Porosity and metallurgical characteristics of AA5356 aluminum alloy cylindrical components made by wire arc additive manufacturing process

B. Prasanna Nagasai*, S. Malarvizhi, V. Balasubramanian

Centre for Materials Joining & Research (CEMAJOR), Annamalai University, Annamalainagar, Tamilnadu, India

KEYWORDS

Wire Arc Additive Manufacturing,
Al-Mg Alloy,
Porosity,
Metallurgical Characteristics.

ABSTRACT

AA5356 (Al-Mg) alloys can reach medium strength without a solid solution and quenching treatment, thereby avoiding product distortion caused by quenching, which has attracted the attention of wire arc additive manufacturing (WAAM) researchers. However, challenges during the additive manufacturing of aluminum alloys, such as porosity or poor mechanical properties, can be overcome by using arc technologies with low heat input. This paper presents metallurgical characteristics and mechanical properties of wire arc additive manufactured AA5356 alloy cylindrical components fabricated by Gas Metal Arc Welding (GMAW) and Cold Metal Transferred (CMT) arc welding processes. Herein, comparison between the welding processes and the resulting heat input show the effect on resulting microstructural characteristics of additively manufactured AA5356 parts. Firstly, the influence of heat input on the porosity was analyzed. Subsequently, the effect of heat input on the microstructural characteristics of the components was studied. The component produced by CMT process exhibits fewer and smaller pores with finer grains and reduced segregation of β-(Al_3Mg_2) phases than the GMAW process.

1. Introduction

Additive manufacturing (AM) has developed in recent decades as a new technology for manufacturing parts, particularly interior structures, which have very complicated geometry. The AM technology enables a physical object to be produced directly from its CAD model with no additional resources, such as cutting tools, jigs and cooling fluids. AM utilizes only the amount of materials required to manufacture parts and support structures if necessary. As a result, material waste and environmental effects might be minimised. Topological optimization for raw material savings is also possible with AM. AM technologies, particularly metallic AM technologies, are now widely employed in the fields of aeronautics, automobiles, and biomedical engineering (Gan et al., 2017).

Wire arc additive manufacturing (WAAM) is a variant of AM that uses a welding arc as the heat source and metal wire as the feeding material. The use of powder instead of wire has many drawbacks: high cost, different powder quality, and complexity of feed. The heat source melts filler wire and transforms it into a melt pool during the WAAM process, and then solidifies it into a melt pool and creates designed components. WAAM is a droplet-based additive manufacturing technique that has a lot of potential for direct production of thin-and thick-walled complicated components (Willy et al., 2018). WAAM has a high deposition rate that is useful for the production of large components. Moreover, WAAM offers advantages like low cost and low waste rate. Therefore, WAAM is an excellent alternative additive manufacturing process for manufacturing large scale components to other electron and laser beams (Xiong et al., 2017).

WAAM offers low equipment costs, shortened lead-time, high deposition rates, and high density parts. The heating and cooling phases of the WAAM process influence the metallurgical and mechanical behaviours, which have a significant impact on the strength to ductility ratio in manufactured components (Donghong et al., 2015). Aluminium has a unique set of characteristics, the most notable of which are its excellent corrosion resistance and high strength-to-weight ratio. Furthermore, the ability to add tiny amounts of various alloying elements makes this material extremely attractive. There are many issues with aluminium alloys, including hot

*Corresponding author,
E-mail: nagasaibellamkonda143@gmail.com

Table 1
Chemical composition (wt %) of ER5356 filler wire.

Wire	Si	Cu	Fe	Mn	Mg	Cr	Zn	Ti	Be	Al
ER5356	0.25	0.1	0.4	0.07	4.5	0.06	0.1	0.06	0.0003	Bal.

Table 2
Optimized WAAM process parameters.

Parameters	GMAW	CMT
Wire feed speed (m/min)	6.4	6.4
Current (A)	121	105
Voltage (v)	13.5	13.0
Travel speed (mm/min)	250	250
Contact tip to work distance (mm)	15	15
Arc length correction (%)	----	0
Dynamic correction	0.0	0.0
100% Ar (lit/min)	18	18
Heat Input (kJ/mm)	0.313	0.262

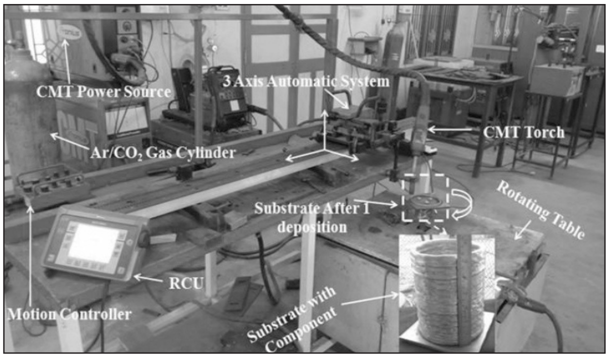

Fig. 1. WAAM platform used to manufacture Al-Mg cylindrical components.

cracking and porosity, which can significantly limit the mechanical characteristics of the component. Many factors contribute to porosity, including welding processes, process parameters, quality of filler wire, and alloy composition (Gierth et al., 2020). The heat input of the newly deposited layer can lead to the development of pores in a multipass WAAM process.

