Original scientific paper

Received: May 01, 2018
Accepted: Jun 08, 2018
DOI 10.2478/rmzmag-2018-0015

Wire arc additive manufacturing of mild steel

3D obločno oblikovno navarjanje z žico iz konstrukcijskega jekla

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Abstract

This paper presents an overview of additive manufacturing technologies for production of metal parts. A special attention is set to wire arc additive manufacturing (WAAM) technologies, which include MIG/MAG welding, TIG welding and plasma welding. Their advantages compared to laser or electron beam technologies are lower investment and operational costs. However, these processes have lower dimensional accuracy of produced structures. Owing to special features and higher productivity, the WAAM technologies are more suitable for production of bigger parts. WAAM technology has been used together with welding robot and a cold metal transfer (CMT) power source. Thin walls have been produced using G3Si1 welding wire. The microstructure and hardness of produced structures were analysed and measured. 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.

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

Povzetek

Ta članek prikazuje pregled dodajalnih tehnologij na področju izdelave kovinskih izdelkov. Podrobneje je predstavljen postopek 3D obločnega oblikovnega navarjanja z žico – WAAM (ang. Wire and arc additive manufacturing), ki temelji na postopkih navarjanja MIG/MAG, TIG ali plazemskega navarjanja. Njegova prednost v primerjavi z navarjanjem z žarki, kot sta laser in elektronski snop, so nizki investicijski stroški in operativni stroški. Omejitev teh tehnologij je njihova nižja dimenzijska natančnost. Zaradi posebnosti postopkov navarjanja in velike produktivnosti je tehnologija izdelave WAAM bolj primerna za izdelavo izdelkov večjih dimenzij. Pri eksperimentalnem delu smo uporabili vir varilnega toka CMT in varilnega robota. Tanke stene smo izdelali z varilno žico G3Si1. Izmerili in analizirali smo mikrostrukture in trdoto navarjenih sten. Z raziskavo smo določili optimalne parametre za izdelavo tankih sten z nizko valovitostjo. Za generiranje kode za 3D navarjanje reprezentativnega izdelka enostavne geometrije smo uporabili programsko okolje SprutCAM.

Ključne besede: robotsko navarjanje MIG/MAG, trdota, oblikovno obločno navarjanje z žico (WAAM), SprutCAM.

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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 process, additive technology, 3D printing, rapid prototyping and rapid tooling [1].

The development of additive manufacturing of technologies of metal and polymer parts does not progress evenly. Existing market solutions enable manufacturing of complex parts in tight tolerances. The cost of parts depends on precision and quality of manufacturing. For example, development of polymers' rapid prototype is already at a high level. One can buy low-cost 3D printers, which are available for home use. The advantages of these systems is user friendliness and inexpensiveness, but they have limitations in the manufacturing process [1, 2].

There are many different technologies that 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 of 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 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. This means that 72 million tons of titanium will be a waste material [5–8].

Additive manufacturing of metal parts can be divided based on technologies using beams and arcs (Figure 1). Laser beam or electron beam could be used for printing of metal parts. Filler material in this case is powder or wire. In laser systems, the feed powder can be added with gas (blowing), 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 to the welding spot. In case of welding with electron beam, we use the Sciaky system. MIG, TIG and plasma are most common in arc welding. In all variations, the feeding material in the form of wire is being used. The common expression for all these technologies is wire arc additive manufacturing – WAAM [5]. The most common system used for WAAM is industrial robot, where welding torch is installed. The price of such a system is up to 300 k€ for building less complex parts. For production of high-quality parts suitable for aerospace technology, systems consisting of high-cost CNC and robot are required. Their price are in the range of 0.2–2 M€ [2]. Structure stiffness, dynamic accuracy and vibration damping of CNC machines are 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, complexity of feed unless the side feed system is being used, low efficiency (40–60%), careful handling because of safety aspects and head rotation problems if feed is added from side. When adding the wire filler material, the price of materials is medium–high and the quality of the material is high (Ti, Fe, Ni), but this 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 and head rotation problems turn up only when using plasma and TIG welding. Feed material outside 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 pre-

