ISSN 2063-5346

MICROSTRUCTURE AND MECHANICAL PROPERTIES OF MATERIALS FABRICATED BY COLD METALTRANSFER BASED WAAM – A REVIEW

A.Kumaravel[1], M.Abishek[1], E.Kalaiarasan[1], R.P.Kishorepradeep[1]

Article History: Received: 01.02.2023 Revised: 07.03.2023 Accepted: 10.04.2023

Abstract

Additive Manufacturing (AM) has grown in popularity in the manufacturing sector over the last three decades, particularly for the production of part designs and prototypes due to its flexibility in terms of shape, size, and design of intricate and net-shaped functional parts with no geometrical limitations. The automotive, aerospace, defence, biomedical, and other sectors as well as other applications predominantly use AM methods. Wire and Arc Additive Manufacturing (WAAM) might be an useful alternative way for generating the high-quality, intricate parts that are typically required in these applications since they are not suited for standard manufacturing procedures with long product lead times. The WAAM method has been used with a variety of power sources, including Metal Inert Gas (MIG), Tungsten Inert Gas (TIG), Plasma, and Cold Metal Transfer (CMT). CMT-WAAM is a viable option for large-part production because of its numerous advantages. The various types of recently developed CMT processes are CMT + Pulse, CMT Advanced, CMT Pulse Advanced, CMT Dynamic. To maximize the benefits of CMT based WAAM, it is necessary to understand the microstructure which is closely related to mechanical properties of the layer deposition. The impact of process parameters such as wire feed, wire diameter, voltage speed, deposition speed, current and argon gas etc. on the microstructure and mechanical properties were analyzed and summarized. The study presented the summary table of published data on the microstructure and mechanical properties of various materials prepared via CMT based WAAM to explore as a quick reference to the researchers.

Keywords— *Additive Manufacturing, Wire and Arc Additive Manufacturing (WAAM), Cold Metal Transfer (CMT) Mechanical Properties and Microstructural Properties*

[1]*Department of Mechanical Engineering, K. S. Rangasamy College of Techanology,Tiruchengode-637215,Tamil Nadu, India*

DOI:10.31838/ecb/2023.12.s1-B.230

I. INTRODUCTION

Additive manufacturing is gaining market domination for metal components because of its adaptability and processing capacity. Due to its flexibility in terms of shape, size, and design of intricate and net-shaped functional parts without geometrical limitations, additive manufacturing has attracted more attention in the manufacturing sector over the past three decades, particularly for the production of part designs and prototypes.By stacking materials, additive manufacturing (AM) is a process for producing components from 3D model data[1].Automotive, aerospace, defence, biomedical, and other industries, as well as other applications, are the main sectors where AM methods are used. The Direct Energy Deposition (DED) method, sometimes referred to as the Wire and Arc Additive Manufacturing method, is one of the most productive and successful Additive Manufacturing procedures [2-4]. Wire and Arc Additive Manufacturing can be a good alternative method for producing the high quality, complicated parts that are frequently needed in these applications since they are not suited for conventional manufacturing techniques with lengthy product lead times[5]. In comparison toconventional processing, WAAM has a number of benefits, such as high degrees of design flexibility quick production cycles low material and equipment costs, and high deposition rates and efficiency [6-10].

The various power sources used in WAAM method are Metal Inert Gas (MIG), Tungsten Inert Gas (TIG), Plasma, and Cold Metal Transfer (CMT)[11]. Fig.1 shows the ,

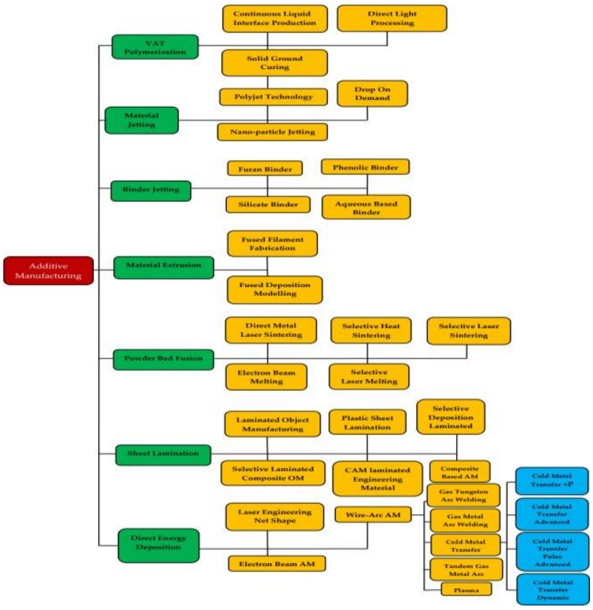

Figure 1 Methods Additive Manufacturing process [2]

A rapid and inexpensive method for generating high-quality metal goods digitally through continuous surfacing is Wire Arc Additive Manufacturing (WAAM), which is based on cold metal transfer and employs an arc as a heat source to fuse the wire[12]. The schematic diagram of a system for Cold Metal Transfer-based Wire Arc Additive Manufacturing is shown in Figure 2.

