Доклади на Българската академия на науките
Comptes rendus de l'Académie bulgare des Sciences

Tome 77, No 11, 2024

ENGINEERING SCIENCES

Electronics

INFLUENCE OF HEAT INPUT ON FORMATION OF LAYERS IN WAAM

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Received on June 7, 2024
Presented by Ch. Roumenin, Member of BAS, on October 29, 2024

Abstract

Experiments are carried out on WAAM using solid wire grade G3Si1 as additive material. The layers are deposited with single beads. Metallographic macro sections are made from the obtained samples and are used to determine the geometric dimensions of the layers, i.e. width, height and lateral waviness. The correlation coefficients between the heat input and the geometrical dimensions of the obtained layers are determined and their significance is proved according to the Student's distribution. Based on the correlation coefficients, the coefficients of determination are calculated. It is proved that over 90% of the changes in the layer's width and over 76% of the changes in the layer's height are due to changes in the heat input. The analysis of the obtained results shows that the heat input is determining for the geometric dimensions of the layers and the lateral waviness can be decreased by increasing the travel speed.

Key words: WAAM, heat input, geometric dimensions

Introduction. In recent years, the technologies for WAAM using metals and alloys have made it possible to achieve cost-effective manufacturing of parts of medium size and complexity in single-unit production [1]. The three electric arc methods that are most often used for WAAM of parts are TIG, MIG/MAG, and plasma welding [2, 3]. The highest efficiency is achieved in the MIG/MAG

This work was supported by the Bulgarian National Science Fund Project "Studying the structure and the properties of layers obtained by selective plasma melting", No. KP-06-H57/10.
https://doi.org/10.7546/CRABS.2024.11.07

process. MIG/MAG is also the easiest to implement, but it has one drawback in comparison with TIG and plasma welding that the amount of the additive material fed is related to the magnitude of the current and, respectively, to the power of the process. This relationship makes MIG/MAG method less flexible compared to the other two methods in terms of layer height. However, TIG and plasma welding have lower efficiencies. The three methods are used in combination with a wide range of materials: aluminum 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 number of publications in journals with SCOPUS index. For example, the number of publications before 2015 are 24, and the number of publications in 2023 are 611.

The alternative technologies for WAAM of parts from metals and alloys are electron beam and laser remelting of metals in the form of powder. The main advantages of WAAM compared to these technologies are related to the higher efficiency and the lower cost 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 implement the new technological processes [6]. Compared to the processes of casting and forging, the advantages of WAAM are expressed both in the absence of expensive equipment and in the possibility to manufacture details with more complex geometry and use 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 the material [4]. The products that are currently being made through WAAM can be divided into two groups: the first one called demonstrator parts is intended to demonstrate the capabilities of the technology and the achievements of the individual researchers in the field, while the second group are parts for industrial application where additional mechanical processing is often required [4,6,7].

The typical height of the layers obtained in WAAM is $1 \div 2$ mm [1], but it can reach up to 5 mm [4]. This is also one of the main geometric dimensions, the knowledge of which is necessary to realize the programming of the process. Another basic dimension is the width of the layer obtained in a single bead. It strongly depends on the technology used; the widest range (from 0.5 to 50 mm) is obtained when using plasma arc [4]. A characteristic feature of the WAAM-ed walls is their waviness, the typical value being 500 µm [1]. It is often removed by additional machining after the part is built. To reduce or eliminate the waviness, accompanying technological processes such as rolling, forced cooling or heating are proposed [2]. These accompanying processes also affect the structure of the metal, its mechanical properties and residual stresses. Heat input is considered

the main factor affecting the quality of the manufactured parts [5]. Therein, it is also indicated that the low heat input leads to a decrease in waviness.

The main imperfections and defects observed in WAAM are pores, cracks, stresses, deformations, distortions, anisotropy of the properties, disturbances of the phase composition. The appearance of defects is highly dependent on the material used and the parameters of the technological mode. The main technological possibilities for managing the process to obtain a good quality product are reduced to the correct distribution of the input energy and material in time and space. In practice, this means using an optimal combination of arc mode parameters, trajectory, travel speeds, and dwell times. The parameters of the mode of the electric arc and the travel speed during arc burning determine the heat input. The heat input together with the dwell times and the tool trajectory determine the interlayer temperature. As the heat input increases, the temporary and residual stresses and strains increase. Increasing the interlayer temperature leads to decrease of temporary and residual stresses, but it should be noted that the increased interlayer temperature also results in decrease of heat input (usually by increasing the travel speed).

