

Manufacture of Large-Scale Space Exploration Components using Wire + Arc Additive Manufacturing

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Abstract

Cranfield University, Thales Alenia Space and WAAM3D together, combining their expertise knowledge and technologies on Wire + arc additive manufacture (WAAM), created a route for manufacturing large-scale space exploration Components using WAAM which could be used in future large scale-space exploration component manufacturing. In this project, several different sections of the development of WAAM technology are applied to manufacture a large-scale space exploration component including FEA simulation, inter-layer machining and cold work, intelligent toolpath planning and sustainability calculations. WAAM proved to be a very promising technique in future large-scale component manufacturing.

Keywords: Wire + Arc Additive Manufacturing, inter-layer machining and cold work, intelligent tool path planning, FEA distortion prediction, sustainability and environment protection

1. Introduction

Cranfield University, Thales Alenia Space and WAAM3D together, combining their expertise knowledge and technologies on Wire + arc additive manufacture (WAAM), created a route for manufacturing large-scale space exploration Components using WAAM, which could be used in future large scale-space exploration component manufacturing. The project is sponsored by Thales Alenia Space and led by Cranfield University.

WAAM is a novel manufacturing process which can produce large, near-net shape metallic components with full density. In this process, wire is fed into an electric arc and melted onto a substrate or previously deposited layer. It has gained significant interest from the industry due to its potential for significantly reducing cost and lead times as well as benefits in sustainability and environment protection. The WAAM process has been applied to production of components in many materials which are widely used in the aerospace industries, including titanium, aluminium, and nickel alloys. Excellent material integrity and mechanical properties have been achieved.

WAAM has the potential to provide a cost-effective means of manufacturing large metal structures, eliminating expensive and long lead-time castings and forgings [1]. Various technologies are competing for the market share of large-scale metal AM, with each technology having its advantages and disadvantages. WAAM is selected as the preferred deposition method as it has the following advantages:

- High deposition rate can be achieved for WAAM.
- Good quality feedstock is available, and good mechanical properties and 100% density can be achieved
- WAAM does not necessarily require a completely sealed enclosure so in principle has an unrestricted part size
- Significant cost savings can be achieved by WAAM due to the relatively low cost and complexity of the robots, machines, and power sources.

Further advantages can be seen in optimising the structure of the component to reduce stress concentration, reducing the overall weight and environmental impact of the component [2]. Future lightweight, complex and topology-optimized component designs can be manufactured using WAAM.

Cranfield University has been working on WAAM process development for more than fifteen years, as well as on part manufacture, using different processes and materials. Component manufacturing requires extensive knowledge to achieve the correct geometry without distortion and no defects. Most previous research focuses on the manufacture of simple structures such as walls and parts without any intersections, and many of them do not appreciate how challenging it is to manufacture large-scale components.

Thales Alenia Space with its heritage in the development and realization of large pressurized structures for Human exploration, provides the necessary experience to judge the suitability of the process through the identification of study cases of complex shape and acceptability of out of tolerance dimensions, embedded and superficial defects to support industrialisation of WAAM process for application in future exploration projects.

In this project, several different sections of the development of WAAM technology are applied to manufacture a large-scale space exploration component.

2. Manufacturing setup and tools

2.1 Deposition process

The process we chose to use and investigate at Cranfield University for aluminium deposition was Cold Metal Transfer (CMT – Fronius) combined with integrated machining and inter-layer cold work peening process. Figure 1 below shows the integrated machining tool working together with the CMT torch and interlayer peening tool.

