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The Use of Arc Welding Processes in the Additive Manufacturing of Metallic Products

Abstract: The article presents examples of additive manufactured products obtained using MIG /MAG welding processes (13). The research-related tests revealed that it is possible to make products of unalloyed steels having the structure similar to castings subjected to heat treatment. Products made of maraging steel require homogenising (heat treatment). It is possible to produce bimetallic products, e.g. unalloyed steel-bronze.

Keywords: MIG/MAG welding, additive manufacturing, unalloyed steel, maraging steel, bronze

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Introduction

Additive manufacturing, being one of the fastest developing production technologies, consists in the making of a 3D object on a layer-after-layer basis. A product created in the aforesaid manner can be made of nearly every engineering material including metals, plastics, ceramics or composites consisting of two or three of the above-named materials. Table 1 presents the primary division of additive manufacturing processes.

Table 1. Categories of processes used in additive manufacturing [1–3]

Process	Description
Binder jetting	Liquid binding agent deposited selectively to bind powdery materials
Directed energy deposition	Direct deposition of a material melted in a concentrated energy beam
Material extrusion	Selective proportioning (extruding) of a material through a nozzle or an opening
Material jetting	Selective deposition of drops of molten material on a backing bar
Powder bed fusion	Selective melting of powder (in a powder bed) by a concentrated energy beam
Sheet lamination	Selective deposition of a material from a leaf/sheet
Vat photopolymerisation	Selective solidification of liquid polymer in a container through UV light-activated polymerisation

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Additive manufacturing is used in the making of both prototypes or ready functional products and their parts. Among other things, this manufacturing technology is used to make tools, e.g. forging dices or casting moulds. Any of the additive manufacturing processes referred to in Table 1 requires a specialist machine, control and configuration software as well as additional equipment including peripherals. Additive manufacturing processes can be performed using various technical solutions. Solutions used in additive manufacturing are usually protected by trademarks e.g. DMLS®, FDM®, SLS® or SLA®. An important and continuously developing group of additive manufacturing processes includes increasingly popular directed energy deposition techniques based on arc welding processes and referred to in publications as Wire Arc Additive Manufacturing (WAAM).

Additive manufacturing based on arc welding processes

The primary advantages resulting from the use of welding processes in additive manufacturing include the possibility of making large elements of metallic materials, high process efficiency, low equipment-related costs and a low negative impact on the natural environment. In comparison with conventional production methods (and depending on the size and geometry of a given element), the use of additive manufacturing may reduce production time by 40-60% and time needed for machining by 15–20%. Arc process-based additive manufacturing may involve the use of arc TIG welding (14), plasma welding (15) and MIG/MAG welding (13) in one and multi-electrode variants and low-energy methods involving the controlled transfer of a metal drop to the liquid metal pool. The above-named methods are used, among other things, in the aviation, automotive and shipbuilding industries to make elements of iron, aluminium and titanium alloys as well as of nickel alloys and superalloys. Filler metals used in additive manufacturing usually have the form of solid welding or surfacing wires. However, the market offer also includes specialist materials dedicated to WAAM processes [4–5]. The article presents examples of simple products made using additive manufacturing methods based on gas-shielded metal arc welding processes. The objective of the research work was the assessment of the usability of unconventional filler metals in the production of prototypes and in batch production.

Development of an additive manufacturing technology based on MIG/MAG process (13)

Additive manufacturing developmental tests involved the use of a robotic MIG/MAG (13) welding station equipped with a Fanuc ARC Mate 100i welding robot, a Kemppi ProMig 520R welding power source and a Kemppi ProMig 120R filler metal wire feeder. The additive manufacturing process was performed layer after layer, where the subsequent movement of the robot was designed during the cooling of the previous layer. A heat input was determined using method A described in ISO/TR 18491 (1):

$$Q = \eta \frac{I \cdot U}{v_{sp}}, \frac{kJ}{mm} \qquad (1),$$

where Q – heat input, I – current, U – arc voltage, v_{sp} – welding torch travel rate (welding rate), η – arc efficiency (η = 0.8 in accordance with EN 1011-1).

Table 2. Parameters used in the additive manufacturing process based on MIG/MAG welding (13)

Layer	Current *I*, A	Arc voltage *U*, V	Filler metal wire feeding rate v_{dr}, m/min	Welding rate v_{sp}, m/min	Electrode extension *l*, mm	Heat input Q, kJ/mm
1–24	160.5±3	18.6±0.08	4.25±0.05	0.225	12	0.64±0.01

Additive manufacturing of a product in fine-grained unalloyed steel

The additive manufacturing of a product in a material corresponding to unalloyed steel S460N involved the use of an Outhershield-MC710-H flux-cored consumable filler metal wire (EN ISO 17632-A: T 46 3 M M 2 H5) (Lincoln Electric). The process parameters are presented in Table 2.