Qi et al. (2017) documented that heat input is an important factor for reducing porosity and should be below 300 J/mm. The effect of interpass temperature on the formation of porosity was also investigated by (Derekar et al., 2019). The percentage of porosity was reduced due to higher temperatures between successive layers during fabrication of the component, and it was confirmed by X-rays. Kohler et al. (2019) observed anisotropy in tensile properties and hardness of aluminum components (5356 and 4047) in parallel to building direction and transverse direction due to non equiaxed microstructure and porosity of the component in the interlayer region. Gierth et al. (2020) manufactured aluminum 5356 linear wall part with cold metal transfer (CMT) arc welding technology. The authors observed almost similar mechanical properties due to low porosity below 0.5%, and the equiaxed microstructure in building direction and deposition direction.

From the published data, it is conceived that most of the research was done on the WAAM of microstructure and mechanical properties of linear wall aluminum components. There is no document on the effect of welding processes on the porosity, microstructural characteristics of wire arc additive manufactured AA5356 aluminum alloy cylindrical components. Therefore, the need for an effective welding process, control and monitoring system is essential. The motivation behind the current study is to compare the GMAW and CMT processes for homogeneous microstructural characteristics of wire arc additive manufactured (WAAM) AA5356 aluminum alloy cylindrical components. The effect of heat input on microstructural was studied in different zones of GMAW and CMT based AA5356 aluminum alloy cylindrical components.

2. Experimental Procedure

2.1 Fabrication of cylindrical components

Table 1 shows the chemical composition of the ER5356 (Al-Mg) filler wire (ϕ = 1.2 mm) used in this study. A welding machine (CMT Advanced 4000 R) capable of functioning in both GMAW and CMT modes was used to produce cylindrical components. Table 2 shows the optimised process parameters for GMAW and CMTAW processes. The welding torch is fixed with a three-axis automatic motion system and rotating table setup (Fig. 1). The aluminium 6061 (250 × 250 × 10 mm) substrate was cleaned prior to deposition, and the arc torch was held perpendicular to the surface of the substrate throughout the process. Meanwhile, a mechanical motor system will rotate the substrate. The dimensions of the manufactured GMAW and CMTAW cylindrical components are presented in Table 3. Fig. 2 shows the photographs of Al-Mg cylindrical components built via GMAW and CMT processes. The bottom and top regions of the manufactured Al-Mg cylindrical components were separated and a CNC lath machine was used to remove excessive material. The heat input (kJ/mm) was calculated using following Equation 1.

$$HI = \eta \times V \times I \times 60 / S \times 1000 \quad ....(1)$$

Where η is the process efficiency in % which is equal to 0.8, V is the arc voltage in volts, I is the average arc current in amperes and S is the travel speed in mm/m.

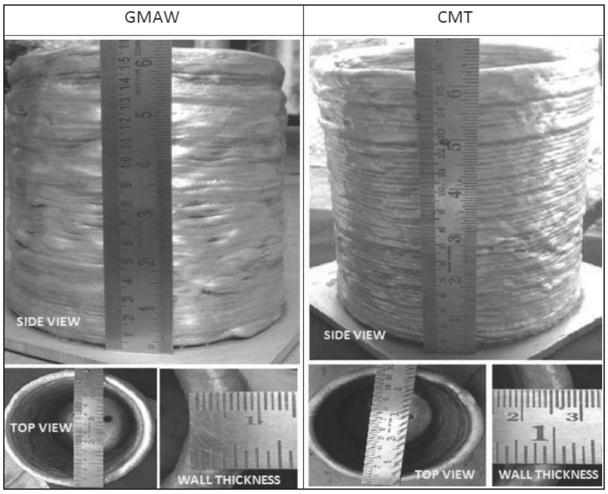

Fig. 2. Photographs of manufactured cylindrical components.

