Strojniški vestnik - Journal of Mechanical Engineering 51(2005)3, 160-171
UDK - UDC 621.9.048:621.753.5
Strokovni članek - Speciality paper (1.04)

Uporabnost obdelave z abrazivnim vodnim curkom v orodjarstvu

The Versatility of Abrasive Water-Jet Machining in the Toolmaking Industry

Boštjan Juriševič - Davorin Kramar - Mihael Junkar

Obdelava z abrazivnim vodnim curkom (AVC) je neobičajni postopek, ki temelji na odnašanju materiala obdelovanca kot posledice erozije trdih abrazivnih delcev, pospešenih z vodnim curkom velikih hitrosti. Prednost AVC pred drugimi odrezovalmini postopki je v zmožnosti obdelave praktično kateregakoli materiala in zanemarljivi toplotno prizadeti coni v obdelovancu. Poleg tega je obdelava z AVC ekološko zelo sprejemljiva, saj uporablja le vodo in naravne abrazive. Področje uporabe AVC sega od čiščenja in utrjevanja površin, kjer se večinoma uporablja le vodni curek (VC), obrisnega rezanja, teksturiranja, frezanja pa vse do preoblikovanja in uporabe v medicini. Razvoj tehnologije z namenom povečati natančnost obdelave gre v smeri uporabe višjih tlakov ter manjših premerov curkov in finejših abrazivov, kar bi odprlo številne možnosti na področju mikro obdelave. V prispevku so opisane najnovejše raziskave s področja obdelave z AVC in VC, pri katerih je bil Laboratorij za alternativne tehnologije (LAT) dejavno udeležen.

(Ključne besede: orodjarstvo, obdelave s curkom, curek vodni, curek abrazivni)

Abrasive water jet (AWJ) is a non-conventional machining process in which the material-removal process in the workpiece takes place as a result of the erosion caused by high-speed abrasive particles. Several characteristics, like the ability to machine practically any known material and the absence of any relevant heat-affected zone (HAZ), make the AWJ process highly competitive, especially in the case of hard-to-machine materials. The process is environmentally acceptable, since only water and natural abrasives are used. The range of applications is wide: from cleaning and surface preparation to cutting, deep-hole drilling, turning and milling. Since its introduction, a wide range of applications and new opportunities (medicine, forming) are showing all the potentials of this technology. This contribution aims to present the latest research in the field of AWJ and WJ implementation in the toolmaking industry that have been tested and researched at the Laboratory for Alternative Technologies (LAT).

(Keywords: toolmaking, machining processes, abrasive water jets)

0 UVOD

Obdelava z AVC spada v široko skupino postopkov, pri katerih je orodje curek z velikimi hitrostmi. Poleg obdelave z AVC je zelo razširjena obdelava z VC, ki se uporablja za čiščenje, obdelavo in utrjevanje površin, preoblikovanje, rezanje mehkejših materialov, kot podpora pri običajnih odrezovalnih postopkih, recikliranju ter nenazadnje v medicinskih uporabah. Obdelava z abrazivnim curkom (AC), pri katerih so abrazivni delci pospešeni s tokom zraka z velikimi hitrostmi, se večinoma uporablja za obdelavo površin

0 INTRODUCTION

AWJ belongs to a wide group of machining processes, but unlike traditional, rigid machining tools, the tool is a high-speed jet of water. Besides AWJ, which is mostly used for cutting, the WJ process has a dominant role in the field of cleaning, surface preparation and hardening, forming, cutting of softer materials, assisting to conventional cutting processes, recycling and medical applications. Another process from this group is abrasive jet machining (AJM), where a high-speed air jet accelerates the abrasive particles. This process is mostly used for surface treatments like cleaning, engraving, tex-

(čiščenje, teksturiranje, graviranje, poliranje). Skupne lastnosti obdelav s curkom z velikimi hitrostmi so velika koncentracija energije, odsotnost toplotno prizadete cone v obdelovancu ter majhne sile na njem. Vsi navedeni postopki so mehanski, orodje (curek) pa se neprestano obnavlja.

Za obdelavo trših materialov, uporabljenih v orodjarstvu je najbolj primerna obdelava z AVC, kateri bo v nadaljevanju posvečene največ pozornosti. Po kratkem pregledu razvoja postopka obdelave z AVC so v nadaljevanju predstavljena osnovna načela delovanja. Sledi pregled področja uporab ter smeri nadaljnjega razvoja tehnologije. Na koncu so podani sklepi z razpravo o možnostih uporabe postopka predvsem na področju orodjarstva.

Namen predstavljenega prispevka je prikazati možnosti za uporabo AVC in VC na področju orodjarstva, ne le pri izdelavi orodij, ampak tudi pri načrtovanju tehnologije preoblikovanja. Izkazalo se je, da se lahko predstavljena tehnologija uporabi pri izdelavi prototipov pri preoblikovanju pločevine, čemur bo posvečena posebna pozornost.

1 RAZVOJ POSTOPKA

Postopek obdelave z AVC je bil razvit v zgodnjih osemdesetih letih prejšnjega stoletja iz postopka obdelave z VC. Izkazalo se je, da lahko curek pare ali stisnjenega zraka pri poškodbah napeljav prereže leseno palico [1] ter da vodne kapljice lahko poškodujejo površino kril na letalu [2], kar je privedlo do prve uporabe VC v industrijske namene [3]. Dejansko pa prve uporabe VC v rudarstvu segajo na začetek 20. stoletja [4]. Leta 1983 je bil izdelan in patentiran prvi tržni sistem za obdelavo z AVC [5], kjer so z dodajanjem abrazivnih delcev v VC omogočili obdelavo praktično vseh materialov.

Od takrat je razvoj postopka obdelave z AVC hitro napredoval in je dandanes eden izmed najobetavnejših. Leto kasneje je bil razvit prvi suspenzijski sistem, ki se zaradi velike stopnje obrabe komponent in počasnih odzivnih časov kjub številnim prednostim (večja energijska učinkovitost, kakovostnejša obdelava, nižji tlaki vode itn.), ni uveljavil v praksi. Slika 1 prikazuje razvoj obdelave z AVC.

turing, and polishing. A common feature of all these jet-based processes is a high energy concentration, small forces on the workpiece and the absence of a relevant HAZ. All these processes are mechanical, and the tool (a high-speed jet) is self renewing during whole of the machining process.

