

Uporaba vodnega curka za postopno preoblikovanje pločevine

The Application of Water-Jet Technology for Incremental Sheet-Metal Forming

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V zadnjih desetletjih je tehnologija obdelave s curki z velikimi hitrostmi doživela velik razvoj. Od prvih primerov uporabe v zgodnjih sedemdesetih letih prejšnjega stoletja se je uporaba močno povečala. Med vsemi postopki, ki temeljijo na uporabi curkov z velikimi hitrostmi, ima vodilno vlogo rezanje z abrazivnim vodnim curkom (AVC), pri katerem vodni curek z velikimi hitrostmi (VC) pospešuje trde abrazivne delce, ki razjedajo material obdelovanca. Po drugi strani se VC uporablja za rezanje mehkejših materialov, čiščenje, površinsko obdelavo ter za uporabo v medicini in živilski industriji. V zadnjem času se VC uporablja tudi pri preoblikovanju, predvsem za utrjevanje površine izdelka, nekaj raziskav pa je pokazalo, da ima VC velike možnosti kot orodje za postopno preoblikovanje pločevine (PPP).

V tej raziskavi smo preučili možnosti uporabe vodnega curka z velikimi hitrostmi kot orodja za PPP. Prikazana je vplivnost postopkovnih parametrov kakor sta tlak in pretok vode, prav tako je definirana najbolj primerna geometrijska oblika vodne šobe za tvorbo curka. Predstavljen je tudi primer postopnega preoblikovanja 0,5 mm debele pločevine iz aluminijeve zlitine v preprosto obliko z VC.

Med primerjavo PPP z orodjem z določeno obliko se izkaže, da je predlagana tehnologija ekološko bolj sprejemljiva, saj ni potrebe po uporabi mazalnih sredstev. Prve raziskave nakazujejo, da se izboljša preoblikovalnost pri uporabi VC kot orodja za PPP.

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(Ključne besede: preoblikovanje pločevine, postopki nekonvencionalni, izdelava prototipov hitra, curek vodni)

High-speed jetting technology has developed quickly over the past few decades. Since its first introduction in the early 1970s the number of applications has rapidly increased. Of the high-speed jet-based processes, cutting with an abrasive water jet (AWJ) is the most common. In this process, hard abrasive particles, which are accelerated by a high-speed water jet (WJ), can erode practically any known material. On the other hand, a plain WJ is used mostly for cutting softer materials, cleaning, surface preparation, applications in medicine and food processing. Recently, WJs have been used in forming, mostly as a tool for surface peening, but some research has shown great potential for a WJ as a tool for incremental sheet-metal forming (ISMF).

In this study we analyzed the possibility to apply a high-speed WJ as a tool for ISMF. The importance of process parameters such as water pressure and volume flow were determined, and the most appropriate water-nozzle geometry was defined as well. A case study is included, where a simple geometry was incrementally formed by a WJ in 0.5-mm-thick aluminum-alloy plate.

Compared to ISMF with a rigid tool, the proposed technology is more environmentally friendly, since no lubrication is required, and from our first investigation it seems that the formability is increased as well.

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(Keywords: sheet-metal forming, nonconventional processes, fast prototyping, high speed water jet)

0 UVOD

V sodobni proizvodnji, pri kateri so serije izdelkov vedno manjše, je navzočnost neobičajnih postopkov zelo močna. Med razvojem novega izdelka ali optimizaciji že znanega obstoja zelo velika potreba po postopkih za hitro prototipno proizvodnjo.

0 INTRODUCTION

The presence of advanced, non-conventional processes is very strong in modern production, where production series are becoming smaller. During the development phase of a new product or the optimization of an existing one, fast-

Pomanjkljivost postopkov prototipne izdelave je, da v velikem številu primerov izdelki nimajo vseh lastnosti, ki so zahtevane pri končnem izdelku. V primeru, ko je treba izdelati večje število prototipnih izdelkov ali manjše serije, so ti postopki stroškovno in časovno neprimerni. Rešitev bi bila v tehnologiji, ki bi omogočala izdelavo prototipov in majhnih serij ustreznih izdelkov v razumnem času in stroškovno ugodno, kar bi pripomoglo k večji konkurenčnosti teh izdelkov na trgu. Na področju preoblikovanja pločevine je eden od takih postopkov, ki vsebuje zgoraj naštetih zahteve, postopno preoblikovanje pločevine z vodnim curkom (PPPVC).

Pri postopnem preoblikovanju pločevine (PPP) se orodje preproste oblike giblje po definirani poti vzdolž trdno vpete pločevine. Pri tem se postopno preoblikuje pločevino v končno obliko z nadzorovanim vnosom plastičnih deformacij na lokalno omejeno področje. Na področju PPP z orodjem z določeno obliko je bilo opravljenih več študij ([1] do [4]). Ta tehnologija je že bila uspešno uporabljena v avtomobilski in letalski industriji [5]. V primerjavi z običajnim preoblikovanjem pločevine, pri katerem orodje deloma ali v celoti vsebuje obliko izdelka, so pri PPP stroški orodja bistveno nižji, obenem pa je izboljšana preoblikovalnost postopka. Po drugi strani je čas izdelave posameznega izdelka z PPP daljši, kar nakazuje, da je postopek bolj primeren za prototipno izdelavo in majhne serije izdelkov.