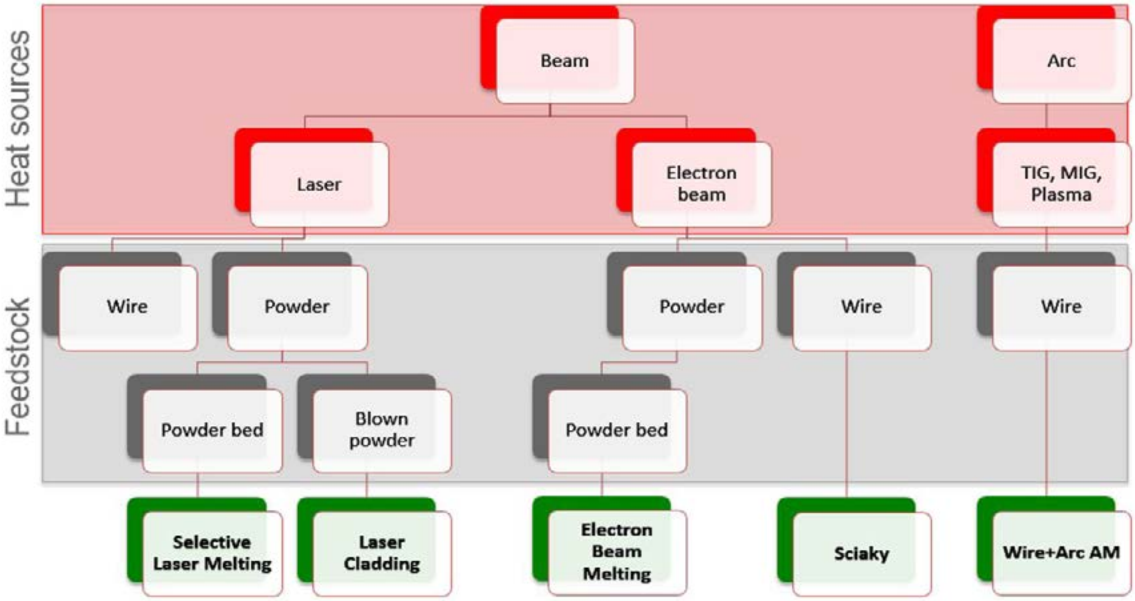


Figure 1: *The partition of additive manufacturing of metal parts [5].*

liminary welding have been analysed. 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, the CMT process has been selected for future optimisation. During welding in different positions, PA, PC and PG temperatures of layers have been measured. Demonstration products were made with optimal welding parameters using the SprutCAM software [9].

Comparing energy inputs by laser or arc technologies show high investment and operational costs when using laser and low cost when using plasma or MIG. Total efficiency and joining efficiency are approximately 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 that of arc technologies. Minimum thickness of 0.2 mm layer can be achieved with laser technologies compared to 1 mm with arc technologies [5].

Comparison between layer heights, build rate and horizontal resolution suggests that powder bed technologies have the lowest build rate and a high resolution, while technologies based on blowing powder have a high build rate and a low resolution. WAAM technology has a 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 to width ratio, usually is the best in 1.5 layer to height ratio [5], because low-resolution parts commonly need post-machining treatment process to fit the geometrical tolerances. Treatment can be done intermediately or post process, depending 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.

Experiment

MAG process has been used on S355 structural steel base plate in dimensions 100 × 22 × 8 mm. G3Si1 welding wire in 1.2 mm diameter has been used with shielding gas CORGON 18 (82% Ar + 18% CO_2) with a flow rate of 10 l/min. Fronius TransPuls Synergic 3200 CMT power source and welding robot ABB IRB 140 have been used as a WAAM equipment. From the produced structures, specimens have been sectioned for analysis of microstructure, Vickers hardness and tensile strength at different orientations relative to the direction of welding wire feed. Zwick/Z250 machine has been used for tensile tests and 2% nital etch (a solution of nitric acid and alcohol) for preparation of specimens for analysis of structure using optical microscope Mitutoyo TM.

