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Important findings in Wire + Arc Additive Manufacturing

Značajni nalazi u adiktivnoj proizvodnji žica za elektrolučno zavarivanje

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Abstract

The paper presents a set of findings important for a Wire Arc Additive Manufacturing using a welding robot. At the beginning an overview of additive manufacturing technologies for production of metal parts is presented. A special attention is set to wire arc additive manufacturing (WAAM) technologies. The advantage of WAAM compared to laser or electron beam technologies are lower investment and operational costs, while the disadvantage could be a lower dimensional accuracy. Due to higher productivity the WAAM technologies are more suitable for production of bigger parts. In this paper results study of WAAM using a welding robot and a CMT power source is presented. Thin walls have been cladded using G3Si1 welding wire. The microstructure and hardness of produced structures were measured and analysed. A research was done to determine the optimal welding parameters for production of thin walls with smooth surface. A SprutCAM software was used to make a code for 3D printing of sample part. It was find out that weld interpass temperature and workpiece to contact tip length play an important role in WAAM technologies.

1. Introduction

American Society for Testing and Materials – ASTM defined additive manufacturing as a process of joining materials layer by layer to make objects from 3D data. There are many differences between additive manufacturing compared to subtractive manufacturing. Many terms are used for this technology: additive manufacturing, additive

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Key words: robotic MIG/MAG weld surfacing, hardness, wire-arc additive manufacturing (WAAM), SprutCAM

Rezime

U radu je predstavljen niz nalaza koji su važni za adiktivnu proizvodnju žičanih elektroda za elektrolučno zavarivanje koristeći robota za zavarivanje. Na početku je dat pregled tehnologija aditivne proizvodnje metalnih delova. Posebna pažnja posvećena je tehnologiji aditivne proizvodnje žica za elektrolučno zavarivanje (WAAM). Prednost WAAM-a u odnosu na tehnologije laserskih ili elektronskih zraka je manja investicijska i operativna cena, dok bi nedostatak mogao biti manja tačnost dimenzija. Zbog veće produktivnosti, WAAM tehnologije su pogodnije za proizvodnju većih delova. U ovom radu predstavljena je studija rezultata WAAM-a upotrebom zavarivačkog robota i izvora napajanja CMT. Tanki zidovi su obloženi žicom za zavarivanje G3Si1. Izmerena je tvrdoća i analizirana mikrostruktura proizvedenih konstrukcija. Obavljeno istraživanje da bi se utvrdili optimalni parametri zavarivanja za proizvodnju tankih zidova sa glatkom površinom. Za pravljenje koda za 3D štampanje uzorka dela korišćen je softver SprutCAM. Otkriveno je da međuslojna temperatura i radni komad i dužina kontaktnog vraha igraju važnu ulogu u WAAM tehnologijama.

1. Uvod

Američko društvo za ispitivanje i materijale- ASTM definiše adiktivnu proizvodnju kao proces spajanja materijala sloj po sloj radi pravljenja predmeta iz 3D podataka. Mnogo je razlika između adiktivne proizvodnje u poređenju sa substraktivnom proizvodnjom. Za ovu tehnologiju se koriste mnogi izrazi: aditivna proizvodnja, aditivni proces, process, additive technology, 3D printing, rapid prototyping and rapid tooling [1]. The development of additive manufacturing of metal and polymer parts technologies does not progress evenly. Existing market solutions enable complex parts manufacturing in tight tolerances. The costs part depends on precision and quality of manufacturing. For example, development of polymers rapid prototype is already at high level. One can buy low-cost 3D printers, which are available for home use. The advantages of these systems is in user friendliness and inexpensiveness, but they have limitations in manufacturing process [1, 2].

There are many different technologies which are developed in additive manufacturing of metal parts. “Electric arc using heat as power source for 3D parts by welding in layers” was patented in 1926 by Baker. Pressure vessels were made with SMAW and TIG welding by using different filler wires for building walls by Ujiie (Mitsubishi) in 1971. Shape welding was used for producing large, 79 tons heavy high quality nuclear structural parts made from 20MnMoNi 5 with build rate 80 kg/h by Kussimaul in 1983. In 1993 Prinz and Weiss patented the process which was the combination of welding and CNC milling and named it “Shaped Deposition Manufacturing – SDM” [3], [4] for the Rolls Royce Company for castings. Through the years they developed a variety of processes and materials, the process itself is still used in manufacturing. In 2006 companies expressed the need for rapid prototyping from titanium. Engineers tried to find the replacement for non-sustainable traditional subtractive manufacturing. The prediction for the next 20 years is, that aircraft industry will need over 18 million tons of titanium wherein the buy-to-fly ratio is 5. That means 72 million tons of titanium will be waste material [5–8].