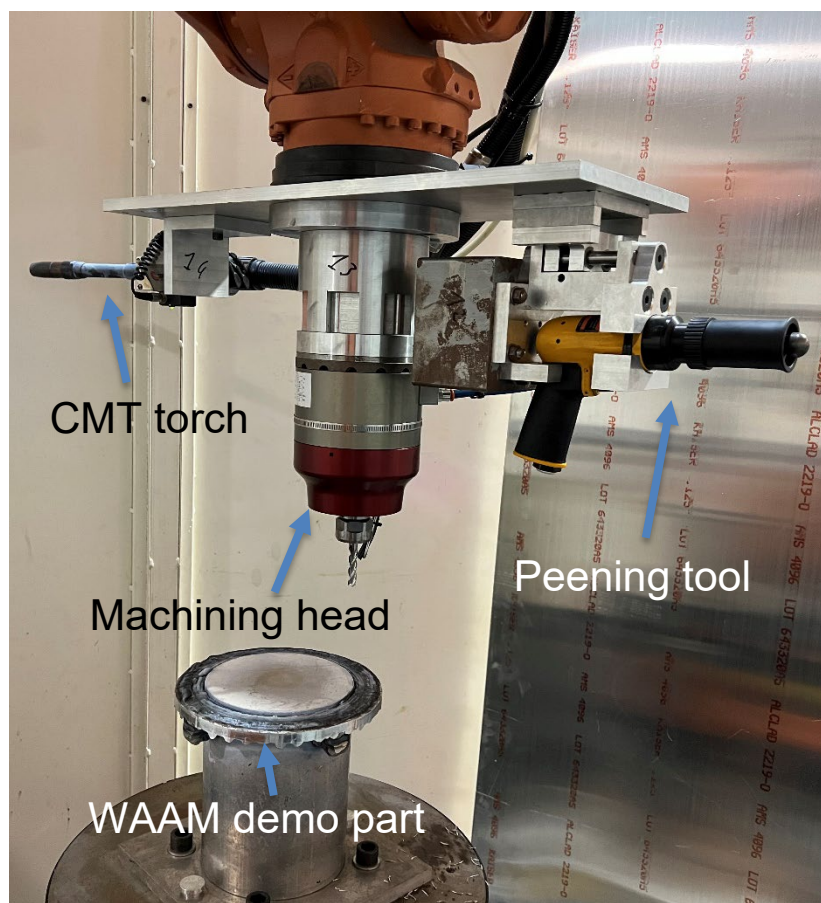


Figure 1 - Multi-functional tool with CMT torch combined with interlayer machining head and peening tool

The use of CMT is widely reported in the literature for aluminium WAAM. One of the significant advantages of CMT, and any other Gas Metal Arc Welding process, is the coaxially of the wire with the torch, which results in a more straightforward tool path design [3]. However, CMT lacks flexibility: the heat input of this process directly depends on the wire feed rate. Both heat input and wire feed rate are the key elements to control when depositing a component. This becomes a major issue when depositing intersections and hence the requirement for inter-layer machining,

2.2 Interlayer machining and cold work

The Peening process introduces dislocations in the material and refines the grain structure during the remelting process of WAAM. This increases the strength and isotropy of the material compared to as-deposited material. [4,5] Furthermore, the interlayer cold work process can reduce the porosity amount and hence increase the mechanical property of the deposited material. [6] By combining the peening process with CMT deposition process, we achieved the required material properties without further heat treatment. The machining tool's purpose was to ensure the required geometry has been achieved during deposition. And it also allows the deposition on the side of as-deposited surfaces of the component to prevent potential lack of fusion [7].

2.3 Intelligent tool path planning (3-D intersections)

3-D intersections or multi-orientation joints are also included the demonstrator and the space exploration component. Strengthening structures are deposited between already deposited horizontal and vertical walls. Figure 2 below shows an example of the 3-D intersection. Both sides will be deposited first and machined to prevent lack of fusion during the intersection and turning point. This process includes the rotation of the torch and complex movement of the robot to ensure the final product is deposited without any defects.

