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Wire Arc Additive Manufacturing of Aluminium Alloys †

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Abstract: Additive manufacturing is used to produce parts with complex near-net shape geometries. It can also be used to repair parts that have worn out in service using specific processes such as Wire Arc Additive Manufacturing (WAAM) and Directed Energy Deposition (DED). Wire additive manufacturing processes allow for relatively high deposition rates compared to powder technologies but necessitate a stable welding process and a controlled heat input. As the perfect transfer mode for low welding energy and low spatter, Cold Metal Transfer (CMT) is the process of choice for WAAM. In this project, parts made from aluminium 4943 and 6061 were additively manufactured using CMT technology. The deposition rate, porosity level, and mechanical properties are discussed herein. For the 6061 alloy, after heat treatment, it is possible to attain properties that are close to those obtained for T6 for wrought products or even higher when samples are hot-isostatically pressed.

Keywords: wire arc additive manufacturing; aluminium alloys; welding; heat treatments

1. Introduction

Wire arc additive manufacturing (WAAM) is a process in which a metal wire is supplied into the welding arc at a controlled rate, allowing for the newly deposited wire to be completely melted, while the previous layer is only partially melted. This process allows for a higher deposition rate compared to powder technologies like binder jetting, directed energy deposition, and powder bed fusion. It is an inexpensive and fast process compared to other metal-additive-manufacturing processes on the market. Therefore, its use is advantageous when the amount of material to be deposited is high. If the material to be printed is available in GMAW or MCAW wire spools, it is possible to print prototypes with the WAAM process. The first reported use of this process dates back to 1925 [1], but the literature on this topic was scarce until the 1990s, when researchers and industrials began using CNCs and robotic systems to build complex shapes and for rapid prototyping [2,3]. In this work, a robotic system was used to print both 4943 and 6061 parts in order to determine if 6061 alloy can be printed without hot cracking and to verify if the mechanical properties of WAAM products can match those of wrought products.

2. Materials and Methods

An ABB IRB 140 six-axis robot, a 2-axis IRBP A-250 positioner, and a Fronius TPS400i current source were used in this project to print parts from which tensile and metallography specimens were extracted. Using robotics, it is possible to change the parameters upon part printing. To obtain a good degree of fusion between the part and the substrate, the starting parameters generally have to be high. For subsequent passes, without extinguishing the arc, it is possible to decrease the parameters until the heat dissipation rate in the part is constant. When the part temperature and cooling rate reach a steady state, the welding parameters remain constant until completion. For all the examples presented in this paper, printing was continuous, without the arc being extinguished. The deposition rate is a function of

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the wire speed, and the latter depends on the wall width to be printed. For the specimens printed in his work, an average deposition rate of around 11.5 g/min was used.

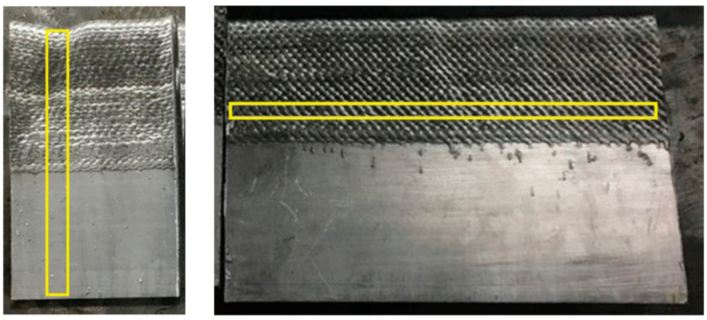
Two different geometries were printed in this work. For the 4943 alloy, zigzag type parts were made (Figure 1a) using 1.2 mm diameter wire. The advantage of this part is that tensile test samples can easily be machined from it. For the 6061 alloy, the shapes and sizes to be printed are more restrictive. To avoid hot cracking, a rapid cooling rate is required. It is therefore necessary to opt for a transfer mode with very low energy welding parameters and to limit the width of the walls to be printed. By reducing the width of the deposit and optimizing the welding parameters, it was possible to perform additive manufacturing via arc welding using 6061 aluminium wire with a diameter of 1 mm. However, 6061 aluminium alloy wire is not available in a spool of wire for welding. Therefore, a coil of 6061 alloy wire in the annealed state has been purchased from a manufacturer that produces wires for various applications, such as electrical conductors and reinforcements. The filler metal was not optimized to perform the desired work, but it was the only one that was economically viable to be procured as part of a feasibility study project.

(**a**) (**b**)

Figure 1. Part geometries printed using (**a**) 4943 and (**b**) 6061.

In this work, square samples were printed (Figure 1b). The thickness of the base plates forming the square is 10 mm, and the deposit has an average width of 11 mm. After printing, different heat treatments were performed. A complete T6 heat treatment was carried out by first heating the part at 530 °C for 2 h (solution heat treatment (SHT)) followed by water quenching and aging for 8 h at 175 °C, while for the "only aged" treatment, the parts were aged for 8 h at 175 °C with no prior SHT. Some aluminium 6061 samples were also hot-isostatically pressed at 103 MPa before the complete T6 heat treatment.