Številni argumenti nakazujejo primernost uporabe VC namesto orodja z določeno obliko za PPP. Predštudija, narejena pri sodelovanju Univerze v Ljubljani, Slovenija in Univerzo uporabnih znanosti Aargau, Windisch, Švica [6], je pokazala, da se lahko preoblikovalnost izboljša, ko se kot orodje za PPP uporabi VC. Torne razmere med VC in pločevino so bolj ugodne, med prehodom curka deluje na površino pločevine enakomerno porazdeljen tlak. Zelo verjetno ima tudi nihanje sile VC, ki jo povzroči periodično nihanje tlaka vode, pozitiven vpliv na tok materiala med preoblikovanjem. Poleg tega je rezanje z abrazivnim vodnim curkom (AVC) zelo razširjen postopek, ki se je v zgodnjih 80. letih prejšnjega stoletja razvil iz rezanja z VC, ki omogoča rezanje praktično kateregakoli materiala, ne da bi pri tem nastalo omembe vredno toplotno prizadeto področje. Standardni stroj za rezanje z AVC se lahko razmeroma preprosto dogradi v napravo za PPPVC. Ker so v slednjem primeru zahtevani nižji tlaki in večji pretoki vode kakor pri rezanju z AVC, je potrebna dodatna črpalka. Za pridobivanje primerne VC za PPP pa je potrebna posebna preoblikovalna glava, katero se pritrdi na vodila stroja poleg glave za rezanje z AVC. Za dogradnjo stroja za rezanje z AVC v stroj za PPPVC potrebujemo še vpenjalo za pločevino, ki ga namestimo na obdelovalno mizo. S temi spremembami bi bil na voljo stroj, na katerem bi bilo mogoče rezanje in

prototyping techniques are required. However, a common disadvantage of fast-prototyping techniques is that in many occasions they cannot produce a prototype that incorporates all the demanded characteristics of the final product. In the case where more prototypes or a small batch is required, those techniques fail due to unacceptable production costs or time. The solution would be a technology that would allow the production of prototypes or a small batch series of functional products in a reasonable time and for acceptable costs in order to make such a product competitive on the market. In the field of sheet-metal forming, water-jet incremental sheet-metal forming (WJISMF) seems to be a technology with all the above attributes.

In incremental sheet-metal forming (ISMF) the procedure involves a tool of simple geometry moving along an arbitrary geometry over a fixed metal sheet. It incrementally forms the workpiece to the final shape by introducing plastic deformations over a small controlled region. Many studies were made on ISMF with a rigid tool ([1] to [4]). This process was also successfully applied in the automotive and aerospace industries [5]. Compared to conventional sheet-metal forming processes, where the tool has to fully or partially reflect the product geometry, in ISMF the tooling costs are substantially reduced and the formability is increased. On the other hand, more time is required to produce a single part, which makes ISMF more suitable for prototyping and small batch production.

There are many arguments in favour of using a high-speed WJ instead of a rigid tool in ISMF. A feasibility study made in a collaboration between the University of Ljubljana, Slovenia and the University of Applied Sciences of Aargau, Windisch, Switzerland [6] showed that the formability might be further increased when a WJ is used as a tool. Friction conditions at the interface between the WJ and the workpiece are better, and the hydrostatic pressure is evenly distributed during the passage of the WJ over the sheet-metal surface. It is also very likely that the WJ force oscillation due to the oscillation of water pressure has a positive influence on the flow of workpiece material. Furthermore, abrasive water-jet (AWJ) machining is already a well-established cutting process developed from WJ cutting in the early 1980s, able to cut virtually any material, and no relevant heat-affected zone is produced. A standard AWJ cutting machine can be relatively easily upgraded to a WJISMF platform. Since lower water pressures and higher volume flows of water compared to AWJ cutting are required for WJISMF an additional water pump is needed. To produce a WJ that is able to incrementally form a sheet of metal, a special forming head has to be mounted on the AWJ's machine steering system. The last thing needed to upgrade an AWJ cutting system to a WJISMF machine is a sheet-metal holder that can be placed on the working table. The result is a machine where cutting and sheet-metal forming can be carried

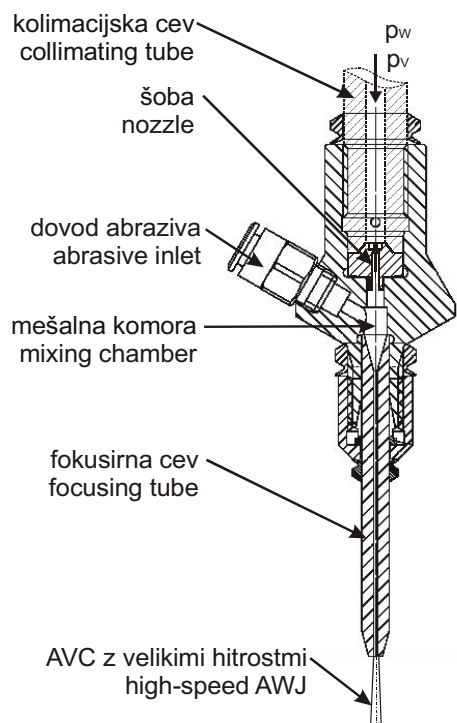
preoblikovanje pločevine. Takšen stroj bi bil zelo uporaben za izdelavo prototipov in majhnih serij pločevinastih izdelkov.