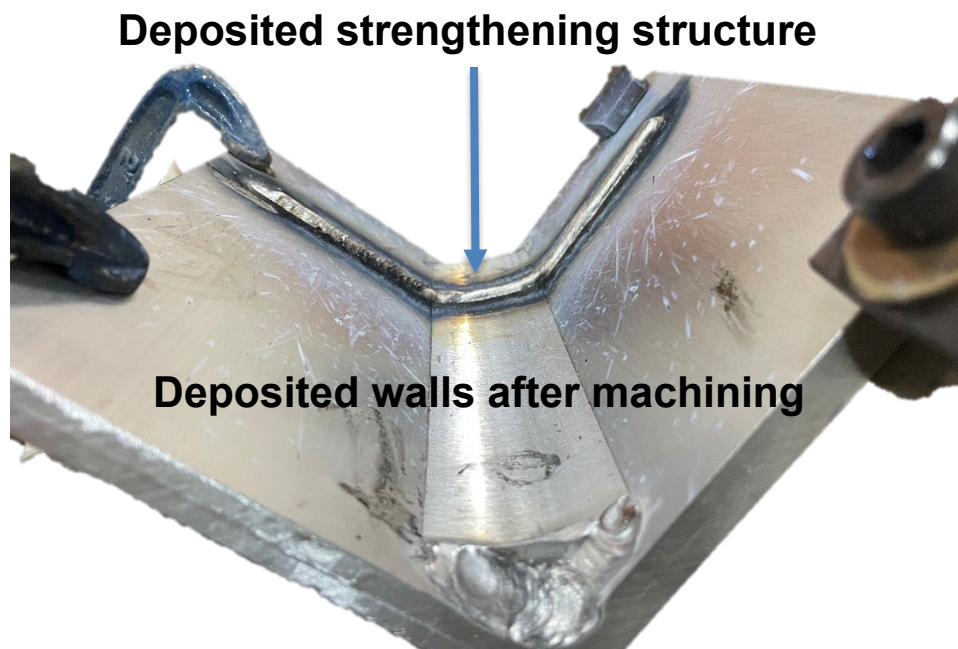


Figure 2 - 3-D intersection deposition demo with complex torch and robot movement

Figure 3 below shows an alternative 3-D intersection deposition path during the manufacturing of the demonstrator, which allows more flexibility in the manufacturing process. An angled area is machined from the deposited wall to allow joining the strengthening structure without any

defects. We believe the combination of the two strategies will allow us to deposit more complex components with different deposition orientations in the future. This can further reduce the Buy to Fly (BTF) ratio and production cost of large-scale aerospace components.

