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EFFECT OF HEAT INPUT ON MICROSTRUCTURE AND MICROHARDNESS IN WAAM

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Abstract

Experiments were carried out for WAAM of samples using electric arc and additive material in the form of solid wire grade G3Si1. The layers were built-up with one transition each. Metallographic macro- and microsections were made from the obtained samples. The macro- sections are used to determine the locations of microhardness measurements. The microsections were used to measure the microhardness and to illustrate the microstructure. The analysis of the obtained results shows that the heat input and the interlayer temperature are of crucial importance for the obtained mechanical characteristics of the built-up samples. The microstructure of the obtained layers varies along the height of the built-up samples thus witnessing for the thermal treatment occurring in each layer except the last one as a result of applying the subsequent layers.

Key words: wire and arc additive manufacturing, microstructure, microhardness

Introduction. In recent years, the technologies for wire and arc additive manufacturing (WAAM) using metals and alloys have made it possible to achieve cost-effective production mainly of medium-sized and complex parts in single-unit production [1]. The electric arc welding and overlay welding methods that are most often used for WAAM of parts are TIG, MIG/MAG and plasma welding

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[2,3]. The highest efficiency is achieved using MIG/MAG process. It is the easiest to implement, but it has one drawback compared to TIG and plasma welding: the amount of filler material fed is related to the current strength and, respectively, to the energy of the process. This makes the other two methods more flexible in terms of layer thickness, but their efficiency is lower. These methods are used in combination with a wide range of materials: aluminium alloys, titanium alloys (most often Ti-6Al-4V), copper alloys, unalloyed, alloyed and high-alloyed steels, magnesium alloys, etc. [3]. The relevance of research in the field of WAAM can be judged by the increasing number of publications in journals with SCOPUS index: until the end of year 2015 the total number of publications is 24; in 2016 it is 18; in 2017 it is 37; in 2018 it is 86; in 2019 it is 154; in 2020 it is 282; in 2021 it is 356; in 2022 it is 490; and in 2023 it is 611. Alternative technologies for WAAM of parts from metals and alloys are electron beam and laser remelting of metal powders. The main advantages of WAAM with respect to technologies for electron beam and laser remelting of metal powders are related to the higher efficiency and the lower costs of additive materials [1,3,4]. Another advantage, especially when using high-strength steels, is the lower cooling rate, which decreases the risk of formation of hardening structures and cold cracks. The technologies for WAAM are similar to the technologies of welding and overlay welding [5], which allows using the equipment developed for these conventional technologies to realize the new technologies [6]. Compared to the processes of casting and forging, the advantages of WAAM are expressed both in the absence of expensive equipment and the possibility of manufacturing parts with more complex geometry or using materials that do not have the necessary technological properties to implement the conventional processes. When comparing WAAM with mechanical processing, the advantages are usually related to the more efficient use of material [4]. The products that are currently being made through WAAM can be divided into two groups. The first group includes demonstrator parts intended to show the capabilities of the technology and the achievements of the researchers in the field, while the second group includes parts for industrial application which are often machined additionally [4,6,7].

One of the critical problems in fusion welding is the resulting coarse grained dendritic structure of the weld, which results in lower yield strength and higher anisotropy. Different approaches can be used to improve the microstructure of the weld: pulsed welding processes and/or arc oscillation; appropriate chemical composition of the additive material; introduction of modifiers in tubular wires welding; varying the mode parameters, e.g. current, voltage, welding speed and heat input; type of the shielding gas; electromagnetic stirring of the welding pool; use of additional hot or cold wire. Since the WAAM process is similar to welding, almost any of these techniques are applicable in both cases. There are also some additional possibilities in WAAM: practically multilayer structures are always obtained, and each subsequent layer heat treats the previous ones. The effect

of the heat treatment depends on the interlayer temperature. This means that the tool (i.e. the welding arc) movement strategy and the possible pauses are essential. The heat input is considered the main factor affecting the quality of the obtained parts [5]. The use of high heat input energies is at odds with the drive to increased productivity. Controlling the interlayer temperature during WAAM can dramatically change the thermal deformation cycle and the resulting microstructure in the manufactured parts [5].

The aim of the present work is to investigate the effect of the welding current and heat input on the microstructure of the layers and the resulting microhardness.

Materials and methods. Steel plates grade S273JR according to standard BDS EN 10028 with dimensions $6 \times 120 \times 150$ mm were used as substrates. After mechanical cleaning of the plates, five layers were applied to make the welded samples using the modes specified in Table 1. During the experiments on building the walls, the arc movement speed was 165 mm/min. The values of wire feeding speed (V_W) and the arc voltage (U_A) were set. The welding wire according to standard BDS EN ISO 14341-A:G 42 3CM 3Si1 (i.e. G3Si1) has diameter of 1.0 mm and chemical composition in weight percentage (according to the certificate) as follows: C – 0.08, Mn – 0.43, Si – 0.83, P – 0.006, S – 0.010, Ni – 0.02, Cr – 0.03, Mo – 0.000, V – 0.004, Cu – 0.03, and N – 0.0099.