Additive manufacturing of metal parts can be divided on technologies using beams and technologies using arc (Fig. 1). For printing of metal parts could be used laser beam or electron beam. Filler material in that case is powder or wire. In laser systems the feed powder can be added with gas (blowing), we speak then about a process called laser cladding. In Selective Laser Sintering (SLS) or Electron Beam Melting (EBM) powder in containers can be used. In laser systems wire is added from side or perpendicular on the welding spot. In case of welding with electron beam we use Sciaky system. MIG, TIG and plasma are most common in arc welding. In all variations the feeding material in a form of wire is being. Common expression for all these technologies is Wire + arc Additive Manufacturing – WAAM [5].

aditivna tehnologija, 3D štampanje, brzo izrađivanje prototipa i brza izrada alate [1]. Razvoj tehnologije aditivne proizvodnje metala i polimernih delova ne napreduje ravnomerno. Postojeća tržišna rešenja omogućavaju izradu složenih delova u strogim tolerancijama. Deo troškova zavisi od preciznosti i kvaliteta izrade. Na primer, razvoj polimernog prototipa za brzi prototip je već na visokom nivou. Možete kupiti jeftine 3D štampače koji su dostupni za kućnu upotrebu. Prednosti ovih sistema su u lakoći rukovanja i jeftinosti, ali imaju ograničenja u procesu proizvodnje [1, 2]

Postoji mnogo različitih tehnologija koje su razvijene u aditivnoj proizvodnji metalnih delova. "Električni luk koji koristi toplotu kao izvor energije za 3D delove zavarivanjem u slojevima" patentirao je 1926. Baker. Posude pod pritiskom rađene su zavarivanjem SMAW i TIG korišćenjem različitih žica za ispunu zidova Ujiie (Mitsubishi) 1971. Zavarivanje oblikovanjem korišćeno je za proizvodnju velikih, 79 tona teških visokokvalitetnih nuklearnih konstrukcionih delova izrađenih od 20MnMoNi 5 sa radnom snagom 80 kg / h od strane Kussimaula 1983. Godine 1993. Prinz i Weiss su patentirali postupak, koji je bio kombinacija zavarivanja i CNC glodanja i nazvali ga „Oblikovana taložna proizvodnja - SDM“ [3], [4] za kompaniju Rolls Roice za livenje. Kroz godine razvijanja različitih procesa i materijala, sam proces se još uvek koristi u proizvodnji. Kompanije su tokom 2006. godine izrazile potrebu za brzim prototipovima od titana. Inžinjeri su pokušali pronaći zamenu za neodrživu tradicionalnu substraktivnu proizvodnju. Predviđanje za narednih 20 godina je da će vazduhoplovnoj industriji biti potrebno preko 18 miliona tona titana, pri čemu je odnos kupovine i letenja 5. To znači da će 72 miliona tona titana biti otpadni materijal [5–8].

Aditivna proizvodnja metalnih delova može se podeliti na tehnologije pomoću snopa i tehnologije koje koriste luk (slika 1). Za štampanje metalnih delova može se koristiti laserski snop ili elektronski snop. Dodatni materijal u tom slučaju je prah ili žica. U laserskim sistemima prah može da se doda gasom (duvanjem), tada govorimo o procesu koji se zove lasersko oblaganje. U posudama se može koristiti prah selektivnog laserskog sinterovanja (SLS) ili pretapanje elektronskim snopom (EBM). U laserskim sistemima žica se dodaje sa strane ili upravno na mesto zavarivanja. U slučaju zavarivanja elektronskim snopom koristimo Scyaky sistem. MIG, TIG i plazma su najčešći u elektrolučnom zavarivanju. U svim varijacijama je materijal u obliku žice. Zajednički izraz za sve ove

Most common system used for WAAM is industrial robot to which is install welding torch. Price of such system is up to 300 k€ for building of less complex parts. For production of high quality parts suitable for aerospace technology are systems consist of high cost CNC and robot. Their price are in range of 0.2-2 M€ [2]. Structure stiffness, dynamic accuracy and vibration damping of CNC machines is higher so they are more appropriate for manufacturing by WAAM [3].

There are many disadvantages of using powder instead of wire: High costs, variable powder quality, the feed is complex unless the side feed system is being used, low efficiency (40-60 %), careful handling because of safety aspects, head rotation problems if feed is added from side. If adding wire filler material, the price of materials is medium-high, the quality of material is high (Ti, Fe, Ni) but also could be different when using aluminium alloys. The efficiency of feed material is close to 100%, the feeding system is already developed, the recycling of materials is not necessary, head rotation problems turn up only when using plasma and TIG welding. Feed material outside from the required position is possible [5].

The purpose of this research was to determine optimal technological welding parameters for WAAM of thin welds that could result with stable depositions in heights at different welding positions. Standard MAG (with shielding gas CO_2), impulse MIG (with shielding gas Ar) and Cold Metal Transfer (CMT) process at preliminary welding have been analyzed. Different welding currents (40 A, 90 A, 140 A) and welding speeds (3 mm/s, 7.5 mm/s, 12 mm/s) were investigated. Based on preliminary tests, to achieve optimal welding conditions CMT process has been selected for future optimization. During welding in different positions PA, PC and PG temperatures of layers have been measured. Demonstration products were made with optimal welding parameters using SprutCam software [9].