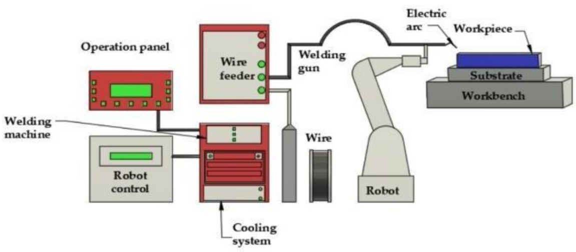

Figure 2. Wire and Arc Additive Manufacturing System Using Cold Metal Transfer (CMT) Diagram

Numerous WAAM review papers have been authored by top experts in the field and include cutting-edge systems, design, utilisation, process monitoring, and in-process control and sensing. However, a thorough analysis of the features of various

WAAM-processed materials is still necessary, as is a summary of current and upcoming research goals aimed at improving the quality of the pertinent alloy classes[13].

CMT-WAAM is a possible option for producing big components given its impressive advantages. Examining the microstructural and mechanical characteristics of the produced CMT-based WAAM components is crucial as a result [14]. The goal of the current study is to thoroughly examine the mechanical characteristics and microstructure of a variety of metals, including steel, titanium and its alloys, aluminium and its alloys, alloys based on nickel, and other intermetallic materials produced using Cold Metal Transfer based Wire and Arc Additive Manufacturing processes.

II WAAM METHODS

The WAAM method has been used with a variety of power sources, including Gas Tungsten Arc Welding (GTAW), Gas Metal Arc Welding(GMAW) ,Plasma, and Cold Metal Transfer (CMT).

A. *Gas Tungsten Arc Welding (GTAW)*

Gas Tungsten Arc Welding (GTAW) [15] is one of the most challenging fabrication processes for WAAM in recent years, with a maximum 83% welding efficiency. Oliveria et al. [16], despite the depth of their investigation, found that the materials utilized in welding methods had an impact on how successfully a material may be welded. It is necessary to employ coil of wire as a filler material in WAAM [15], and they will be in charge of deposition alone for the development of a certain structure, together with sufficient current supply and shielding gases to avoid any kind of corrosion over the molten pool [17,18]. Wire may melt when a tungsten tip is used [19], The welding torch serves as the cathode and the work piece serves as the anode for the biased heat generation over the work piece. To simplify the WAAM processing for GTAW and PAW based WAAM, Williams et al. [20] built a TIG torch (TOPTIG) with an integrated wire feeding mechanism (step wire feeding). The inert shielding gas argon, which has a purity of 99.999% and is frequently employed in the GTAW-based WAAM process, aids in preventing oxidation over the molten pool of wire to enable a surface devoid of flaws [19]. Genga et al. [21] specifically mention metals made of aluminium. GTAW (EWM, Tetrix 521 Synergic AC/DC) was recommended by [21] for its impeccable workmanship. Despite the fact that it is obvious that the rate at which wire is provided may directly influence the pace at which material is deposited, they pointed out that heat input has no effect on the length of the arc. When the setup is moving, the non-consumable electrode must always be in front of thewire feeder.

B. *Gas Metal Arc Welding (GMAW)*

Sometimes referred to Metal Inert Gas (MIG) welding, Gas Metal Arc Welding is a quick and affordable procedure. During this procedure, an arc is created between the base metal and a consumable electrode that is continually supplied, providing filler metal for the weld. The electrode is empty; it has no core or covering. A combination of helium, argon, or carbon dioxide is often used as the external gas that provides the shielding, which prevents the molten metal from interacting with elements of the environment. When welding with this method, a sizable amount of smoke may be produced. The electrode is consumed rather than the base metal during GMAW, which results in the majority of the fume being produced[22].

C. *Plasma Arc Welding (PAW)*

WAAM took a distinctive turn since it was aware that Plasma Arc Welding may be employed. The first time PAW was utilised to produce ER308L Stainless Steel for additive manufacturing was in 2006 [23]. This calls for the use of a PAW torch setup with an inert electrode often constructed of tungsten and filled with inert gases like argon that is assisted by plasma. Using a wire feeder, wire is fed into the PAW flame, where it melts and deposits on the substrate. With regular use, the material layer builds up.

D. *Cold Metal Transfer (CMT)*

The CMT process is an improved version of the WAAM based on GMAW procedure . The four essential components of the CMT-WAAM system are the robot, wire feeding motor drive, welding apparatus, and computer controller. The mechanism for metal droplet separation distinguishes the GMAW and CMT most significantly. The reason the procedure is as called CMT is that it produce less heat than the standard GTAW-WAAM procedure. reduced heat input makes it feasible to achieve reduced spatter and regulated metal deposition rates. All process in this technique are digitally managed. About 3.6 kilograms of metal are deposited every hour. The arc begins at the metal feed wire tip as it advance in the direction of the substrate (base plate). Boosting of the arc can occur as the wire begins to move towards the weld pool. A system short circuit may form by the time the feed wire tip contacts the weld pool.The feed wire polled back up to a specific height when the short circuit occurred. Droplet separated from the wire's tip during this motion backward and fed into the weld pool. Weld pool heat generation is reduced as a result of the short circuit that occurred during deposition. The key benefit of this procedure is that. CNC has created sophisticated procedures, such as CMT Pulse (CMT-P), CMT sophisticated (CMT-ADV), and CMT Pulse Advanced (CMT-PADV) [23]. explains how droplet deposition works.