The aim of the present work is to investigate the influence of heat input, tool travel speed and wire feed speed on the formation of the layers, their geometrical dimensions and the waviness of the WAAM-ed walls.

Materials and methods. Plates of steel grade S275JR in accordance with BDS EN 10028 with dimensions 6×120×150 mm were used as substrates. The plates were mechanically cleaned and overlay welded samples were produced by depositing 5 layers. The following feed rates (V_W) were used for overlay welding: 2.0, 2.4, 2.7, 3.0 and 3.5 m/min. At these feed rates, the arc voltage (U_A) was set to 14.4, 15.0, 15.1, 14.8 and 15.9 V, respectively. The travel speeds (V_T) used were 120, 165, 210, 255 and 300 mm/min. In conducting the experiments, all combinations of feed rate and travel speeds were used. The additive material is welding wire with a diameter of 1.0 mm, brand BDS EN ISO 14341-A:G 42 3CM 3Si1 (G3Si1) and chemical composition (in accordance with the manufacturer's certificate) shown in Table 1. According to the certificate the mechanical characteristics are as follows: yield strength R_{eL} = 428.15 MPa, ultimate strength R_m = 540.12 MPa, and relative elongation 27.2%.

Table 1

Chemical composition of the input material, wt. %

Element	C	Mn	Si	P	S	Ni
Concentration	0.08	0.43	0.83	0.006	0.010	0.02
Element	Cr	Mo	V	Cu	N	Fe
Concentration	0.003	0.000	0.004	0.03	0.0099	rest

The experiments on WAAM of walls were carried out with a specially made apparatus, described in [8] and a welding current source PARWELD XTM 21 D1. The apparatus was used to investigate the influence of the heat input over microstructure. [9]. The movement of the welding torch was realized along a closed trajectory (Fig. 1a). The time to deposit a single layer was 3 min. From the built-up walls, metallographic samples were cut out and macro sections were prepared. The geometric characteristics were determined from the photographs of macro sections (Fig. 1b). For this purpose, the scale was first determined using the reference length. The width measurements are averaged and the layer width is obtained. The height of the layer is calculated by dividing the height of the welded sample by the number of layers. The total waviness of the sample is determined as the sum of the maximum unevenness on both sides ($\delta = \delta_1 + \delta_2$). During the experiments, the voltage U_A and the current I_A of the arc are read from the readings of the current source. Based on these values, the heat input q_L is calculated, assuming that the efficiency coefficient is $\eta = 0.7$.

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

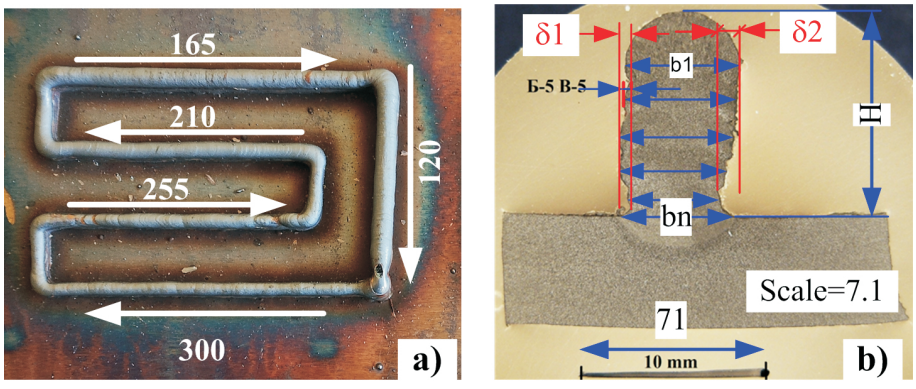


Fig. 1. Trajectory and travel speeds, mm/min (a), and determination of geometric dimensions (b)

Results. The welding current (I_A) depends on the wire feed rate and the values recorded during the process are 40, 58, 70, 82 and 100 A, respectively. The calculated heat input (q_L) and the measured geometric dimensions are shown in Table 2.

Discussion. The data in Table 3 shows that the increase of current and the decrease of deposition rate result in a general tendency for increase of the layer width and height. The waviness of the walls δ increases when the current increases and decreases with the increase of the travel speed. It should be noted that these trends are not so clearly expressed. This means that in order to obtain layers that need minimal subsequent mechanical processing, the maximum possible travel torch speeds should be used.