Comparing energy inputs by laser or arc technologies show high investment and operational costs when using laser and low when using plasma or MIG. Total efficiency and joining efficiency are approx. 10 % using laser and 80 % using arc. There is also a high safety risk when using laser technologies, but they have medium to high build rate compared to arc technologies. Minimum thickness of 0.2 mm layer can be achieved with laser technologies compared to arc where minimum thickness is 1 mm [5].

tehnologije je aditivna proizvodnja žica i luka - WAAM [5].

Najčešći sistem koji se koristi za WAAM je industrijski robot na koji je ugrađen gorionik za zavarivanje. Cena takvog sistema je do 300 k € za izgradnju manje složenih delova. Za proizvodnju visokokvalitetnih delova pogodnih za vazduhoplovnu tehnologiju su sistemi koji se sastoje od CNC-a i robota visokih cena. Njihova cena je u rasponu od 0,2-2 miliona evra [2]. Čvrstoća konstrukcije, dinamička tačnost i prigušivanje vibracija CNC mašina su veće pa su one pogodnije za proizvodnju od strane WAAM [3].

Postoje mnogi nedostaci upotrebe praha umesto žice: visoki troškovi, promenljiv kvalitet praha, dodavanje je složeno ukoliko se ne koristi sistem bočnog uvlačenja, niska efikasnost (40-60%), pažljivo rukovanje zbog bezbednosnih aspekata, problemi sa rotacijom glave ako je dodavanje sa strane. Ako se dodaje materijal žica, cena materijala je srednje visoka, kvalitet materijala je visok (Ti, Fe, Ni), ali takođe može biti drugačiji kada se koriste legure aluminijuma. Efikasnost sirovina je blizu 100%, sistem dodavanja je već razvijen, recikliranje materijala nije potrebno, problemi sa rotacijom glave pojavljuju se samo kada se koristi plazma i TIG zavarivanje. Moguće je umetanje materijala izvan pozicije [5].

Svrha ovog istraživanja bila je utvrđivanje optimalnih tehnoloških parametara zavarivanja za WAAM tankih zavara koji mogu rezultovati stabilnim taloženjem u visinu na različitim položajima zavarivanja. Analizirani su standardni MAG (sa zaštitnim gasom CO_2), impulsni MIG (sa zaštitnim gasom Ar) i proces hladnog metala (CMT) pri prethodnom zavarivanju. Ispitivane su različite struje zavarivanja (40 A, 90 A, 140 A) i brzine zavarivanja (3 mm/s, 7,5 mm/s, 12 mm/s). Na osnovu preliminarnih testova, za postizanje optimalnih uslova zavarivanja, odabran je CMT postupak za buduću optimizaciju. Tokom zavarivanja u različitim položajima izmerene su temperature za PA, PC i PG. Demonstracijski proizvodi napravljeni su sa optimalnim parametrima zavarivanja pomoću softvera SprutCam [9].

Poređenje ulaza energije laserskom ili elektrolučnom tehnologijom pokazuje velike investicione i operativne troškove kada se koristi laser i niske kada se koriste plazma ili MIG. Ukupna efikasnost i efikasnost spajanja su oko 10% korišćenjem lasera i 80% korišćenjem luka. Takođe, postoji visok bezbednosni rizik kada se koriste laserske tehnologije, ali one imaju srednju do visoku stopu izrade u poređenju sa elektrolučnim tehnologijama. Minimalna debljina

Comparison between layer heights, build rate and horizontal resolution suggest that technologies with powder in container have the lowest build rate and high resolution, while technologies based on blowing powder have high build rate and low resolution. WAAM technology has higher build rate and lowest resolution compared to powder technologies. When melting efficiency is maximal the build rate depends on squared layer height for single axially symmetric source. Resolution has many influencing factors and it depends on layer height and width ratio. Usually is the best in 1.5 layer to height ratio [5]. Because of low resolution parts commonly need post-machining treatment process to fit the geometrically tolerances. Treatment can be done as intermediate or post-process, depends on requirement result. Intermediate machining done between deposited layers allows adjustment of layer thickness and machining of internal surfaces in case of shell parts in comparison to post machining which does not support such machining but is less time consuming. sloja od 0,2 mm može se postići laserskim tehnologijama u poređenju sa lukom gde je najmanja debljina 1 mm [5].