For the 6061 alloy (square part), samples were cut in 2 different directions (Figure 2), with some being cut in the longitudinal direction (LD) and others in the transverse direction (TD) relative to the direction of deposition.



(**a**) (**b**)

Figure 2. Location for (**a**) transverse direction (TD) samples and (**b**) longitudinal direction (LD) samples.

3. Results and Discussion

3.1. Aluminium Alloy 4943

Aluminium alloy 4943 is a filler material similar to 4043 but with a higher percentage of magnesium, which makes it more responsive to heat treatment. After welding, its properties can be improved through ageing. It is typically used to weld 6xxx parts, so the artificial ageing treatment is similar to that used for these alloys. In this work, some samples were only aged for 8 h at 175 °C (artificially aged (AA)), while others were solution-treated at 530 °C for 2 h and water-quenched before ageing (T6). Tensile tests were performed according to the ASTM E8 standard [4]. Figure 3 presents the results obtained from the tensile tests. Even if the heat treatments improved the properties of the samples printed using WAAM (from 70 to 160 MPa for tensile strength), the properties in the AA and T6 conditions are not as good as those advertised by the suppliers. This could be due to the fact that cooling after deposition was relatively slow for our parts. In the next stage, the parts were printed on thicker base plates to assess the effect of the cooling rate on their mechanical properties.

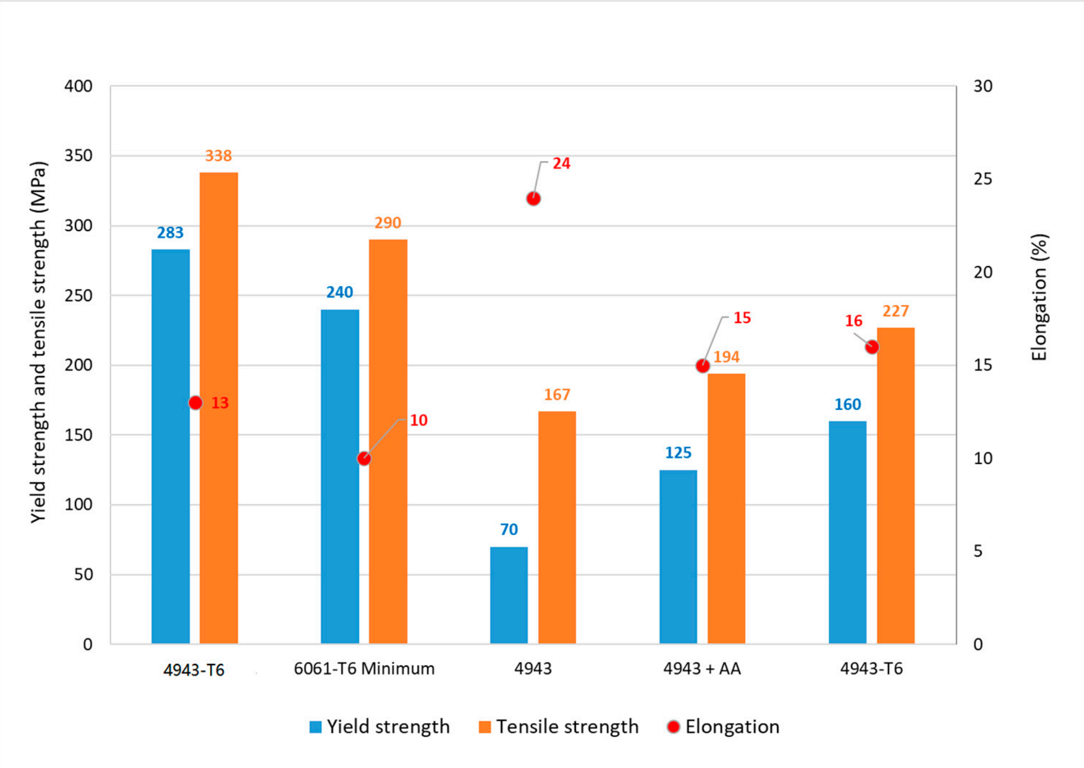


Figure 3. Mechanical properties of the 4943 samples in the as-deposited condition (4943), only-aged condition (4943 + AA), and solution heat-treated, quenched, and aged condition (4943-T6) [3] compared to the minimum requirements of the ASTM B209 standard [5] for 6061-T6 and to 4943, for which the results were taken from reference [6].

3.2. Aluminium 6061 Alloy

A hot isostatic pressing (HIP) treatment was carried out on certain samples of 6061 to reduce the number of pores in the deposit and measure the mechanical properties not affected by the porosity rate (Figure 4). During the HIP treatment, the porosity level was reduced from 1.95% to 0.04%. Tensile tests were performed according to the ASTM E8 standard [4], and the results are shown in Figure 5, in which they are compared to the minimum requirements for 6061 plates of the same thickness.

