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Development of a repair strategy for a thin aerospace component with dot-by-dot deposition approach

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Abstract. This study presents a repair strategy for an aerospace component manufactured from a 2000-series aluminium alloy. Wire Arc Additive Manufacturing (WAAM) with a dot-by-dot deposition approach was applied to mitigate the heat input and minimise distortion, enabling the reconstruction of thin-walled features with satisfactory surface finish and accuracy. The four-step process comprises the removal of damaged material, the reference geometry definition, the new material deposition, and the finish machining. First, the research focused on determining the most effective surface preparation methods and on optimising deposition parameters and strategies to minimise the occurrence of porosity, excessive melting, and humping during the repair of thin ribs, which have been identified as geometrically-critical features. Second, a preliminary environmental assessment was conducted to evaluate the carbon footprint associated with the proposed repair solution.

Introduction

The transition to more environmentally friendly production methods is essential for the sustainable growth of the global economy. The European Union has established a comprehensive framework for sustainable development, resulting in the European Commission circular economy action plan (CEAP). In a circular economy, resources are used for as long as possible, maximising their value before products and materials are recovered and regenerated at the end of their life cycle. From a practical standpoint, retaining a product within the value chain largely depends on approaches such as reuse, repair, and remanufacturing. Repair involves mending or restoring damaged or worn products to extend their useful life, thereby preventing waste, reducing the demand for new items, and conserving resources and energy. The distinction between repair and remanufacturing lies in the extent of restoration: repair focuses on restoring the functionality of a product or component after a fault or wear, without necessarily returning it to a like-new condition, which is an objective that characterises remanufacturing [1]. Repairing metal components is particularly advantageous due to their substantial production costs in terms of materials and energy consumption. Unlike plastic parts, metal components can often be restored to their original quality without any loss in performance [2]. Moreover, the repair of high-value metal parts has proven to be economically viable [3], particularly in sectors such as aerospace, oil and gas [4, 5], as well as in the production of moulds and dies [6]. The restoration of metal components requires a technique capable of reconstructing their damaged or worn geometrical features, a task made feasible by advances in the field of Additive Manufacturing (AM). Nevertheless, the use of AM for repair is not straightforward, and its application in this domain is restricted by various limitations. A primary constraint is the need to apply new material to existing worn surfaces, which proves challenging with Powder Bed Fusion (PBF) technologies owing to the frequent non-planarity of such surfaces. By contrast, Directed Energy Deposition (DED) processes show promise for the repair of metal components. These employ a high-density energy source (such as a laser, plasma, electron beam, or electrical arc) to melt a metallic medium (such as powder or wire), and deposit the liquefied material onto an existing surface. By synchronising the material feed and the energy source, DED technologies build geometrical features layer by layer, thereby enabling the formation of new material beads [7].

The DED approach selected for this study is Wire Arc Additive Manufacturing (WAAM), a process that exploits an electric arc as the heat source to fuse wire feedstock into layers, creating near-net-shape components, which is often used for repair applications [8, 9]. One of the key features of WAAM is the high deposition rate, coupled with low equipment and operational costs. Additionally, using wire instead of powder results in a safer working environment for operators and lower material costs [10]. Due to the thermal cycles that components experience during the WAAM process, several studies have examined the mechanical properties of WAAM-fabricated components to determine deposition setups capable of ensuring the quality of the repaired material, and particularly the relationship between heat input and microstructure, which can affect both product lifespan and deposition direction. Research has shown that the geometry, microstructure, and wettability of aluminium alloys depend on the WAAM transfer mode, identifying viable solutions for these materials [11]. Moreover, WAAM has been recognised as a sustainable solution for repairing large-scale metal components, with the potential to reduce environmental impact by using less energy and resources than other manufacturing routes [12, 13]. The control of heat input is crucial, especially when thin structures, such as those in the aerospace sector, need to be repaired. Hence, the goal of this study is to optimise the process parameters and, consequently, the heat input of the deposition process to repair such geometries by adopting a strategy for fine-tuning the transferred heat through the deposition of single dots of material.