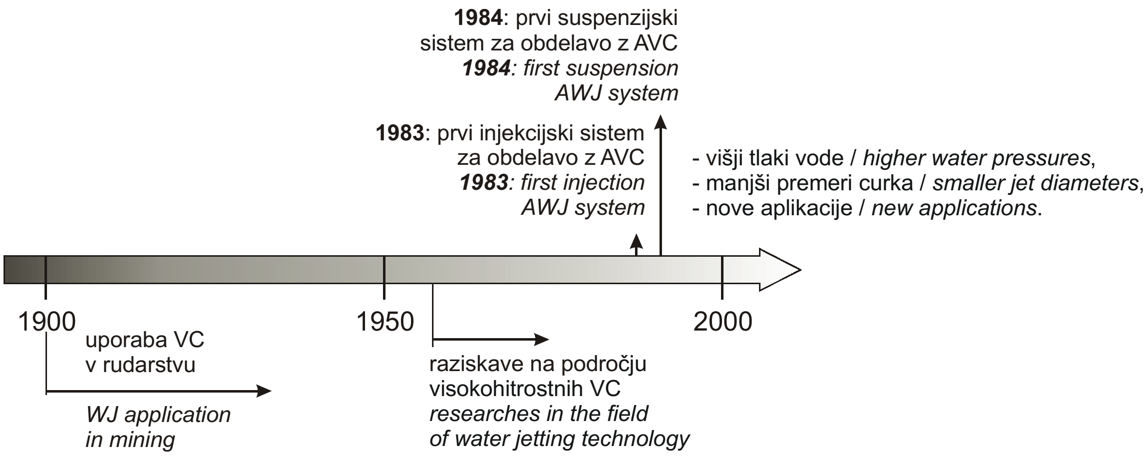
For hard-to-machine materials, as is the case in toolmaking, the AWJ machining process is very appropriate, and will be explained in more details in the following sections. A short overview of the AWJ process will be given, and its working principles will be explained. After a short preview of the applications, and predictions of the further developments and expectations of high-speed jet technology, special attention will be given to the fields of AWJ 3D machining and WJ incremental-forming investigations, which have been performed in our laboratory. Finally, the role of both AWJ and WJ machining process in the toolmaking industry will be described.

The objective of this contribution is not only to show the possibilities of AWJ and WJ machining for tool and die production, but also to point out the possibilities of using this technology in technology planning, such as in the case of sheet-metal forming. An emerging application is WJ incremental sheet-metal forming, which can be used for prototype and small-batch production.

1 DEVELOPMENT OF AWJ TECHNOLOGY

AWJ technology was developed in the early 1980s from the WJ process. Earlier, in the 1960s, it was observed that a jet of steam or air in a pipeline leakage could easily cut a wooden beam [1]. In the same period it was also known that high-speed water droplets could damage airplane wings [2]. These findings led to the first uses of high-speed WJs in industrial applications [3], while the first application of WJs in mining began at the start of the 20th century [4]. In 1983 the first commercial system, known as injection AWJ, was available [5]. In this system, hard abrasive particles are added to the WJ, which makes it possible to machine practically any material.

Since then the AWJ process has evolved very rapidly, and today it is one of the most promising technologies. A year later, the first suspension AWJ was developed; in this case a suspension of water and abrasive is pressed through a nozzle where a high-speed jet is formed. Even if the suspension system is, in many aspects, (higher efficiency, better machining performance) superior to the injection AWJ system, it is not used so much due to the higher degree of wear of the components and the longer starting and stopping times for the jet. Figure 1 shows the historical development of the WJ and AWJ technologies.



Sl. 1. *Razvoj postopka obdelave z VC in AVC*
Fig. 1. *Historical development of WJ and AWJ technology.*

Dandanes se najbolj uporabljajo tako imenovani injekcijski sistemi za obdelavo z AVC, katerih načelo delovanja je podrobneje predstavljen v naslednjem poglavju.

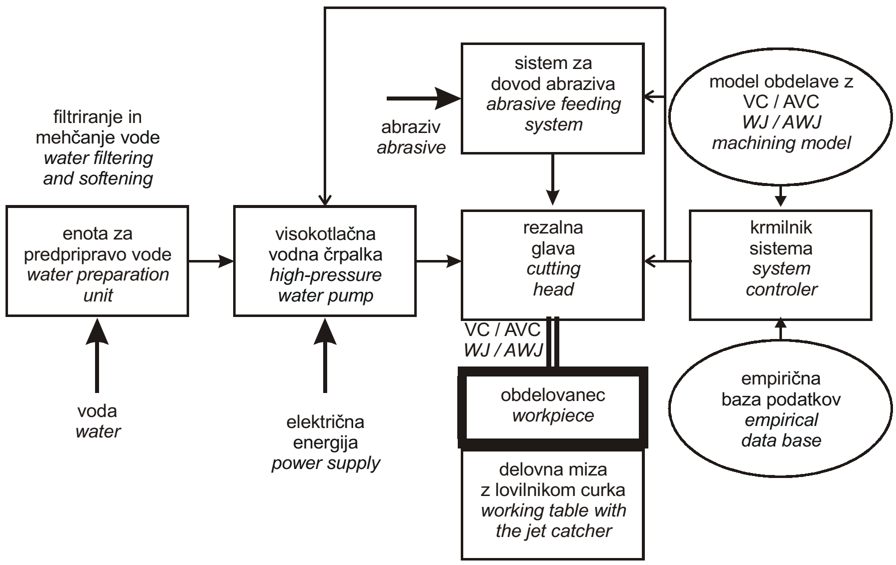
As mentioned before, today, the most common systems are AWJ, the working principle of which is explained in more detail in the next section.

2 NAČELO DELOVANJA INJEKCIJSKEGA SISTEMA Z AVC

2 WORKING PRINCIPLE OF THE INJECTION AWJ SYSTEM

Injekcijski sistem za obdelavo z AVC v splošnem sestavljajo: visokotlačna vodna črpalka (batna črpalka ali hidravlični ojačevalnik), rezalna glava, sistem za dovod in doziranje abraziva, delovna miza, lovilnik curka po obdelavi ter krmilni sistem, kakor prikazuje shema na sliki 2.

The main components of an injection AWJ system are: a high-pressure water unit (plunger pump or hydraulic amplifier), a cutting head, an abrasive feeding system, a working table, a jet catcher and a controlling unit, as shown in Figure 2.