Results and discussion

Welding parameters that allow stable welding for thin walls have been determined. One layer deposited on base plate of 8 mm thickness built with welding current 40 A is shown in Figure 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 a 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 a welding speed of 7.5 mm/s and energy input of 94 kJ/m. All welds were of sufficient quality when using CMT at all welding speeds and also at a higher energy input (34.3 kJ/m). Welds were wider than in other cases.

Welds made by the CMT process at a welding current of 40 A are shown in Figure 3. In the picture above were welding took place from right to left, on the median and lower from left to right. Welds were acceptable only when welding was carried out at a speed of 3 mm/s. There were problems with the arc ignition at the start and melting of material at the end. Because of the unstable process, cavity 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 optimisation, at a welding current of 90 A and a welding speed of 3 mm/s from right to left, is shown in Figure 4a. It can be noticed that the 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 in Figure 4b.

Figure 2: *Welding at 40 A a) standard, b) pulse and c) CMT (different welding speeds from bottom to top: 3, 7.5 and 12 mm/s).*

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

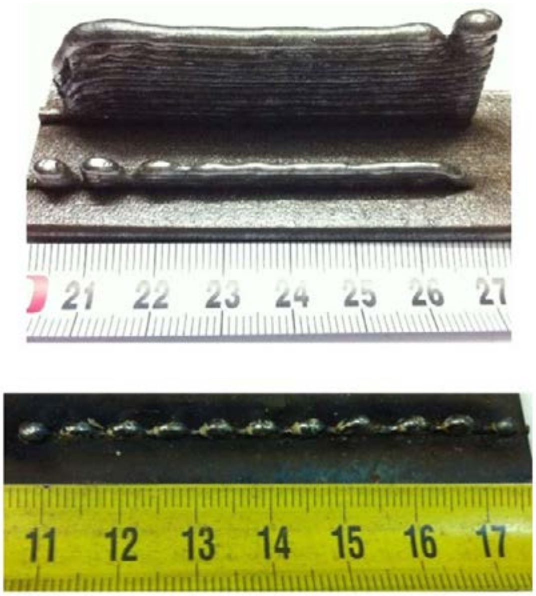


Figure 3: *Welding by CMT process at welding current 40 A (different welding speed from top to bottom: 3, 7.5, 12 mm/s).*