The additive manufacturing process was performed without preheating; interpass temperature did not exceed 50°C. The obtained products were in the form of plates. The dimensions of the first product were 150 mm × 50 mm ×9.5 mm (length×height×width), whereas those of the second product were 80 mm × 20 mm × 9.5 mm. The additive manufactured products are presented in Figure 1. The analysis of the macro and microstructure was based on the cross-section of the smaller (second) product (Fig. 2). The structure of the product was homogenous; the last layer contained the coarse-grained dendritic structure (Fig. 2a). The microstructure (Fig. 2b) contained polygonal, lamellar (Widmanstätten) and fine-lamellar (acicular) ferrite. The penultimate run of the HAZ, formed during the making of the last run, contained an overheated area containing relatively large grains, a normalised area containing slightly smaller grains and a partially recrystallised area containing variously sized grains (Fig. 2c–e). The microstructure contained polygonal ferrite and relatively many non-metallic inclusions. The subsequent layers only contained two HAZ areas, i.e. a normalised area and a partially recrystallised area. The appropriate adjustment of process parameters was responsible for the fact that the range of the weld and of the heat affected zone fully included the previous layer and the overheated HAZ area of the previous layer. The foregoing resulted in the obtainment of a product, the microstructure and properties of which were similar to those of cast steel subjected to normalising.

Fig. 1. Main view of the additive manufactured products made using the Outhershield-MC710-H wire

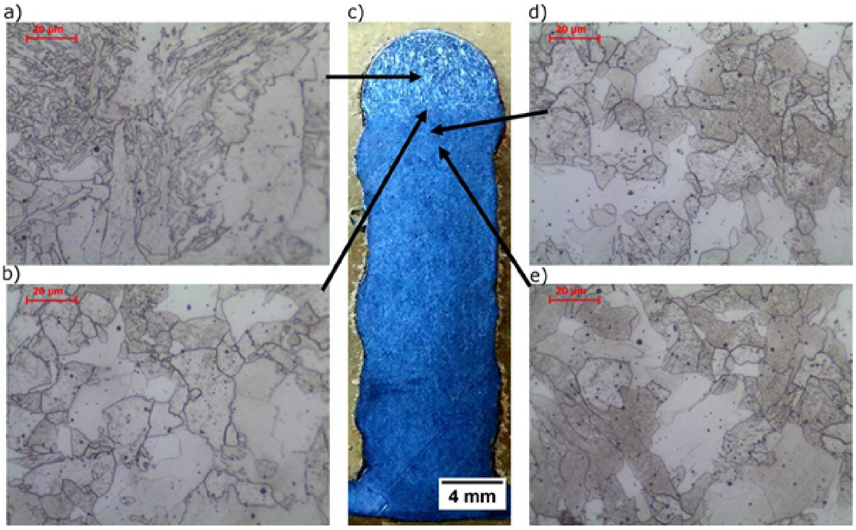

Fig. 2. Structure of the element manufactured using the Outhershield-MC710-H wire: a) macrostructure of the product, b) microstructure of the last layer, c) microstructure of the overheated HAZ area in the penultimate layer, d) microstructure of the normalised HAZ area in the penultimate layer and e) microstructure in the partially recrystallised HAZ area in the penultimate layer; etchant: 4% Nital

Table 3. Parameters used in the additive manufacturing process based on MIG/MAG welding (13)

Layer	Current I, A	Arc voltage U, V	Filler metal wire feeding rate v_{dr}, m/min	Welding rate v_{sp}, m/min	Electrode extension l, mm	Heat input Q, kJ/mm
1–10	143.5±2	18.7±0.18	4.25±0.05	0.375	12	0.34±0.01

Additive manufacturing of a product in maraging steel

Another stage of tests involved the additive manufacturing of a product in a material corresponding to maraging X2NiCoMoTi18-12-4 steel, using a COREWELD NiCoMo metallic flux-cored filler metal wire (DIN 8555: MF 4-UM-350-CKPSTZ) (METALWELD FIPROM POLSKA). The process parameters are presented in Table 3.

The additive manufacturing process was performed without preheating; interpass temperature did not exceed 50°C. Based on related reference publications [6] it was assumed that the maintaining of the aforesaid temperature regime would enable the martensitic transformation during the cooling of each successive run ($M_f \approx 60$°C).

The obtained product had the form of a plate having dimensions of 80 mm × 19 mm ×8.5 mm (length×height×width). The main view of the additive manufactured product is presented in Figure 3. The analysis of the macro and microstructure was based on the cross-section (Fig. 4). In the last 5 layers the macrostructure was not revealed through etching. The subsequent layers contained the structure with clearly visible HAZ areas of the successively deposited layers (Fig. 4a). The microstructure of the first 5 layers (Fig. 4b) contained the dual-phase structure of martensite and retained austenite along crystallite boundaries. The subsequent layers contained (Fig. 4c) the dual-phase structure of aged martensite and retained austenite along crystallite boundaries. In both cases it was possible to observe large primary precipitates located primarily in the retained austenite. The obtainment of appropriate structure (aged martensite) required the performance of homogenising heat treatment subsequently combined with ageing.