Sl. 2. *Shema sistema za obdelavo z AVC*
Fig. 2. *Main components of an injection AWJ cutting system*

Z visokotlačno črpalko se tlak vode dvigne na nekaj sto MPa. Danes se za AVC običajno uporablja tlak 400 MPa, kar je odvisno od uporabe, v prihodnosti pa se bodo najverjetneje uporabljali tlaki do 1000 MPa. V rezalni glavi nastane curek vode z veliko hitrostjo, abraziva in zraka, ki predstavlja orodje. Sama rezalna glava je sestavljena iz vodne šobe, kjer najprej nastane vodni curek z veliko hitrostjo, ki gre skozi mešalno komoro, v katero se dovaja abrazivne delce. Pod mešalno komoro je nameščena fokusirna šoba, kjer se abrazivni delci pospešujejo do hitrosti, ki omogočajo odnašanje materiala obdelovanca. Zaradi VC z veliko hitrostjo se ustvari podtlak, kar ima za posledico vsesavanje zraka skozi dovod abraziva. Tok zraka ima pomembno funkcijo prenosa abraziva v mešalno komoro in začetnega pospeševanja abraziva. Obdelovanec je običajno vpet na delovno mizo, podajalno gibanje pa opravlja rezalna glava (orodje), ki je pritrjena na postavljalni sistem. Celoten sistem za obdelavo z AVC je računalniško krmiljen in nastavlja optimalne obdelovalne parametre (podajalna hitrost, tlak vode, masni tok abraziva itn.). Sila curka je običajno med 10 in 20 N, kar omogoča preprosto vpenjanje in rezanje kompozitnih materialov in tankostenih struktur brez poškodb. Pri obdelavi z AVC je treba poudariti, da obdelovanec pride v stik z vodo, kar je treba upoštevati pri materialih, občutljivih na vodo.

3 PODROČJE UPORABE TEHNOLOGIJ VC IN AVC

Zaradi svoje enkratne lastnosti obdelave praktično vseh materialov je AVC vsestransko orodje. Sistemi za obdelavo z AVC omogočajo tudi obdelavo z VC, kar bistveno razširi področje uporab rezanja na utrjevanje in pripravo površin ter celo na preoblikovanje pločevine. Na sliki 3 so prikazane uporabe VC in AVC.

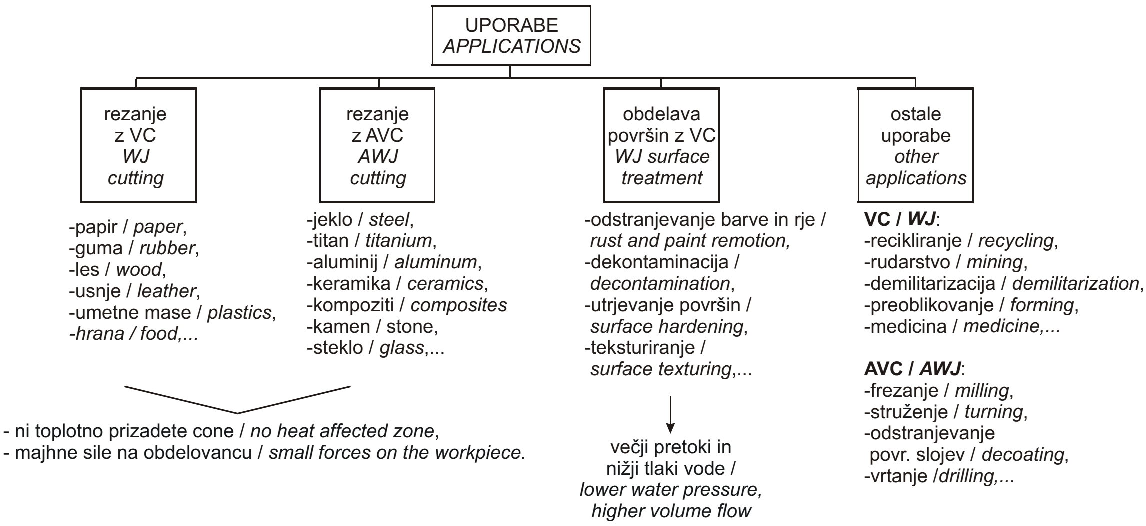
V nadaljevanju so predstavljene uporabe AVC in VC, ki so zanimive predvsem na področju orodjarstva, tako izdelave orodij kakor tudi pri načrtovanju tehnologije preoblikovanja. Prikazano je koračno preoblikovanje pločevine z VC, izdelava 3D oblik, vrtanje globokih lukenj in odstranjevanje trdih površinskih slojev z AVC.

The water pressure is raised in the high-pressure unit to several hundreds of MPa, depending on the selected application. For AWJ, today, the most commonly used water pressure is up to 400 MPa, but in the future it seems that pressures up to 1000 MPa are very likely to be used. A high-speed AWJ composed of abrasive, water and air is formed in the cutting head, which represents the tool. There is an orifice at the top of the cutting head, where a high-speed WJ is formed. The fully developed WJ passes through the mixing chamber, where abrasive particles are entrained from the abrasive feeding system. The focusing tube is fixed on the other side of the mixing chamber and aligned with the orifice. There the abrasive particles are accelerated to velocities that enable the material-removal process in the workpiece. In the mixing chamber, an under pressure is established as a result of the high-speed WJ, and this initiates an air flow through the abrasive inlet. This air flow has an important role in the acceleration process of the abrasive and in its transportation into the mixing chamber. In most cases the workpiece is fixed on the working table and the jet moves along the contour that has to be cut. The control unit optimally adjusts the process parameters (cutting-head kinematics, water pressure, abrasive mass flow, stand-off distance, impact angle of the jet, etc.). Because the force of the jet is relatively small (in the range of 10 to 20 N), no special clamping systems are required, and the process is adequate for machining composite and hollow structure parts. In the case of machining water-sensitive material, it is important to take into account that the workpiece will come into contact with water.

3 APPLICATION FIELDS OF WJ AND AWJ TECHNOLOGY

Due to its unique characteristic of being able to machine practically any known material, the AWJ is a multifunctional tool. All commercial AWJs can also be used for WJ machining, which further increases the application fields from cutting to surface preparation, cleaning, forming, etc. Figure 3 shows the application fields of this technology.