Pred uporabo predlagane tehnologije je treba preučiti številne dejavnike. Najprej je treba definirati optimalne vrednosti pomembnih postopkovnih parametrov, iz česar bosta izhajali oblikovanje primerne šobe in izbira ustrezne črpalke, kar bo prikazano v nadaljevanju. V predstavljenem primeru je opisano PPPVC, pri katerem je bila izdelana preprosta oblika iz 0,5 mm debele pločevine iz aluminijeve zlitine. V sklepu so predstavljene načrtovane dejavnosti na področju PPPVC.

1 NAČELA PPPVC

V primerjavi z rezanjem z AVC, pri katerem VC z velikimi hitrostmi pospešuje trde abrazivne delce, mora pri PPPVC, VC izpolnjevati drugačne zahteve. Površinski tlak med VC in pločevino mora biti dovolj majhen, da ne pride do erozije obdelovanca. Hkrati pa naj bo sila VC dovolj velika, da povzroči plastično deformacijo pločevine.

Pri rezanju AVC nastaja v rezalni glavi, ki jo sestavljajo šoba, mešalna komora, dovod za abraziv in fokusirna šoba. Rezalna glava je pritrjena na kolimacijsko cev, ki stabilizira tok tekočine pod visokim tlakom. Na začetku rezalne glave nastaja vodni curek že v šobi, pri čemer se potencialna energija vode pod visokim tlakom spremeni v kinetično energijo vodnega curka z velikimi hitrostmi. VC z velikimi hitrostmi vstopi v mešalno



Sl. 1. Rezalna glava za obdelavo z AVC
Fig. 1. Cutting head for AWJ machining

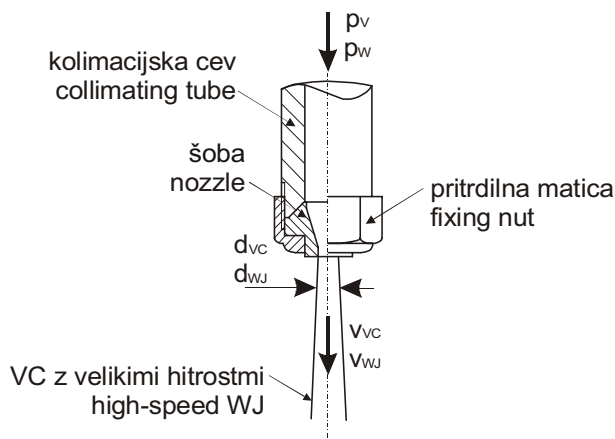
out. Such a machine could be very useful for prototyping and the small batch production of sheet-metal products.

In order to apply the proposed technology, several issues have to be addressed. First, the optimal values of relevant process parameters have to be defined, from which an appropriate nozzle can be designed and a suitable water pump selected. This is presented in what follows. Then a case study on WJISMF is described, where a simple geometry was incrementally formed using a WJ and 0.5-mm-thick aluminum alloy. In the conclusions we describe our activities planned for the future.

1 PRINCIPLES OF WJISMF

Compared to AWJ cutting, where hard abrasive particles are accelerated by a high-speed jet of water, a WJ for ISMF must meet different requirements. The resulting pressure of the WJ on the workpiece metal sheet surface has to be much smaller in order to not initiate the erosion process. At the same time, the jet force has to be high enough to enable plastic deformations of the plate.

In AWJ cutting, the jet is continuously generated in the cutting head, which is composed of a nozzle, a mixing chamber, an abrasive inlet and a focusing tube. The cutting head is connected to the collimating tube, which has the function of stabilizing the water flow. The nozzle at the beginning of the cutting head converts the potential energy of the water under high pressure to the kinetic energy of a high-speed water jet. Such a high-speed WJ enters the mixing chamber and



Sl. 2. Preoblikovalna glava za PPPVC
Fig. 2. Forming head for WJISMF

komoro, v kateri sesa abrazivne delce in zrak skozi dovod za abraziv, ki je nameščen na steno mešalne komore. Abrazivni delci pospešujejo v fokusirni šobi, ki je pritrjena pod mešalno komoro. Rezultirajoči curek je sestavljen iz vode, abrazivnih delcev in zraka. Ko AVC zadene površino obdelovanca, abrazivni delci razjedajo material. Na sliki 1 je prikazana rezalna glava z vsemi glavnimi sestavinami.

Preoblikovalna glava za PPPVC se nekoliko razlikuje od glave za rezanje z AVC. Načeloma ne potrebuje mešalne komore, dovoda za abraziv in fokusirne šobe. Najpomembnejša komponenta je šoba, v kateri nastaja VC. Zamisel take preoblikovalne glave je predstavljena na sliki 2.

Prvi vtis bi bil, da je preoblikovalna glava v bistvu glava za rezanje z AVC brez mešalne komore, dovoda za abraziv in fokusirne šobe. Naše izkušnje [6] so pokazale, da je za PPPVC bolj primeren drugačen tip šobe kakor pri rezanju z AVC. V slednjem primeru se največ uporabljajo šobe z ostrim robom, medtem ko so za PPPVC bolj primerne zvezne šobe. Obe zasnovi šob sta prikazani na sliki 3.