III. CMT Based WIRE ARC ADDITIVE MANUFACTURING (WAAM) SYSTEMS

There are several CMT technology variations available, such as traditional CMT, CMT pulse (CMT-P), CMT advance (CMT-Adv), CMT pulse advanced (CMT-PADV) and more.

A. *Techniques of CMT*

Robots frequently perform the CMT welding process. When a short circuit is identified during the operation, the machine sends a signal to retract the wire carrying it. Before adding the subsequent droplet, give the junction adequate time to cool and the filler material to dry. In contrast to joints created using conventional procedures, a consistent and better joint is produced as a consequence [23,24]. However, CMT may be used to weld even thin metal sheets, which are vulnerable to wrapping and burning when fused using conventional methods.When compared to traditional methods, this CMT welding offers for significant cost savings [25] and is suitable for both larger sections and thinner sheets (9 mm). Furthermore, because this CMT welding technology is computer-controlled, the welding proces is extremely accurate and precise, resulting in a fully smooth connecting segment. The categories below represent the most current CMT welding process advances.

A. *CMT+P*

The innovative CMT + P (or CMT with pulses addition) technique of CMT welding is created by fusing a short circuit-based projected method of transfer that transfers one droplet per pulse when the system is cool [26,27]. In other words, the CMT + P welding technique adds explicit and fluctuating pulses, acelerates joining, increases heat input, and enhances flexible and perform well. The CMT + P welding technique separates one extra droplet with each cycle, increasing the deposition speeds. Similar to the regular CMT procedure, the wire retracts during the beginning stages of the CMT + P welding operation. As the wire moves closer to the metal plates that need to be welded during the pulsed arc phase, the droplet splits. The CMT cycle has begun since the arc has been completely destroyed. the method for CMT + P welding, according to Tapiola. [28]. This CMT + P welding technique has been the subject of several experiments. Zhao et al. [29], forinstance.

B. *CMT – Advanced*

The rate of deposition may be controlled very precisely throughout the procedure known as the CMT advanced welding technology by employing negative and positive process cycles. Given that polarity is reversed during the short circuit phase, the cutting-edge CMT technique guarantees the huge stability of this cold category of joining [30,31]. Benefits of the CMT advanced welding technique include regulated heat input, greater deposition rates without an increase in heat input, zero fumes, and zero deformation. Built on the arc combination with negatively and positively charged CMT cycles, this enhanced joining CMT process. The pole reverses during the short circuit phase, preserving the arc's stability. The joining of plates occurs during the negative pole phase at a quicker rate of deposition and with better capacity to bridge the gap. Targeted heat input and exact droplet transfer concurrently reflect the positive crucial cycles [32, 33].

C. *CMT – Pulse Advanced*

In the CMT advanced welding process, the +ve and

-ve polarity electrodes are combined with the CMT cycles, and the +ve and -ve cycles are alternated throughout [34,35]. This technique for CMT welding uses less heat input and results in a greater rate of deposition during the - negatively poled phase. The poles are inverted to the positively poled cycles of pulse during a short circuit, which enables the benefit of the non-short circuit category of droplet transfer. This type of CMT welding allows for extremely flexible adjustment of the ratio between the +ve and -ve process cycles dependent on the requirements.

Superior strength steels may be joined together using this CMT advanced pulse approach while also achieving a good higher rate of deposition and a reduced heat input. [36,37].

D. *CMT – Dynamic*

The CMT Dynamic welding method is one of the most recent innovations related to CMT welding. This method was created specifically for combining thicker portions of metals, both comparable and different. The limit of operation of the CMT method has been increased in this technique by escalating the forward and reverse process motions to a value of 130 HZ. This increase in wire movement allows for deeper penetration, which enables quicker joining speeds and a higher rate of wire feed, which increases deposition rates. This innovative CMT dynamic welding process uses a greater energy input through a bigger heat input and an intensified pressured arc.[38–40].

IV STUDIES ON MICROSTRUCTURE OF CMT BASED WAAM MATERIALS

The materials employed, the developed high temperature, the rate of cooling, and the rate of deposition all affect the microstructure and phase change with WAAM [41]. Mechanical qualities are also impacted by process- produced flaws [42]. Recent research have mainly focused on adding certain post-processing approaches to reduce the defects including porosity, surface cracking, deformations, and gas inclusions in order to enhance the mechanical characteristics. This essay looks at the post-processing methods utilized today to improve the mechanical qualities of components made using the as-fabricated (AF) manufacturing process. Delamination is frequently a visible flaw that cannot be eliminated by post-processing methods or heat treatments, but it can be prevented by adhering to the best process parameters to reduce recurrent fluctuating stresses and by taking the properties of the deposited alloy into consideration [43,44]. Defects can be categorised using a variety of groups. levels of WAAM-treated flaws in various metals In addition to the T6 heat treatment, Chengpeng et al. [42] state that hot deformation was used in various fractions of the GTAW method of WAAM to eradicate the porosity defects in Al-Li alloys. The porosity was discovered to be almost 30 microns lower from 100 microns at 42% of hot deformation and T6 heat treatment. Also demonstrated as having assisted the solidification breaking was this hot deformation. To reduce the porosity effects on the deposited metal in case of CMT-based WAAM Al-Mg components manufactured using various deposition processes (Hatching or circling), a variety of gas shielding (Ar + O2+N2O) and controlled gas flow rate were used. They discovered that if the indicated treatments are applied at lower gas flow rates, porosity may be decreased to 0.035%.