Poređenje između visine sloja, stepena sakupljanja i horizontalne rezolucije sugeriše da tehnologije sa prahom u posudi imaju najnižu stopu nakupljanja i visoku rezoluciju, dok tehnologije zasnovane na prahu za puhanje imaju visoku stopu nakupljanja i malu rezoluciju. WAAM tehnologija ima višu stopu izrade i najmanju rezoluciju u poređenju sa tehnologijama praška. Kada je efikasnost topljenja maksimalna, brzina sastavljanja zavisi od visine kvadratnog sloja za jedan aksijalno simetrični izvor. Rezolucija ima mnogo uticajnih faktora i zavisi od odnosa visine i širine sloja. Obično je najbolji u odnosu između 1,5 i visine sloja [5]. Zbog delova male rezolucije obično je potreban postupak obrade nakon mašinske obrade kako bi se prilagodile geometrijsei tolerancije.. Tretman se može obaviti kao srednji ili post-proces, zavisno od rezultata. Međusobna obrada između nanesenih slojeva omogućava podešavanje debljine sloja i obradu unutrašnjih površina u slučaju delova školjke u odnosu na naknadnu obradu koja ne podržava takvu obradu, ali zahteva manje vremena.

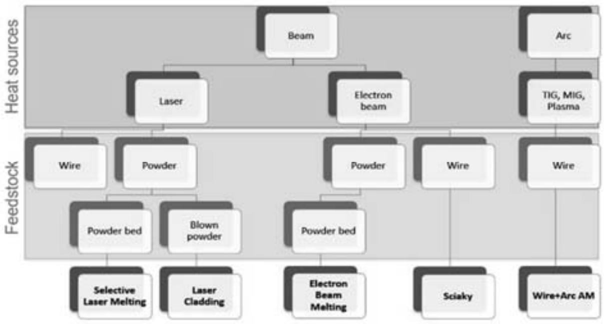

***Figure 1**. Division of additive manufacturing of metals [5]*
***Slika 1.** Odeljenje aditivne proizvodnje metala [5]*

2. Materials and methods

MAG process has been used on S355 structural steel base plate in dimensions 100×22×8 mm. G3Si1 welding wire of 1.2 mm in diameter was used for WAAM, with shielding gas (82 % Ar + 18 % CO_2) flow rate of 10 l/min. Fronius TransPlus Synergic 3200 CMT power source and welding robot ABB IRB 140 were used. From the produced structures, specimens were sectioned for microstructure analysis, measurement of Vickers hardness and Zwick/Z250 tensile testing machine was used for tensile tests. A 2 % nital etchant was used for for analysis of microstructure, which was analysed at optical microscope Mitutoyo TM.

2. Materijali i metode

MAG postupak je korišćen na ploči od konstrukcionog čelika S355 dimenzija 100 × 22 × 8 mm. Za WAAM korišćena je žica za zavarivanje G3Si1 prečnika 1,2 mm, sa protokom gasa (82% Ar + 18% CO2) od 10 l / min. Korišćeni su izvor napajanja Fronius TransPlus Sinergic 3200 CMT i robot za zavarivanje ABB IRB 140. Od proizvedenih struktura uzorci su isečeni za analizu mikrostrukture, merenje tvrdoće po Vickersu. Mašina za ispitivanje zatezne čvrstoće Zvick / Z250 korišćena je za ispitivanja zatezanjem. Za analizu mikrostrukture korišćen je 2% nital. koja je analizirana na optičkom mikroskopu Mitutoio TM.

3. Results and discussison

Welding parameters which allow stable welding for thin walls have been determined. One layer deposited on substrate 8 mm thickness built with welding current 40 A is shown on Fig. 2. In the case of standard control of wire feed, the weld was acceptable only at the lowest speed of welding and highest energy input (137.3 kJ/m). Energy input at higher welding speed was too low to build an acceptable weld. In the case of pulse control of wire feed an acceptable weld has been made with the welding speed 7.5 mm/s and energy input 94 kJ/m. All welds were of sufficient quality when using CMT at all welding speeds and also at higher energy input (34.3 kJ/m). Welds were wider than in other cases.

3. Rezultati i diskusija

Određeni su parametri zavarivanja koji omogućavaju stabilno zavarivanje tankih zidova. Jedan sloj nanesen na podlogu debljine 8 mm izveden strujom zavarivanja 40 A prikazan je na slici 2. U slučaju standardne kontrole dovoda žica, zavarivanje je bilo prihvatljivo samo pri najmanjoj brzini zavarivanja i najvećem unosu energije (137,3 kJ / m). Ulaz energije pri većoj brzini zavarivanja bio je previše nizak da bi se dobio prihvatljiv zavar. U slučaju kontrole impulsa dovoda žice napravljen je prihvatljivi zavar brzine zavarivanja 7,5 mm / s i unosa energije 94 kJ / m. Svi zavari su bili dovoljnog kvaliteta kada su koristili CMT pri svim brzinama zavarivanja i takođe pri većem unosu energije (34,3 kJ / m). Zavareni spojevi su bili šira nego u drugim slučajevima.