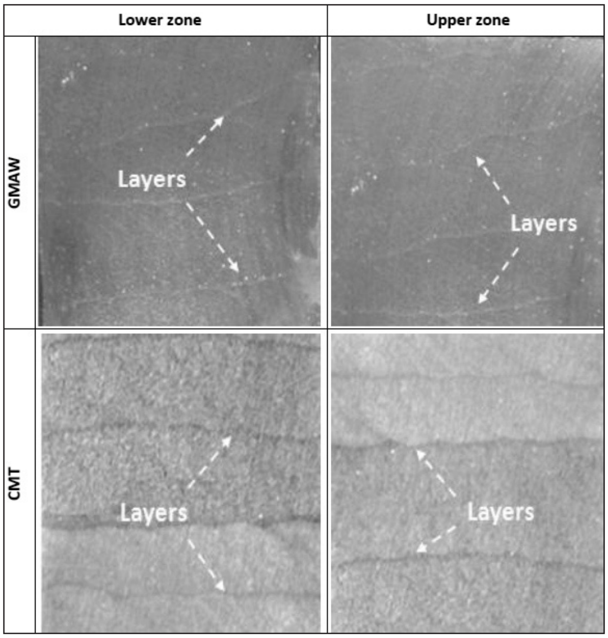

Fig. 3. Macrostructure of cylindrical components.

2.2 Macrostructure and microstructural analysis

Both the bottom and top regions of the GMAW and CMT cylindrical component specimen were polished with different sized microns of emery paper. As per the ASTM E3-11 standard, samples were polished and Keller's reagent was used as an etchant to reveal macro and micro-structural characteristics of the bottom and top regions of cylindrical components. A stereozoom microscope was used to examine the macrostructures of the bottom and top regions. The microstructures of different zones were examined using a light optical microscope. The grain size and porosity of cylindrical components were measured using the Image J programme.

Table 3
Dimensions of WAAM cylindrical components.

Geometry	Unit	GMAW	CMT
Number of deposited layers	-	55	56
Average single layer height	mm	2.95±2	2.85±2
Diameter of the cylinder	mm	122±5	120±7
Total cylindrical component height	mm	160	160

Table 4
Porosity analysis.

Process	Location	Number of pores	Total porous area (mm^2)	Pore diameter (μm)	Percentage of porosity (%)
GMAW	Bottom	68	1.360	96.75	2.60
	Top	60	1.248	86.93	2.30
CMT	Bottom	31	0.577	57.89	0.90
	Top	20	0.357	47.73	0.68