S.No	Materials	Process	Properties	REFERENCE
1.	INCONAEL 825-SS316L	CMT	Yield strength= 222 Mpa, Tensile strengths= 494 Mpa, Microhardness/Hv 300gm= 224, Distance substrate in mm= 64, Elongation= 61.5 %	[24]
2.	Inconel 625	CMT	Yield strength= 376.9Mpa, Tensile strengths= 647.9Mpa, Elongation= 46.5%	[74]
3.	2Cr13 thin-wall	CMT	Yield strength= (834 MPa) and asQTed BM (1366 MPaMpa, Tensile strengths= 1246 MPa to 1344 MPa,	[75]
4.	Bimetal components	CMT	Tensile strength= 447.79Mpa, Vickers Hardness test 1.96 N for 10 sec (from ER80S-G & MF6 -55GP to test point).	[69]
5.	2219 Aluminium alloy	1.)CMT & CMT + P 2.)CMT Advanced 3.)Pluse Advanced	Tensile strength= CMT 263 Mpa, CMT advance= 255 Mpa, CMT+ P = 275 Mpa, CMT+P Advance= 285 Mpa	[70]
6.	2205 Duplex stainless steel	CMT	Tensile strength= 844 Mpa to 795 Mpa, Elongation= 18% to 31%	[71]
7.	Ti6Al-4V alloy	CMT	Tensile strength= 1017 MPa to 841 MPa, Elongation= 7.54% to 4.83%	[76]
8	Ti-6Al-4V and AlSi5 dissimilar alloys	CMT	Tensile strength= 83 MPa and 79 MPa, Elongation= 8% and 6%	[73]
9.	ER2594	CMT	Yield strength= 607 ± 11 MPa, Tensile strength= 855 ± 11, Elongation= 42.9 ± 1.7%	[72]
10	Ti6Al4V and Al6.21Cu	CMT	Yield strength= 94.4 ± 3.9 MPa, Elongation=0.349 ± 0.157%, Tensile strength= 0.349 ± 0.157%,	[77]

V. STUDIES ON MEcHANICAL PROPERTIES OF CMT BASED WAAM MATERIALS

The material created by WAAM is heated similarly to how a welded material is heated[45–50], where it is crucial to look closely at the microstructural characteristic. Materials containing aluminium alloys[51], mild steel[52], stainless steel[53], titanium alloys[54], and magnesium alloys[55] were often used in research. Vickers Hardness (HV) and tensile tests are used to evaluate the mechanical qualities, and samples are cut from treated materials in accordance with predetermined standard [56].Additionally, an anisotropy degree of less than 11% was found, and the mechanical qualities of the deposited particles were enhanced [57].]. When TiNi particles were injected during the Ti64 deposition using WAAM, the grain size was lowered and the structure was modified from columnar to equiaxed grains with a size of 300 m, enhancing the mechanical properties. [58]. The orientation in which a substance is put will affect its mechanical characteristics. Low carbon, low alloy steel blocks were created using the GMAW method from WAAM in one of the most recent projects. They took tensile samples from that block and sliced them vertically, horizontally, and at 45-degree angles to the deposition plane. They found that the vertical samples had inferior mechanical characteristics to the horizontal and 45-degree samples [59,60]. Inter layer hammering is now included in WAAM 2319 Aluminium alloy components manufactured utilizing CMT. Three interlayer deformation level (0%, 21.8%, and 50.8%) were evaluated in that study. It was demonstrate that the grains size significantly improved as the levelof deformation is increased. Fine and elongated grains are formed beyond the deformation threshold of 50.8%, and their mechanical properties greatly improved (yield strength increased by 60.6%, tensile strength by 13%). As a result, aircraft applications can utilise the aluminium alloys developed by WAAM [61] However, aluminium alloy porosity continues to be a problem. Observations show that when shielding gas flow rates increase, less time is available for the melt pool to solidify, leading to more porous aluminium components. Lower gas flow rates are thus suggested [62] to achieve acceptable mechanical characteristics in aluminium components produced from WAAM. A key component in the development of the thin-wall components is arc stability. The weld bead may not deposit uniformly and may not be linear due to its instability.

VI. Merits and Demerits of CMT

Its main advantages are its accuracy and precision in CMT welding. Unlike TIG and MIG welding, this joining method uses both background and foreground based phases in the current, enabling flawless electronic control of the heat input of the pulse and its accuracy, precision, and control. Its high level of effectiveness is another another distinguishing quality of this CMT method. Similar to other joining methods, the proficiency of the operator and welder has some bearing on the uniformity of the CMT welding procedure. The CMT approach, on the other hand, has a completely electrical foundation, which greatly reduces the possibility of human operator mistake while also greatly increasing consistency and efficiency [62].