From this wide field of application we will further present the incremental forming of sheet metal with a WJ, the machining of 3D features, small deep-hole drilling and decoating or hard-top-layer removing with the AWJ. All these applications have tremendous potential in the toolmaking industry for producomg tools and for technology-planning purposes.



Sl. 3. *Uporabe obdelave z VC in AVC*
Fig. 3. *Application fields of AWJ and WJ technology*

3.1 Koračno preoblikovanje z VC

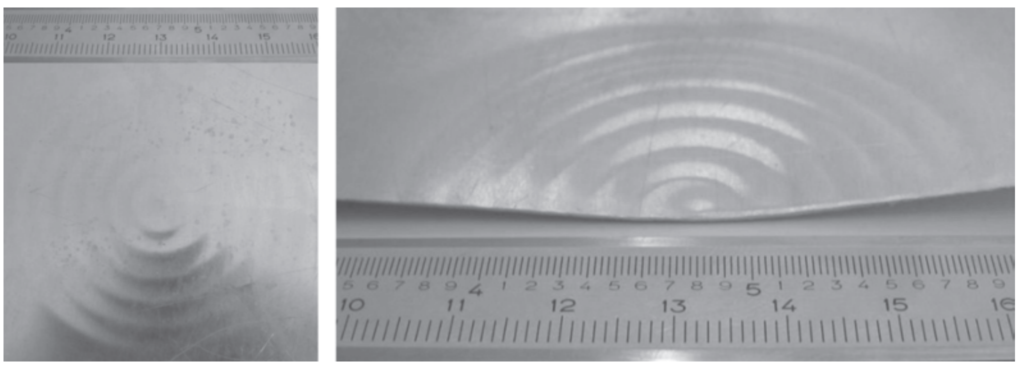
Na področju preoblikovanja smo opravili raziskavo možnosti uporabe VC z velikimi hitrostmi za koračno preoblikovanje pločevine [6]. Prvi rezultati so pokazali, da se lahko VC uporabi kot orodje, ki s primerno nastavitvijo parametrov postopka preoblikuje pločevino v poljubno obliko. Na sliki 4 je prikazan rezultat poskusa koračnega preoblikovanja aluminijaste pločevine debeline 0,3 mm. Izkazalo se je, da je v material mogoče vnesti plastične deformacije, ne da bi se pri tem poškodovala površina obdelovanca.

Že samo rezanje z AVC je zelo uporabno pri izdelavi rondel in preizkušancev na področju preoblikovanja pločevine. Cene običajnih sistemov

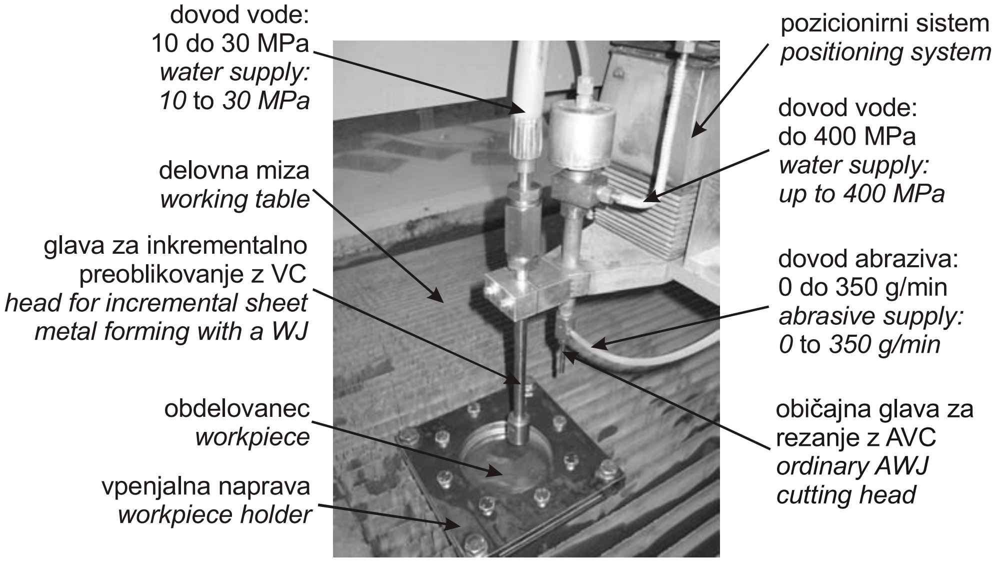
3.1 Incremental sheet-metal forming with a WJ

In the field of forming we made a feasibility study of incremental sheet-metal forming with a high-speed WJ [6]. The first results are extremely encouraging and show that it is possible to form sheet metal with a desired shape by using a WJ with the proper process-parameters setup. Figure 4 shows one of the first results of incremental sheet-metal forming of a 0.3-mm-thick aluminum alloy plate. By using a WJ as a forming tool it is possible to put plastic deformations in the material without damaging the workpiece surface.

AWJs are already widely used as cutting tools in sheet-metal forming, especially in prototype development and for material-testing purposes. Today, a commercial system for AWJ cutting costs be-



Sl. 4. *Koračno preoblikovanje pločevine z VC [6]*
Fig. 4. *Incremental sheet-metal forming with a high-speed WJ [6]*



Sl. 5. *Kombiniran sistem za rezanje z AVC in koračno preoblikovanje z VC [6]*
Fig. 5. *Combined system for AWJ cutting and WJ incremental forming [6]*

za obdelavo z AVC se gibljejo med 150 in 300 tisoč evrov. Za nadgradnjo takega sistema v sistem, ki bi omogočal tudi koračno preoblikovanje bi bilo treba vložiti še nadaljnjih 50 do 100 tisoč evrov, ker je za preoblikovanje potrebna črpalka z večjim pretokom vode. Primer take nadgradnje je prikazan na sliki 5, kjer je poleg običajne glave za rezanje z AVC pritrjena še dodatna glava za koračno preoblikovanje z VC.

Sistem, prikazan na sliki 5, omogoča rezanje in koračno preoblikovanje pločevine, kar je zelo uporabno predvsem v prototipnih in majhnih serijah ter pri raziskavah in načrtovanju tehnologije preoblikovanja pločevine.

