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Učinkovitost rezanja in dosegljiva kakovost pri uporabi abrazivnega vodnega curka pri tlaku 6000 bar

Cutting Performance and Obtainable Quality when Applying 6000-Bar Abrasive Water-Jets

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UHDE HPT razvija, oblikuje in gradi visokotlačne ojačevalnike že več ko 40 let za različne vrste uporabe. Trenutni tlaki, ki se jih da doseči, dosežejo neverjetne vrednosti do 14.000 bar (203,280 psi).

Za obdelavo z vodnim curkom je UHDE HPT razvil dva osnutka za doseganje 6.000 bar (87,000 psi). Oba osnutka sta se že izkazala v praktični uporabi. Povišanje tlaka pri rezanju z abrazivnim vodnim curkom daje:
- večje rezalne hitrosti
- izboljšano kakovost reza ob enakih rezalnih hitrostih
- globlje reze brez abraziva
- manjše obratovalne stroške

V tem prispevku je predstavljena primerjava pri rezanju z abrazivnim vodnim curkom s 3.500 bar in 6.000 bar.

(Ključne besede: rezanje s curkom, curek vodni, curek abrazivni, učinkovitost rezanja, hrapavost površin)

UHDE HPT has been developing, designing and building high-pressure intensifiers to cover the widest range of applications for more than 40 years. The operating pressure can reach an incredible 14,000 bar (203,280 psi).

For water-jet technologies UHDE HPT has developed two concepts for the 6,000 bar (87,000 psi) pressure range. Both concepts have proven themselves in practical applications. The incremental increase of the working pressure greatly improves the working efficiencies and the economic benefits:
- higher cutting speed,
- improved cutting quality at the same cutting speed,
- deeper cuts without adding abrasives,
- low operating costs.

In this paper the results of comparisons between 3,500- and 6,000-bar abrasive water-jet cutting operations will be presented.

(Keywords: abrasive water jet cutting, cutting performance, surface roughness)

1 HIGH-PRESSURE INTENSIFIER

For industrial applications typical intensifiers are designed for a 3,500 to 3,800 bar design pressure and operate at pressures of 2,500 to 3,800 bar, depending on the required cutting application. Since water-jet cutting is competing with a lot of other cutting processes, like laser-cutting or plasma-cutting, it has to prove to be a superior technology to expand its market share. Therefore, a further development in the direction of higher cutting speeds and better accuracy has to be achieved.

To achieve this goal higher operating pressures for the intensifiers and the nozzle system have to be obtained. Therefore, the development of intensifiers for higher pressures is an important factor to increase the productivity of the process.

The above-described tendency to increase the pressure has already been taken into account by all intensifier manufacturers, and that is why they are now offering pumps for service pressures up to 4,200 bar.

Certainly, this is a step in the right direction, to increase cutting speeds, but the result is limited and has to be paid for with a shorter life for the HP components.

A real step to revolutionise the process is to have a system operating at 6,000 bar. Only by having such pressures available at the cutting nozzle would it be possible to cut metals or other hard materials without abrasives at an acceptable speed.

Therefore, the development of the Uhde intensifiers to pressures of up to 6,000 bar has been undertaken.

This development was based on Uhde's long-standing experience in building autofrettage pumps for 14,000 bar and the experience related to pumps for food pasteurisation systems up to 6,000 bar.

Thus, all the basic data about the fatigue life of high-pressure components under such pressures are available within Uhde and can be used for the further development of reliable intensifiers.

1.1 The flexible two-stage HP intensifier concept

In order to overcome the fatigue problems, a flexible 6 kbar two-stage pump concept was chosen to get practical experiences with such a system in a job shop during day-to-day operation. Furthermore, the investment costs of such a pumping system have to be affordable and the investment risk has to be limited by using standard – or only slightly modified – catalogue HP intensifiers as a developmental basis. One standard water-jet cutting pump (Type HP19/37-S) operates at 3.5 kbar and delivers into a buffer vessel. The pump is pressure controlled and operates in such a way that the buffer vessel is held at a constant pressure. The second-stage pump (Type HP19/45-S) is connected with its suction piping to that buffer vessel and compresses the water to the final discharge pressure of up to 6 kbar.

The flexible system arrangement shown in Figure 1 permits either the independent or joint operation of both HP intensifiers according to the specified basic characteristics of the installed pressure intensifiers for the single mode.

The use of various electrically/pneumatically actuated high-pressure valves permits the easy selection of the relevant modes (single-stage or two-stage) on the control panel of the cutting installation [1].