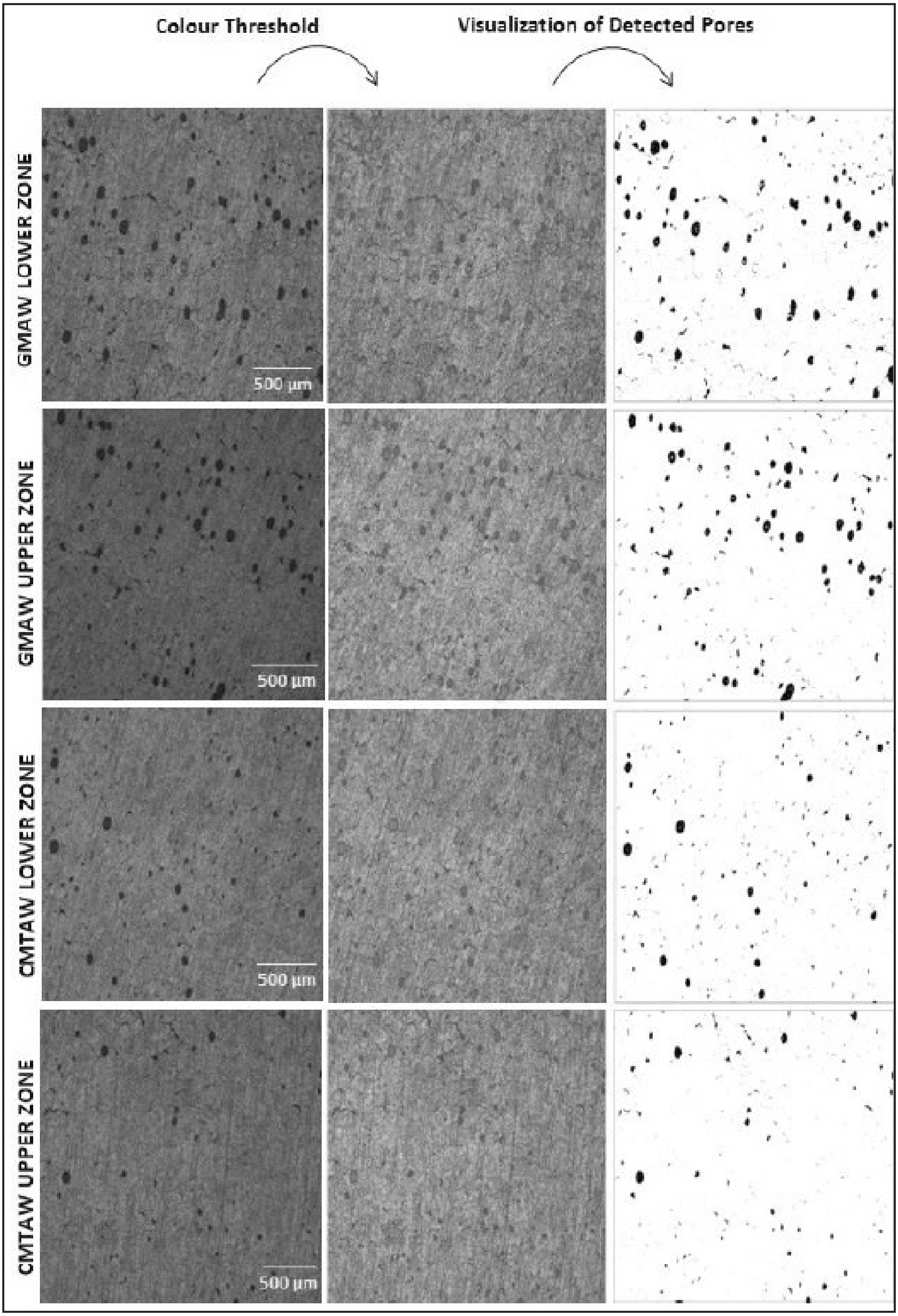

Fig. 4. Representation of the process of porosity analysis.