3.2 Izdelava 3D oblik z AVC

Pri izdelavi orodij je poleg 2D oblik treba narediti številne 3D oblike v težko obdelovalne materiale. V ta namen smo opravili raziskavo uporabnosti AVC ter primerjavo z drugimi primernimi postopki, to so žična erozija, lasersko rezanje ter frezanje z velikimi hitrostmi [7]. Določili smo dva načina obdelave. Prvi način vsebuje obdelavo oblik, ki se lahko izdela brez nadzora penetracije AVC, ter jo poimenovali 2,5D obdelava. V drugo skupino smo uvrstili obdelavo tistih oblik, pri katerih je treba nadzorovati globino penetracije curka, kar smo označili kot 3D obdelavo.

Pri 2,5D obdelavi z AVC je treba upoštevati določene značilnosti postopka, to sta

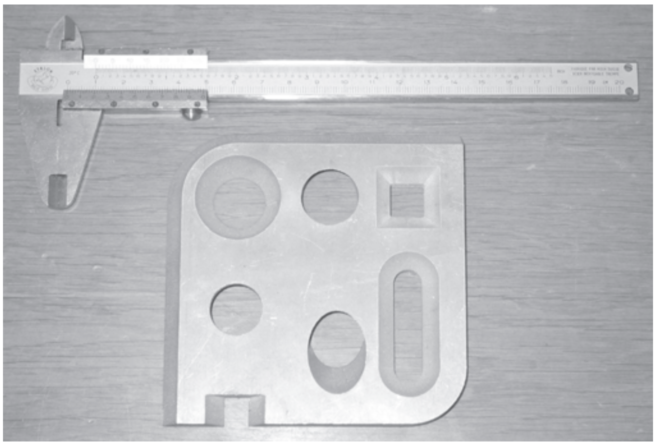
tween 150 and 300 thousand euros. To upgrade such a system in order to have a combined cutting and incremental forming system, an additional investment of 50 to 100 thousand euros is required. For such an application, an additional forming head and water pump are needed, because for forming operations a pump with a higher water-flow rate is required. This kind of combined system is shown in Figure 5, where besides an AWJ cutting head, a head for incremental forming is placed.

The system shown in Figure 5 is very useful for prototype and small-batch production, but also as a powerful tool for technology planning in the field of sheet-metal forming, where the development time can be drastically reduced.

3.2 Machining of 3D features with an AWJ

In the toolmaking industry, as well as 2D, many 3D features are also commonly encountered, which have to be machined in hard-to-machine materials. In order to define the possibilities of AWJ in the toolmaking industry, we made a comparison with high-speed milling, wire EDM and laser cutting [7]. We have defined two types of machining, 2.5D and 3D. In the first case we controlled the process in two directions, while in case of 3D machining we also controlled the depth of penetration of the AWJ in the workpiece.

In 2.5D machining some characteristics of the AWJ process, like the taper of the cut and the curvature of the cutting front, have to be taken into



Sl. 6. *Izdelava 2,5D oblik z AVC [7]*
Fig. 6. *Machining of 2.5D features with a AWJ [7]*

stožčasta oblika reza in ukrivljenost rezalnega čela v obdelovancu. Slednje je še posebej pomembno pri spremembah smeri obdelave. Na sliki 6 so prikazane 2,5D oblike, izdelane z AVC.

2,5D oblike na sliki 6 so bile, zaradi primerjave z drugimi postopki, izdelane tudi z žično erozijo in rezkanjem z velikimi hitrostmi. Iz študije je bilo razvidno, da običajni sistemi za rezanje z žično erozijo ne omogočajo izdelave posameznih oblik, v primeru rezanja z velikimi hitrostmi pa so potrebna številna prevpenjanja.

Bistveno bolj zahtevna je izdelava 3D oblik, kjer je treba nadzorovati globino penetracije AVC v obdelovanec. To je mogoče izvesti s krmiljenjem parametrov postopka med samo obdelavo ter z ustrezno kinematiko AVC vzdolž obdelovanca. Primer 3D oblik je podan na sliki 7, kjer sta bila z AVC izdelana pravokotna žepa v aluminij in jeklo.

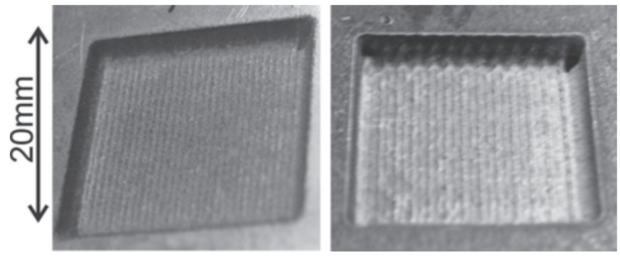
V obeh primerih se je postopek obdelave z AVC izkazal kot primerna tehnologija, predvsem zaradi zmožnosti obdelave praktično kateregakoli

account. It is very important to know how much the cutting front is curved and take appropriate control actions, especially when cutting corners. Figure 6 shows some 2.5D features made by AWJ.

To compare the AWJ process with other processes, the features in Figure 6 were also machined by wire EDM and high-speed milling. It was observed from these studies that a standard wire EDM system cannot machine all the features, and in the case of high-speed milling, some overclamping of the workpiece would be required.

3D features are much more complicated to machine, where the depth of penetration of the AWJ in the workpiece has to be controlled. The depth-of-penetration control can be executed using the appropriate kinematics or by optimal control of the process parameters. As a case study we machined two rectangular pockets in aluminum alloy and steel, as shown in Figure 7.

In both cases, 2.5D and 3D AWJ machining proved itself as a useful technology in the toolmaking industry for its unique capability to machine practically any kind of material. Furthermore, no relevant HAZ is present on the machined surface. Taking into account



Sl. 7. *Izdelava 3D oblik z AVC [7]*
Fig. 7. *Machining of 3D features with a AWJ [7]*

materiala ter odsotnosti toplotno prizadete cone. Z nadaljnjim razvojem ima obdelava z AVC veliko možnosti za nadomestitev že uveljavljenih tehnologij na področju orodjarstva.

3.3 Vrtanje majhnih in globokih lukenj z AVC

V orodjarstvu, še posebej pri izdelavi kalupov za brizganje, se pojavlja veliko povpraševanje po izdelavi majhnih globokih lukenj v materiale, ki jih drugače težko obdelujemo. Navadno v takih primerih uporabljamo elektroerozijo, laser in elektronski snop. Slaba stran vseh teh postopkov je, da na površini luknje povzročajo toplotno vplivno območje (TVO). V primeru vrtanja z AVC je TVO praktično zanemarljivo. Izvedena je bila raziskava [8], pri kateri smo opazovali vpliv parametrov postopka na obliko izvrtane luknje v aluminij in v orodno jeklo OCR 12 (utrjeno in neutrjeno). Slika 8 prikazuje rentgensko fotografijo izvrtanih lukenj.