The advantage of this concept is that the pulsations from 0 to 6,000 bar are distributed in two stages (Figure 2). The dynamic load on the second-stage pumps is reduced to an acceptable level of 2.5 kbar. All the critical components (check-valves, packing, HP cylinder) benefit from that reduction in load.

The cylinder can be designed without problems for an infinite life [2]; this also applies for the check-valve body. The load on the check-valve seat is also greatly reduced, since the closing element is supported by the first-stage pressure and does not experience the full pressure loading from the high pressure.

Another advantage of this flexible two-stage system is that the user can decide to cut, e.g., with three of four abrasive cutting heads under normal pressures or one abrasive cutting head at 6 kbar.

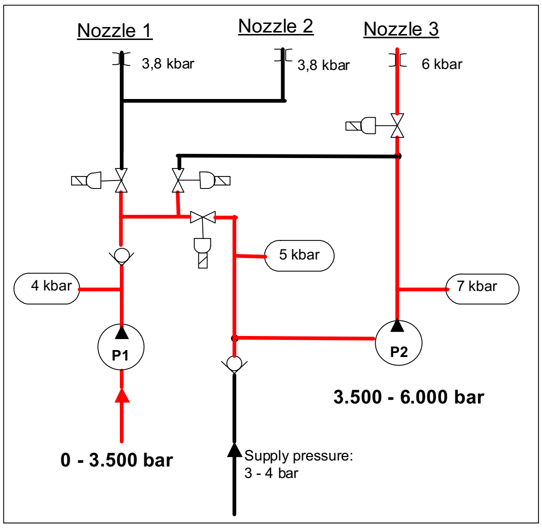

Fig. 1. *Flexible two-stage pump concept*

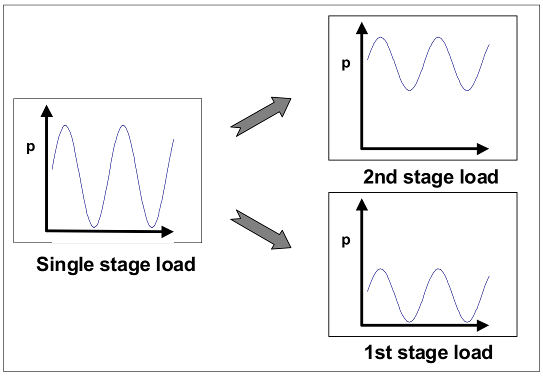

Fig. 2. *The two-stage operation for pressure load*

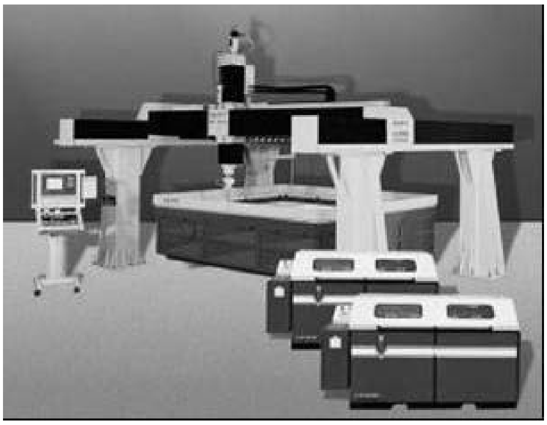

Fig. 3. *Numerically controlled 6 kbar AWIJ portal system*

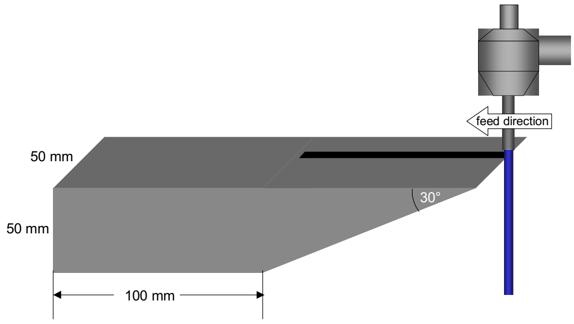

Fig. 4. *Experimental setup (schematic)*

Figure 3 shows the HP pumping system in front of a five-axis portal handling system.

1.2 HP piping

The HP piping used is made of the material HP160, which was subjected to an autofrettage treatment:

Two dimensions were chosen:

- Fixed piping: outer diameter 9.53 / inner diameter 3.21 mm
- Flexible piping: outer diameter 6.35 / inner diameter 2.39 mm

The average water discharge rate (real) through the orifice is represented by the following equation:

$$V_{eff} = c_D \cdot A_{nozzle} \cdot \sqrt{\frac{2(p_1 - p_2)}{\rho}}$$

The resulting flow rate is V_{eff} = 1.4 l/min when using an orifice of d_W = 0.20 mm at an operating pressure of 6,000 bar.