Repair cycle definition

The selected case study is a ribbed thin shell with a large diameter, used for space application. Its ribs have variable thicknesses depending on the location of the cylinder, ranging from 2 to 5 mm. The component is made from precipitation-hardened 2000-series aluminium, starting with the forging of a hollow cylinder, followed by material removal through machining to create the internal structure. Due to the size of the part and the associated machining time, the lead time of this component is long, making the repair process a critical step to avoid huge costs and mission delays when some problems occur during the production phase.

In most cases, manufacturing defects that require repair arise during the machining phase, with the most common being the unintended removal of part of a rib. Repairing such defects appears to be an interesting strategy to avoid discarding a component that is still in the processing stage, thereby preventing significant economic losses and the long lead time required to produce a replacement part. To carry out the repair, an aluminium alloy 2319 was selected. Although not identical to the base material, it is very similar to the substrate (differing only slightly in its zirconium and titanium content) and is chemically compatible. In addition, the alloy offers good weldability and is available in the diameter required for Gas Metal Arc Welding (GMAW). The wire used, produced by Safra, had a diameter of 1.2 mm. The chemical compositions of both the wire and the substrate are listed in Table 1.

Table 1. *Chemical composition of wire and substrate*

	Al	Zr	Si	Fe	Cu	Mn	Mg	Zn	Ti	Be	V
Wire	Bal.	0.10 - 0.25	<0.20	<0.30	5.8 - 6.8	0.20 - 0.40	<0.02	<0.10	0.10 - 0.20	<0.0003	0.05 - 0.15
Sub.	Bal.	0.05 - 0.15	<0.20	<0.30	5.8 - 6.8	0.20 - 0.40	<0.02	<0.10	0.02 - 0.10	-	0.05 - 0.15

Aluminium is widely used in manufacturing due to its corrosion resistance, low weight, and visually appealing qualities, making it suitable for a broad range of applications. However, its high thermal conductivity and low melting point result in a narrower processing window compared to other metals. Welding aluminium presents several challenges, such as the formation of a thin oxide film that melts at a higher temperature than the base metal, requiring elevated heat levels. However, excessive heat can lead to over-melting, potentially causing holes in the substrate. This risk is particularly critical when working with thin substrates, as is common in aerospace applications. Given the small thickness of such substrates, the phenomenon of part heating during deposition is quite relevant and may lead to a noticeable change in the bead geometry even under low heat input. This effect is shown in Figure 1 for a 3-mm substrate.

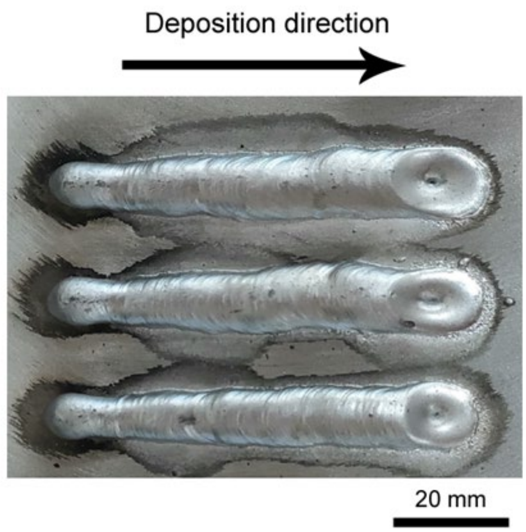

Figure 1. *Continuous deposition of aluminium alloy*

One solution to mitigate this issue is the use of Cycle Step Cold Metal Transfer (CS-CMT), a deposition technique that is a variant of the CMT technology patented by Fronius®. It combines the traditional pulsed modes of the most common GMAW sources with a micro-movement of the wire to control the detachment of a single small drop of material. The CS-CMT is characterised by a highly controlled and low heat input, as it can accurately define the number of drops produced by a CMT cycle and use a waiting time between the successive depositions. This makes it possible to locally reach the heat required for an appropriate melting of the substrate and define a time for cooling down the melt pool before starting a new deposition cycle. By correctly tuning the CS-CMT parameters, it is possible to find a stable thermal equilibrium that allows for good repeatability of the bead dimensions, avoiding the 'thermal runaway' which typically characterizes the deposition of aluminium on a thin substrate (see Figure 1).