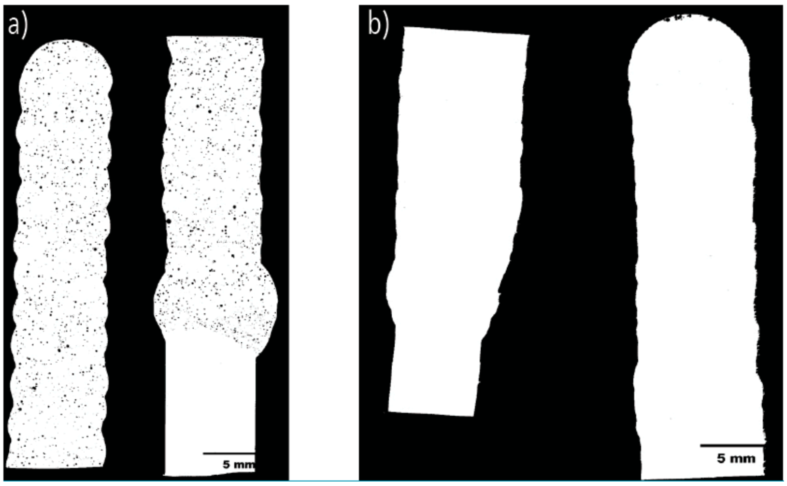


Figure 4. Aluminium 6061 alloy samples in the (**a**) as-welded condition and (**b**) after isostatic pressing.

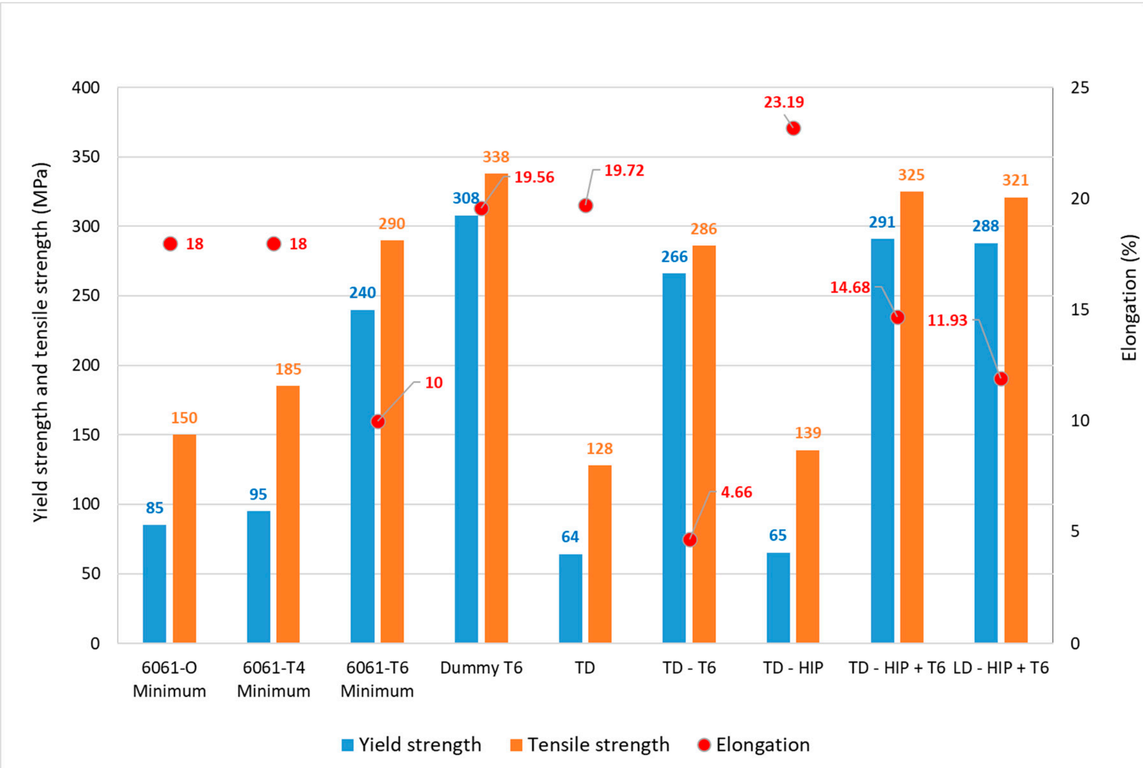


Figure 5. Mechanical properties of the 6061 samples in as-deposited condition (TD), in T6 condition (TD − T6), in HIPed condition (TD − HIP), and in HIPed+T6 condition, in the transverse direction (TD − HIP + T6) and longitudinal direction (LD − HIP + T6), compared with minimum requirements from ASTM B209 standard [5]. A reference sample taken from a commercial 6061-T6 plate (dummy) was also tested.

All the samples in T6 condition have yield and tensile strengths that are higher than the minimum value, but their elongation at break is lower. This lower elongation at break is probably due to the presence of porosity. The surface quality of the wire used in this work certainly had an influence on the porosity level. Further testing will be performed using better-quality wire, and the properties will be re-assessed.

4. Conclusions

Aluminium 6061 and 4943 parts were printed using wire arc additive manufacturing. The samples of 4943 acquired interesting properties after heat treatment, but they were not as good as the properties advertised for welds. Future work is needed to assess the effect of the cooling rate on these parts' properties. The results obtained for the 6061 samples are very interesting, with tensile and yield strengths over the minimum values required for plates in a T6 temper.

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