

FORMATION AND CHARACTERIZATION OF ER4043 WELDING WIRE LAYERS BY CA-WAAM ON COPPER SUBSTRATES

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Abstract

In this work, the possibility of forming aluminium ER4043 layers using a wire arc additive manufacturing (WAAM) setup in the cold arc (CA) mode on copper substrates was investigated. This is a challenging process due to the poor miscibility of copper and aluminium, and due to the possible formation of intermetallic compounds (IMCs), which would result in accelerated formation of defects, particularly cracks, in the zone of contact between the two materials. The effect of two different technological parameters was investigated, namely the wire feeding rate (WFR), the application of pulses to the process (+SP), and the formation of layers without pulses (−SP). Wire feeding rates of 67 mm/s and 133 mm/s were employed. The results indicated that in the case of applying a layer using a WFR of 133 mm/s without pulses a homogeneous, dense structure was formed with a preferred crystallographic orientation towards the {311} family of planes. In this case, the obtained microhardness was also the highest with an average value of 100 HV_{0.1}. During the investigations, no IMCs were detected. The results indicate that the formed layer can be successfully implemented in the field of wire arc additive manufacturing as a foundation for the manufacturing of bimetallic components made of, in this case, copper and aluminium alloy ER4043.

Key words: copper, aluminium, ER4043, WAAM, gas metal arc welding, cold arc, layer formation

Introduction. Wire arc additive manufacturing (WAAM) of components using metals and their alloys is a relatively new method that could potentially be implemented in industrial design and production. The demand for such a technique is already present and described in detail in [1]. Different approaches are used for manufacturing components which can be most commonly divided into three categories based on the applied heat source – laser, electron beam, and electric arc deposition [1].

One of the most commonly used materials in practice is aluminium and its alloys. This is attributed to its excellent mechanical, electrical, thermal, and corrosion resistance [2]. Of course, every aluminium alloy is prepared differently either in regards to the alloying elements and their contents, or in regards to the preparation procedure itself (such as preheating, annealing, heat-treating, etc.) [3, 4]. When additive manufacturing is considered, employing laser and electron beam methods for producing aluminium components is economically inefficient, except when the manufacturing of small, high-precision components is required [5], or the production of components with the newly studied aluminium matrix composites (AMCs) [6]. The most efficient method for manufacturing aluminium components both in regards to the raw material preparation cost and the deposition rate is wire arc additive manufacturing. It employs the conventional gas metal arc welding (GMAW) technique which can be modified using different special modes of operation. One such mode is the cold metal transfer (CMT) one, which is most commonly studied due to its low heat input and high controllability. However, other modes are present such as cold arc (CA), pulsed arc plasma, and more [7, 8]. These methods are much less studied in the scientific literature, but are no less potentially applicable in industrial fields, and also provide a high grade of controllability.

A big known issue is the manufacturing and joining of bimetallic components (ones with different thermophysical properties). In the industry, it is sometimes necessary to conjoin copper and aluminium components. This process can be achieved in various ways such as laser welding [9], friction stir welding [10], casting [11], and others, however, wire arc additive manufacturing could be potentially used for the manufacturing of ready-made components with high quality (good electrical, mechanical, and thermal properties) with complex shapes and minimal material waste. Previous investigations indicate the possibility of forming components using Cu-Al bimetallic alloys using WAAM [12], however, very few investigations were performed to study the possibility of formation of aluminium components on copper substrates. In this case, the bimetallic joint is limited to the one formed at the connecting point between the two materials.

Due to the limited information regarding the possibility of direct deposition of bimetallic components using WAAM in the cold arc mode, the present work studied the formation of ER4043 aluminium layers atop Cu substrates using different wire feeding rates (WFRs) and with and without pulses. The structure and

microhardness of the obtained layers were characterized. The results could give a basic understanding of the potential application of this method for the deposition of initial (intermediate) layers between the two materials.

Experimental part. For the purpose of this work a pure copper substrate was used with 99.99% purity with dimensions of $100 \times 50 \times 8$ mm, which due to its size was mounted to an ER6082 plate with dimensions of $300 \times 70 \times 15$ mm, and with the following chemical composition in wt%: 0.25% Cr, 0.1% Cu, 0.5% Fe, 0.6–1.2% Mg, 0.4–1.0% Mn, 0.7–1.3% Si, 0.1% Ti, 0.2% Zn, 0.15% others, balance Al. The last was secured to the welding table using mechanical clamps. The aluminium layer was formed using a welding wire comprised of ER4043 with the following chemical composition in wt%: 4.5–5.5% Si; < 0.6% Fe; < 0.3% Cu; < 0.15% Mn; < 0.2% Mg; < 0.1% Zn; < 0.0003% Be, < 0.15% Ti; < 0.15% others; balance Al. The diameter of the wire was 1.2 mm. The used setup can be seen in Fig. 1a.