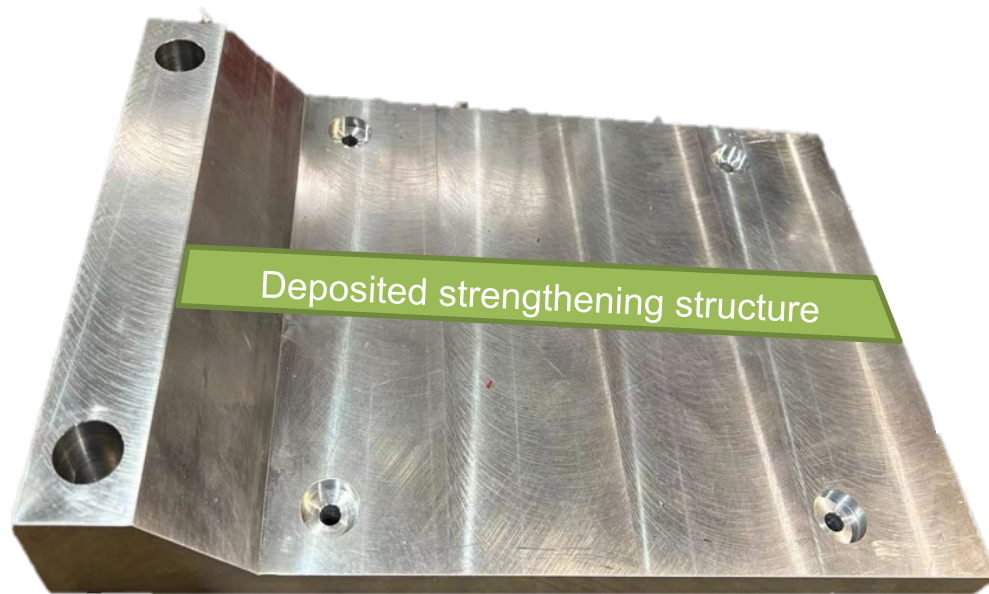


Figure 3 - Alternative 3-D intersection deposition demo with angled joining wall

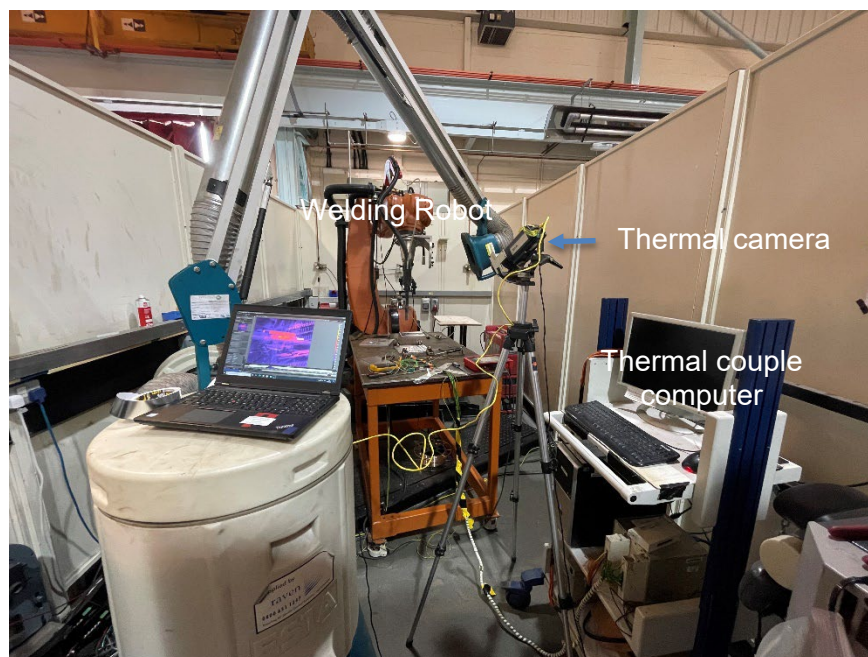


Figure 4 - Experimental set-up

2.4 FEA calibration and stress prediction

The Finite Element Analysis (FEA) heat source calibration experiment was set up as shown in Figure 4; it included a Kuka 6 axis industrial robot with a MTB500 Cold Metal Transfer (CMT) torch and Fronius power supply. During the experiment, an arc monitor device (AMV4000) was used to measure the current and voltage from the power supply, a FLIR A600 series camera was used to measure the temperature across the weld bead, and thermocouples were used to measure the temperature history away from the melt pool on the base plate. The type-K thermocouples were placed 10mm, 20mm, and 30mm away from the centerline of the first weld bead, as demonstrated in Figure 5.

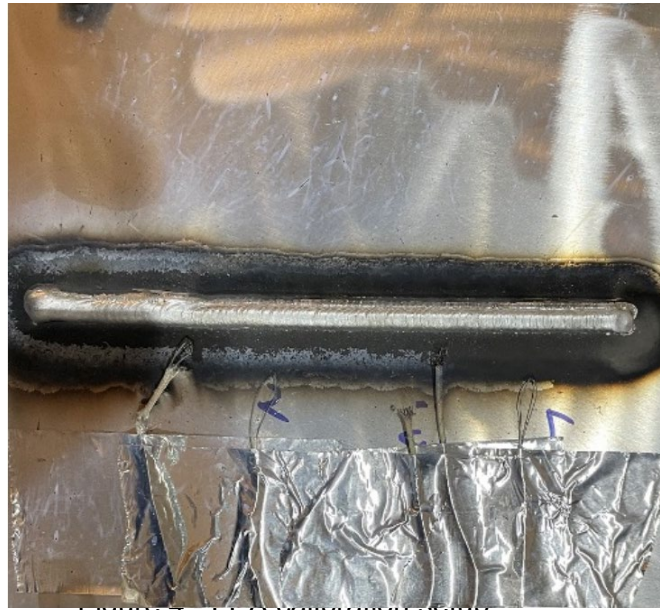


Figure 5 - Thermocouple placement relative to the centerline

Two weld passes were completed during the FEA heat source calibration experiment, and the parameters used are listed in Table 1 below:

Skin	
Process	CMT-Pulse
Synergic line	CMT1679 with 1.2mm wire
Gas	Pureshield Argon
Wire	Al-6Mg-0.3Sc [8,9]
Arclength correction	0%
Wire feed speed	8m/min
Travel speed	10mm/s
Bead Width	6mm
In process temperature	~20°C

Table 1 - Process Parameters

A commercially available FEA software ABAQUS was used for the FEA model and calibration. Two calibrations were carried out, one heat source calibration with a steady-state model for the substrate and one heat source calibration with a transient model for the deposited bead.

Both experiments have their relative data compared with both the thermal camera and the thermal couple. The energy efficiency used for the FEA model is 90% as this is the general efficiency of the CMT-P process, and the heat source details can be found below:

Skin	
Process	CMT-Pulse
Efficiency	90%
Type of heat source	Double ellipsoid
Width(m)	0.003
Depth(m)	0.0035
Length 1(m)	0.0015
Length 2(m)	0.003
Melting temperature	550°C
Element size	1mm

Table 2 - FEA heat source model parameters

Figure 6 shows the comparison between the FLIR thermal camera and the steady-state FEA model for the substrate calibration. The FLIR thermal camera was calibrated against the thermal couple mounted on the substrate and achieved good accuracy with the thermal couple when the emissivity was set to 0.3.

The expected bead width was also calibrated to the same width as the experiment, which is 6mm wide. Here the FEA model is only showing half of the bead to save computational time.

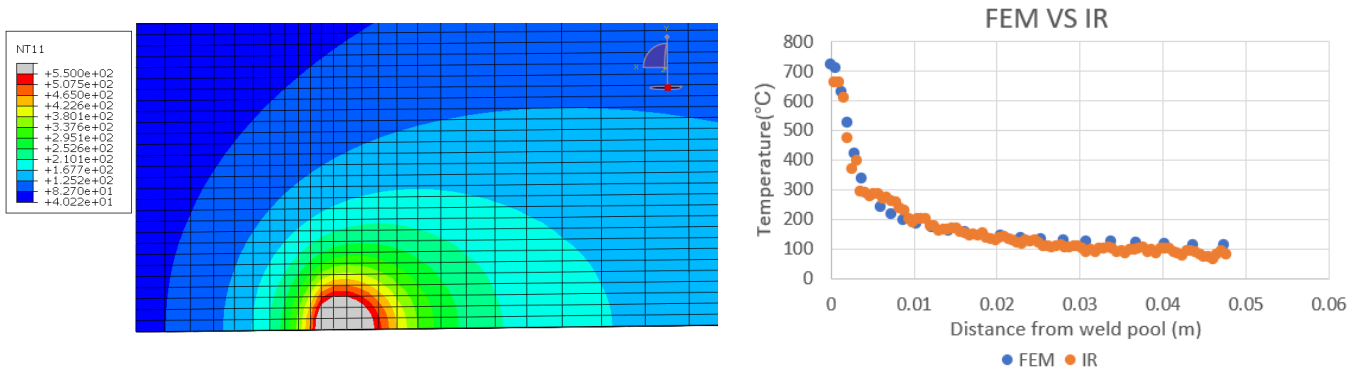


Figure 6 - FEA steady-state model compared with thermal camera with 0.3 emissivity

Distortion is also one of the main challenges of when manufacturing the demonstrator and a FEA shrinkage model has been used to determine the distortion direction and amount. The FEA model is the further used for tool design, deposition path design and optimisation. The amount of sacrificial material is also determined using the FEA shrinkage model to mitigate the distortion in certain areas. Figure 7 is an example of the FEA model for very early stages of the demonstrator.