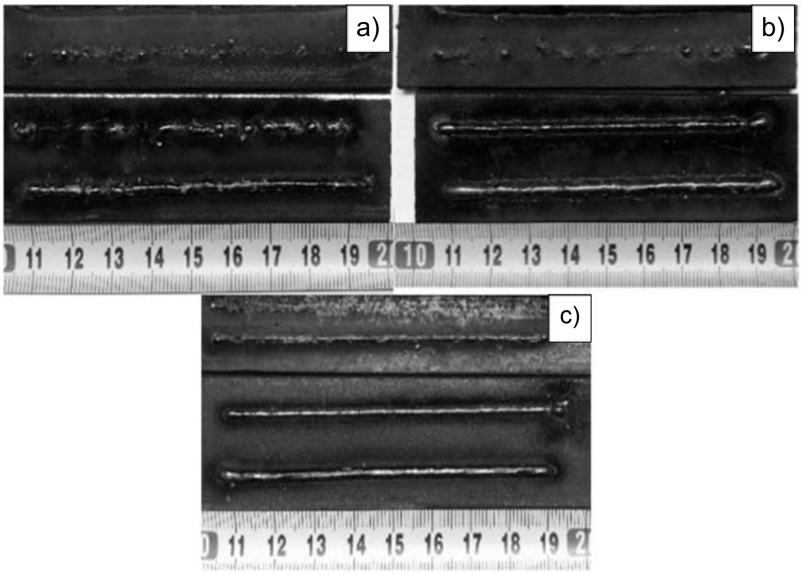

Figure 2. *Welding at 40A a) standard, b) pulse c) CMT (different welding speed from bottom to top: 3, 7.5, 12 mm/s)*
Slika 2. *Zavarivanje na 40A a) standardno, b) impulsno c) CMT (različita brzina zavarivanja odozdo prema gore: 3, 7,5, 12 mm / s)*

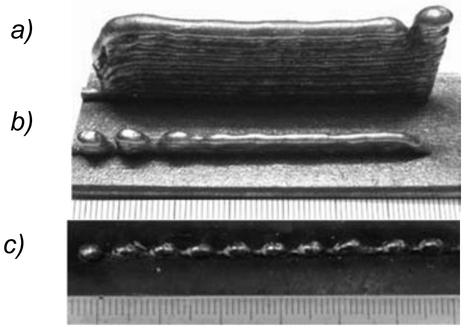

Figure 3. *Welding by CMT process at welding current 40 A (different welding speeds from top to bottom: 3, 7.5, 12 mm/s)*
Slika 3. *Zavarivanje CMT postupkom na zavarivačkoj struji 40 A (različite brzine zavarivanja od vrha do dna: 3, 7,5, 12 mm / s)*

Welds made by CMT process at welding current 40 A are shown at Fig. 3. In the picture above were welding took place from right to left, on the median and lower from left to right. Weld were acceptable only when welding at speed 3 mm/s. There were problems with the arc ignition at the start and melting of material at the end. Because of unstable process cavity has occurred at start of the welds. If energy input is decreased, stability of welding process is reduced when welding walls. The process of welding cannot be performed at the deposition of only a few layers. The welding of the wall after process optimization, at welding current 90 A and welding speed 3 mm/s from right to left is shown at Fig. 4a. It can be noticed that thickness of wall increased and sloping appeared. This is because of wall overheating at the end of welding and spilling of deposited material. Sloping can be partially improved by changing welding direction by the welding of each layer which is shown on Fig. 4b.

Zavarivanja napravljena CMT postupkom pri struji zavarivanja 40 A prikazana su na slici 3. Na gornjoj slici zavarivanje se odvijalo s desna na levo, na srednjem i nižem s leva na desno. Zavarivanje je bilo prihvatljivo samo za zavarivanje brzinom od 3 mm / s. Bilo je problema sa uspostavljanjem luka na početku i topljenjem materijala na kraju. Zbog nestabilne procesne šupljine došlo je do početka zavarivanja. Ako se smanji unos energije, smanjuje se stabilnost procesa zavarivanja zidova. Postupak zavarivanja ne može se izvesti samo nanošenjem nekoliko slojeva. Zavarivanje zida nakon optimizacije procesa, pri struji zavarivanja 90 A i brzini zavarivanja 3 mm / s s desna na levo, prikazano je na slici 4a. Može se primetiti da se debljina zida povećavala i naginjala. To je zbog pregrevanja zida na kraju zavarivanja i prosipanja nataloženog materijala. Nagib se može delimično poboljšati promenom smera zavarivanja zavarivanjem svakog sloja, što je prikazano na slici 4b.