The velocity in the HP pipe, having a nominal width of 2.39 mm and taking into account turbulent flow, is calculated as follows:

$$v = \frac{V_{eff}}{A_{ti}}$$

The resulting velocity for the smallest tube within the HP unit is v = 5.4 m/s.

2 CUTTING PERFORMANCE

The cutting performance of the ultra-high-pressure abrasive water-jet at 6,000 bar was tested in comparison with a state-of-the-art 3,500 bar AWIJ. The cutting tests were performed at L&D JobShop by applying a three-axis CNC handling system. The cutting samples were wedge-shaped aluminium blocks (see Figure 4). The aim of this geometrical selection is the utilisation of the complete jet power by transferring the cutting process to a kerfing process. This also simplifies the evaluation of the test results because of the possibility of using one sample block for various cutting/kerfing trials. The aluminium block is not cut into pieces and the cutting performance for the chosen parameters can easily be read off by measuring the length of the "cutting track" on the bottom side of the sample block and dividing it by two. This works if the angle of the wedge is chosen to be 30°, because of the known angular relation sin30° equals 0.5.

On every specimen up to 10 tracks were placed and afterwards measured by reading off the distance between the tip of the wedge and the first boundary on the bottom side of the block (see Figure 5, right-hand side). This means that a restarted cutting behind a "metal bridge" will not be taken into account for the evaluation.

2.1 Test results

Cutting tests were performed with an Allfi-Centerline cutting head and an Allfi-Typ-VI-Slimline HP valve. The dimensions of the water orifice and the focussing tube were fixed as shown in Table 1.

The abrasive material used for the tests was Garnet Mesh 80.

In the first step the optimal mass flow rate of the abrasive material was investigated. Due to

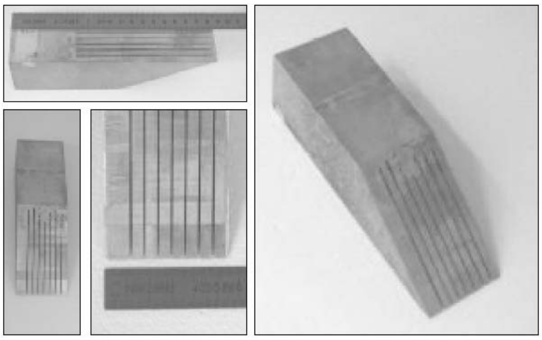

Fig. 5. *Specimen after cutting/kerfing*

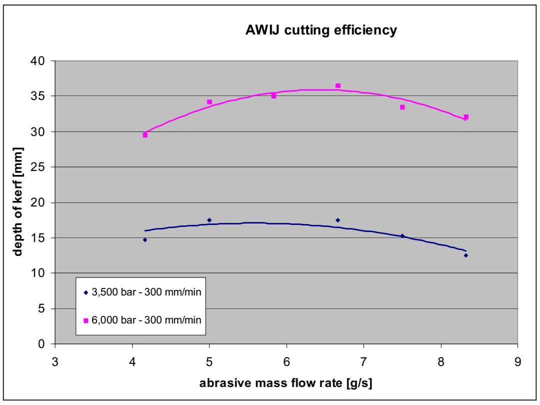

Fig. 6. *Variation of abrasive mass flow rate for finding an optimum*

Table 1. Dimensions of the abrasive cutting head

	water orifice	focussing tube
inner diameter	$d_W = 0.20$ mm	$d_F = 0.76$ mm

Table 2. Optimal abrasive mass flow rate for selected parameters

	3,500 bar	6,000 bar
opt. mass flow rate [g/s]	$m_{opt,\ 3,500} = 5.33$	$m_{opt,\ 6,000} = 6.67$

different volume rates of the water flow through the orifice based on the different pressure levels (3,500 and 6,000 bar) the capacity of the pure jet to be mixed with abrasive grains is not identical.

Therefore, cutting tests with a variation of the abrasive mass flow rate (Figure 6) were performed with the goal to find an optimum for each pressure level.

Figure 6 shows idealized graphs for finding the optimal abrasive mass flow rates, which are listed in Table 2.

In the second step the evaluated optimal mass flow was applied for further tests. Now a comparison of the cutting efficiencies of both the 3,500- and the 6,000-bar abrasive water jet could be undertaken under fair conditions.

Figure 7 shows the results of a cross-over comparison using the optimal mass flow rate for our own and the test partner's parameters (Figure 7). This is to demonstrate that the cutting performance with reduced abrasive consumption is also highly efficient.

