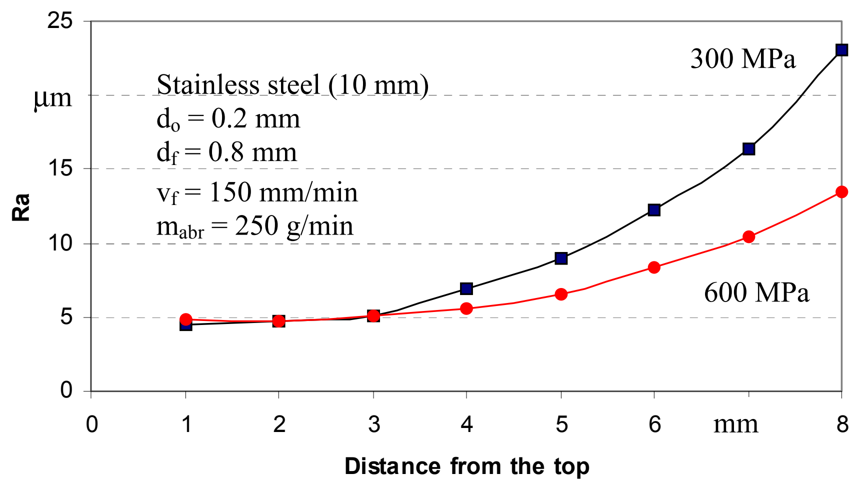

Figure 10. Surface quality along the cutting depth

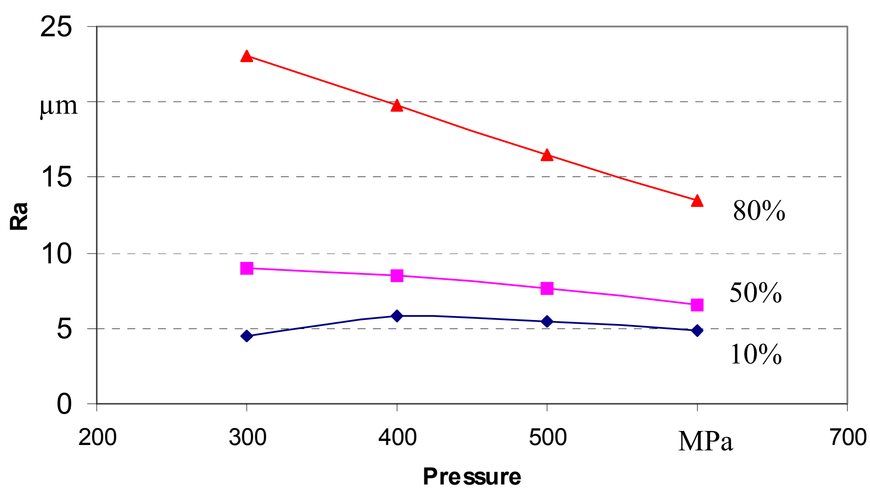

Figure 11. Surface quality as a function of pressure at various depths