The deposition process consists of alternating phases of material melting and waiting time; hence, it is discontinuous and results in a dot-by-dot bead morphology. It is worth noting that this approach is unnecessary for bulkier geometries, where well-established methods based on continuous beads, allowing for higher deposition rates, can be adopted instead. The most influential parameters to be set are (*i*) the number of CMT cycles, which is directly related to the volume of material deposited in a single drop, and (*ii*) the waiting time, which must be adjusted to provide sufficient time for the substrate to cool down between drops. This allows to control the heat input quite accurately and to determine of the optimal processing value within the narrow window characteristic of aluminium.

The welding unit used for the experiments was a Fronius TPS320i GMAW-CMT source with synergic curves for Al-Cu alloys, mounted on a 3-axis cartesian machine retrofitted for WAAM applications. The initial tests aimed to define the optimal parameters for creating a rib starting from a thin section of material. Various thicknesses (e.g., 3, 4, and 5 mm) were tested. As an example, the parameters used for a 3-mm substrate are shown in Table 2. The results of the initial tests were used to identify the process parameters that ensured good penetration with no over-melting phenomena, and to determine the dot size for toolpath planning during deposition. The best outcome for the 3-mm case was obtained in Test #2, which employed two sequences of 20 cycles each, with a 1-second pause between them.

Table 2. *Experimental tests with a 3-mm substrate*

Test ID	CMT Cycle	Idle time [s]	N. of repetitions	WFS [m/min]	Width [mm]	Height [mm]
1	20	1	2	10	Over-melting	
2	20	1	2	10	6.5	2
3	20	1	2	10	6	2.5
4	10	1	3	10	Over-melting	
5	10	1	3	10	7	2.3
6	10	1	3	8	4.7	2.9
7	10	1	3	9	5.5	2.9

Transitioning from single-dot to a semi-continuous (dot-by-dot) deposition introduced additional complexity, as the substrate temperature gradually increased, potentially altering both penetration and dot geometry. Establishing a stable equilibrium condition thus required fine-tuning the heat flux to the part. This was achieved by adjusting the interval between successive drops. Figure 2 presents the results for waiting times of 10, 20, and 30 seconds between drops on a 4 mm rib, using a step-over between the drops of 60% of their dimension. A 30-second idle time resulted in under-heated deposition, as the lack of adhesion between dots compromised the machining allowance. The optimal configuration for these tests was achieved with a 20-second waiting time.

Figure 2. *Semi-continuous dot-by-dot tests*

To perform the repair, the deposition surface must first be prepared by creating a reference geometry for material deposition. This preparation must also consider torch accessibility and the ability of individual dots to form a continuous layer, as some configurations may lead to unwanted arcs to nearby areas of the component. A trapezoidal cavity was chosen as the simplest and most practical geometry for rib repair, with the size of the removal area tailored to fully encompass the defect. An alternating toolpath strategy (Figure 3*a*), regarded as the most effective method for building thin walls [14], was adopted.