VII. Conclusion

With an emphasis on microstructure and mechanical qualities, a thorough analysis of current technological advancements in the WAAM process has been given. Automatic Manufacturing (AAM) is a manufacturing process that is automated and is managed by a computer control system. It works well for manufacturing components with complicated and asymmetrical forms. Metal deposits can be made using already-in-use welding processes. The type of welding process used will affect how quickly metal is deposited and heat output. WAAM is effective in situations when there is a need for lower component costs overall and lower material utilisation. Residual loads, porosity, and delamination were the main causes of damage for WAAM components. The porosity phenomena has been the main area of study. Its capacity will be improved by more study into residual stresses and delamination faults.

REFERENCES

[1].Behzad Parvaresh, Reza Miresmaeili, Morteza Yazdizadeh. Characterization of wire arc additive manufactured products: A comparison between as-deposited and inter-layer cold worked specimens, Manufacturing Process, 57 (2020) 61-71.

[2]. Nilesh Kumar , Het Bhavsar , P.V.S. Mahesh , Ashish Kumar Srivastava b , Bhaskor J. Bora , Ambuj Saxena , AmitRai Dixit. "Wire Arc Additive Manufacturing – A revolutionary method in additive manufacturing", Materials Chemistry And Physics, 285 (2022) 126144.

[3] (A Review on Additive Manufacturing of Titanium Alloys for Aerospace Applications: Directed Energy Deposition and Beyond Ti-6Al-4V).

[4] (Additive Manufacturing in Aerospace and Defence Industries: A Review), (The role of additive manufacturing for biomedical applications: A critical review)

[5].C. Wang, P. Zhu, F. Wang, Y.H. Lu, T. Shoji, Anisotropy of microstructure and corrosion resistance of 316L stainless steel fabricated by wire and arc additive manufacturing, 206 (2022) 110549.

.[6]. N. Rodriguez, L. V´azquez, I. Huarte, E. Arruti, I. Tabernero, P. Alvarez, Wire and arc additive manufacturing: a comparison between CMT and TopTIG processes applied to stainless steel, Weld. World 62 (2018) 1083–1096.

[7] S.W. Williams, F. Martina, A.C. Addison, J. Ding, G. Pardal, P. Colegrove, Wire + Arc additive manufacturing, Mater. Sci. Technol. 32 (2016) 641–647.

[8] T.F. Lam, Y. Xiong, A.G. Dharmawan, S. Foong, G.S. Soh, Adaptive process control implementation of wire arc additive manufacturing for thin-walled components with overhang features, Int. J. Adv. Manuf. Technol. 108 (2019) 1061–1071.

[9] J. Ding, P. Colegrove, J. Mehnen, S. Ganguly, P.M. Sequeira Almeida, F. Wang, S. Williams, Thermo-mechanical analysis of Wire and Arc Additive Layer Manufacturing process on large multi-layer parts, Comput. Mater.Sci. (2011).

[10] X. Xu, S. Ganguly, J. Ding, S. Guo, S. Williams, F. Martina, Microstructural evolution and mechanical properties of maraging steel produced by wire + arc additive Manuf process, Mater. Charact. 143 (2018) 152–162).

[11].Jianglong Gu, Shouliang Yang, Minjie Gao, Jing Bai, Kun L iu, Influence of deposition strategy of structural interface on microstructures and mechanical properties of additively manufactured Al alloy, Additive Manuf, vol.34 pp.101370, (2020).

[12]. Xizhang Chen, Chuanchu Su, Yangfan Wang, Arshad Noor Siddiquee, Konovalov Sergey, S. Jayalakshmi , R. Arvind Singh, Cold Metal Transfer (CMT) Based Wire and Arc Additive Manufacture (WAAM) System, Neutron Tech12, 1278 – 1284 (2018).

[13].Bintao Wu , Zengxi Pan , Donghong Ding , Dominic C uiuri , Huijun Li , Jing Xu , John Norrish,A review of the wire arc additive manufacturing of metals: properties, defects and quality improvement, ManufProc, 35 (2018) 127-139.

[14]. Wang Yangfan, Chen Xizhang, Su Chuanchu,Microstructure and mechanical properties of Inconel 625 fabricated by wire arc additive manufacturing, Surface And Coat Tech, 374 (2019) 116-123.

[15]. H. Geng, J. Li, J. Xiong, X. Lin, F. Zhang, Optimization of wire feed for GTAW based additive manufacturing, J. Mater. Process.Technol. 243 (2017) 40–
47.

[16] Gas tungsten arc welding of as-rolled CrMnFeCoNi high entropy alloy, Mater. Des.189 (2020) 108505.

[17]. C. Shen, Z. Pan, D. Cuiuri, D. Ding, H. Li, Influences of deposition current and interpass temperature to the Fe3Al-based iron aluminide fabricated using wirearc additive manufacturing process, Int. J. Adv. Manuf. Technol. 88 (2017), 2009–18.