Table 2

The results from measurement and calculations

No.	b, mm	h, mm	δ ,mm	q_L, J/mm
1	4.20	1.96	1.17	201.60
2	3.76	1.59	1.05	146.62
3	3.56	1.42	0.8	115.20
4	3.43	1.28	0.65	94.87
5	2.59	1.09	0.63	80.64
6	5.87	2.23	1.9	304.50
7	5.13	1.93	1.74	221.45
8	4.25	1.68	0.52	174.00
9	3.80	1.56	1.05	143.29
10	3.71	1.37	0.91	121.80
11	6.48	2.65	1.68	369.95
12	5.41	2.13	0.91	269.05
13	4.52	1.92	1.15	211.40
14	4.36	1.62	1.02	174.09
15	4.03	1.61	1.27	147.98
16	6.81	2.45	1.96	424.76
17	6.06	1.91	2.25	308.92
18	5.37	1.79	1.15	242.72
19	4.99	1.44	1.6255	199.89
20	4.51	1.59	1.62	169.90
21	7.71	2.77	2.27	556.50
22	5.98	1.97	1.36	404.73
23	5.91	2.39	1.44	318.00
24	4.24	1.76	0.57	261.88
25	4.24	1.27	1.04	222.60

To evaluate the relationship between the heat input and the measured values, the coefficient of correlation (r) between them is calculated:

$$r_{q,y} = \sum_{i=1}^{N} (q_i - \bar{q})\,(y_i - \bar{y}) \Bigg/ \sqrt{\sum_{i=1}^{N} (q_i - \bar{q})^2 \sum_{i=1}^{N} (y_i - \bar{y})^2}. \tag{2}$$

Here N is number of experiments; q_i is heat input; $\bar{q}$ is the average value of heat input; y_i are the obtained respective values for width and height of the layer and the waviness of the wall; $\bar{y}$ is the average value of the respective quantity. The results obtained are shown in Table 3. It is usually accepted that when $|r| > 0.9$ the relationship between the quantities is very strong, and when $0.7 < |r| < 0.9$ the relationship is strong. To accept this hypothesis the correlation coefficient r shall be significant and the Student's distribution is used to prove the significance. For each correlation coefficient the quantity t is determined, where

$$t = r \Big/ \sqrt{(1 - r^2)/(N - 2)}. \tag{3}$$

The obtained values are shown in Table 3. According to Student's distribution the critical value for a significance level of 0.05 and a number of degrees of freedom of 23 is 2.068, which means that all correlation coefficients are significant. Another parameter that gives good enough information is the coefficient of determination r^2, which is equal to the square of the correlation coefficient. It shows how much of the change in the result is due to the change in the factor. The calculated values of this parameter are shown in Table 3. Analyzing the obtained results, it can be noted that the width and height of the layer can be expressed by the heat input using correlation equations. The waviness of the wall depends significantly on other factors as well.

T a b l e 3

Characteristics of the dependencies of the measured values on the heat input

Quantity	b	h	δ
r	0.951	0.876	0.702
t	14.75	8.70	4.73
r^2, %	90.4	76.7	49.3
a_0	2.463981109	1.031124725	
a_1	0.010077538	0.003332604	

Correlation equations of the type $y = a_0 + a_1 x$ are derived by the method of least squares and the coefficients are determined as follows:

$$a_1 = \frac{\sum\limits_{i=1}^{N} q_i y_i - \bar{x} \sum\limits_{i=1}^{N} y_i}{\sum\limits_{i=1}^{N} q_i^2 - \bar{q} \sum\limits_{i=1}^{N} q_i} \quad a_0 = \bar{y} - a_1 \bar{q}. \tag{4}$$

The values obtained are shown in Table 3.

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

1. The heat input determines the width and height of the obtained layers and its correlation relationship with these parameters is very strong.

2. There is a correlation between the heat input and the waviness of the resulting walls, but it is not so strong: 49% of the changes in the waviness are due to a change in the heat input.

3. Over 90% of the change in layer width and over 76% of the change in its height is due to a change in heat input.

4. Over 50% of the change in lateral waviness of the wall is due to other factors (interlayer temperature, type of shielding gas, surface tensions, etc.) besides the heat input.

5. Correlation equations are derived for the width and height of the layer depending on the heat input.

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