Wire Arc Additive Manufacturing integrated in Flexible Manufacturing Systems

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ABSTRACT

A flexible manufacturing system (FMS) is a production method that can quickly adapt to changes in the kind and quantity of work being produced. Machinery and autonomous machines, particularly subtractive machines such as CNC, are currently being set up to cover a wide variety of parts at various levels of output. Additive manufacturing methods are an up-and-coming process being employed in various industries from aviation, space, marine, etc. Additive manufacturing has a big scope with intensive capital and research being employed in Wire Arc Additive Manufacturing (WAAM). This research tries to study the developments of WAAM from literature presented as a comprehensive tabular form with different materials and operating parameters. The scope of this paper is not only limited to WAAM's developments but also its integration in a flexible manufacturing system.

Keywords: *additive manufacturing, flexible manufacturing, WAAM, operating parameters*

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1. INTRODUCTION:

The development of the Flexible Manufacturing System (FMS) has paved the road for manufacturing companies to increase their performance while also achieving flexibility. It makes it possible to combine greater flexibility, productivity, and minimal work-in-process stocks. Furthermore, it is designed in such a way that the adaptability of job shops is combined with the efficiency of specialized production systems. In addition, extreme caution must be exercised in order to meet the needs in the shortest amount of time possible. Additive manufacturing technology involving concurrent exposure of the material to two or more different energy variables, processing innovations based on new physical principles, processing on innovative machines, and so on have all been fast evolving in recent years. WAAM (Wire Arc Additive Manufacturing) is a production method that may be used to 3D print or repair metal items. It's a member of the Direct Energy Deposition family of Additive Production methods. WAAM works by laying down layers of metal onto top of each other till a required three-dimensional shape is achieved.

The comprehensive overview of the additive flexible manufacturing system is discussed in this paper, including the selection of primary and alternative technical components, process routes for various part categories, and management systems both for individual technological processes and the additive flexible manufacturing system as a whole. The usage of canned cycles is recommended as a method for unifying the dialogue programming process of equipment using CNC equipment from various vendors. It's a production system that can respond to unanticipated, relevant changes in number of orders, mix, and delivery date. FMSs enable eight different forms of operational flexibility. These are the most important for this research. The ability of a machine to manufacture new products or novel combinations of existing products is known as mobile flexibility. The flexibility to employ numerous pathways to create the same item or multiple devices to conduct the same activity is referred to as route flexibility. Changes in various refers to the capacity to adjust the order quantity without changing the cost. This is accomplished mostly through almost immediate set-up procedures.

2. WAAM LITERATURE REVIEW:

Table – 1: Literature review of WAAM process on varying materials and different operating properties.

S. No.	Researcher Name (Year)	Material	Operating Parameter	Properties	Results and Conclusion
1	J.L. Prado-Cerqueira, J.L. Dieguez, A.M. Camacho (2017)	S235JR, AWS ER 70S-6	WAAM, CMT equipment, CNC milling machine; WS=0.1-0.4m/s; I= 27-110A; deposition rate = 70 drops/s	For welding speeds greater than 200 mm/min, the intensity rises.; optimum welding speed is 400 mm / m; A 100% increment entails a 35 percent rise in altitude and a 106 percent increase in width.	WAAM was utilised in conjunction with CMT and a CNC milling machine. Reduced heat generation from GMAW, analysis of different positioning factors, and identification of a relationship among wire feed rate and current strength.
2	Fatemeh Hejripour, Daniel T. Valentine, Daryush K. Aidun (2018)	Stainless Steel alloys (Alloy 410, Alloy 718)	WAAM/CWT, Simulation on COMSOL Multi-physics 5.3; I=150A; V=14V; TS=3-4mm/s; WFR=12-18 mm/s	Max velocity= 0.087-0.099 m/s; max temp = 2271-2421 K; length of the WP (x-direction) = 6.5- 6.9 mm; half width (y- direction) = 2.3-2.5 mm;	Examples by adjusting travel rate and wire feed rate were done and validated by analytical data, and it was discovered that raising the wire feeding velocity led to increased mixing in the liquid metal and elimination of the UMMZ (unmixed melted zone).
3	Fangda Xu, Vimal Dhokia, Paul Colegrove, Anthony McAndrew, Stewart Williams, Andrew Henstridge & Stephen T. Newman (2018)	Ti-6Al-4V	Review, WAAM machine retrofitted with CNC machine; O2 conc. level=80-200 ppm; WFS=2.4m/min; shielding gas= 10L/min	Current data before arc extinguished= 213.1 A, 1016.5 Variance, Current data after arc extinguished= -7.2A, 2830.3 variance	Review on process monitoring and control, proposed a model of multi-sensor framework called iMUST with monitors WAAM process parameters such as voltage/current, suggested an enhanced current and voltage process control technique that can screen out far more precise current and voltage information based on component profile and ecological O2 level
4	Dongsheng Wu, Shinichi Tashiro, Ziang Wu, Kazufumi Nomura, Xueming Hua, Manabu Tanaka (2019)	low carbon steel plates (SS400)	Hybrid KPAW-GMAW, CFD simulation using FLOW3D; plate thickness=12mm; KPAW electrode setback=3 mm; GMAW torch angle=70; welding WS=3mm/s; I=265,230A; V=25.2V,26.4V	On the upper surface, the measured and theoretical weld widths are 12.95 mm and 11.94 mm, the experimental and calculated weld depth is 5.43 mm and 5.43 mm, and the measured and theoretical weld reinforcing is 1.47 mm and 2.55 mm, respectively.	To probe heat transfer and material flow, a 3-D electrode-arc-droplet-weld pool model was proposed. It discovered that Marangoni force and arc shear stress were the dominating concentrated forces for the "Pull-Push" flow, which were created under the influence of arc stresses and Lorentz Force.
5	Sergio Ríos, Paul A. Colegrovea, Filomeno Martinaa, Stewart W. Williamsa (2018)	Ti-6Al-4V	Plasma WAAM, TIG, PTA, I= 120-220A, TS= 2-6mm/s, WFS=1.2-4 m/min	arc efficiencies of 70% and 45% for P-TIG and plasma; predict the weld power with an accuracy of ± 20%	Proposed a methodology to assess layer height and wall width from process variables, which was confirmed with experimental data and was capable to estimate weld-power within the precision of 20%, and evaluated the geometry's susceptibility to various parameters.