AVC omogoča vrtanje v vsak material. Celo v steklo, ki se uporablja kot akustični izolator v notranjosti stavb. Primer take uporabe je prikazan na sliki 9, kjer so luknje s premerom manj kot 1 mm zvrtane v steklo debeline 5 mm.

Glavni problem pri vrtanju lukenj z AVC v steklo je zanesljivost postopka. Zahteva naročnika je izvrtati do 40.000 lukenj na kvadratni meter steklene plošče. V primeru napake na eni sami luknji nastane izmeček. Najbolj pogost vzrok za napako je zamašitev dotoka abraziva. V takem primeru sama voda razbije steklo na mestu, kjer bi morala biti luknja.

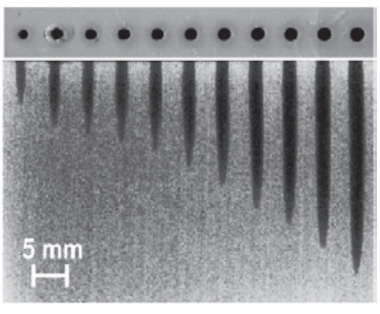
all of these facts, it can be concluded that by using AWJ instead of other processes, complex features in materials with advanced properties can be machined much better, more safely, and more quickly.

3.3 AWJ small and deep hole drilling

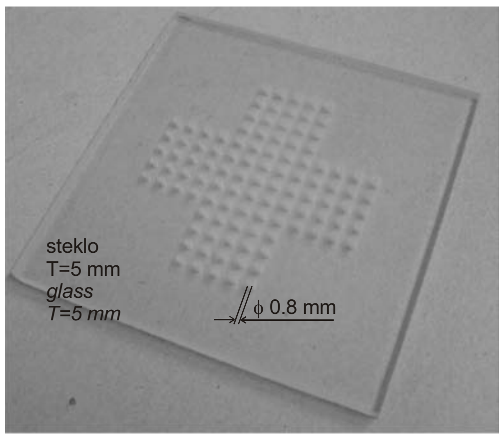
In the toolmaking industry, especially in the production of molding tools, there is a big demand for the machining of small deep holes in hard-to-machine materials. For small- and deep-hole drilling in such materials EDM, laser and electron-beam machining (EBM) are normally used. The weak point of all these processes is that they produce a HAZ on the surface of the hole. In the case of AWJ drilling the HAZ is practically irrelevant. A study was carried out [8] where the influence of the process parameters on the hole shape drilled in aluminum alloy AlMg1SiCu and steel OCR12 (hardened and non hardened) was observed, as shown in Figure 8.

Using AWJ, holes can be drilled in any material, even in glass, which can be used as acoustic isolation in buildings. An example of this application is shown in Figure 9, where holes of less than 1 mm in diameter are drilled in 5-mm-thick glass.

The main problem of drilling in glass for this application is the reliability of the process. The customer requirement is to drill up to 40,000 holes on 1 square meter of glass plate. If just one of these holes is not machined well, a useless product has been made. The most common reason for this is abrasive jamming. This problem happens when the water alone breaks the glass in the place where the hole was meant to be.



Sl. 8. *Rentgenska slika v aluminij izvrtanih lukenj [8]*
Fig. 8. *An X-ray photograph of holes drilled in aluminum alloy [8]*



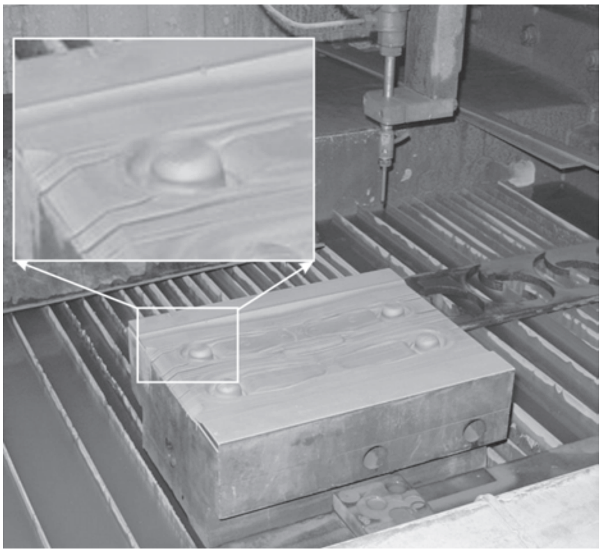
Sl. 9. *Luknje, vrtane z AVC v 5 mm debelo steklo*
Fig. 9. *Holes drilled by AWJ in 5-mm-thick glass*

3.4 Odstranjevanje utrjenih površinskih slojev

V primeru obnove obrabljenega orodja za hladno utopno kovanje je problematičen utrjen površinski sloj, ki ga je treba odstraniti. Običajno to izvajamo z rezanjem z velikimi hitrostmi s posebno trdimi nanosi na rezkalnem orodju. Tudi pri takih rezalih je opazna obraba. Za odstranitev utrjenega sloja s površine 400 kvadratnih mm poškodujemo ali uničimo kar nekaj rezkalnih orodij, kar nanese skupaj s stroški obdelave te površine okrog 400 evrov, za to pa porabimo več ko dve uri. Odstranjevanje utrjenih površinskega sloja takega orodja z AVC je prikazano na sliki 10 in je bilo izvedeno v LAT. V tem primeru smo porabili manj ko 1 uro časa, obdelava pa je stala okrog 150 evrov.

3.4 Decoating of hard surface layers

The hard layer on a worn cold forging tool is always difficult to remove when the renewing of such a tool is planned. Conventionally, this is done by high-speed milling with an extra-hard-coated tool. Even with such a tool, however, rapid wear is present. To remove the hard coating from a 400-square-mm area, several milling tools are damaged or destroyed, together with the machining costs of around 500 euros, and it takes more than two hours to complete the process. The decoating with AWJ of such a tool, shown in Figure 10, was performed in LAT. In this case it takes less than 1 hour and costs about 150 euros.