Postopkovni parametri za PPPVC se prav tako razlikujejo od tistih, uporabljenih za obdelavo z AVC. Da ne pride do erozije obdelovanca pri PPPVC, mora biti površinski tlak med curkom in pločevino znižan, kar se doseže z nižjim tlakom vode. Trenutno so za rezanje z AVC uporabljeni tlaki vode do 400 MPa, v prihodnosti, ko bodo na voljo novi tipi črpalk, pa se bodo delovni tlaki zvišali do 1000 MPa. Pri uporabi VC v preoblikovanju, tlak vode ne presega 25 MPa.

Poleg površinskega pritiska je zelo pomembna lastnost sila VC, ki mora biti dovolj velika da plastično deformira obdelovanec. Ker je tlak vode definiran z največjim dopustnim površinskim tlakom, se lahko silo curka poveča z večanjem premera šobe. Pri obdelavi z AVC je premer šobe med 0,1 in 0,3 mm ter premer fokusirne šobe med 0,3 in 0,8 mm. Pri PPPVC pa mora biti premer šobe vsaj 2 mm, da je mogoče

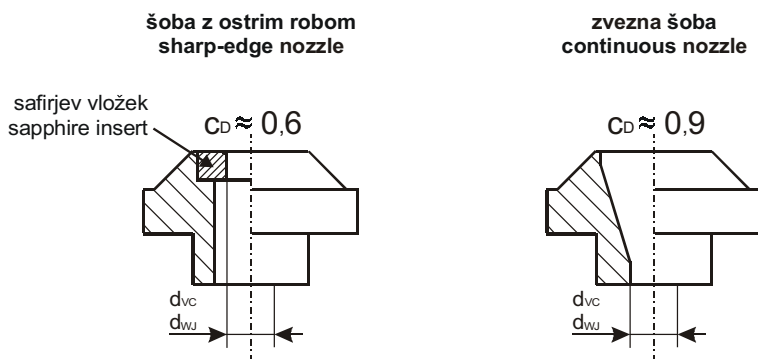
sucks abrasive particles and air through the abrasive inlet placed on the side of the mixing chamber. Once the abrasive has been inserted it accelerates inside the focusing tube placed downstream of the mixing chamber. The resulting jet is therefore composed of a stream of abrasive particles, water and air. When such a high-speed AWJ hits the workpiece, the abrasive particles remove the material by eroding it. Figure 1 shows an AWJ cutting head with all its main components.

A forming head for WJISMF differs slightly from an AWJ cutting head. The main difference is that it does not need a mixing chamber, an abrasive inlet and a focusing tube. The most important component is the nozzle, where a high-speed WJ is generated. A schematic of such a forming head is presented in Figure 2.

At this point the first impression would be that a forming head is actually an AWJ cutting head, where the abrasive inlet is closed and the focusing tube is removed. Nevertheless, our experiences [6] showed that a different type of nozzle is more appropriate for generating a WJ for ISMF. In AWJ cutting, sharp-edge nozzles are commonly used, while in WJISMF a continuous nozzle gives much better results. Both types of nozzles are shown in Figure 3.

The process parameters in WJISMF are different from those used in AWJ machining. In order to prevent any erosion of the workpiece material in WJISMF, the surface pressure at the interface between the WJ and the metal sheet has to be reduced by reducing the water pressure. Currently, in AWJ cutting the water pressure is up to 400 MPa, and it seems that in the near future this operating pressure will be raised to 1000 MPa, as new pumps will soon be available. In WJ forming applications, the water pressure does not need to exceed 25 MPa.

Another crucial attribute of the WJ is the jet force, which has to be high enough to allow plastic deformation of the workpiece. Because the water pressure is defined by the highest allowed surface pressure, the jet force can be increased by increasing the nozzle diameter. In AWJ machining the nozzle diameter is between 0.1 and 0.3 mm and the focusing tube diameter between 0.3 and 0.8 mm. In WJISMF



Sl. 3. Šoba z ostrim robom in zvezna šoba za obdelavo s curki z velikimi hitrostmi
 Fig. 3. Sharp-edge and continuous nozzles in high-speed jet technology

preoblikovati pločevino iz aluminijeve zlitine z debelino 1 mm.

Za zvezno šobo, prikazano na sliki 3, se površinski tlak p_p in silo $VC F_{VC}$ lahko dovolj natančno popiše z enačbo (1) oz. enačbo (2):

$$p_p = 2 \cdot c_D^2 \cdot p_v \quad (1)$$

$$F_{VC} = 2 \cdot c_D^2 \cdot A_{VC} \cdot p_v \quad (2),$$

kjer je p_v tlak vode, A_{VJ} prečni prerez curka in c_D razbremenilni koeficient šobe. Za zvezno šobo je vrednost razbremenilnega koeficienta okoli 0,9. Iz zgoraj navedenih enačb se lahko opazi, da je površinski tlak odvisen od tlaka vode, medtem ko je sila VC odvisna od tlaka vode in premera curka za določen tip šobe.

