WIRE AND ARC ADDITIVE MANUFACTURE OF HIGHLY CONDUCTING PURE COPPER

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ABSTRACT

Copper has many applications exploiting its properties of very high thermal and electrical conductivity. Additive manufacture of copper has proved to be very challenging for many processes due to its high reflectivity and high thermal conductivity. Furthermore it is difficult to use powder based processes as 100% material density is required in order to benefit from the inherent high conductivity of copper. Wire plus arc additive manufacture was used to deposit pure copper and very high electrical conductivity (102%) was obtained under optimised conditions.

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INTRODUCTION:

Additive manufacture (AM) of copper has many important potential applications due to its high thermal and electrical conductivity. Copper is widely used in the fields of heating and cooling equipment and electrical and electronic devices because of its excellent thermal and electrical conductivity. However copper has proved to be very challenging for many AM processes due to its high reflectivity and thermal conductivity. Furthermore it is difficult to use powder based AM processes as 100% material density is required in order to achieve the high conductivities needed for copper applications.

Laser based additive manufacturing processes have been tested for fabrication of copper components. When Powder Bed Fusion (PBF) is used for AM of Cu the main problems faced were high heat loss and inadequate melting of powder. That was due to high thermal conductivity and high reflectivity of Cu and the parts built with this method had low strength because of internal defects e.g. porosity and grooves [1]. In the attempted manufacturer of heat exchangers there were also issues due to the high reflectivity of Cu when melting it with laser for AM [2].

The Wire + Arc Additive Manufacture (WAAM) process is a manufacturing technique which uses layer by layer deposition of specific materials to construct 3D objects using an electrical arc as the power source. WAAM uses common arc power sources and wire as feedstock to build parts and components [3]. It has great potential for the deposition of copper as pore free deposits are easily achieved and high heat input is possible, overcoming the high thermal losses. Furthermore there are no energy coupling issues associated with laser based processes into Cu wires and substrates due to its high reflectivity.

In this study WAAM was investigated for the deposition of pure copper and the electrical conductivity measured, dependent on the wire type and shielding gas conditions.

1. EXPERIMENTAL APPROACH

1.1 Equipment

A Lincoln electric Invertec V310-T AC/DC synergic power source equipped with a Migatronic KT4 wire feeder with 1mm feeding rollers was used in the non-pulse DCEN polarity mode for copper WAAM. To avoid damage caused by overheating, a Lincoln electric Magnum water cooler was used for the cooling of the power source and torch. The torch was mounted on a 3-axis CNC system as shown in Figure 1.

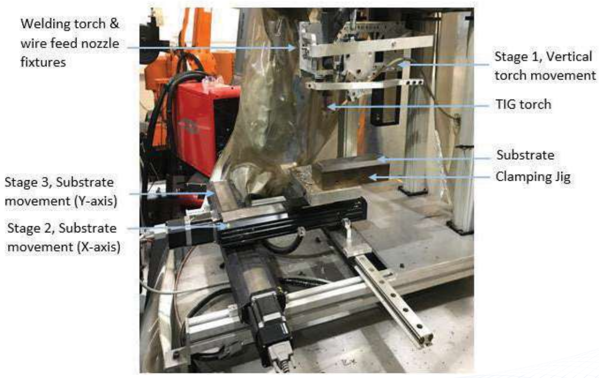

Figure 1 - Cu WAAM setup

An air tight flexible enclosure was used with an inert atmosphere. The oxygen level was reduced to below 800 ppm by filling the chamber with argon (figure 2).

Figure 2 - Cu WAAM flexible enclosure

1.2 Material

Two different wires with 1 mm of diameter were used and their chemical composition are shown in the tables 1 and 2.

Table 1 - CW1860 welding wire with 1 mm diameter.

Chemical analysis wt %	Cu	Pb	Al	Mn	Si	Sn	P
	98.26	0.01	0.01	0.38	0.41	0.91	0.019

Table 2 - 99.99 % pure Cu, bare Cu wire used as electrical wire with 1 mm diameter.

Chemical analysis (ppm)	Cu	Ag	Al	Bi	Ca	Cr	Fe	Mg	Mn	Na	Ni	Pb	Si	Sn
	Bal	100	1	1	1	<1	2	1	<1	<1	2	2	2	1

Mild steel was used as the substrate. Pure Argon was used as the shielding gas used for both the local shielding and the global shielding experiments.