The cutting performance, represented by the obtained depth of kerf, is shown in Table 3 for different traverse rates.

Table 3. Obtained depths of kerfs by varying the traverse rate

	3,500 bar 5.33 g/s	6,000 bar 5.33 g/s
200 mm/min	22.5 mm	42.1 mm
250 mm/min	20.0 mm	37.0 mm
300 mm/min	17.3 mm	32.8 mm
350 mm/min	14.8 mm	30.4 mm

(5.33 g/s ≅ 320 g/min)

3 SURFACE ROUGHNESS

One critical point when machining materials with abrasive water jets is the obtainable surface roughness on the cutting edge. Due to the energy loss of the jet on its way through the workpiece the surface roughness becomes worse if the energy level falls below a boundary value.

If the jet parameters are stable the quality of the cut can be influenced by the traverse rate. That means that a disproportional increase of cutting speed will lead to a loss of quality.

3.1 Test results

Tests were performed with different materials (aluminium, stainless steel) with different thicknesses for each particular sample group (20mm, 50 mm, 100 mm).

After cutting the surface roughness of each sample was measured at different positions (see Table 4) with fixed distances to the point of the jet's entrance (top side of the sample). The measurement results were generated by a sensing device working with a small diamond on the tip.

Table 4. Positions for the measurement of surface roughness

material thickness [mm]	measurement positions [mm]
20	7 /15
50	9 / 25 / 41
100	10 / 40 / 60 / 90*

* due to selected parameters the roughness could not be measured (see Figure 8)

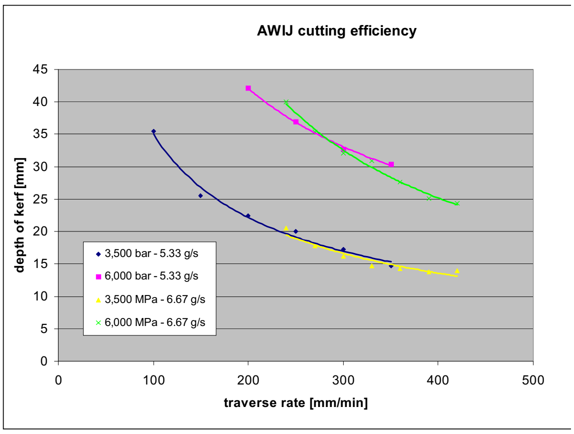

Fig. 7. *Comparison of 3,500 and 6,000 bar AWIJs with used cross-over abrasive mass flow rates*

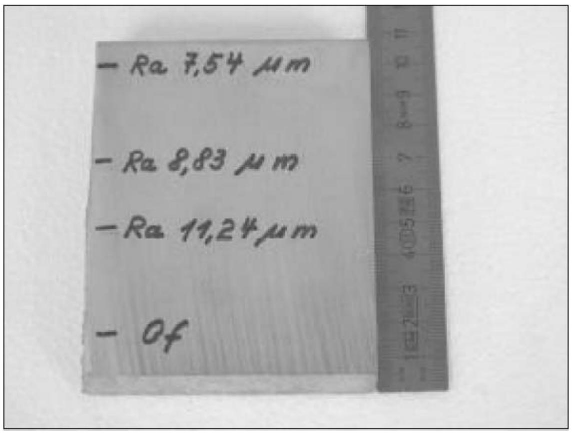

Fig. 8. *100-mm aluminium sample marked with the results of the roughness measurement*

Figure 8 shows a photograph of a 100-mm sample after measuring and marking.

In the bottom position the surface profile is presented by striation marks; the surface is both rough and wavy. The used sensing device is not able to generate data on such a profile ("Of" means "no function").

For a visualization the results from the samples can be transferred to a bar graph (Figure 9).

This shows the general trend of increasing roughness values with both an increasing traverse rate and an increasing distance from the jet's point of entrance.

In Figures 10 and 11 the results from stainless-steel samples are compared. In these graphs the points represent one combination of pressure level and measuring position (e.g., position 25 mm and 3,500 bar) are aligned with an idealized straight line.