Table 1

Experimental modes

No	V_W, m/min	U_A, V	I_A, A	q_L, J/mm
1	2.0	14.4	40	146.62
2	2.4	15.0	58	221.45
3	2.7	15.1	70	269.05
4	3,0	14.8	82	308.92
5	3.5	15.9	100	404.73

The experiments for WAAM of walls were carried out on specially made equipment, described in [8], using welding current source PARWELD XTM 21 D1. During the experiments, the arc voltage U_A and current I_A are recorded. Using their values, the heat input (q_L) is calculated, assuming that the efficiency factor is $\eta = 0.7$

$$q_L = \eta I_A U_A / V_W. \tag{1}$$

Samples for metallographic analysis and microhardness measurements were cut from the WAAMed walls and microsections were prepared through sanding with sandpaper up to No. 2000, manual polishing with diamond paste and developing in nital (4% solution of nitric acid (HNO_3) in ethanol (C_2H_5OH)). The microhardness is measured using micro hardness tester Micro-Duromat 5000

(Reichert-Jung) at preset loading 0.50 N, loading time 10 s and hold time under load 10 s. Photographs of the microstructure and the impressions from the indenter of the microhardness tester were taken with a Polyvar Met light microscope at magnifications ×200 and ×500. The microhardness was tested at 10 different points for each specimen as shown in Fig. 1.

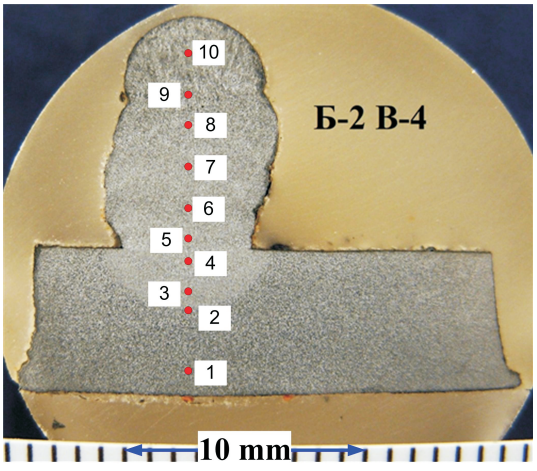


Fig. 1. Points for microhardness measurements

Results. The values of welding current (I_A) recorded during the WAAM process and the calculated heat input are shown in Table 1. The results of the microhardness measurements are shown in Table 2. Table 2 also shows the deter-

Table 2

Measured micro hardness values, MPa

Point No	No of the sample – welding current I_A					s, MPa	s/M, %
	2 – 40A	7 – 58A	12 – 70A	17 – 82A	22 – 100A		
1	1812.30	1629.87	1522.00	1447.50	1685.76	127.09	7.85
2	2591.90	1812.27	1389.60	1553.30	1421.96	444.70	25.36
3	2113.30	1668.11	1744.60	1790.70	1463.15	210.94	12.01
4	1880.90	1656.34	1739.70	1372.90	1531.80	173.91	10.63
5	1731.90	1867.19	1561.20	2170.20	1578.87	223.82	12.56
6	1755.40	1899.55	1601.40	2499.70	1639.67	327.20	17.41
7	2057.40	2113.33	1504.30	2075.10	1827.00	228.76	11.94
8	2198.80	2091.76	1878.00	2268.30	1976.04	142.33	6.83
9	1995.70	1724.01	1711.30	1761.30	1531.80	148.42	8.51
10	2162.40	1716.16	2068.20	1995.70	1877.97	154.95	7.89

Microstructures in the points of micro hardness measurements: ferrite; ferrite+perlite; mostly ferrite; mostly perlite.

mined root mean square deviations (s) and their ratio to the average value (M) in each point. Table 2 shows the structures in the points of hardness measurements by means of colour marking.