Zaradi uporabe večje šobe mora črpalka dovajati precej večji prostorninski tok vode v primeru uporabe VC v preoblikovanju. V primeru obdelave z AVC prostorninski tok vode ne presega 5 l/min, za PPPVC pa mora biti prostorninski tok vsaj 50 l/min, po navadi celo več, ko se preoblikuje pločevino večje debeline.

Zgoraj opisane značilnosti in zahteve obdelave z VC/AVC na eni strani in uporab VC v preoblikovanju na drugi strani so povzete v preglednici 1.

the nozzle diameter has to be at least 2 mm in order to form an aluminum alloy plate of thickness up to 1 mm.

In the case of a continuous nozzle, which is shown in Figure 3, Equation 1 and 2 can approximate accurately enough for the proposed application the surface pressure, p_s , and the WJ force, F_{WJ} .

where p_w is the water pressure, A_{WJ} the jet's cross-sectional area and c_D the nozzle discharge coefficient. For a continuous nozzle the discharge coefficient is around 0.9. It can be observed from the above equations that the surface pressure is a function of the water pressure, while the WJ force is a function of the water pressure and the jet dimension for a given type of nozzle.

As a direct consequence of a larger nozzle diameter, the pump has to generate a much higher volume flow of water in the case of WJ forming applications. While the required volume flow for AWJ cutting usually does not exceed 5 l/min, for WJISMF the volume flow has to be at least 50 l/min, but usually even more, especially when thicker plate has to be incrementally formed.

The above described characteristics and requirements for WJ/AWJ cutting and WJ forming are summarised in Table 1.

2 PRIMER UPORABE

Pred kratkim smo opravili poskusno raziskavo na področju PPPVC [6]. Zaradi pomanjkanja izkušenj na

2 CASE STUDY

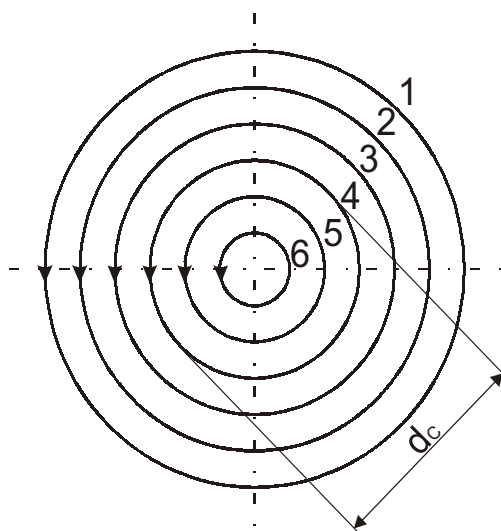
We have recently made an experimental investigation of WJISMF [6]. As we had no

Preglednica 1. Primerjava med rezanjem z CV/AVC in preoblikovanjem z CV
Table 1. Comparison of WJ/AWJ cutting and WJ forming

Zahteva / značilnost Requirements / characteristic	Rezanje z VC/AVC WJ/AWJ cutting	Preoblikovanje z VC WJ forming
tlak vode water pressure	čim višji trenutno 400 MPa, v prihodnosti do 1000 MPa as high as possible currently 400 MPa, in future up to 1000 MPa	do 25 MPa, da ne pride do erozije obdelovanca up to 25 MPa in order to prevent erosion of the workpiece
vrsta črpalke type of water pump	hidravlično ojačevalo (nespremenljiv tlak) hydraulic intensifier (constant pressure)	batna črpalka (nespremenljiv volumnski tok) plunger pump (constant volume flow)
premer šobe nozzle diameter	0,3 mm ali manj 0.3 mm or less	1 mm ali več 1 mm or more
vrsta šobe nozzle type	z ostrim robom ($c_D \approx 0,6$) sharp-edge ($c_D \approx 0,6$)	zvezna ($c_D \approx 0,9$) continuous ($c_D \approx 0,9$)
prostorninski tok vode volume flow of water	nekaj l/min up to a few l/min	do 50 l/min in več up to 50 l/min or more
sila curka jet force	čim manjša as small as possible	čim večja as high as possible

tem področju smo kot izhodišče predstavljene raziskave uporabili rezultate, ki jih je dobil Iseki [7] na Tokijskem tehnološkem inštitutu na Japonskem. Glede na razpoložljivo literaturo je njegovo delo prvo na področju PPPVC. V našem preizkusu smo preoblikovali stopničasto stožčasto obliko iz 0,5 mm debele pločevine iz aluminijeve zlitine AlMgSi1. Končno obliko pločevine smo dosegli z večkratnim izvajanjem sosrednjih krogov, kar je prikazano na sliki 5. Kinematika VC vzdolž pločevine je podana v preglednici 2.

experience in this field we used, as a starting point, the results of Iseki [7] from the Tokyo Institute of Technology, Japan. According to the available literature he made pioneering work in the field of WJISMF. In our trial we formed a stepped conical shape in 0.5-mm-thick AlMgSi1 aluminum alloy by passing several times along concentric circles as showed in Figure 4. The kinematics parameters are listed in Table 2.