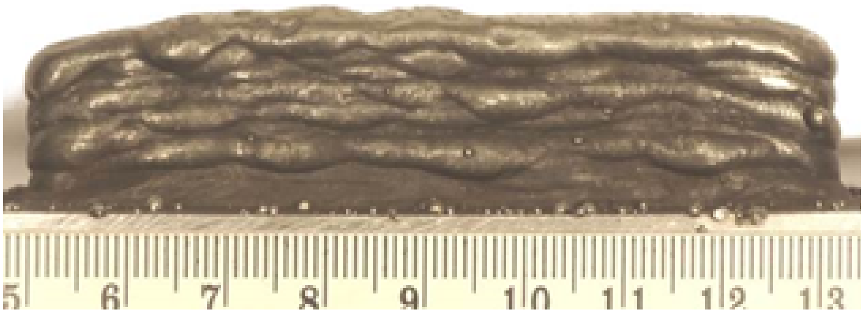

Fig. 3. Main view of the additive manufactured product made using the COREWELD NiCoMo wire

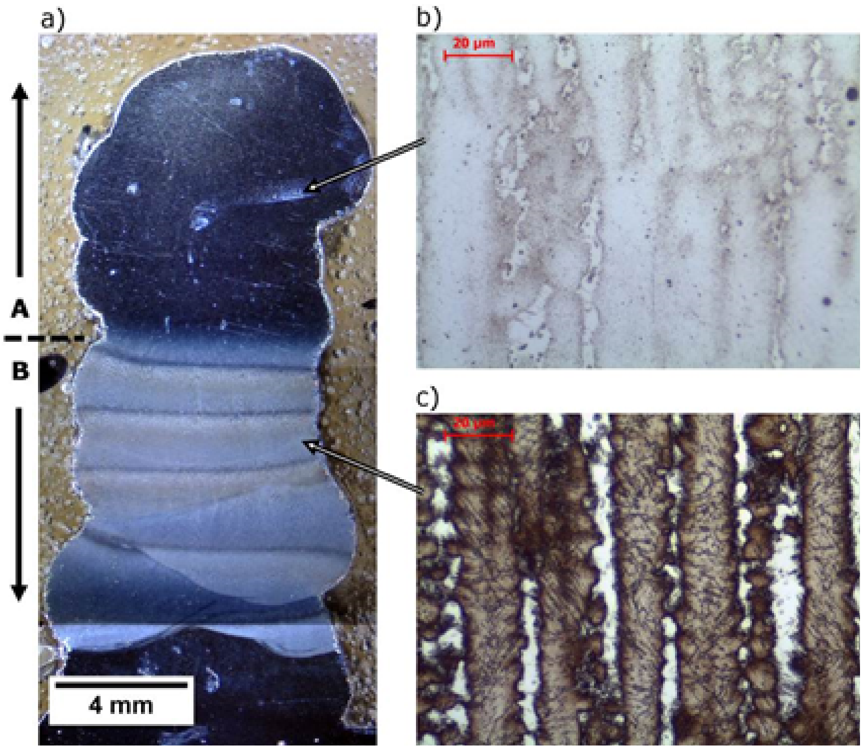

Fig. 4. Structure of the additive manufactured element made using the COREWELD NiCoMo wire: a) macrostructure – visible effects of supersaturation (A) and ageing(B), b) microstructure in the first 5 layers and c) microstructure in the remaining layers; etchant: 4% Nital

Additive manufacturing of a bimetallic steel-bronze product

The additive manufactured bimetallic product (unalloyed steel–silicon bronze) was made using the Outhershield-MC710-H flux-cored consumable wire (EN ISO 17632-A: T 46 3 M M 2 H5) (Lincoln Electric) and solid wire grade CuSi3Mn1. The additive manufacturing process parameters are presented in Table 4. First, layers were made using the steel wire. Afterwards, layers were made using the bronze wire.

Table 4. Parameters used in the additive manufacturing process based on MIG/MAG welding (13)

Layer	Current I, A	Arc voltage U, V	Filler metal wire feeding rate v_{dr}, m/min	Welding rate v_{sp}, m/min	Electrode extension l, mm	Heat input Q, kJ/mm
1–10	198.1±1.8	18.6±0.07	5.72±0.05	0.111	12	1.6±0.01
11–17	190±0.05	13.8±0.02	6.15±0.03	0.111	11	1.13±0.01

The additive manufacturing process was performed without preheating; interpass temperature did not exceed 50°C. The obtained product had the form of a plate (120 mm × 70 mm× 9.5 mm (length×height×width). The main view of the additive manufactured product is presented in Figure 5. The analysis of the macro and microstructure was based on the cross-section of the transitional area between successive runs (Fig. 6).