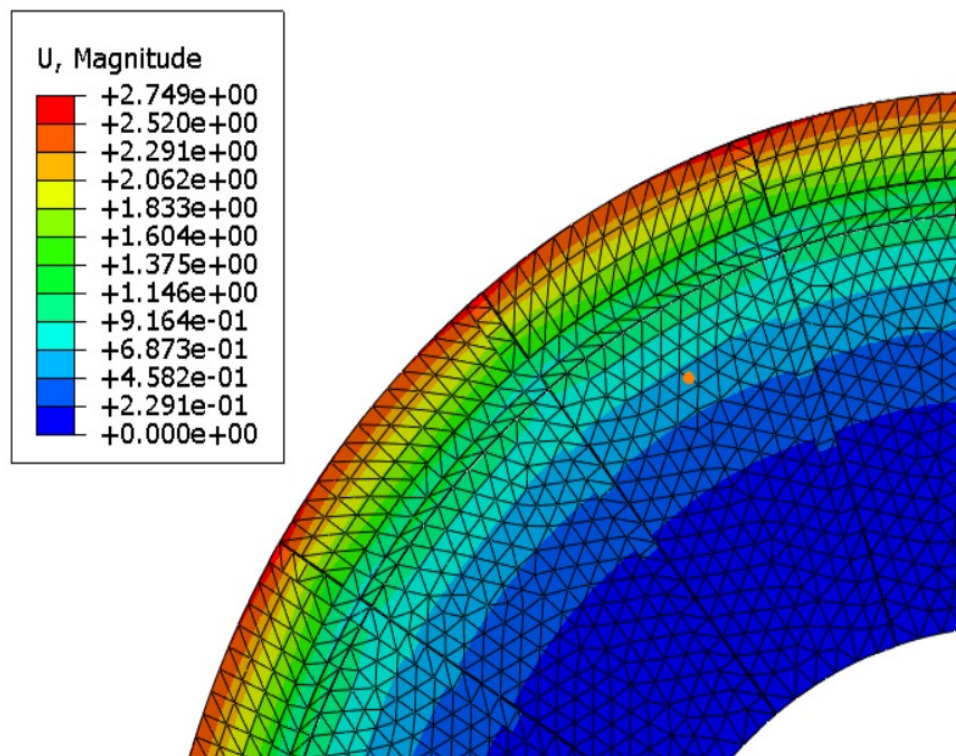


Figure 7 - FEA shrinkage model of the final demonstrator predicting the distortion amount and direction in millimetres