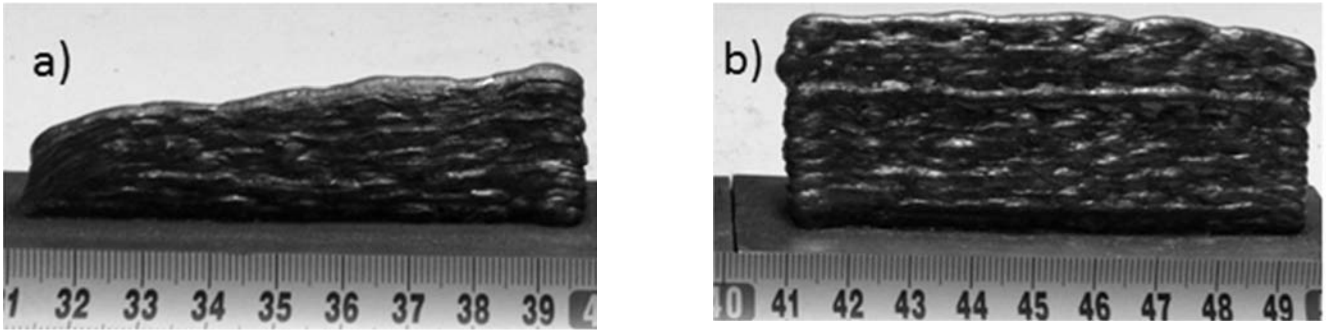

Figure 4. Welding influence at I = 90 A, v = 7.5 mm/s a) at left b) alternate on both sides
Slika 4. Uticaj zavarivanja pri I = 90 A, v = 7,5 mm / s a) na levoj strani b) naizmeničan je na obe strane

Based on parametric analysis and geometry measurement weld width and height decreased if welding speed was increased (shown on Fig. 5). If welding current increased, consequently welding wire feed speed, energy input, welding height and width increased, too. In case of welding many layers with high weld inter-pass temperature (200 °C), weld width increased and weld height decreased at constant volume. One of impacts on weld height and width besides welding parameters is also inter-weld temperature.

Na osnovu parametrijske analize i mjerenja geometrije širina i visina zavarienog spoja su se smanjivali ako se povećala brzina zavarivanja (prikazano na slici 5). Ako se povećala struja zavarivanja, posljedično se povećala i brzina zavarivanja žice, ulazna energija, visina i širina zavarenog spoja. U slučaju zavarivanja mnogih slojeva sa visokom inter-propusnom temperaturom zavarivanja (200 °C), širina zavarenog spoja se povećava, a visina zavarenog spoja smanjuje se na konstantnu zapreminu. Jedan od uticaja na visinu i širinu šava pored parametara zavarivanja je i temperatura zavarivanja

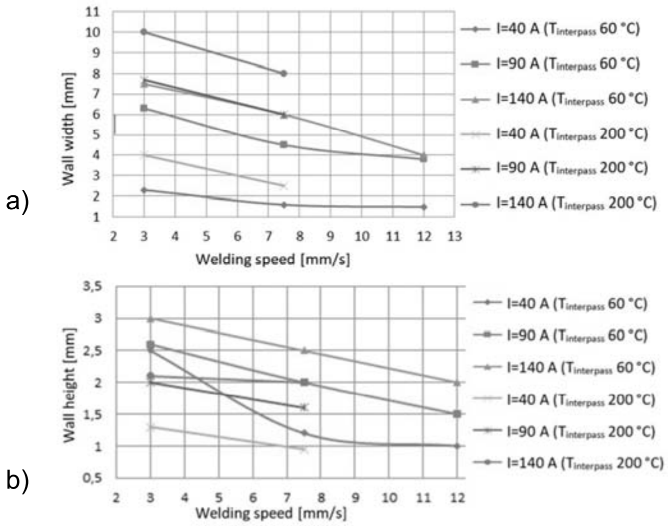

***Figure 4.** Influence of welding parameters for CMT process on: a) bead width b) weld height.*
***Slika 5.** Uticaj parametara zavarivanja na CMT postupak na: a) širinu zavara b) visinu šava*

Welding in difficult positions and different angles of torch were also performed. The inter-weld temperature had, besides energy input, great influence in all cases. Welds made in PA position with different energy input are shown at Fig. 6a. Torch angle was 60°and was equal to the wall angle which was built. Welding made in PG position (welding from up to bottom) by increasing weld inter-pass temperature developed a droplet of material at the end of weld because of gravity influence (shown at Fig. 6b.) The height of weld increased, too.

Izvršeno je i zavarivanje u teškim položajima i različitim uglovima gorionika. Temperatura zavarivanja je osim unosa energije imala veliki uticaj u svim slučajevima. Zavarivanja napravljena u PA položaju sa različitim unosom energije prikazana su na slici 6a. Ugao gorionika bio je 60 ° i bio je jednak uglu zida koji je rađen. Zavarivanje izvedeno u PG položaju (zavarivanje odozdo na dno) povećanjem inter-propusne temperature zavarivanja razvilo je kapljicu materijala na kraju zavara zbog uticaja gravitacije (prikazano na slici 6b.) Visina zavara se takođe povećala.