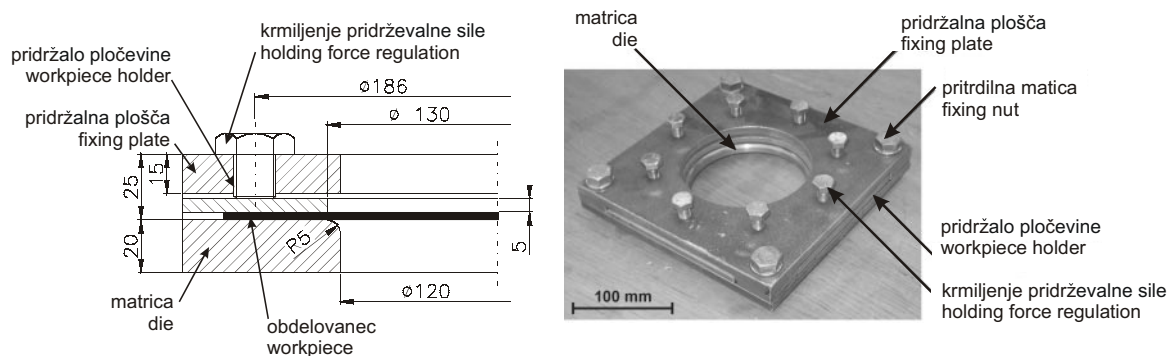
Sl. 4. Kinematika VC vzdolž obdelovanca [6]
 Fig. 4. Kinematics of the WJ over the workpiece [6]

Preglednica 2. Kinematika VC [6]
 Table 2. WJ kinematics parameters [6]

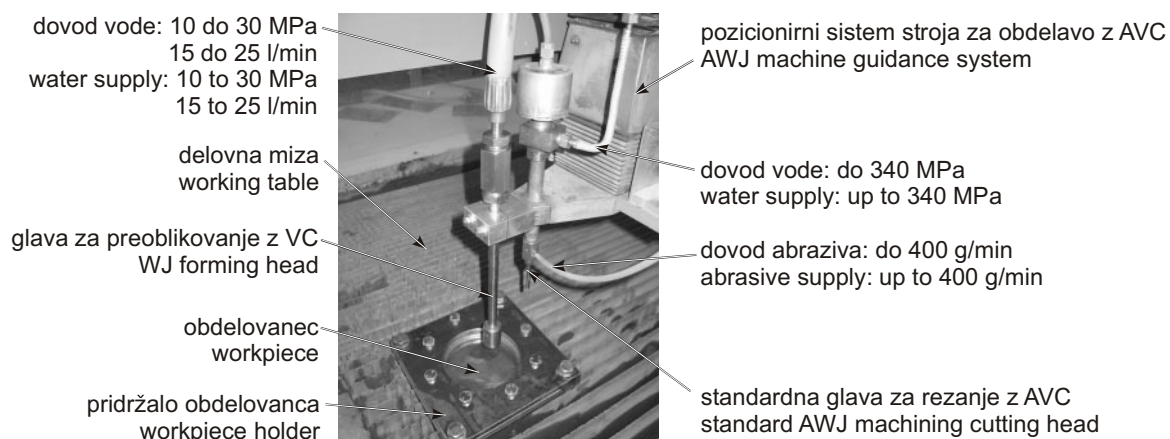
Krog Circle	d_c mm	n_p 1	t_o / t_M s	E_{VC} / E_{WJ} kJ
1	60	2	377	1943
2	50	3	471	2428
3	40	4	503	2590
4	30	5	471	2428
5	20	6	377	1943
6	10	7	220	1133
skupaj total			2419	12465

Razdalja med šobo in obdelovancem je bila nastavljena na 30 mm, podajalna hitrost VC vzdolž obdelovanca pa je bila 1 mm/s. Preizkus je bil opravljen na predelanem sistemu za rezanje z AVC tipa PERENDORFER WSS 1010 z delovno površino 1×1 m, dvema RNK vodenima osema in ročno vodeno navpično osjo. Za dvigovanje tlaka vode in dovajanje ustreznega prostorninskega toka je bila uporabljena batna črpalka tipa WOMA 180 Z P18, ki omogoča prostorninski tok vode 21 l/min pri največjem tlaku 200 MPa in moči 78 kW. Obdelovanec je bil vpet v posebej razvitem pridržalu, prikazanem na sliki 5, in položen na obdelovalno mizo kakor prikazuje slika 6.

The stand-off distance between the nozzle and the workpiece was set to 30 mm and the traverse rate of the jet over the workpiece was 1 mm/s. This experiment was performed on a modified PERNDORFER AWJ cutting system WSS 1010 with a working area of 1×1 m, two CNC driven axis and a manually driven vertical axis. To generate high-pressure water with the required volume flow we used a WOMA plunger pump type 180 Z P18 with a water volume flow of 21 l/min at a maximum pressure of 200 MPa and a power of 78 kW. The workpiece was fixed in a specially designed holder shown in Figure 5 and placed on the working table as shown in Figure 6.