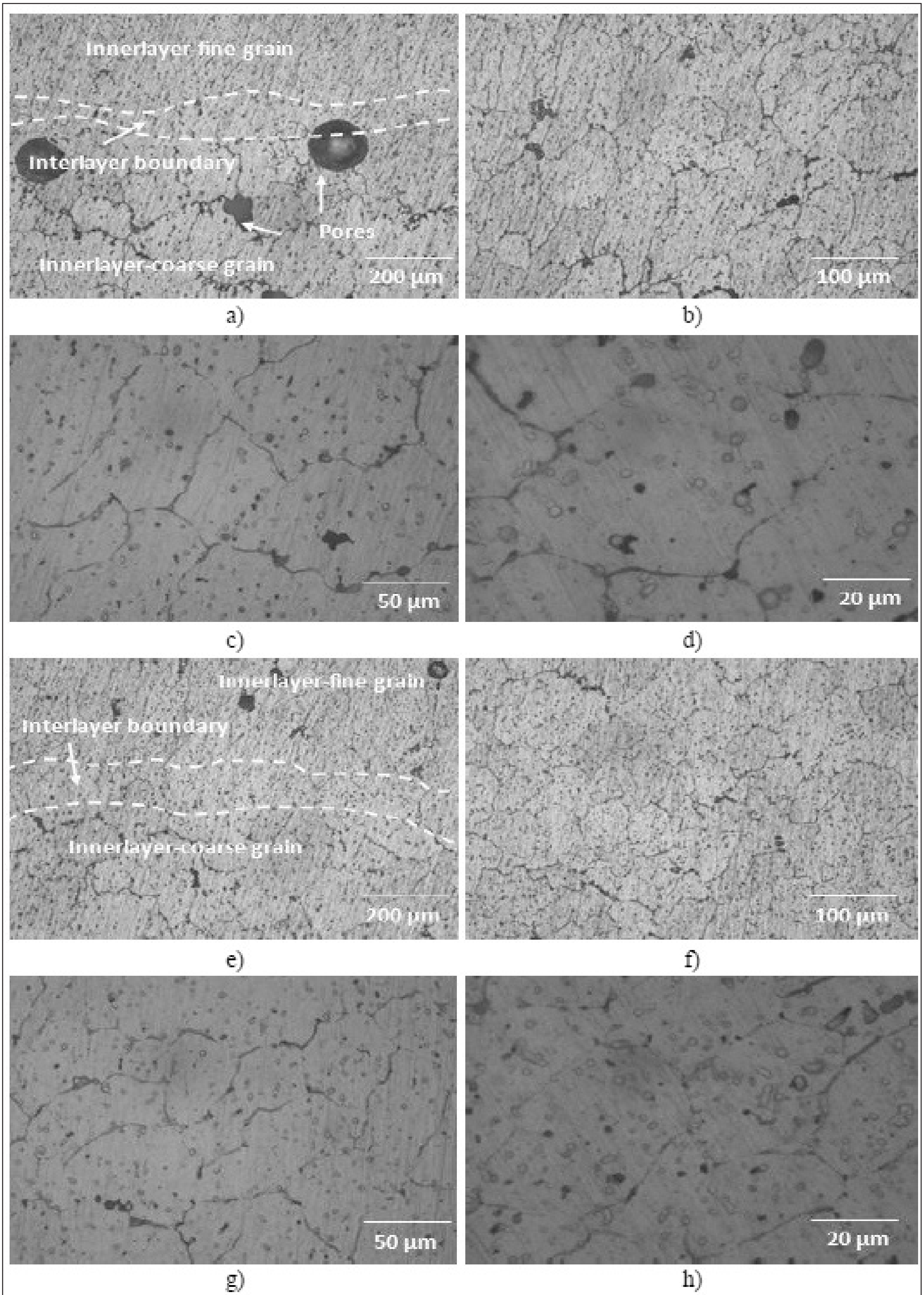

Fig. 5. Optical micrographs of lower zones: a-d) GMAW e-h) CMT.

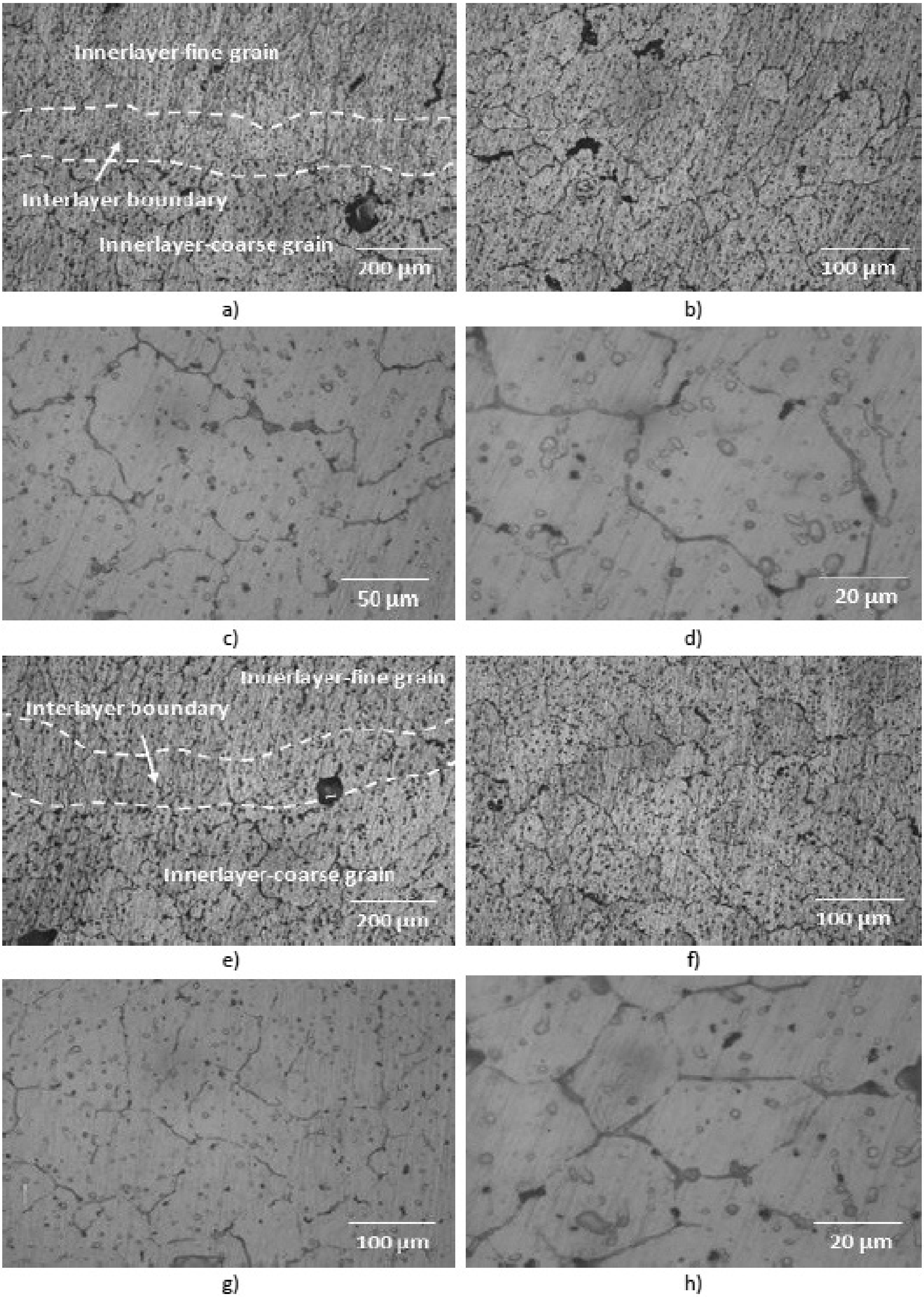

Fig. 6. Optical micrographs of upper zones: a-d) GMAW e-h) CMT.