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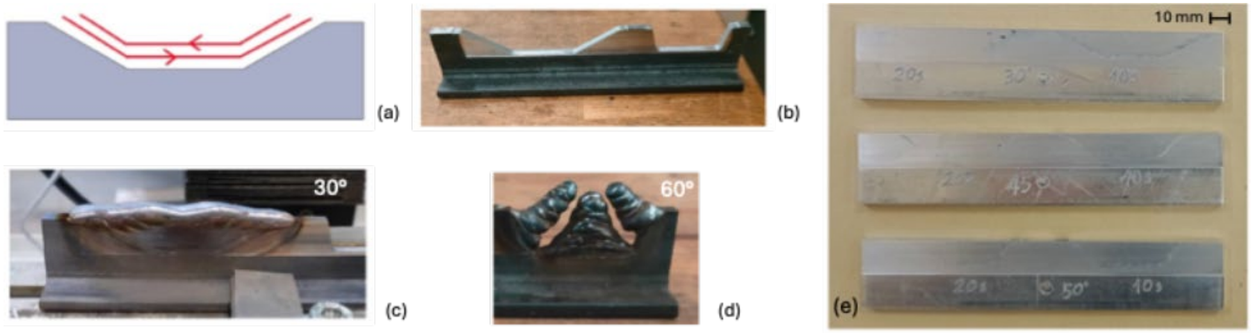

Figure 3. *Tests on sample ribs showing the deposition strategy (a), the surface preparation (b), the results at 30° (c) and 60° (d), the part after milling (e)*

Several tests were conducted to define the optimal angle of the trapezoid (Figure 3*b*). A larger angle (measured with respect to the horizontal plane) would require less material removal, thus reducing the machining waste. However, this could pose challenges in accessing the welding torch. Conversely, a smaller angle necessitates more space to create the trapezoidal cavity but ensures better access to the torch, even with a smaller contact tip-to-work-distance (CTWD). Some results are shown in Figure 3*c-d*, where excessively high angles caused the formation of a 'horned' shape, due to the sparking of the arc on the surface closer to the torch rather than on the previously deposited layer. This phenomenon is self-regenerative and leads to process defects. The minimum safe angle for this geometry was approximately 45°, which was used for the repair tests. Figure 3*e* shows the results of some tests with the suggested parameters on a thin 4-mm plate. All configurations yielded satisfactory results, with no lack of fusion observed after milling. After defining the process parameters, the developed repair strategy was applied to a small part of the selected test case, starting from the removal of material to simulate a manufacturing error. The steps of the approach and the results are illustrated in Figure 4.

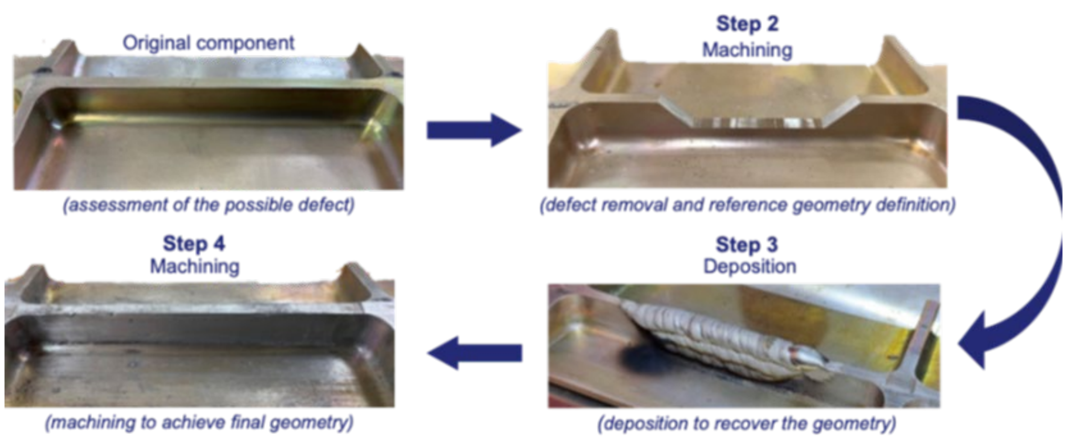

Figure 4. *Repair step for the test case*

At this stage of the ongoing research, only superficial and geometrical analyses have been carried out, while the analysis of the mechanical properties and micrographic analysis are planned.