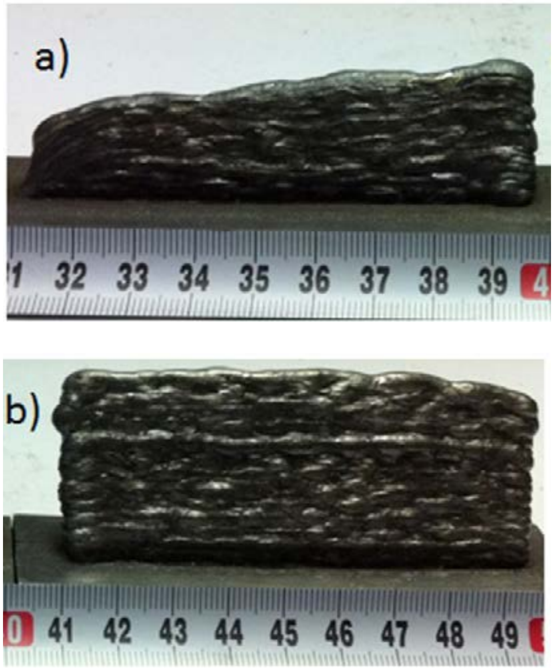
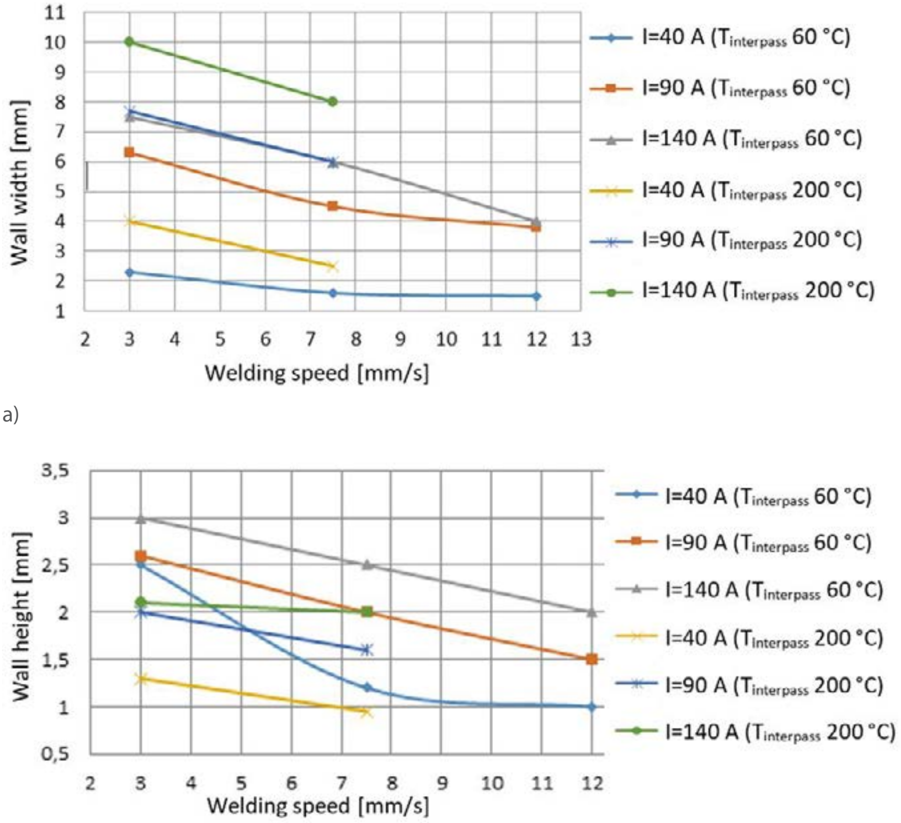


Figure 4: *Welding influence at I = 90 A, v = 7.5 mm/s a) at left and b) alternate on both sides.*



a)

b)

Figure 5: *Influence of welding parameters for CMT process on: a) bead width and b) weld height.*

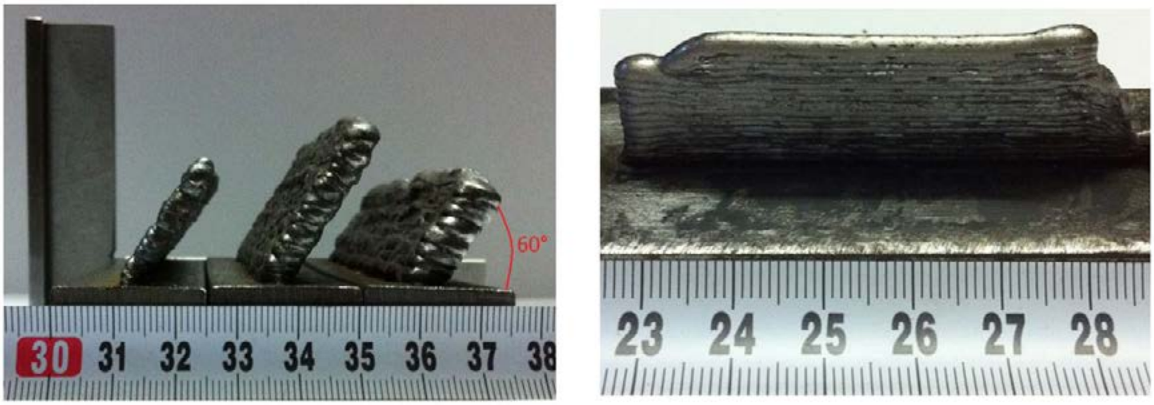


Figure 6: *Welding in a) PA position at parameters: I = 40 A, v = 5mm/s; I = 90 A, v = 7.5 mm/s; I = 140 A, v = 7.5 mm/s and angle of torch 60° and b) PG position at parameters: I = 40 A, v = 5mm/s.*