Table 5
Average grain size of cylindrical components.

Process	Location	Inner-layer fine grain size (µm)	Inner-layer coarse grain size (µm)
GMAW	Bottom	62.40±3.2	90.64±4.1
	Top	59.20±2.5	85.32±3.10
CMT	Bottom	45.30±3.0	65.09±2.1
	Top	42.10±2.9	63.12±3.3

3. Results and Discussion

3.1 Macrostructure and porosity

Fig. 3 shows the macrostructure of the bottom and top regions of the additively manufactured Al-Mg alloy cylindrical components. The deposited beads are properly merged into one another in the manufactured cylindrical components. The weld beads are free from visual defects.

The pores are distributed parallel to the deposited layers in the bottom and top regions of the GMAW component. The distribution of pores in the CMT cylinder is shown in Fig. 4, and it is found that the pores are uniformly distributed. Table 4 presents the percentage of porosity, average pore size, number of pores, and total porous area of the Al-Mg alloy components. The pores with a diameter greater than 10 µm are measured in the components. As can be seen in Fig. 4, the GMAW component has a large number and size of pores. The number of pores and pore size were lower, and the percentage of porosity was reduced in the CMT component. There are two main reasons why the CMT process reduces porosity: i) The CMT arc reduces the burning loss of magnesium. Because magnesium is a very active element, when it is burned in the WAAM process, it produces loose magnesium oxide. These magnesium oxide particles float on top of each subsequent deposition layer. This oxide absorbs moisture from the air, resulting in the formation of pores and the production of hydrogen in the deposition. Magnesium evaporates slowly in the CMT process because the heat input is lower. Lower heat input reduces Mg evaporation, resulting in reduced porosity. ii) With reduced heat input energy in the CMT process, the viscous nature of the Al-Mg component melt raises and the total temperature of the material fall. The pore escape rate increases as liquid viscosity decreases. Table 4 shows that the component produced by the CMT process has a layer height of 2.95±2 mm. This is substantially lesser than the height of the layer deposited by the GMAW process (2.85±2 mm). As a result of the CMT arc forming, the bubble overflow path is reduced, allowing bubbles to quickly overflow and minimise deposit pores. Similar behaviour was observed by Ren et al. (2021) in Al-6Mg-0.3Sc alloy parts deposited by double-wire arc additive manufacturing. Moreover, without the use of electromagnetic force, the CMT process can provide a considerable oxide cleaning effect on the end of the Al-Mg wire due to droplet detachment during the short-circuit. This helps to reduce the hydrogen in the melt pool. This minimises the amount of hydrogen in the melt pool, which helps with gas pore escape (Zhang et al., 2018).

3.2 Microstructural analysis

Fig. 5 shows the microstructures of the bottom region of the Al-Mg cylindrical components manufactured via GMAW and CMT processes. Fig. 5 (a-d) shows the microstructure of the bottom region of the GMAW component. The microstructure of the bottom region of the CMT component is shown in Fig. 5 (e-h). The interlayer boundary between each deposition is observed in the microstructure, which is due to the alternating overlaying of deposited layers. When WAAM cylindrical walled samples are divided into two areas (the inter-layer region and the inner-layer region), the top layer of deposited bead re-heats the previous layer of deposited bead. Three distinct zones with different metallurgical characteristics were identified in the layer structure at the bottom region of the GMAW and CMT components (shown in Figs. 5(a) and 5(e)). Fig. 5b and f show the fine grain microstructure near the fusion line boundary in both the components. Figs. 5(c) and 5(g) show the coarse grain microstructure below the interlayer boundary. The thermal effect of the subsequent layer in WAAM is the reason for the grain growth and at higher magnification shown in Fig. 5(d) and 5(h).