[18] Full article, Obtaining uniform deposition with variable wire feeding OydS_VuFCBzJ56tPis0 direction during wire-feed additive manufacturing, TGENgMPdN1TL4R-wvII-l.(Accessed 31 August 2021)

[19] T. Xu, S. Tang, C. Liu, Z. Li, H. Fan, S. Ma, Obtaining large-size pyramidal lattice cell structures by pulse wire arc additive manufacturing, Mater. Des.187 (2020) 108401.

[20] F. Martina, S. Williams, Wire+arc Additive Manufacturing vs. Traditional Machining from Solid: a CostComparison, 2015.

[21]. D. Ding, Z. Pan, D. Cuiuri, H. Li, S. van Duin, N. Larkin, Bead modelling and implementation of adaptive MAT path in wire and arc additive manufacturing, Robot. Comput. Integrated Manuf. 39 (2016) 32–42.

[22] W. Aiyiti, W. Zhao, B. Lu, Y. Tang, Investigation of the overlapping parameters of MPAW-based rapid prototyping, Rapid Prototyp. J. 12 (2006) 165–172.

[23]. J.M. ANTONINI8.04 - HEALTH EFFECTS ASSOCIATED WITH WELDING .8 (2014) 49-70.

[24]. T.S. Senthil, S. Ramesh Babu, M. Puviyarasan, V. Dhinakaran, Mechanical and microstructural characterization of functionally graded Inconel 825 - SS316Lfabricated using wire arc additive manufacturing, Mater Res and Tech, 2021;15:661-669.

[25]. Kun Liu, Xiaoqing Jiang, Shujun Chen, Tao Yuan, Zhaoyang Yan, Effect of SiC addition on microstructure and properties of AleMg alloy fabricated by powder and wire cold metal transfer process Mater SciTechnol 2022;17: 310-319.

[26]. YinbaoTiana, JunqiShena, ShengsunHua, JianGoua, Yan Cui, Effects of cold metal transfer mode on the reaction layer of wire and arc additive-manufactured Ti-6Al-4V/Al- 6.25Cu dissimilar alloys Materials Science and Technol,74 (2021) 35-45.

[27]. JianGoua , JunqiShena, ShengsunHua , YinbaoTiana, Ying Liang, Microstructure and mechanical properties of as-built and heat-treated Ti6Al-4V alloy prepared by cold metal transfer additive manufacturing, Manufacturing process, 42 (2019) 41-50.

[28].K.W. Wei, M. Gao, Z.M. Wang, et al., Mater. Sci. Eng.A 611 (2014) 212–222.

[29]. Ji Bi, JunqiShen, Shengsun Hu , Yahui Zhen , Fengliang Yin, Xianzheng Bu, Microstructure and mechanical properties of AZ91 Mg alloy fabricated by cold metal transfer additive manufacturing, Mater Letters, 276 (2020) 128185.

[30]. 6] X. Yang, J.R. Liu, Z.N. Wang, et al., Mater.Sci.Eng.A 774 (2020), https://doi.org/ 10.1016/j.msea.2020.138942.

[31]. Y.Y. Guo, H.H. Pan, L.B. Ren, et al., Mater. Lett.247 (2019) 4–6, https://doi.org/ 10.1016/j.matlet.2019.03.063.

[32]. F. Shu, Y. Lv, Y. Liu, F. Xu, Z. Sun, P. He, B. Xu,

Residual stress modeling of narrow gap welded joint of aluminum alloy by cold metal transferring procedure,Constr. Build. Mater.54 (2014) 224–235.

[33]. C. Wang, T.G. Liu, P. Zhu, Y.H. Lu, T. Shoji, Study on microstructure and tensile properties of 316L stainless steel fabricated by CMT wire and arc additive manufacturing, Mater. Sci. Eng., A 796 (2020).

[34]. C.G. Pickin, K. Young, Evaluation of cold metal transfer (CMT) process for welding aluminium alloy, Sci. Technol. Weld. Joining 11 (5) (2006) 583–585.

[35] P. Sevvel, C. Satheesh, K.R. Senthil, Generation of regression models and multiresponse optimization of friction stir welding technique parameters during the fabrication of AZ80A Mg alloy joints, Trans. Can. Soc. Mech. Eng. 44 (2) (2020) 311–324.

[36] J. Tapiola, Cold Metal Transfer cladding of wear and corrosion resistant coatings in engine applications.2017.

[37]. F. Shu, Y. Lü, Y. Liu, F. Xu, Z. Sun, P. He, B. Xu,

FEM modeling of softened base metal in narrow-gap joint by CMT+P MIX welding procedure, Trans. Nonferrous Met. Soc. China 24 (6) (2014) 1830–1835.

[38]. X. Wang, Y. Wu, H. Pan, C. Yao, J. Huang, Microstructure and softening of advanced high-strength steel QP1180 lap joints welded with CMT, Mater. Lett.287 (2021).

[39]. I. John Solomon, P. Sevvel, J. Gunasekaran, A review on the various processing parameters in FDM, Mater. Today: Proc. 37 (2) (2021) 509–514.

[40]. D. Wang, C. Wu, Y. Suo, L. Wang, Z. Liang, Effect of pulse frequency on arc behavior and droplet transfer of 2198 Al–Li alloy by ultrahigh-frequency pulse AC CMT welding, J. Mater. Res. Technol. 8 (5) (2019) 3950–3958.