Sl. 5. Posebej razvito pridržalo pločevine za PPPVC [6]
 Fig. 5. Specially developed workpiece holder for WJISMF [6]



Sl. 6. Namestitev obdelovanca na obdelovalno mizo [6]
 Fig. 6. Positioning of the workpiece on the working table [6]

Preglednica 3. Glavne lastnosti VC pri različnih tlakih vode
 Table 3. Relevant WJ attributes for different water-pressure levels

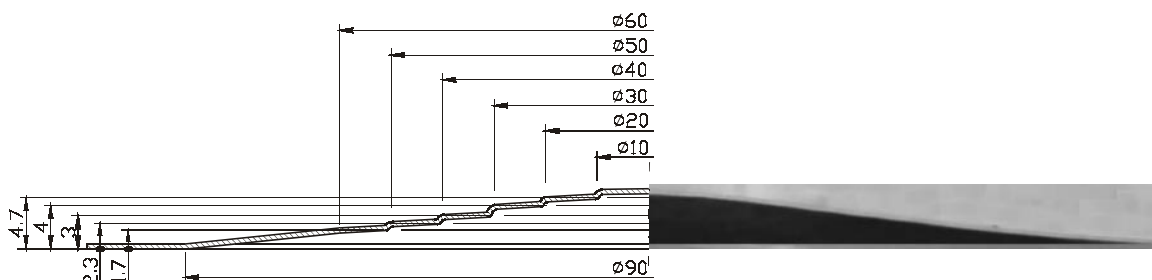
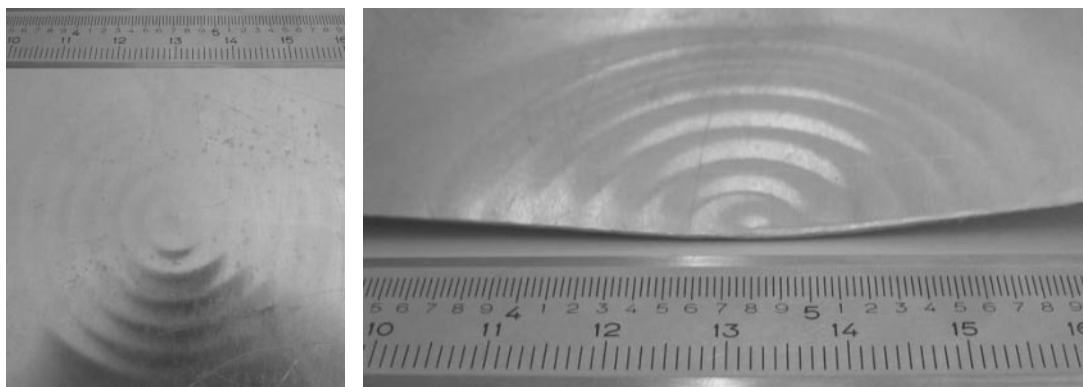
Značilnosti šobe: Nozzle characteristics:	p_V / p_W MPa	V_V / V_W l/min	F_{VC} / F_{WJ} N	P_{VC} / P_{WJ} kW	p_p / p_s MPa
$d_s=1,5$ mm $d_o=1.5$ mm vrsta: zvezna type: continuous $c_D=0,9$	10	13,5	28,6	1,82	16,2
	20	19,1	57,3	5,15	32,4
	30	23,4	85,9	9,47	48,6

Ob upoštevanju tipa šobe se lahko izračuna glavne lastnosti VC za PPPVC, ter določi ustrezen tlak vode. V preglednici 3 so navedene pomembnejše lastnosti VC pri treh različnih tlakih vode za uporabljeno šobo.

V svojem delu [7] je Iseki uporabil tlak vode 19,5 MPa in zvezno šobo premera 1,34 mm, kar se je kazalo v prostorninskem toku vode 15 l/min. V njegovem primeru je preoblikoval pločevino iz aluminijeve zlitine debeline 0,3 mm. Glede na te parametre smo se odločili uporabiti tlak vode 20 MPa, pri čemer so drugi postopkovni parametri in lastnosti VC ustrezali vrednostim, navedenim v preglednici 3. Rezultirajoča geometrijska oblika izdelka po PPPVC je prikazana na sliki 7.

By taking into account the type of nozzle it is possible to calculate the WJ attributes that are relevant in WJISMF and set the appropriate water pressure accordingly. Table 3 lists the relevant WJ attributes at three values of water pressure for the applied nozzle.

In his work Iseki [7] used a water pressure of 19.5 MPa and a continuous nozzle of diameter 1.34 mm, which resulted in a volume flow of 15 l/min. In this case the workpiece was a 0.3 mm annealed aluminum sheet. Taking this into account, we chose a water pressure of 20 MPa with the corresponding process parameters and WJ attributes listed in Table 3. The resulting geometry is shown in Figure 7.



Sl. 7. Stopničasta stožčasta geometrijska oblika preoblikovana z PPPVC [6]
Fig. 7. Stepped conical geometry formed by WJISMF [6]

Rezultati predstavljene raziskave so zelo spodbudni. Uspelo nam je definirati ustrezne postopkovne parametre za postopno preoblikovanje 0,5 mm debele pločevine iz aluminijeve zlitine AlMgSi1 brez kakršnekoli poškodbe površine. V tem primeru ni bilo uporabljeno nikakršno podporno orodje ali matrica, geometrijska oblika je bila enakomerno preoblikovana, kar nakazuje visoko stopnjo stabilnosti postopka.

3 SKLEPI IN NADALJNJE DELO

Podobno kakor na številnih področjih se je tehnologija obdelave s curki z velikimi hitrostmi izkazala tudi pri preoblikovanju, kjer se lahko VC uporabi kot orodje za PPP. Dejstvo, da se lahko običajni sistem za obdelavo z AVC preprosto dogradi v stroj za PPPVC, odpira veliko možnosti predstavljene tehnologije na področju hitre izdelave prototipov in maloserijske proizvodnje izdelkov iz pločevine.