Similar microstructural features were observed in the top region of the fabricated cylindrical components. Fig. 6 shows the microstructural features of the bottom region of the Al-Mg alloy cylindrical components. Fig. 6(a-d) shows the microstructure of the top region of the GMAW component. The microstructure of the top region of the CMT component is shown in Fig. 6(e-h). The upper part (shown in Figs. 6(a) and 6(e)) is also characterised by the three distinct zones with different metallurgical characteristics. Fig. 6(b) and 6(f) show the fine grain microstructure above the interlayer boundary in the upper zone. Fig. 6(c) and 6(g) show the coarse grain microstructure below the interlayer boundary in both the components. The microstructure of the fabricated WAAM-based GMAW and CMT Al-Mg components was almost similar. However, the welding processes have an effect on the grain size of the bottom and top regions of the components.

Table 5 shows the differences in the grain size in the bottom and top regions of the components. The differences in the grain sizes in the components are mainly due to the different heat inputs of the welding processes (presented in Table 5). The cylinder manufactured by the GMAW process revealed larger grains in the bottom and top regions (Figs. 5(c) and 6(c)). The high current and voltage involved in the GMAW process increased the heat input in the cylinder. The solidification and cooling times rise as the heat input increases. The grains become larger as a result of this. The fine grains were formed in the bottom and top regions of the component manufactured by the CMT process shown in Figs. 5(g) and 6(g). The grain size decreased due to the reduced solidification and cooling times with the low heat input of the CMT process. Ren et al. (2021) studied the microstructure and mechanical properties of double wire arc additive manufacturing of Al-Mg-Sc alloy parts. The authors observed fine grain microstructure in the double wire arc additively manufactured Al-Mg-Sc parts than in the single wire arc additively manufactured parts due to the low heat input in the double wire arc additive manufacturing process.

The secondary phase (β) will segregate at grain boundaries when the Mg content is more than 3 wt% due to the lower solubility of Mg (1.9 wt %) in aluminium at room temperature. The segregation of these (β) phases will affect the mechanical properties of WAAM parts. CMT is a variant of GMAW; it is a novel method for WAAM. It uses mechanism for wire retraction which delivers signal that retracts filler wire, offers weld time to cool back each drop. The wire moves continuously until the short circuit takes place in the CMT process. During the deposition, current is constant in GMAW, current varies from peak value (in peak phase) to base value (in base phase), resulting in a short-circuit at zero current (in short circuit phase) in CMT process (Ramaswamy et al., 2020). The following structural changes were identified due to the low heat input of the CMT process: i) Because of the fast cooling due to low heat input, the CMT component produced a finer grain size than the GMAW cylindrical component. From the microstructural analysis, it is confirmed that the element Mg did not precipitate in time and the maximum amount of Mg dissolved in the α-Al matrix (Hyde et al., 2001). Al-Mg alloy cylindrical component manufactured by CMT-WAAM produced a fine primary α-Al phase that acted as fine grain strengthening, as well as changed the structure of the segregated phase.

4. Conclusions

In this study, the mechanical properties and microstructural features of AA5356 aluminum alloy cylindrical components manufactured via the GMAW and CMTAW processes were evaluated. The important conclusions are:

1. The GMAW and CMTAW processes allow building Al-Mg alloy cylindrical components with high density and without macro level defects. The deposited layers are properly merged with one another, and free from faults and defects.
2. The surface of the CMT cylindrical component is more uniform and precise than the GMAW cylindrical component. The number of pores and pore size are lower, and the percentage of porosity is reduced in the CMT component.
3. Moreover, grain size is finer and the segregated β-(Al_3Mg_2) phases are lower and thinner, and the solid solution of Mg increased in aluminum, which increased the solid solution strengthening effect in the cylinder.

Acknowledgements

The first author is grateful for the financial assistance provided by the Department of Science and Technology (DST), Ministry of Science and

Technology, Government of India, New Delhi, through the PURSE-Phase-2 Fellowship scheme. The authors express their gratitude to M/s. Fronius India Pvt. Limited, Chennai, for their technical assistance.

References

Cong, B., Qi, Z., Qi, B., Sun, H., Zhao, G., & Ding, J. (2017). A comparative study of additively manufactured thin wall and block structure with Al-6.3%Cu alloy using cold metal transfer process. *Applied Sciences, 7*(3), 1-10.

Derekar, K., Lawrence, J., Melton, G., Addison, A., Zhang, X., & Xu, L. (2019). Influence of Interpass Temperature on Wire Arc Additive Manufacturing (WAAM) of Aluminium Alloy Components. *MATEC Web Conferences, 269*(7), 1-6.

Donghong, D., Zengxi, P., & Dominic, C. (2015). A multi-bead overlapping model for robotic wire and arc additive manufacturing (WAAM). *Robotics and Computer- Integrated Manufacturing, 31*(2), 101-110.