For each pressure level these lines intersect at that point where the traverse rate is reached, which leads to similar surface qualities on both the top and

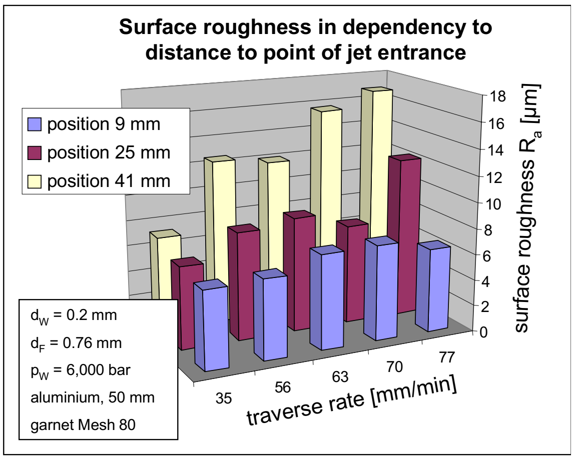

Fig. 9. *Allocation of roughness values on the cutting edge, depending on the cutting speed*

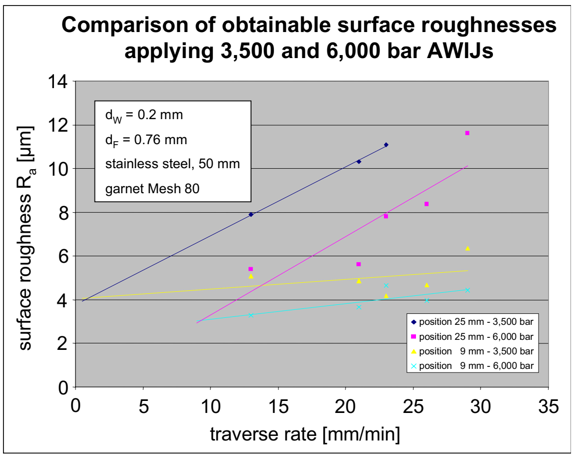

Fig. 10. *Prediction of the maximum tarverse rates for quality cuts (50-mm stainless steel)*

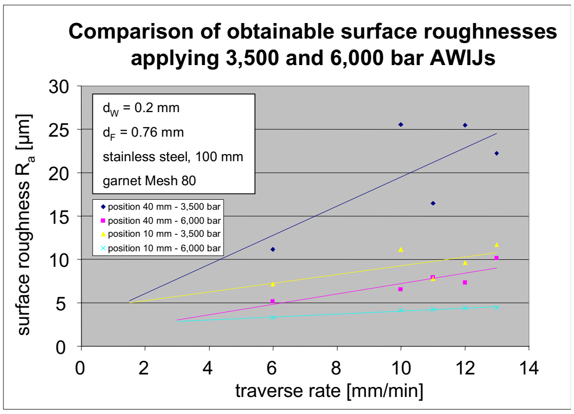

Fig. 11. *Prediction of the maximum tarverse rates for quality cuts (100-mm stainless steel)*

Table 5. *Obtained surfaces qualities on 50-mm samples*

traverse rate [mm/min]		surface roughness R_a [µm]		
		measurement position		
aluminium	st. steel	9 mm	25 mm	41 mm
	13	3.27	5.38	7.86
	21	3.64	5.62	11.90
	23	4.65	7.81	--
	26	3.96	8.35	--
	29	4.42	11.63	--
35		5.97	6.33	7.28
56		6.10	8.27	12.58
63		7.28	8.81	12.08
70		7.36	7.62	15.73
77		6.43	12.28	16.95

the bottom of the cutting edge. This means a quality cut with a constant roughness over the whole surface.

As expected, the cutting speed for quality cuts with a 6,000 bar AWIJ is much higher than that of the compared 3,500 bar AWIJ.

Table 5 shows the results of trials with 50-mm samples.

4 CONCLUSIONS AND OUTLOOK

The tests made at L & D JobShop show an increase in the machinable material thickness at a proportion of about 87%. This result is reached by an increase in the pressure of 71%. To find reliable data for the particular top cutting speed of each selectable parameter field the number of trials must be increased enormously.

The increase of cutting performance with a constant abrasive mass flow rate gives an extra economic benefit for the application of this ultra-high-pressure technology. By doubling the cutting speed compared to the 3,500 bar systems a 6,000 bar AWIJ consumes only half of the abrasive material for the same cutting application. Being aware of the large proportion of cutting cost that results from the consumption of abrasive material, the increase of pressure leads to an effective opportunity to save money.

The cutting efficiency of 6,000 bar abrasive water injection jets brings further progress for this technology, being in continuous competition with other unconventional cutting technologies, like laser beam, flame, or plasma-arc cutting. The increase of the cutting speed at stable qualities of the cutting edge in comparison with 3,500 bar systems allows us to offer JobShop activities where in the past no economic success was achievable.

Also, the enhancement of possible material thickness that can be machined opens new application fields for this innovative technology.

The ongoing development with the goal to increase the lifetime of wear parts in, e.g., the pump units will lead to further acceptance for what is still referred to as an unconventional tool.

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