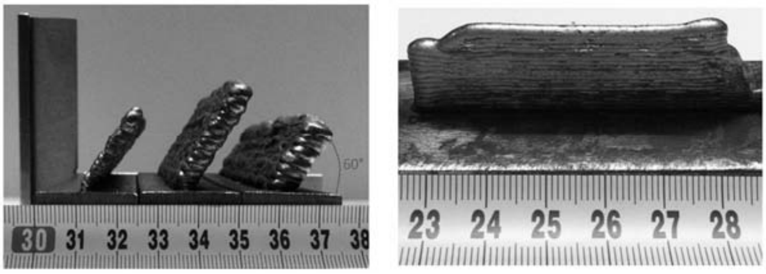

***Figure 5.** Welding in a) PA position at parameters: I = 40 A, v = 5mm/s; I = 90 A, v = 7.5 mm/s; I = 140 A, v = 7.5 mm/s and angle of torch 60°, b) PG position at parameters: I = 40 A, v = 5mm/s*
***Slika 6.** Zavarivanje u a) položaju PA kod parametara: I = 40 A, v = 5 mm / s; I = 90 A, v = 7,5 mm / s; I = 140 A, v = 7,5 mm / s i ugao baklje 60 °, b) pozicija PG kod parametara: I = 40 A, v = 5 mm / s*

Fig. 7a presents macro of weld made at welding current 59 A and welding speed 5 mm/s. First weld is narrower and higher because of increased heat transfer into colder substrate. Weld thickness in layers above was increased because of lower heat transfer and higher inter-weld temperature. Hardness in layers is shown at Fig. 7b.

Hardness was measured in different spots in HAZ, where it was increased up to 280 HV value. Measuring hardness value of substrate was 190 HV. Hardness at layers above was measured in the middle of each layer. Failure of welds in upper layers has been detected. Hardness decreases

Sl. 7a prikazuje makrostrukturu zavara izrađenog pri na struji zavarivanja 59 A i brzini zavarivanja 5 mm / s. Prvi šav je uži i veći zbog povećanog prenosa toplote u hladniju podlogu. Debljina šava u gornjim slojevima povećana je zbog nižeg prenosa toplote i veće temperature između zavara. Tvrdoća u slojevima je prikazana na slici 7b.

Tvrdoća je merena na različitim mestima u ZUT-u, gde je povećana do 280 HV. Vrednost merenja tvrdoće podloge bila je 190 HV. Tvrdoća gornjih slojeva merena je u sredini svakog sloja. Otkriven je lom na gornjim slojevima. Tvrdoća se smanjuje from value 200 HV to 160 HV. Welded layer was softer compared to the substrate for approx. 20 HV.

sa vrednosti 200 HV na 160 HV. Zavareni sloj je bio mekši u odnosu na podlogu za otprilike. 20 HV

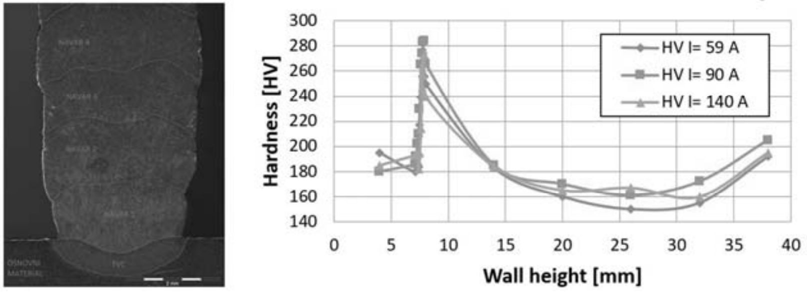

Figure 6. *a) Macro made at welding current 59 A and welding speed 5 mm/s b) Hardness changing at different welding parameters (5 mm/s (59 A), 7,5 mm/s (90 A in 140 A).*

Slika 7. *a) Makrostruktura napravljena pri struji zavarivanja 59 A i brzini zavarivanja 5 mm / s b) Tvrdoća koja se menja pri različitim parametrima zavarivanja (5 mm / s (59 A), 7,5 mm / s (90 A u 140 A).*

A 3D model of demonstration part built with WAAM technology is shown at Fig. 8. Process was continuous without controlling inter-weld temperature. Inter-weld temperature was high which can be seen on the middle picture where the part being built was still glowing. Shape of 3D model corresponds to the shape of part made with WAAM technology. Because of higher inter-weld temperature there is a rough surface and material spillage over the part built. Smoother surface caused with few-second of pause which provided lower inter-weld temperature.