2.5 Jig design

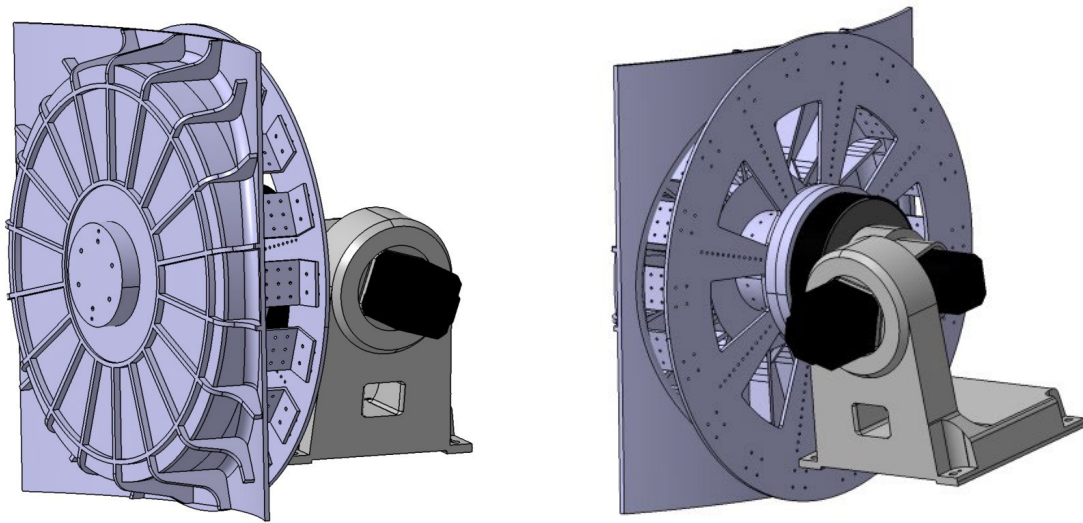


Figure 8 – Jig design of proposed demonstrator

With the help of FEA stress and distortion prediction, we were able to design a multi-functional modular jig to counter the stress and control the distortion to a minimum. The jig will act as a supporting frame for deposition, peening and machining processes and minimize the side effects of the above processes. Figure 8 is the proposed jig design for the final phase of the deposition.

3. Conclusion

Cranfield University, Thales Alenia Space and WAAM3D believe that WAAM process has great potential and is the go-to process for manufacturing large-scale aerospace space exploration components. With the combination of multi-functional tools, intelligent tool path planning and FEA simulation, the cost and lead time can be significantly reduced in future component manufacture, and the sustainability can be significantly increased due to the reduced in BTF ratio and material wasted.

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References

- [1] J. Gu, B. Cong, J. Ding, S. W. Williams, and Y. Zhai, "Wire+Arc Additive Manufacturing of Aluminium," SFF Symp. Austin Texas, pp. 451–458, 2014.
- [2] J. Fixter, J. Gu, J. Ding, S. W. Williams, and P. B. Prangnell, "Preliminary Investigation into the Suitability of 2xxx Alloys for Wire-Arc Additive Manufacturing," in *Materials Science Forum*, 2017, vol. 877, pp. 611–616.
- [3] B. Cong, J. Ding, and S. Williams, "Effect of arc mode in cold metal transfer process on porosity of additively manufactured Al-6.3%Cu alloy," *Int. J. Adv. Manuf. Technol.*, vol. 76, no. 9–12, pp. 1593–1606, 2015.
- [4] Ahmad B, Zhang X, Guo H, Fitzpatrick ME, Neto LMSC, Williams S. Influence of Deposition Strategies on Residual Stress in Wire + Arc Additive Manufactured Titanium Ti-6Al-4V. 2022.
<https://doi.org/10.3390/met12020253>
- [5] Xiong X, Qin X, Ji F, Hu Z, Hua L. Microstructure and Mechanical Properties of Wire + Arc Additively Manufactured Mild Steel by Welding with Trailing Hammer Peening. 2021.
<https://doi.org/10.1002/srin.202100238>
- [6] Gu J, Ding J, Williams SW, Gu H, Ma P, Zhai Y. The effect of inter-layer cold working and post-deposition heat treatment on porosity in additively manufactured aluminum alloys. 2016.
<https://doi.org/10.1016/j.jmatprotec.2015.11.006>
- [7] J. Gu et al., "The strengthening effect of inter-layer cold working and post-deposition heat treatment on the additively manufactured Al-6.3Cu alloy," *Mater. Sci. Eng. A*, vol. 651, pp. 18–26, Jan. 2016.
- [8] L. Ren *et al.*, "The Microstructure and Properties of an Al-Mg-0.3Sc Alloy Deposited by Wire Arc Additive Manufacturing," *Metals (Basel)*, vol. 10, no. 3, p. 320, Feb. 2020.
- [9] L. Ren et al., "Effect of Sc Content on the Microstructure and Properties of Al-Mg-Sc Alloys Deposited by Wire Arc Additive Manufacturing," *Met. Mater. Int.*, pp. 1–10, Jun. 2020.



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