V primerjavi z rezanjem s VC/AVC je treba pri preoblikovanju s VC tlak znižati na 25 MPa in manj, da se prepreči erozija obdelovanca. Hkrati je treba povečati silo curka, kar se doseže s povečanjem premera šobe. S tem je potreben večji prostorninski tok vode v primerjavi z rezanjem z VC/AVC, iz česar izhaja, da je batna črpalka bolj primerna od hidravličnega ojačevala za preoblikovanje s VC.

V predstavljenem primeru je bila oblikovana preprosta geometrijska oblika iz 0,5 mm debele pločevine iz aluminijeve zlitine AlMgSi1. V prihodnosti bodo dejavnosti na področju PPPVC

The results of the presented feasibility study are extremely encouraging. We were able to predict the appropriate process parameters to incrementally form a 0.5-mm-thick AlMgSi1 aluminum alloy with a damage-free surface. In this case no special tool or die was used, while the final geometry was evenly formed, indicating a high degree of process stability.

3 CONCLUSIONS AND FUTURE WORK

High-speed jet technology has proved itself in forming, where a high-speed WJ can be applied as a tool for ISMF. The fact that a conventional AWJ cutting machine can be relatively easily upgraded to a WJISMF platform makes the proposed technology very attractive in the field of rapid prototyping and the small batch production of sheet-metal parts.

Compared to WJ/AWJ cutting, in forming applications the water pressure has to be reduced down to 25 MPa, or even less, in order to prevent the erosion of the workpiece. At the same time the jet force has to be increased, which is achieved by increasing the nozzle diameter. This means that the required water volume flow is higher than with WJ/AWJ cutting applications, which makes a plunger pump more appropriate than a hydraulic intensifier for WJ forming.

In a case study a simple geometry was formed in 0.5-mm-thick AlMgSi1 aluminum alloy. Our future activities in the field of WJISMF will consist of building an experimental installation at the University

obsegale gradnjo preizkuševališča na Univerzi v Ljubljani. V ta namen bo uporabljena batna črpalka s prostorninskim tokom vode 50 l/min in tlakom do 25 MPa.

Prav tako so načrtovane raziskave na področju PPPVC na krojenih prirezih, zvarjenih s tornim gnetenjem, kar bo v primeru uporabnih rezultatov vodilo v neposredno uvajanje predlagane tehnologije v industrijo.

Vpliv tlaka vode (prostorninskega toka vode) in karakteristik šobe na PPPVC je definiran. Trenutno lahko določimo primerne postopkovne parametre ter izberemo ustrezno šobo. Vseeno pa je treba raziskati še številne vidike, med katerimi je najbolj pomemben razvoj geometrijske oblike preoblikovalne glave. Prav tako bo treba raziskati še številne postopkovne parametre, npr. razdalja med šobo in obdelovancem ter kinematiko VC vzdolž obdelovanca.

4 ZAHVALA

Avtorji se zahvaljujejo Univerzi aplikativnih znanosti Aargau v Švici za podporo med eksperimentalnim delom.

of Ljubljana. A plunger pump is anticipated, which will allow a water flow of 50 l/min and a pressure up to 25 MPa.

We also plan to apply the presented technology for ISMF of tailor blanks welded by friction stir welding (FSW), which if successful would lead to a direct implementation of the proposed technology in industry.

The influence of the water pressure (volume flow) and nozzle characteristics on WJISMF is understood. We are now able to define appropriate process parameters and select a suitable nozzle. Nevertheless, many issues remain to be addressed, among which the most important seems to be a development of an advanced forming head with better performance. Also, the influence of process parameters, such as stand-off distance and WJ kinematics, over the workpiece have to be further investigated.

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5 OZNAKE 5 NOMENCLATURE

abrazivni vodni curek	AVC/AWJ	Abrasive Water Jet
postopno preoblikovanje pločevine	PPP/ISMF	Incremental Sheet-Metal Forming
postopno preoblikovanje pločevine z vodnim curkom	PPPVC/WJISMF	Water-Jet Incremental Sheet-Metal Forming
vodni curek	VC/WJ	Water Jet
prečni prerez vodnega curka	A_{VC}/A_{WJ}	mm ² water-jet cross-sectional area
razbremenilni koeficient šobe	c_D	- nozzle discharge coefficient
premer krogov	d_C	mm circles diameter
premer vodnega curka	d_{VC}/d_{WJ}	mm water-jet diameter
energija vodnega curka	E_{VC}/E_{WJ}	J water-jet energy
silna vodnega curka	F_{VC}/F_{WJ}	N water-jet force
število prehodov	n_P	- number of passes
površinski tlak	p_P/p_S	MPa surface pressure
tlak vode	p_V/p_W	MPa water pressure
moč vodnega curka	P_{VC}/P_{WJ}	W water-jet power
čas obdelave	t_O/t_M	s machining time
prostorninski tok vode	V_V/V_W	l/min water volume flow
hitrost vodnega curka	v_{VC}/v_{WJ}	m/s water jet velocity

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