Carbon footprint of the repair operation

The groove volume measured 1376 mm³, whereas the deposited material required to fill it amounted to 4130 mm³. Consequently, 2754 mm³ of material was removed to achieve the final surface finish after the deposition. The deposition phase required 46 dots and took approximately 410 seconds, with the majority of this time attributed to process idle, whereas only 41.5 seconds were effectively spent on the actual material deposition. To conduct a preliminary assessment of the carbon footprint associated with the repair process, a Life Cycle Assessment (LCA) was performed using CO_2-equivalent emissions as the environmental stress metric. This analysis accounted for the contributions of material consumption, energy usage, and resource expenditure throughout the various phases of the repair process. In addition, the impact associated with the production of the metal wire consumed during the active deposition phase was considered, as shown in Figure 5*a*. The carbon footprint of a unit mass of wire was estimated to be 14.6 ±7% $kgCO_2/kg$, based on modelling the unit processes from raw material production through the subsequent hot shape rolling and wire drawing stages, which have yield factors of 0.95 and 0.88, respectively. The carbon footprint of raw material production was evaluated at 8.4 ±8% $kgCO_2/kg$, considering a recycled content of 43% ±5% in the current material supply, and assuming primary and secondary production emissions from the data in the CES Selector database v.17.2.0. Moreover, according to the same database, the carbon footprint contributions of hot shape rolling and wire drawing were estimated to be 0.5 ±5% $kgCO_2/kg$ and 3.5 ±5% $kgCO_2/kg$, respectively.