Gan, Z., Yu, G., He, H., & Li, S. (2017). Numerical simulation of thermal behavior and multicomponent mass transfer in direct laser deposition of Co-base alloy on steel. *International Journal of Heat Mass Transfer, 104*(1), 28-38.

Gierth, M., Henckell, P., Ali, Y., Scholl, J., & Bergmann, J.P. (2020). Wire Arc Additive Manufacturing (WAAM) of aluminum alloy AlMg5Mn with energy-reduced Gas Metal Arc Welding (GMAW). *Materials, 13*(12), 1-9.

Hyde, KB., Norman, AF., & Prangnell, P. B. (2001). The effect of cooling rate on the morphology of primary Al3Sc intermetallic particles in Al-Sc alloys. Acta Materialia, 49(8), 1327-1337.

Köhler, M., Fiebig, S., Hensel, J., & Dilger, K. (2019). Wire and arc additive manufacturing of aluminum components. *Metals,* 9(5), 608. https://doi.org/10.3390/met9050608

Ramaswamy, A., Malarvizhi, S., & Balasubramanian, V. (2020). Post-weld heat treatment effects on the tensile properties of cold metal arc welded AA 6061-T6 aluminum joints. *Materials Testing, 62*(1), 69-76.

Ren, L., Gu, H., Wang, W., Wang, S., Li, C., Wang, Z., Zhai, Y., & Ma, P. (2021). Microstructure and Properties of Al-6.0Mg-0.3Sc Alloy Deposited by Double-Wire Arc Additive Manufacturing. *3D Printing and Additive Manufacturing*, *2,* 1-10.

Willy, H. J., Li, X., Chen, Z., Herng, T. S., Chang, S., Ong, C.Y.A., Li, C., & Ding, J. (2018). Model of laser energy absorption adjusted to optical measurements with effective use in finite element simulation of selective laser melting. *Materials and Design, 157*(11), 24-34.

Xiong, J., Lei, Y., Chen, H., & Zhang, G. (2017). Fabrication of inclined thin-walled parts in multi-layer single-pass GMAW-based additive manufacturing with flat position deposition. *Journal of Materials Processing Technology, 240,* 397-403.

Zhang, C., Li, Y., Gao, M., & Zeng, X. (2018). Wire arc additive manufacturing of Al-6Mg alloy using variable polarity cold metal transfer arc as power source. *Materials Science and Engineering: A, 711*(1), 415-423.

Bellamkonda Prasanna Nagasai, works as a Research Scholar in the Department of Manufacturing Engineering, Annamalai University, Annamalai Nagar, India. He completed his B. Tech (Automobile Engineering) at Eswar College of Engineering, JNTU University Kakinada in 2017 and received his M.Tech (Machine Design) at Gudlavalleru Engineering College (Autonomous), JNTU University Kakinada, India in 2019. He has published papers in reputed journals and conference proceedings. He has two years of research experience in the area of composite materials and three years of research experience in the area of the welding and additive manufacturing of ferrous and non-ferrous materials. His research interests include metal additive manufacturing, mechanical testing, and the characterization of materials.

Dr. S. Malarvizhi is currently Professor at the Centre for Materials Joining & Research (CEMAJOR), Department of Manufacturing Engineering, Annamalai University, Annamalai Nagar, India. She received her Ph.D at Annamalai University, Chidambaram in 2008. She has published several research papers in National and International Journals and Conferences. She has 22 years of teaching experience and 15 years of research experience. Her areas of interest are welding technology and materials science. She has completed various sponsored R&D projects from various funding agencies such as AICTE, UGC, DST, DRDO, CSIR & MEF (as principal Investigator). (E-mail: jeejoo@rediffmail.com).

Dr. V. Balasubramanian is currently working as Director for Directorate of Research and Development (DRD) in Annamalai University. He is Professor & Director of Centre for Materials Joining & Research (CEMAJOR), Department of Manufacturing Engineering, Annamalai University. He has h-index of 52 and is included in top 2% scientist list in materials by Stanford University, USA. He graduated from Government College of Engineering, Salem, University of Madras in 1989 and obtained his post-graduation from College of Engineering Guindy, Anna University, Chennai in 1992. He obtained his Ph.D from Indian Institute of Technology Madras (IITM), Chennai in 2000. He has 28 years of teaching and 25 years of research experience. He has published 420 research papers in international journals and supervised 22 Ph.D scholars. His areas of interest are Materials Joining, Surface Engineering and Nanomaterials. (E-mail: visvabalu@yahoo.com)