[41]. J.I. Ruiz-Vela, J.J. Montes-Rodríguez, E. Rodríguez- Morales, J.A. Toscano-Giles, Effect of cold metal transfer and gas tungsten arc welding processes on the metallurgical and mechanical properties of Incone 625 weldings, Weld. World 63 (2019) 459–479.

[42]. J. Gunasekaran, P. Sevvel, S.I. John, Metallic materials fabrication by selective laser melting: A review, Mater. Today: Proc. 37 (2) (2021) 252–256.

[43]. M.R.U. Ahsan, M. Cheepu, R. Ashiri, T.-H. Kim, C. Jeong, Y.-D. Park, Mechanisms of weld pool flow and slag formation location in cold metal transfer (CMT) gas metal arc welding (GMAW), Weld. World 61 (6) (2017) 1275–1285.

[44]. Y. Koli, N. Yuvaraj, S. Aravindan, Vipin, Enhancement of Mechanical Properties of 6061/6082 Dissimilar Aluminium Alloys Through Ultrasonic-Assisted Cold Metal Transfer Welding, Arabian J. Sci. Eng. 46 (2021) 12089–12104.

[45]. S. Ramkumar, M. Duraiselvam, P. Sevvel, Acoustic Emission Based Deep Learning Technique to PredictAdhesive Bond Strength of Laser Processed CFRP Composites, FME Trans. 48 (3) (2020) 611–619.

[46]. A. Elrefaey, N.G. Ross, Microstructure and Mechanical Properties of Cold Metal Transfer Welding Similar and Dissimilar Aluminum Alloys, Acta Metall. Sin. (English Lett.)28 (6) (2015) 715–724.

[47]. P. Sevvel, D. Srinivasan, A.J. Balaji,

N. Gowtham,
V.G. KalyanaVaradhan, P. Kumaresh, B.M. Kishore, Design & Fabrication of Innovative Desktop 3D Printing Machine, Mater. Today: Proc. 22 (2019) 3240–3249, https://doi.org/ 10.1016/j.matpr.2020.03.284.

[48]. F. Wang, S. Williams, P. Colegrove, A.A. Antonysamy, Microstructure and mechanical properties of wire and arc additive manufactured Ti-6Al-4V, Metall. Mater. Trans. 44 (2013) 968–977.

[49]. C. Xue, Y. Zhang, P. Mao, C. Liu, Y. Guo, F. Qian, et al., Improving mechanical properties of wire arc additively manufactured AA2196 Al–Li alloy by controlling solidification defects, Addit. Manuf. 43 (2021) 102019.

[50].] G. Moynihan, Concepts, Applications and Emerging Opportunities in Industrial Engineering, BoD – Books on Demand, 2021.

[51]. W.H. Green, V.K. Champagne, A. Birt, X-ray Computed Tomography Inspection and Evaluation of Novel Wire Arc Additively Manufactured Maraging Steel Materials. US Army Combat Capabilities Development Command, Army Research LaboratorySolvus Global, 2021.

[52]. Heat treatment in two phase region and its effect on microstructure and mechanical strength after welding of a low carbon steel - ScienceDirect, n.d, https://www.sciencedirect.com/science/article/abs/pii/S0261306905002876?casa_token=xmtfhF4LqpYAAAAA:wjmuo6HwfmRM4WSyBMNGC90ncrzqo3To54diRliajxi5yyQGclZrjdph3yNjpfFqqJnjma–o.(Accessed 31 August 2021).

[53]. Recovery of mechanical properties of a 6061-T6 aluminum weld by heat treatment after welding | SpringerLink, n.d, https://link.springer.com/article/10.1007/s11661-016-3483-x. (Accessed 31 August 2021).

[54]. Weld P, Srivastava BK, Tewari DSP. Heat Treatmemt (Pwht) on Mechanical Behaviour of Ferrous Metals.(n.d).

[55]. Y. Zhang, X. Jiang, Y. Fang, Y. Fang, B. Liu, H. Sun, et al., Research and development of welding methods and welding mechanism of high-entropy alloys: a review, Mater. Today Commun. 28 (2021) 102503.

[56]. E.S.V. Marques, F.J.G. Silva, A.B. Pereira, Comparison of finite element methods in fusion welding processes—a review, Metals 10 (2020) 75.

[57]. J. Gu, J. Ding, S.W. Williams, H. Gu, P. Ma, Y. Zhai, The effect of inter-layer cold working and post-deposition heat treatment on porosity in additively manufactured aluminum alloys, J. Mater. Process.Technol. 230 (2016) 26–34.

[58]. G. Venturini, F. Montevecchi, A. Scippa, G. Campatelli, Optimization of WAAM deposition patterns for T-crossing features, Procedia CIRP 55 (2016) 95–100.

[59] Wire and arc additive manufactured steel: tensile and wear properties- ScienceDirect, n.d,https://www.sciencedirect.com/science/article/pii/S2214860416301452?casa_token=M8fBjRKLNQAAAAA:zKK44SY96d0GV_GEOVzQrWFnDaSddCvlh3bzfJsV7urxKI4kGvCpcYpdYT-6vjYI3DB-2zSmLQ. (Accessed 1 September2021).