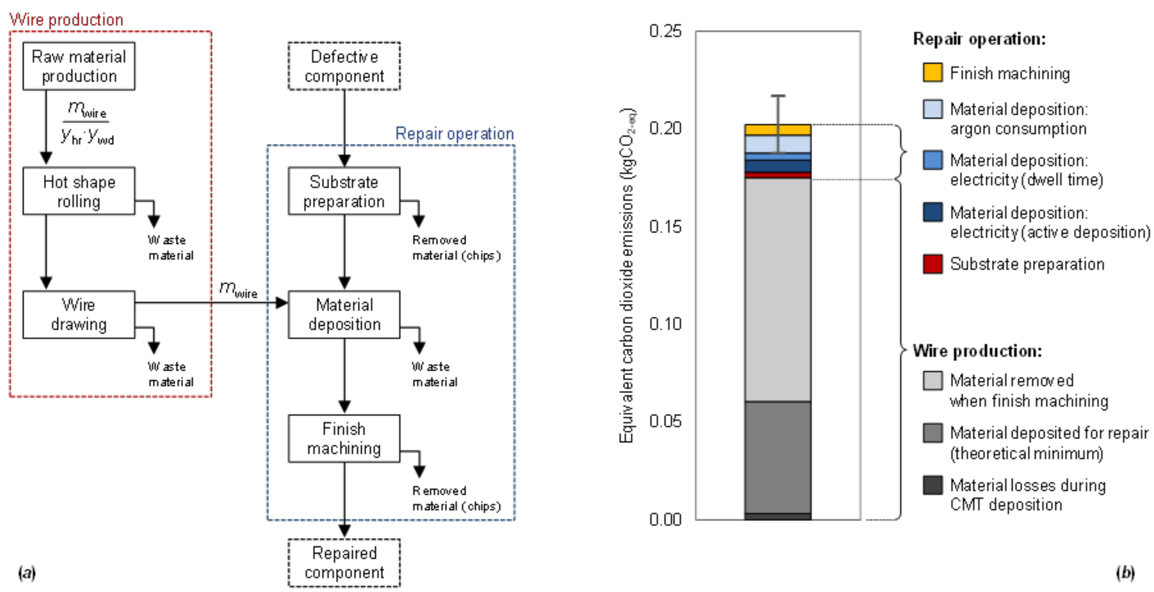

***Figure 5.** Preliminary carbon footprint assessment: system boundaries (a) and main results (b)*

For the repair operation, the specific deposition energy (which accounts for the energy demand for material deposition only, as outlined in [15]) was experimentally measured at 2.5 kWh/kg, while the total energy consumption for the CMT repair operation (including contributions from idle states during both deposition and dwell time) was 4.0 kWh/kg. The specific deposition energy (SDE) values appear to be higher than those reported in the literature [15], as expected, since the dot-by-dot repair process is more time- and energy-intensive than a continuous deposition process. In contrast, comparing the specific energy consumption (SEC) with other studies should be done with caution, as idle times and idle power (which, in this case, is modest at below 0.2 kW) vary depending on the geometry of the part, the deposition path, and the specific equipment used. During the active deposition phase, which accounts for a yield factor of 0.98 to incorporate permanent material losses due to vaporization and sparking, the consumption of argon (grade 5) was quantified at 4.3 kg/kg of deposited material.

The carbon footprint of electricity was assumed to be 0.21 ± 10% $kgCO_2/kWh$, while that of argon was 0.18 ± 10% $kgCO_2/kg$ [16]. For all the machining operations, a carbon footprint of 0.70 ± 5% $kgCO_2/kg$ of material removed was considered (CES Selector v.17.2.0). Based on these considerations and the assumptions underlying the calculation model, the results presented in Figure 5*b* were obtained. The largest share of CO_2 emissions is attributable to the aluminium wire production, while the contributions from the various process phases account for only a minor fraction, less than 15% of the total. Although these results are preliminary, specific to the case study considered, and based on both primary data measured in the laboratory and impact factors derived from secondary sources such as literature and databases, they provide insights for potential process optimization. Most of the impact associated with wire consumption is linked to the material that is first deposited and subsequently removed as chips during finishing operations. Therefore, improving material usage efficiency could yield environmental benefits, as there appears to be significant room for optimization. If the carbon footprint is theoretically limited to only the material required to fill the groove volume, the imbalance between process-related and material-related emissions would be reduced. In any case, the repair operation – especially for small repairs on large components, such as those considered in this study – is expected to be more advantageous than replacing the damaged component with a brand new one, in line with findings from previous studies (see [6] and references therein).

Conclusions

In this study, a dot-by-dot repair methodology for thin aluminium components was developed to increase the control of the heat input. The repair procedure comprised four sequential stages: removal of damaged material, establishment of a reference geometry, additive deposition of replacement material, and machining to remove the excess. Process parameters were selected to achieve a high quality restoration with proper penetration and no overmelting. Moreover, the environmental analysis of the repair process highlighted that the largest share of CO_2 emissions was due to the production of the aluminium wire, whereas process-related contributions accounted for less than 15% of the total. Therefore, in a context where repair operations are deemed more favourable than the replacement of damaged components with newly manufactured ones, improving material utilisation efficiency could offer further environmental benefits.

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References

[1] N. Sandeep and R. Suresh, A Study of the Circular Manufacturing System: Issues and Prospects, Journal of Systems Science and Information 12 (2024) 790–803. https://doi.org/10.21078/JSSI-2024-0088

[2] N. A. Aziz, N. A. A. Adnan, D. A. Wahab, and A. H. Azman, Component design optimisation based on artificial intelligence in support of additive manufacturing repair and restoration: Current status and future outlook for remanufacturing, J. Clean. Prod. 296 (2021) 126401. https://doi.org/10.1016/j.jclepro. 2021.126401

[3] H. Liao, C. Li, Y. Nie, J. Tan, and K. Liu, Environmental efficiency assessment for remanufacture of end of life machine and multi-objective optimization under carbon trading mechanism, J. Clean. Prod. 308 (2021) 127168. https://doi.org/10.1016/j.jclepro.2021.127168