1.3 Experimental procedure

Mild steel substrates were cut to 210x50x12 mm^3, the substrates were cleaned using soap and water to remove any surface dirt, grease. The oxide layer was removed by using a low speed grinder with an abrasive pad and final cleaning was made with acetone before the deposition trails. The wire was fed in front of melt pool and the substrate moved relative to stationary torch. A steel backing bar was used during the deposition trials. Local gas shielding was provided by pure argon at 15 l/min for the local shielding trials. For the global shielding trials the flexible enclosure was filled with Argon to obtain less than 600 ppm of oxygen.

1.3.1 Preliminary Parameter study

The first stage of experiments analyzed the interaction of the electrical arc with the substrates and addition of filler wire for deposition. A preliminary parameter study was carried out by varying one parameter e.g. current (I) and keeping all the other parameters constant. The parameters used in the preliminary tests are detailed in Table 3.

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Table 3 - Cu preliminary trial parameters

Electrode to work piece distance	4-5 mm
Electrode stick out	5-6.5 mm
Polarity	DC (non-pulse)
TS	0.5-3 mm
WFS	9-15 mm
Wire feed position(s)	Side & front
Substrate thickness	6.5-12.5 mm
Current (I)	125-240 A
Shielding gas flow rate	15 l/min

1.3.2 Copper WAAM

Using the best parameters obtained preliminary trials Cu WAAM structures were built. Two different Cu wires were used, CW1860 (welding wire) and electrical grade wire. Both wires were used to build a wall each using local shielding and global shielding. The parameters to build the Cu WAAM walls are shown in Table 4.

Table 4 - Cu WAAM parameters

Current (I)	125-150 A
TS	2 mm/s
WFS/TS	10-12
EWD	4.5 mm
Electrode stick out	6.5 mm

1.4 Sample preparation for SEM analysis

WAAM built walls were cut into three sections and SEM specimen were cut into three equal height sections. Using a hot-pressing moulding machine, they were mounted in conductive resin to analyze the chemical composition using SEM/EDX as shown in Figure 3.

Figure 3 - Marking for analysis, WAAM Cu

The samples were ground using 240, 1200 SiC grit paper followed by 9 µm, 6 µm diamond suspension respectively and 3 µm diamond paste. Final polish was done using 0.05 µm colloidal silica on polishing cloth.

1.5 Samples preparation for electrical conductivity analysis

Just before testing the oxide layer was removed using a low speed grinder with an abrasive pad. They were also cleaned with acetone to remove any impurities present on the surface. Electrical conductivity tests were carried out at Ether NDE using sigmacheck2 equipment at 20 °C. Electrical conductivity measurements were checked at four different locations in the lateral face of the sample e.g. substrate, on the interface, middle of the wall height and close to the top. A 13 mm diameter probe was scanned across the width of the WAAM wall. A schematic of the process is shown in Figure 4.

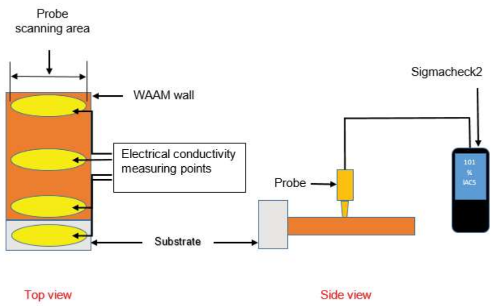

Figure 4 - Schematic of electrical conductivity measurement procedure and equipment

2. RESULTS AND DISCUSSION

From the preliminary parameter study, three samples were selected for further investigation. These samples were made using the same curent, wire feed speed and travel speed. Sample A was a melt run, these autogenous samples were made to verify the stability of the melt pool. The second sample, sample B was a bead on plate sample and served to verify the stability of single bead deposition. Sample C was a four layer deposition and it was made to verify the stability of the deposition of multiple layers.

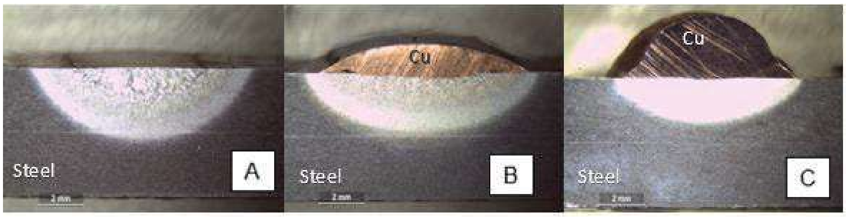

Figure. 5 - Preliminary experiments with steel substrate (etched samples), A – bead in plate melt run (I = 150 A, TS = 2 mm/s), B - Single layer Cu wire deposition (I = 150 A, WFS = 15 mm/s, TS = 2 mm/s), C - four layer wall.