Sl. 10. *Odstranjevanje trdih površinskih slojev na obrabljenem orodju za hladno kovanje*
Fig. 10. *Decoating of hardened layer on a worn cold-forging tool*

4 RAZVOJ NA PODROČJU OBDELAVE S CURKI Z VELIKIMI HITROSTMI

Razvoj na področju obdelave s curki z velikimi hitrostmi, kamor spadata AVC in VC, gre v dveh smereh. Na področju gradbeništva je v velikem vzponu uporaba VC za čiščenje ter AVC za rušenje ter rezanje in vrtanje armiranega betona. Druga smer razvoja pa gre v smeri izboljšanja natančnosti obdelave, miniaturizacije izdelkov ter večosne obdelave.

Slednje je za področje orodjarstva bistveno bolj zanimivo. V zadnjem času so na voljo vodne črpalke, ki omogočajo tlake do 690 MPa, razvijajo pa se nove s tlaki do 900 MPa in več [9]. Na področju

4 FURTHER DEVELOPMENTS IN THE FIELD OF HIGH-SPEED JET TECHNOLOGY

The developments in the field of high-speed jet technology, where the AWJ and WJ have a dominant role, goes in two main directions. In the field of civil engineering and construction WJs are used for cleaning and surface treatment, while AWJs are used for demolition, cutting and drilling of armored concrete. The other direction is the development of multi-axes high-precision machining systems to be used in the field of micro-machining.

From the toolmaking point of view, the developments in the direction of miniaturization are very interesting. The new water-pressure units can reach presrazvoja rezalnih glav se intenzivno iščejo nove rešitve, ki bi omogočale AVC z boljšimi obdelovalnimi lastnostmi. Premeri AVC se manjšajo, obstajajo že curki s premerom 50 mm, razvijajo se abrazivi s premerom nekaj nm [10]. Z namenom izboljšati obdelovalne lastnosti AVC so bile opravljene raziskave na področju dodajanja polimerov v vodo [11]. Veliko pozornosti pa se v zadnjem času posveča izboljšavi samega stroja za obdelavo z AVC v smislu izboljšanja dinamičnih in statičnih lastnosti, ki zagotavljajo večjo natančnost izdelave. Nove tehnike ([12] in [13]) in strategije rezanja, kakršno je rezanje z več prehodi [14], osciliranje curka [15] in modulacijske tehnike [16], pa omogočajo odpravo napak, npr. strijavost in stoščastost reza in izboljšajo hrapavost reza. V določenih primerih, npr. rezanje z AVC v več prehodih [14], smo dokazali, da je mogoče izboljšati kakovost rezanja, pri tem pa skrajšati čas in stroške rezanja.

sures up to 690 Mpa, and the developers of this equipment anticipate an increase in that water pressure up to 900 MPa, and more will be available soon [9]. In the field of cutting heads, new solutions are being developed that will allow the formation of AWJs with better performance. New cutting heads already enable the formation of AWJs with diameters down to 50 mm, by using abrasive particles with sizes of a few nm [10]. Some investigations were done by using polymer additives in water to increase the machining performance [11]. Also, from the machine point of view, the objective is to improve the static and dynamic characteristics of the system in order to achieve better machining precision. New cutting techniques ([12] and [13]) and strategies, like multipass cutting [14], jet oscillation [15] and modulation techniques [16], enable us to reduce the surface roughness and taper of the cut. In some cases, like AWJ multipass cutting [14], we have proved that it is possible to increase the cutting quality and reduce the machining time and costs at the same time.

5 SKLEPI

Obdelava z AVC oz. s curki z velikimi hitrostmi nasploh ima velike možnosti na veliko področjih, od obrtniške proizvodnje in servisnih storitev, vse do avtomobilske in letalske industrije. Zaradi zmožnosti obdelave praktično kateregakoli materiala ima AVC velike možnosti uporabe tudi na področju orodjarstva. Poleg uporab AVC iz predhodne študije [14], se odpirajo nova področja predvsem pri izdelavi orodij iz materialov, ki jih drugače praktično ne moremo obdelati (inženirske keramike, kompoziti) ter pri koračnem preoblikovanju brez poškodbe površine.

Število uporab se hitro širi, prav tako pa se iz dneva v dan vrstijo izboljšave in nadgradnje same tehnologije obdelave s curki z velikimi hitrostmi. Dandanes se ta tehnologija uporablja na področjih, to so medicina, živilska industrija, gradbeništvo, rudarstvo itn. Razvijajo se nove rezalne glave oz. šobe, ki omogočajo nastanek curka z boljšimi obdelovalnimi lastnostmi, obenem pa je veliko dela vloženega v razvoj črpalk, ki omogočajo tlake vode do 1000 MPa.

S tako hitrostjo razvoja bo obdelava z AVC v naslednjih nekaj letih dosegala natančnost, ki je zahtevana v orodjarstvu. Rezanje 3D oblik zagotavlja tehnologiji AVC konkurenčno mesto med orodjarskimi rezalnimi tehnologijami. Žično erozijsko in obdelavo z velikimi hitrostmi prekaša predvsem v območju obdelovalnih materialov, preprostosti vpenjanja

5 CONCLUSION

In general, it can be concluded that high-speed jet technology has great potential in many fields: from workshop production to automotive and aerospace industries, to mention just a few. Due to the ability to machine any material, AWJ is quickly becoming a valuable machining process in the toolmaking industry, where most of the materials are hard to machine. Materials like composites and ceramics can be easily machined by AWJ and new opportunities are arising in the field of incremental sheet-metal forming with a WJ.

The number of applications where high-speed jet technology can be used is growing very rapidly, and new solutions in this field are in constant development. This technology is today applied in fields like medicine, food production, construction, mining, etc. New cutting heads are being developed with improved performance, and many efforts are being made to develop water pumps that will allow pressures up to 1000 MPa.

With such a rapid development, we feel that this technology will reach the precision that is required in the toolmaking industry within the next few years. Machining 3D features makes AWJ competitive with other commonly used technologies in the toolmaking industry. Compared with wire EDM and high-speed milling, AWJ is already superior in many aspects. It can machine virtually any material, zaradi majhnih sil in drugih vplivov na obdelovanec ter v večini primerov večji hitrosti odvzema. S tem bo mogoče zmanjšati stroške izdelave orodij, obenem pa bo mogoče obdelovati materiale, ki pomenijo izziv za postopke odrezovanja in elektroerozije.

there is no need for special clamping and fixing devices due to the small forces on the workpiece, and in most cases it is much faster and has more options. In many cases it was observed that using AWJ instead of other machining processes could drastically reduce the machining time and costs.