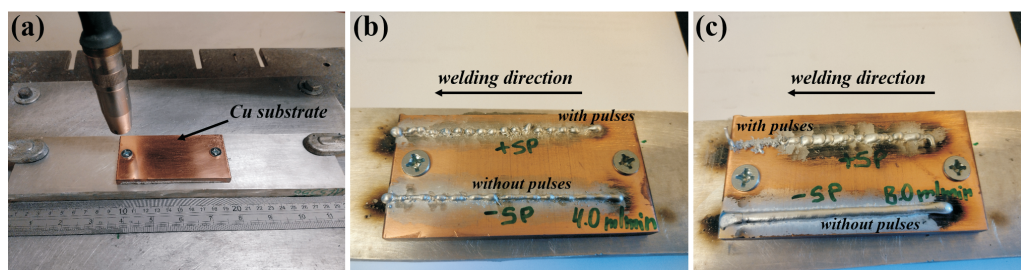


Fig. 1. Images of (a) copper substrate, (b) experiments performed with a WFR of 67 mm/s (4.0 m/min), (c) experiments performed with a WFR 133 mm/s (8.0 m/min)

The process of layer formation was carried out using a wire arc additive manufacturing setup comprised of a KUKA KR 15 robotic arm and an EWM power supply. During the experiments the welding speed was constant with a value of 20 mm/s and the argon gas flow was also constant with a value of 18 l/min. To study the effect of the wire feeding rate on the structure of the formed bead two different rates were used, namely 67 mm/s (4.0 m/min) and 133 mm/s (8.0 m/min). The EWN welding unit is factory setup to vary the output current and voltage values based on the wire feeding rate, so in the case of the lower rate the current was 85 A and the voltage was 18.1 V, totalling to a power of 1539 W. In the case of the higher wire feeding rate the current was 178 A, and the voltage was 22.6 V, totalling to a power of 4023 W. These values were chosen due to the wide range between the power output, which would help to definitively determine its influence on the formation and structure of the layer.

The EWM power supply is unique due to its innovative operating mode called cold arc. Welding in this mode could be performed both continuously and by using pulses. The latter reduces the heat input and complements the welding of thin sheet components. Due to the different physics of the welding process based on

the operating mode both the cold arc and cold arc pulse mode were investigated. The obtained single-track welds using the different wire feeding rates and with (+SP) and without pulses (−SP) are shown in Fig. 1b and c.

The specimens were cut in half and metallographic samples of their cross-section were prepared. The samples were ground using abrasive paper starting from P240 up to P2500. The as-prepared samples were then etched in a 10% solution of HF acid using a cotton swab for 10 seconds.

Optical microscopy was used to obtain data regarding the macrostructure of the cross-section of the obtained layers.

The crystallographic properties of the samples were studied using X-ray diffraction (XRD) in the Bragg–Brentano mode at a 2θ scale from 30 to 80 degrees with a measuring step of 0.1° . A $\text{CuK}\alpha$ radiation was used with a wavelength of $1.54 \text{ \AA}$.

In addition, microhardness experiments were performed. Ten consecutive measurements were performed in agreement with the ISO 6507-1 standard, according to which a minimum distance of three times the diagonal between each indentation needs to be maintained. In all cases, a loading force of 1 N was applied with a dwell time of 10 seconds.

Results and discussion. Optical microscopy images of the obtained samples are shown in Fig. 2. The sample prepared using a wire feeding rate of 67 mm/s without pulses is shown in Fig. 2a, and the sample prepared with the same WFR, but with pulses is shown in Fig. 2b. The ones prepared with a WFR of 133 mm/s without and with pulses are shown in Fig. 2c and d, respectively.