Discussion. The results of the microhardness measurement are shown in Table 2. Point 1 is always located in the substrate (the base steel plate on which layers are deposited) and point 10 is in the last welded layer. In these two cases, we get the same ratio s/M of the root mean square error and the mean value. The relative error is also small in point 9, which is always located in the fusion zone obtained during welding of the last layer. In fact, the same relative error obtained for points 1 and 10 shows that the repeatability of the obtained result for a separate layer is the same as that for the base metal. The differences may occur as a result of heat treatment during the deposition of subsequent layers. Point 2 is located in the heat affected zone in the base metal and the largest relative error was obtained at this point. This can be explained by the different temperature cycles realized in this area. The relative error in the measured hardness of the built-up walls refers to points No. $3 \div 8$. Except for point 8, which is located in the penultimate layer, points $3 \div 7$ have a relatively large dispersion of the microhardness. This proves

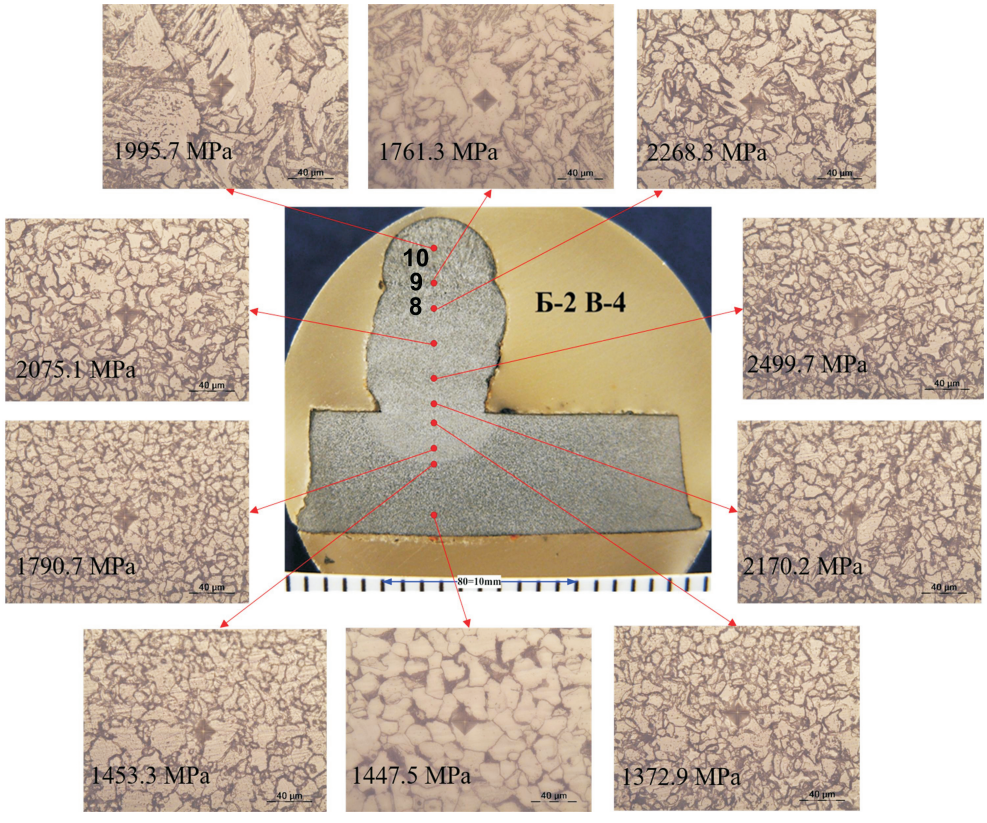


Fig. 2. Microstructures observed in the points of microhardness measurements

that the heat input and the interlayer temperature are crucial for the resulting mechanical properties. Moreover, it can be concluded that more than one layer affects the microstructure and microhardness. The adjustment of the thermal cycle can be done by the movement path and the waiting times. At point 10, Widmanstaetten ferrite and large elongated grains of irregular shape are observed (Fig. 2) forming columnar grains in the macrostructure, as well as possibly bainite. In point 9, besides the irregularly shaped ferrite grains, also few equiaxed ferrite grains and point-like pearlite are observed, and in some of the ferrite grains twins are observed. In point 8, the majority of ferrite grains have equiaxed shape. Ferrite grains of irregular shape are also observed, as well as granular pearlite, which results from the heat treatment during the deposition of the last layer. The ferrite grains are significantly smaller in size than those in point 10 and 9. Twins are observed in some ferrite grains.

Analyzing points $8 \div 10$, it can be noted that the highest microhardness (2268 MPa) was obtained at point 8, which is explained by the finest microstructure observed in that point (Fig. 2).

Conclusions. Based on the experiments carried out, the following main conclusions can be drawn:

1. The heat input and the interlayer temperature are of crucial importance for the obtained mechanical characteristics of the WAAMed parts.

2. The microstructure of the layers is formed and changed during their deposition.

3. The microstructure in the penultimate layer was found to be finer than that in the last layer (points 8, 9 and 10).

4. The measured microhardness in the penultimate layer ($1880 \div 2268$ MPa) is higher than that in the last layer (points 8, 9, and 10).

5. The finishing layers are essential to any WAAMed part. the last layer has a coarser microstructure and lower microhardness than the penultimate layer.

6. The highest microhardness (2500 MPa) found at point 6 confirms the heat treatment occurring within several successively deposited layers.

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