Zahvala

Predstavljene raziskave so bile podprte s strani mreže odličnosti "4M" s področja mikroobdelave; številka pogodbe: NMP2-CT-2004-500274 ter mreže odličnosti "VRL-KCiP" s področja zbiranja znanja v proizvodnem strojništvu; številka pogodbe: NMP2-CT-2004-507487, oboje v sklopu šestega evropskega okvirnega programa.

Acknowledgement

This work has been supported by the "Multi-Material Micro Manufacture: Technology and Applications (4M)" Network of Excellence, Contract Number NMP2-CT-2004-500274 and by the "Virtual Research Lab for a Knowledge Community in Production (VRL-KCiP)" Network of Excellence, Contract Number NMP2-CT-2004-507487, both within the EU 6th Framework Program.

6 LITERATURA
6 REFERENCES

[1] Byran, E., L. (1963) High energy jets as a new concept for wood machining. For. Prod. J. 13 (8), 305.
[2] Sato, H. (1996) A view on east and west through a researcher's experience. Liber Amicorum Prof. Paul Vanherck, 145-155, *Katholieke Universiteit Lueven*, Belgium.
[3] Walstad, O., M., P.W. Noecker (1972) Development of high pressure pumps and associated equipment for fluid jet cutting. In: *Proceedings of the First International Symposium on Jet Cutting Technology*, Paper C3, Coverty, UK, April 1972.
[4] Summers, D., A. (1995) Waterjetting technology. *Chapman & Hall*.
[5] Ojmertz, K.,M.,C. (1994) Abrasive waterjet machining. Licentiate thesis*, Chalmers University of Technology,* Sweden.
[6] Jurisevic, B., K.C. Heiniger, K. Kuzman, and M. Junkar (2003) Incremental sheet metal forming with a high-speed water jet. In Kuzman K., Janssen E., Col A., Kerge R., Kessler L., Lenze F.-J., editors, *Proceedings of the International Deep Drawing Research Group Conference,* IDDRG 2003, 139-148, Bled, Slovenia, 11-15 May 2003. TECOS, Slovenian Tool and Die Development Centre, Celje.
[7] Jurisevic, B., D. Kramar, K.C. Heiniger, and M. Junkar (2003) New perspectives in 3D abrasive water jet precision manufacturing. In Bley H., editor, *Proceedings of the 36th CIRP-International Seminar on Manufacturing Systems: Progress in Virtual Manufacturing Systems*, 507-512, Saarbruecken, Germany, 03-05 June 2003. University of Saarland, Germany.
[8] Orbanic, H., M. Junkar (2003) A feasibility study of drilling small holes with abrasive water jet. In Kuzman K., editor, *Proceedins of the 4th International Conference on Industrial Tools*, ICIT 2003, 343-346, Bled, Slovenia, 8-12 April 2003. TECOS, Slovenian Tool and Die Development Centre.
[9] Louis, H., M. Mohamed, and F. Pude (2003) Cutting mechanism and cutting efficiency for water pressures above 600 MPa. In Summers D., editor, *Proceedings of the 2003 WJTA American WaterJet Conference*, paper 1-A, Houston, Texas, USA, 16-19 August 2003, WJTA, WaterJet Technology Association.
[10] Miller, D., S. (2003) Developments in abrasive waterjets for micromachining. In Summers D., editor, *Proceedings of the 2003 WJTA American WaterJet Conference*, paper 5-F, Houston, Texas, USA, 16-19 August 2003, WJTA, WaterJet Technology Association.
[11] Louis, H., F. Pude and von Rad, Ch. (2003) Potential of polymeric additives for the cutting efficiency of abrasive waterjets. In Summers D., editor, *Proceedings of the 2003 WJTA American WaterJet Conference*, paper 3-D, Houston, Texas, USA, 16-19 August 2003, WJTA, WaterJet Technology Association.

[12] Olsen, J., J. Zeng, C. Olsen and B. Guglielmetti (2003) Advanced error correction methodology applied to abrasive waterjet cutting. In Summers D., editor, *Proceedings of the 2003 WJTA American WaterJet Conference*, paper 5-D, Houston, Texas, USA, 16-19 August 2003, WJTA, WaterJet Technology Association.

[13] Knaupp, M., A. Meyer, G. Erichsen, M. Sahney and C. Burnham (2002) Dynamic compensation of abrasive jet properties through 3-dimensional jet control. In: Lake P., editor, *Proceedings of 16th International Conference on Water Jetting*, 75-90, Aix-en Provence, France, 16-18 October 2002, BHR-Group.

[14] Jurisevic, B., K. C. Heiniger, A. Schuetz and M. Junkar (2003) Feasibilities of abrasive water jet multipass cutting technique. In Summers D., editor, *Proceedings of the 2003 WJTA American WaterJet Conference,* paper 2-A, Houston, Texas, USA, 16-19 August 2003, WJTA, WaterJet Technology Association.

[15] Chen, F., L. and E. Siores (2001) The effect of cutting jet variation on striation formation in abrasive water jet cutting. *International Journal of Machine Tools & Manufacture*, (41), 1479–1486.

[16] Henning, A. and E. Westkamper (2003) Modulation of cutting operation with abrasive waterjets. In Summers D., editor, *Proceedings of the 2003 WJTA American WaterJet Conference*, paper 5-G, Houston, Texas, USA, 16-19 August 2003, WJTA, WaterJet Technology Association.

Naslov avtorjev: Boštjan Juriševič
mag. Davorin Kramar
prof.dr. Mihael Junkar
Fakulteta za strojništvo
Univerza v Ljubljani
Aškerčeva 6
1000 Ljubljana
bostjan.jurisevic@fs.uni-lj.si
davorin.kramar@fs.uni-lj.si
mihael.junkar@fs.uni-lj.si

Authors' Address: Boštjan Juriševič
Mag. Davorin Kramar
Prof.Dr. Mihael Junkar
Faculty of Mechanical Eng.
University of Ljubljana
Aškerčeva 6
1000 Ljubljana, Slovenia
bostjan.jurisevic@fs.uni-lj.si
davorin.kramar@fs.uni-lj.si
mihael.junkar@fs.uni-lj.si

Prejeto:
Received: 26.10.2004

Sprejeto:
Accepted: 2.12.2004

Odprto za diskusijo: 1 leto
Open for discussion: 1 year