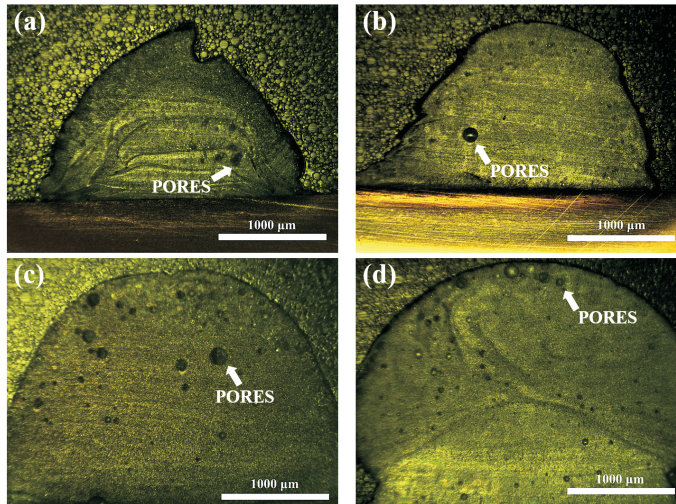


Fig. 2. Optical images of the formed weld beads with (a) 67 mm/s WFR without pulses, (b) 67 mm/s WFR with pulses, (c) 133 mm/s without pulses, (d) 133 mm/s with pulses

The first sample has a maximum width of 1.932 mm, and a maximum height of 1.583 mm, which is similar to the +SP one, which has a width of 1.952 mm and a height of 1.546 mm. The cross-sectional of the layer formed using a WFR of 133 mm/s without pulses has a width of 2.792 mm and a height of 2.169 mm. The one formed using the same wire feeding rate, but with pulses has a width of 2.766 mm and a height of 2.298 mm. The presence of pulses does not affect the physical dimensions of the cross-section of the applied layer. Instead, they are influenced significantly more by the wire feeding rate. The size of the pores of the examined samples was also studied indicating that in the case of the sample prepared using a WFR of 67 mm/s with pulses the largest detected pore had a diameter of 134.56 μm . A crack with a length of 279 μm was also noticed between the layer and the copper substrate. The rest of the pores along the cross-section of this specimen had a diameter of $< 10 \mu\text{m}$. In the case of the specimen produced without pulses using the same WFR a concentration of pores was also observed. The average diameter of the pores in that sample was $65.63 \pm 16 \mu\text{m}$. In the case of the samples prepared using a WFR of 133 mm/s with and without pulses the average pore sizes were $65.03 \pm 28 \mu\text{m}$ and $82.12 \pm 29 \mu\text{m}$, respectively. This indicates that in both cases a higher concentration of pores was observed in the cold arc mode without pulses. This is most probably attributed to two reasons. Firstly, as mentioned above, the increase in the WFR leads to a major increase in the power of the electric arc. This results in slower cooling of the melt pool. As it is known the higher the temperature during the process of welding of aluminium, the higher the absorption of gases (most commonly hydrogen) [13]. This means that the slower recrystallization process improved the absorption of gases within the melt pool, resulting in a higher concentration of pores. Additionally, the larger heat input has also resulted in an accelerated vapourization of aluminium, which also probably hindered the nucleation processes occurring during the solidification stage. The nucleation processes were studied in detail by VISHNYAKOV et al. [14] as a function of the aluminium vapourization.

The phase composition of the samples was investigated using X-ray diffraction and the obtained results are shown in Fig. 3a. Two separate phases were detected, namely copper and aluminium. The phase composition was identified using the database provided by the International Centre for Diffraction Data, PDFs #040836 and #040787. The preferred crystallographic orientation of the aluminium phase was calculated using the equations explained in detail by the authors of [15]. No major changes in the $P_{\{hkl\}}$ of the samples were observed except in the case of the layer deposited using a WFR of 133 mm/s without pulses. In that case, the formation of a specific texture was noticed towards the $\{311\}$ family of crystallographic planes. This is a typical texture formation when aluminium is subjected to high-temperature processes [16]. Due to the low dissolution of copper in aluminium, a common occurrence is the oversaturation of the aluminium solid solution and the formation of intermetallic compounds in the form of eutectic den-