2.1 Copper WAAM

2.1.1 Process stability & wall height

By using the TIG process Cu WAAM walls were built successfully with welding wire and electrical wire. Process stability was not altered by the shielding method and also no significant layer height difference was observed (Figure 6). However there is a clear difference of layer height between the two welding wires used for the same despotion conditions. For welding wire the average layer height was 1.37 mm with minimum height of 0.8 mm and maximum height of 2 mm. The electrical wire solidified faster compared to the CW1860 wire, which resulted in narrower wall width and higher layer heights. This is due to the higher electric and thermal conductivity of this wire. The average layer height was 1.92 mm with a minimum layer height of 1.2 mm and maximum of 2.5 mm.

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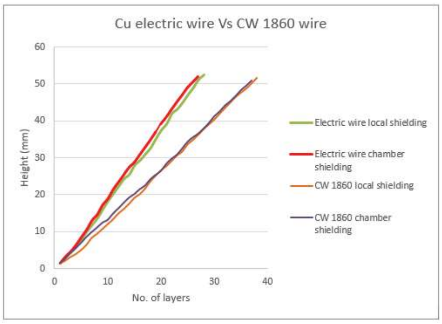

Figure 6 - Layer height comparison between CW 1860 & bare Cu electric wires

2.1.2 Effect of shielding on porosity

Visual inspection of CW1860 welding wire after machining, did not show any porosity in either wall with local and global shielding. On the other hand the sample made with Cu electrical wire showed porosity with local shielding. This could be due to the faster cooling rate of electrical wire, causing entrapment of gas in the deposited metal.

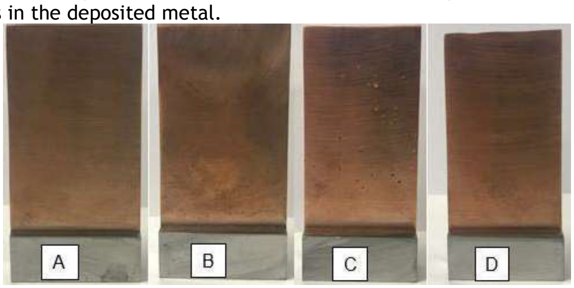

Figure 7 - Cu WAAM machined walls. A and B - Cu welding wire with local and global shielding, respectively. C and D - Cu electrical wire with local shielding and global shielding, respectively.

Both CW1860 wire and electrical wire walls suffered from surface oxidation with local shielding. With argon inert chamber shielding though a shiny surface was obtained when both wires were used. The surface of walls built with local shielding were expected to have oxidation because of the presence of atmospheric oxygen around the wall. While the oxygen level was very low in the inert chamber which prevented surface oxidation to occur. As built Cu WAAM walls are shown in Figure 8.

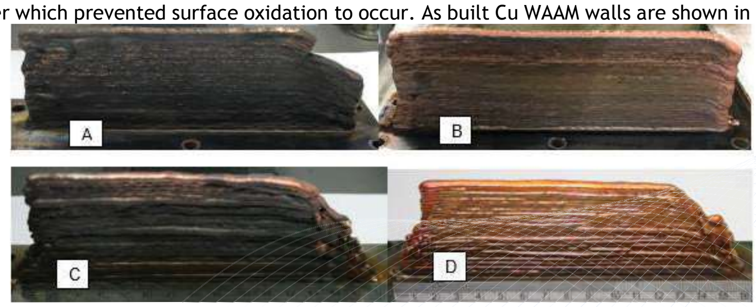

Figure 8 - As build Cu welding & electrical WAAM walls. A - welding wire with local shielding, B welding wire with global shielding, C - electrical wire with local shielding, D electrical wire with global shielding.

Surface oxidation is clear in the sample produced with Cu electric wire with local shielding as seen in Figure 9 which the sufaces obtained with the two shielding methods.

Figure 9 - Surface appearance of Cu electric wire WAAM walls with a) local shielding, b) global shielding.

2.1.3 Cu SEM/EDX analysis

Both CW1860 and bare Cu electrical wire walls had dilution of Iron (Fe) in them close to the interface with the mild steel substrate. This was due to the melting of the mild steel substrate which is mixed with the copper within the copper-mild steel interface. Dendritic growth caused by dilution was observed in SEM/EDX analysis. In the CW1860 walls dendritic growth was observed 1 mm high from interface while electrical wire only reaches 0.5 mm. This is due to the faster cooling in bare Cu electrical wire due to its high thermal conductivity and high purity. From Figure 10, it is observed that copper records a weight percentage of 0 below the interface whilst iron records a value of 100% as we progress upwards, the percentage of copper starts increasing until it reaches 100%. At the same time, the weight of iron reduces as copper increases.