[60]. J. Ding, P. Colegrove, F. Martina, S. Williams, R. Wiktorowicz, M.R. Palt, Development of a laminar flow local shielding device for wire+arc additive manufacture, J. Mater. Process.Technol. 226 (2015) 99–105.

[61]. J. Guo, Y. Zhou, C. Liu, Q. Wu, X. Chen, J. Lu, Wire Arc additive manufacturing of AZ31 magnesium alloy: grain refinement by adjusting pulse frequency, Materials 9 (2016).

[62]. Din En 10002–1, Metallic Materials - Tensile Testing (n.d), Met. Mater. - Tensile Test, 2001, 2001.

[63]. M. Arana, E. Ukar, I. Rodriguez, A. Iturrioz, P. Alvarez, Strategies to reduce porosity in Al-Mg WAAM parts and their impact on mechanical properties, Metals 11 (2021) 524,

[64] J.R. Kennedy, A.E. Davis, A.E. Caballero, S. Williams, E.J. Pickering, P. B. Prangnell, The potential for grain refinement of Wire-Arc Additive Manufactured (WAAM) Ti-6Al-4V by ZrN and TiN inoculation, Addit. Manuf. 40 (2021) 101928.

[65]. M. Rafieazad, A.V. Nemani, M. Ghaffari, A. Nasiri, On microstructure and mechanical properties of a low- carbon low-alloy steel block fabricated by Wire Arc additive manufacturing, J. Mater. Eng. Perform. (2021).

[66]. A. VahediNemani, M. Ghaffari, A. Nasiri, Comparisonof microstructural characteristics and mechanical properties of shipbuilding steel plates fabricated by conventional rolling versus wire arc additive manufacturing, Addit. Manuf. 32 (2020) 101086,

[67]. X. Fang, L. Zhang, G. Chen, K. Huang, F. Xue, L. Wang, et al., Microstructure evolution of wire-arc additively manufactured 2319 aluminum alloy with interlayer hammering, Mater. Sci. Eng.: A 800 (2021) 140168, https://doi.org/10.1016/j.msea.2020.140168.

[68]. T. Eder, C.M.T. The, Process - News and Its Advantages in Industry, SAE Tech. Pap.32 (2010) 0071.

[69]. Shaohua Han , Zhongzhong Zhang, Zhisen Liu, Hong Zhang and DingqiXue, Investigation of the microstructure and mechanical performance of bimetal components fabricated using CMT-based wire arc additive manufacturing, Mate Research, 7 (2020) 116525.

[70]. Xuewei Fang, Lijuan Zhang, Hui Li, Chaolong Li, Ke Huang, Bingheng Lu, Microstructure Evolution and Mechanical Behavior of 2219 Aluminum Alloys Additively Fabricated by the Cold Metal Transfer Process, : 9 April 2018; Accepted: 11 May 2018; Published: 16 May 2018.

[71]. Xiaolin Bi, Ruifeng Li , Zhenxing Hu , JiayangGu, Chen Jiao, Microstructure and Texture of 2205 Duplex Stainless Steel Additive Parts Fabricated by the Cold Metal Transfer (CMT) Wire and Arc Additive Manufacturing (WAAM), Additive Manu Metals, 2022, 12, 1655, https://doi.org/10.3390/met12101655.

[72].Pranav Praveen Nikam, D. Arun, K. DevendranathRamkumara, N.Sivashanmugam, Microstructure characterization and tensile properties of CMT-based wire plus arc additive manufactured ER2594, Mater Chara, 169 (2020) 110671.

[73].YinbaoTiana, JunqiShena,b , ShengsunHua, ZhijiangWanga , Jian Gou, Microstructure and mechanical properties of wire and arc additive manufactured Ti-6Al-4V and AlSi5 dissimilar alloys using cold metal transfer welding, Manuf Process, 46 (2019) 337-344.

[74]. Wang Yangfan, Chen Xizhang, Su Chuanchu, Microstructure and mechanical properties of Inconel 625 fabricated by wirearc additive manufacturing, Surf and Coat Technol, 374 (2019) 116-123.

[75]. JinguoGe, Jian Lin, Yuhong Long, Qingyuan Liu , Liang Zhang , Wei Chen, Yongping Lei, Microstructural evolution and mechanical characterization of wire arc additively manufactured 2Cr13 thin-wall part, Mater Research and Technol, 2021;13:1767-1778.

[76]. JianGoua, JunqiShena, ShengsunHua, YinbaoTiana, Ying Liang, Microstructure and mechanical properties of as-built and heat-treated Ti6Al-4V alloy prepared by cold metal transfer additive manufacturing, ManufProc, 42 (2019) 41-50.

[77]. NaiqiangXu , JunqiShen , Shengsun Hu , YinbaoTian , Ji Bi, Bimetallic structure of Ti6Al4V and Al6.21Cu fabricated by cold metal transfer additive manufacturing via Nb interlayer added by TIG, Mate Lett, 302 (2021) 130397.