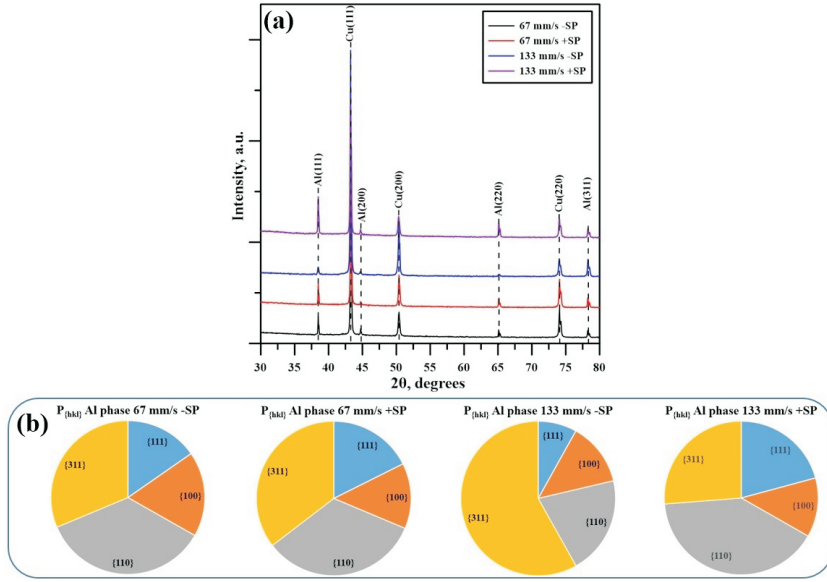


Fig. 3. XRD results obtained for the different samples (a), and preferred crystallographic orientation of the aluminium phase (b)

driftic structures [17]. During the experiments, the formation of such structures was not detected.

Figure 4 presents the microhardness results obtained for the different experiments. The given values are the average calculated based on a multitude of measurements. The layer formed using a 67 mm/s wire feeding rate without pulses

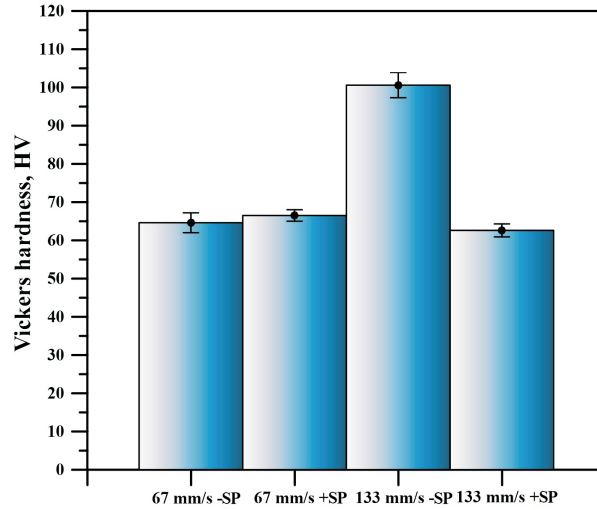


Fig. 4. Microhardness of the formed weld beads

had a microhardness of $64.6 \pm 2.6 \text{ HV}_{0.1}$, and the one formed using the same rate but with pulses had a value of $66.5 \pm 1.5 \text{ HV}_{0.1}$. In this case, no major change in the microhardness as a function of the WFR and the application of pulses was noticed. In the case of applying a wire feeding rate of 133 mm/s without pulses, the microhardness reached values of $100.5 \pm 3.3 \text{ HV}_{0.1}$, and in the case of using pulses, it was $62.6 \pm 1.7 \text{ HV}_{0.1}$. This indicates that in this case the WFR, thus the power of the electric arc, was sufficiently high that the different mode regimes (+SP or -SP) had a substantial influence on the structure of the formed welds. The highest thermal input was achieved using the higher WFR, which resulted in excellent bonding between the Cu substrate and the aluminium layer. This resulted in the formation of a continuous, dense layer with a more homogeneous structure. As a result, the microhardness of this layer was improved compared to the others.

Conclusions. In the current work, the formation of ER4043 aluminium alloy layers on copper substrates using a WAAM setup in the cold arc and cold arc pulse modes was investigated. The results are indicative of the successful deposition of the layers using a wire feeding rate of 133 mm/s in the cold arc mode without pulses. In this case, a continuous, homogeneous layer was formed with high microhardness. A high concentration of pores was detected in this case. The bonding between the copper substrate and the aluminium layer was the greatest in the case of using a WFR of 133 mm/s without pulses. These preliminary experiments indicated that the formed layer can be potentially applied as a junction between copper substrates and WAAM aluminium components for the production of bimetallic components, or the reforming of already existing copper ones. More is to be desired from the macrostructure of the formed layer, particularly the concentration of pores. Optimization of the layer deposition process is in order. Additional experiments also need to be conducted to quantitatively determine the adhesion between the layer and the substrate.

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