3D model demonstrativnog dela izgrađenog WAAM tehnologijom prikazan je na slici 8. Proces je bio kontinuiran bez kontrole temperature zavarivanja. Temperatura zavarivanja bila je visoka, što se može videti na srednjoj slici gde je deo koji se gradi još uvek užaren. Oblik 3D modela odgovara obliku dela izrađenog VAAM tehnologijom. Zbog viših temperatura zavarivanja, na delu se gradi hrapava površina i prosipanje materijala. Glatka površina prouzrokovana je pauzom od nekoliko sekundi, što je omogućilo nižu temperaturu zavarivanja

Figure 7. *3D model and final product welded by CMT and pulse combined process at welding current 59 A and welding speed 5 mm/s.*

Slika 8. *3D model i krajnji proizvod zavaren CMT-om i pulsirajućim lukom kombinovanim postupkom pri zavarivačkoj struji 59 A i brzini zavarivanja 5 mm / s.*

4. Conclusion

A parametric analysis of weld surfacing (WAAM) of thin walls was done using MIG/MAG technology and 1.2 mm in diameter welding filler wire G3Si. It was established:

- a combination of pulse and CMT welding presented the optimal process control program. Optimal welding parameters for weld surfacing of thin layered walls were obtained at welding current of 59 A, welding voltage 8.8 V and welding speed 5 mm/s, where the linear heat input was 103.8 kJ/m,
- welding parameters together with inter-pass weld temperature should be considered to provide stable surfacing process. Inter-pass weld temperature should not exceed 100 °C, to avoid spilling of the molten metal,

4. Zaključak

Parametrijska analiza navarenih slojeva (WAAM) tankih zidova urađena je upotrebom MIG / MAG tehnologije i žice za zavarivanje prečnika 1,2 mm prečnika G3Si. Utvrđeno je:

- kombinacija pulsnog i CMT zavarivanja predstavila je optimalan program kontrole procesa. Optimalni parametri zavarivanja za navarivanje zidova tankim slojevima, dobijeni su pri struji zavarivanja od 59 A, naponu zavarivanja 8,8 V i brzini zavarivanja 5 mm / s, pri čemu je linearni unos toplote 103,8 kJ / m,
- parametre zavarivanja zajedno s međuslojnom temperaturom treba uzeti u obzir da bi se osigurao stabilan proces navarivanja. Međuslojna

- energy input should be between 100-300 kJ/m. If linear energy input is too low wavy surface may appear, if too high there can be a spilling of material with changed height to width ratio,
- hardness of material is very constant, it only changes in HAZ,
- welding in different positions can be done but the most convenient is to do it in PA position. In other positions the influence of gravity, surface tension and inter-pass weld temperature should be considered with keeping energy input minimized.

temperatura ne sme biti veća od 100°C, kako bi se izbeglo prosipanje rastopljenog metala,
- unos energije treba da bude između 100-300 kJ/m. Ako je linearni unos energije prenizak, može se pojaviti talasasta površina, ako je previsoka, može doći do izlivanja materijala sa promenjenim odnosom visine i širine,
- tvrdoća materijala je vrlo konstantna, menja se samo u ZUT-u,
- zavarivanje u različitim položajima može se obavljati, ali najprikladnije je uraditi ga u PA položaju. U drugim položajima treba uzeti u obzir uticaj gravitacije, površinskog napona i međuslojne temperature ako bi se unos energije smanjio na minimum.

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References
Literatura

[1] Frazier, W. E. (2014): Metal additive manufacturing: A review. Journal of Materials Engineering and Performance, 23(6), pp. 1917–1928.
[2] Wong, K.V., Hernandez, A. (2012): A review of additive manufacturing. ISRN Mechanical Engineering, 2012, pp. 1–10.
[3] Merz, R. (1994): Shape deposition manufacturing (Doctoral dissertation), Retrieved from https://www.researchgate.net/publication/30873042_Shape_deposition_manufacturing, pp. 169.
[4] Weiss, L.E., Merz, R., Prinz, F.B., Neplotnik, G., Padmanabhan, P., Schultz, L., Ramaswami, K. (1997): Shape deposition manufacturing of heterogeneous structures. Journal of Manufacturing Systems, 16(4), pp. 239–248.
[5] Williams, S.W., Martina, F., Addison, A.C., Ding, J., Pardal, G., Colegrove, P. (2016): Wire+ arc additive manufacturing. Materials Science and Technology, 32, pp. 641–647.
[6] Martina, F., Roy, M.J., Colegrove, P.A., Williams, S.W. (2014): Residual stress reduction in high pressure interpass rolled wire+ arc additive manufacturing Ti-6Al-4V components. Proc. 25th Int. Solid Freeform Fabrication Symp, pp. 89–94.
[7] [Colegrove, P.A. et al., (2014): High pressure interpass rolling of wire+ arc additively manufactured titanium components. Advanced Materials Research, 996, pp. 694–700.
[8] Nilsiam Y., Haselhuhn, A., Wijnen, B., Sanders, P., Pearce, J.M. (2015): Integrated Voltage—Current Monitoring and Control of Gas Metal Arc Weld Magnetic Ball-Jointed Open Source 3-D Printer. Machines, 3(4), pp. 339–351.
[9] SprutCam software [cited 17/8/2018], Available on: http://www.sprutcam.com