[4] M. Sharma, S. Joshi, M. Prasad, and S. Bartwal, Overcoming barriers to circular economy implementation in the oil & gas industry: Environmental and social implications, J. Clean. Prod. 391 (2023) 136133. https://doi.org/10.1016/j.jclepro.2023.136133

[5] M. Liu, Y. Cai, C. Duan, and G. Li, Key techniques in parts repair and remanufacturing based on laser cladding: A review, J. Manuf. Process. 132 (2024) 994–1014. https://doi.org/10.1016/j.jmapro. 2024.11.039

[6] P. C. Priarone, G. Campatelli, A. R. Catalano, and F. Baffa, Life-cycle energy and carbon saving potential of Wire Arc Additive Manufacturing for the repair of mold inserts, CIRP J. Manuf. Sci. Technol. 35 (2021) 943–958. https://doi.org/10.1016/j.cirpj.2021.10.007

[7] M. Leino, J. Pekkarinen, and R. Soukka, The role of laser additive manufacturing methods of metals in repair, refurbishment and remanufacturing - Enabling circular economy, Phys. Procedia 83 (2016) 752–760. https://doi.org/10.1016/j.phpro.2016.08.077

[8] M. Vishnukumar, R. Pramod, and A. Rajesh Kannan, Wire arc additive manufacturing for repairing aluminium structures in marine applications, Mater. Lett. 299 (2021) 130112. https://doi.org/10.1016/j.matlet. 2021.130112

[9] X. Li, Q. Han, and G. Zhang, Large-size sprocket repairing based on robotic GMAW additive manufacturing, Welding in the World 65 (2021) 793–805. https://doi.org/10.1007/s40194-021-01080-9

[10] J. Obiko et al., A brief review on industrial remanufacturing of structural and functional components: Wire-Arc Additive Manufacturing Technique, Engineering Solid Mechanics 12 (2024) 363–386. https://doi.org/10.5267/j.esm.2024.5.004

[11] S. Ren et al., Comparative study of additive manufacturing thin-walled component with Al–Mg-Sc-Zr alloy using different arc modes, J. Mater. Res. Technol. 35 (2025) 5665–5674. https://doi.org/10.1016/ j.jmrt. 2025.02.053

[12] R. C. Reis, S. Kokare, J. P. Oliveira, J. C. O. Matias, and R. Godina, Life cycle assessment of metal products: A comparison between wire arc additive manufacturing and CNC milling, Advances in Industrial and Manufacturing Engineering 6 (2023) 100117. https://doi.org/10.1016/j.aime.2023.100117

[13] J. Wurst, T. Steinhoff, I. Mozgova, T. Hassel, and R. Lachmayer, Aspects of a Sustainability Focused Comparison of the Wire Arc Additive Manufacturing (WAAM) and the Laser Powder Bed Fusion (LPBF) Process, In: Smart Innovation, Systems and Technologies 338 (2023). https://doi.org/10.1007/978-981-19-9205-6_9

[14] M. Rauch, J.-Y. Hascoet, and V. Querard, A multiaxis tool path generation approach for thin wall structures made with WAAM, J. Manuf. Mater. Process. 5 (2021) 128. https://doi.org/10.3390/jmmp5040128

[15] A. R. Catalano, V. Tebaldo, P. C. Priarone, L. Settineri, and M. G. Faga, CMT deposition of stainless steel: effects of process parameters on energy demand and microstructure, Progress in Additive Manufacturing (2025). https://doi.org/10.1007/s40964-025-01022-7

[16] F. S. Gobber, P. C. Priarone, A. Pennacchio, and M. Actis Grande, Effect of inert gas pressure on the properties and carbon footprint of UNS S32760 powders made from waste materials by gas atomization, J. Mater. Res. Technol. 33 (2024) 8814–8828. https://doi.org/10.1016/j.jmrt.2024.11.195