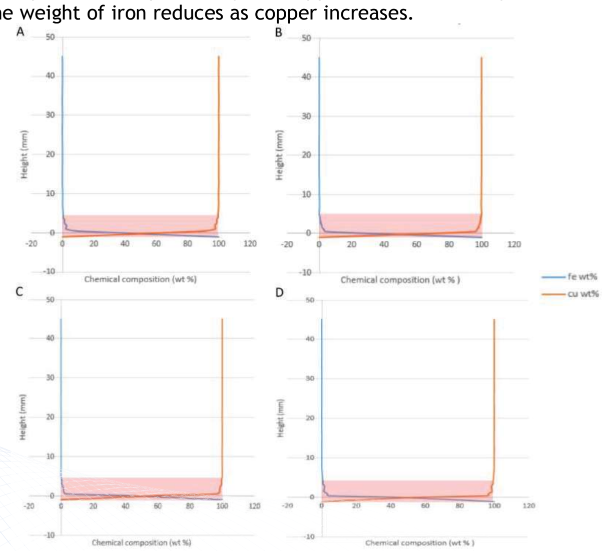

Figure 10 – Diffusion of Fe inside Cu WAAM walls. A – Welding wire local shielding. B – Welding wire global shielding. C – Electrical wire local shielding. D – Electrical wire global shielding.

The low levels of Fe present at the copper interface can also be explained by the low heat input used for this deposition and the lower melting point of Cu when compared with Fe.

2.1.4 Electrical conductivity testing

Electrical conductivity of copper is influenced by the presence of alloying elements. Porosity also plays an important role. Addition of alloying elements in copper increases the number of discontinuities in the mean free path of moving electrons, this reduces the velocity of electrons and lowers the conductivity. The higher the solid solubility of an alloying element results in a higher drop in conductivity [4]. The resistivity of copper is highly affected by impurities in solid solution but there is less effect when present in form of intermetallic compounds or as an oxide layer. This is because they are no longer in the path of free moving electrons [5]. Chapman, [6] argues that 0.30 wt % Ag in Cu has 100 % electrical conductivity, when weight percentage of Ag reduces as alloying element electrical conductivity rises.

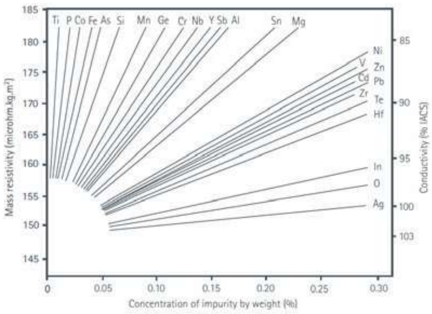

Figure 11 - Effect of alloying element on conductivity of Cu courtesy of Chapman [4].

Cu welding wire walls built with local and global shielding showed the same electrical conductivity as can be seen in the Figure 12 indicating no changes in the alloying elements neither the existence of porosity.

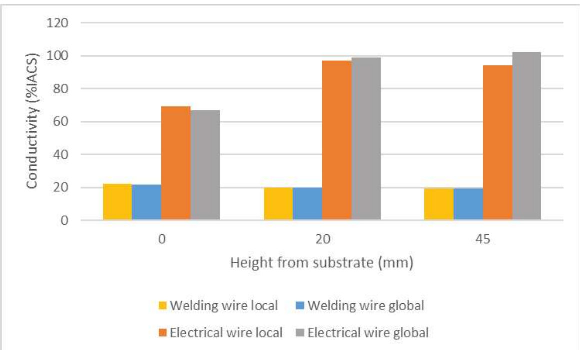

Figure 12 – Different electical conductivity obtained for all WAAM walls.

Figure 12 shows that the electrical copper wire has a higher electrical conductivity than welding wire. The welding wire has a conductivity of around 20% of Cu, this is expected due to presence of several alloying elements in this wire.

As expected the influence of Fe into the electrical conductivity decreases the further we are away from the steel substrate. The maximum electical conductivity is obtained with the elecrtrical wire with global shielding with a maximum of 102% of IACS for a distance of 45 mm from the substrate.

3. CONCLUSION

Using the WAAM process copper with a conductivity of 102% was sucessfully deposited. It was shown that a fully shielded environment is needed to avoid porosity and achieve this very high conductivity level. Copper welding wire is not suitable for copper AM for high conductiviy applications.

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