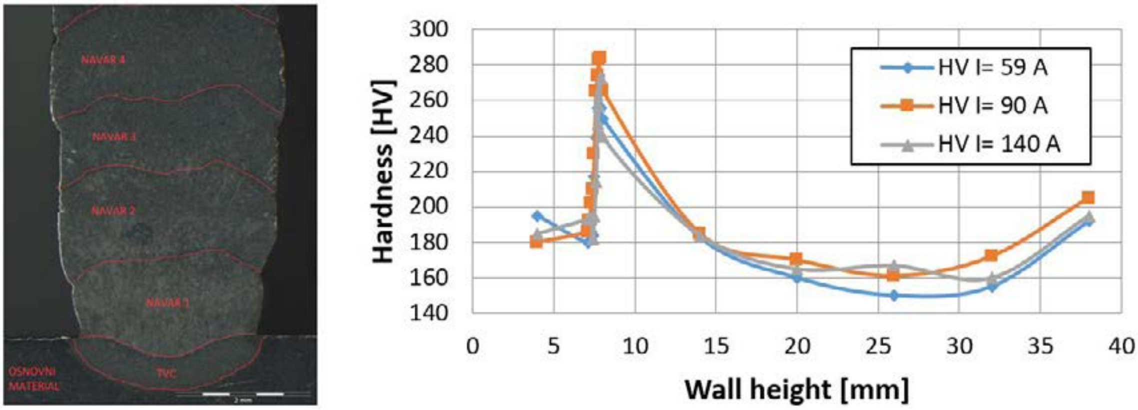


Figure 7:

Figure 8:

Welding in difficult positions and different angles of torch was also performed. The inter-weld temperature had, besides energy input, a great influence in all cases. Welds made in the PA position with different energy inputs are shown in Figure 6a. Torch angle was 60°and was equal to the wall angle, which was built. Welding made in the 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 the influence of gravity (shown in Figure 6b.) The height of weld increased too.

Figure 7a presents macro of weld made at a welding current of 59 A and a welding speed of 5 mm/s. The first weld is narrower and higher because of increased heat transfer into colder base plate. Weld thickness in layers above was increased because of lower heat transfer and higher inter-weld temperature. Hardness in layers is shown in Figure 7b. Hardness was measured in different spots in HAZ, where it was increased up to 280 HV value. The hardness value of the base plate was measured at 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 from value 200 HV to 160 HV. Welded layer was softer compared to the base plate for approximately 20 HV.

The 3D model of demonstration part built with WAAM technology is shown in Figure 8. The 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. The shape of the 3D model corresponds to the shape of the part made with the WAAM technology. Because of higher inter-weld temperature, there is a rough surface and material spillage over the part built. Smoother surface caused with a few second of pause, which provided lower inter-weld temperature.

Conclusion

A parametric analysis of weld surfacing (WAAM) of thin walls was done using MIG/MAG technology and welding filler wire G3Si of diameter 1.2 mm. The following 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 a welding current of 59 A, welding voltage of 8.8 V and welding speed of 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.
- Energy input should be between 100 and 300 kJ/m. If linear energy input is too low, wavy surface may appear, and if it is 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 the PA position. In other positions, the influence of gravity, surface tension and inter-pass weld temperature should be considered with keeping energy input minimised.

Acknowledgements

The authors wish to thank Luka Bricelj and Boris Bell for conducting experimental work, Nikolay Konov for the help with SprutCAM software, company SIJ Elektrode Jesenice for supporting them with filler metals and company GTG plin d.o.o. for support with their shielding gasses. The authors acknowledge the financial support from the Slovenian Research Agency (research core funding no. P2-0270 and Project Nos. L2-8181 and L2-8183). The article is in part the result of work in the implementation of the SPS Operation entitled MAterials and Technologies for New Applications – MARTINA. The investment is co-financed by the Republic of Slovenia and the European Union from the European Regional Development Fund.

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