Fig. 5. Main view of the additive manufactured product made using the Outhershield-MC710-H wire and the CuSi3Mn1 wire

The macroscopic tests revealed the shape of the individual layers (particularly within the bronze area); it was possible to observe the HAZ of successive runs. Because of the lack of phase transformations in bronze, the macroscopically visible HAZ in the bronze was significantly narrower than in the layers made of the iron alloy. The microstructure in the layers made using the Outhershield-MC710-H wire did not differ from that discussed previously. The first layer made using the CuSi3Mn1 wire (Fig. 6b) contained iron precipitates, the presence of which resulted from the partial melting of the last layer of the iron-based weld deposit and dilution in the weld pool. The subsequent layers were characterised by the increasingly low content of iron precipitates (Fig. 6c).

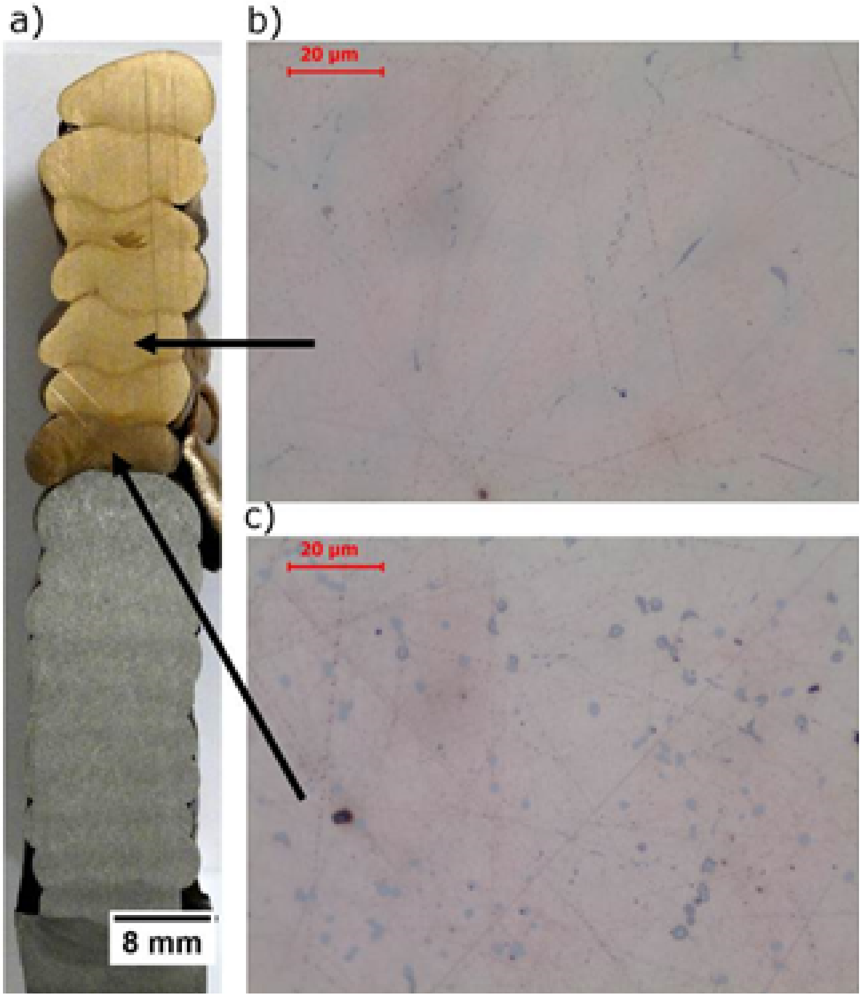

Fig. 6. Structure of the element manufactured using the Outhershield-MC710-H wire (EN ISO 17632-A: T 46 3 M M 2 H5) and solid wire grade CuSi3Mn1: a) macrostructure of the product, b) microstructure in the 1-st layer made using wire CuSi3Mn1 and c) microstructure in the 3-rd layer made using wire CuSi3Mn1; etchant: 4% Nital

Summary

It is possible to use robotic MIG/MAG processes in the additive manufacturing of products made of metal alloys. After manufacturing involving the use of an unalloyed wire and appropriate process parameters, the microstructure of a product is similar to that of cast steel after normalising. As regards maraging steel X2NiCoMoTi18-12-4, the obtained dual phase structure (martensite-retained austenite) required additional heat treatment processes aimed to optimise the initial structure. Both experiments revealed that metallic flux-cored wires and flux-cored consumable wires can be successfully used in additive manufacturing. It is also possible to make bimetals of materials significantly varying in terms of structural and physical properties using two different wires (e.g. steel and bronze).

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