6	Marcel Graf, Andre Hälsig, Kevin Höfer, Birgit Awiszus, Peter Mayr (2018)	Steel G4Si1, magnesium AZ31	GMAW-CMT technology, FEA simulation using MSC Marc; WFR=2.5-5.0 m/min; WS=40cm/min; shielding gas=15 L/min (82% Ar and 18% CO2); I=35-165A; V=9-14.5V	G4Si1 with Vwire = 2.5-5.0 m/min and Vwelding = 40 cm/min; AZ31 with Vwire = 5.0 m/min and Vwelding = 40 cm/min	Simulations were run to predict temperature fields, disruptions, and physical properties, as well as a numerical-analysis of the effect of wire feed and weld path direction on temperature evolution for inter walls made of various materials. In semi-finished items, the thermal resistance was also modelled.
7	Chen Shen, Zengxi Pan, Dominic Cuiuri, Bosheng Dong, Huijun Li (2016)	Fe3Al, DH36	WAAM, GTAW; wire dia=0.9mm; WFS=689-1000mm/min, I=140A; arc length= 3.5mm; interpass temp= 400 C;	width of columnar grains in the lower section= 473µm, at higher =556µm; hardness: 270Hv - 307Hv; UTS = 897.8±58.3 MPa (Y), 851.7±39.9 MPa (Z); 0.2% Yield strength= 810.7±55.8 MPa (Y), 722.6±21.9 MPa(Z); Elongation = 3.5±0.4% (Y), 3.7±0.2% (Z)	Various chemical and mechanical characteristics of Fe3Al cell walls were examined experimentally, as well as how these qualities fluctuate at various positions within the build-up wall. Topology, phase characterisation, hardness measurement, chemical composition, and tensile testing were among the tests performed.
8	A. Queguineur, G. Rückert, F. Cortial1, J. Y. Hascoët (2017)	X2CrNiMo19-12 (AISI 316L), Cu-Al8Ni2Fe2 (Cu-Al alloy).	WAAM using CMT; WFS= 5.0-6.0m/min; TS= 40-70cm/min; I=144-177A; V=13.4-20.6V	Hardness tests = 185–195 HV5; elongation for both directions = 41%; Ferrite average ratio is 8%; Corrosion potential = 280 mV/ECS; laminated reference = − 393 mV/ECS; hardness test: Pulsed mode—monopass 125 HV5, CMT®—monopass 140 HV5; CMT®—multipasses 130 HV5; YS ≥ 300 N/mm2, UTS ≥ 650 N/mm2; potential value = − 300 mV	The mechanical, corrosion, and microstructure features of two distinct materials deposited by the CMT technique, as well as the influence on setup time, were investigated, and it was found that this process is superior than casting, which has cast flaws and a long lead time.
9	Cui Er Seow, Harry Coules, Raja Khan (2018)	Nickel-base superalloy IN625	WAAM using CMT; wire dia=1.0mm; loading rate= 0.02mm/min;	maximum value of J that could be evaluated from the data for CT1 and CT3 are 690.7 N/mm and 692.3 N/mm; validity limit is 412.5 N/mm	Effect of crack orientation on fracture of component, EBSD maps of specimen were taken using electron microscope. Found load CMOD curves, crack driving force estimation, DIC results, neutron diffraction results
10	Chen Shen, Zengxi Pan, Donghong Ding, Lei Yuan, Ning Nie, Dongzhi Luo, Dominic Cuiuri, Stephen van Duin, Huijun Li (2018)	ALUNOX AX-CuAl8Ni6 welding wire, NAB alloy substrate	Robotic WAAM, GMAW, CMT; WFS= 7m/min; deposition rate= 3.73kg/hr; TS= 500mm/min; I=210A; V=22V; interpass temp = 100 C; heat input= 554 J/mm	At 650°C, hardness increases to 192.2±3.3 Hv1; at 750°C hardness decreases to 166.9±2.2 Hv1; UTS Max to Min AF ~ 37 MPa, QT450 ~ 27 MPa, QT550 ~ 24 MPa, QT650 ~ 21 MPa, QT750 ~ 19 MPa; UTS = 610-730	Investigated the influence of anisotropy on the test specimen by several tests including mechanical, microstructures & macrostructures using electron microscope before and after the heat treatment process, X-ray diffraction, grain refinement and precipitate solutions

				MPa, 0.2%YS=250-280MPa, elongation = 15%-18%	
11	Helen Bartsch, Ronny Kühne, Sandro Citarelli, Simon Schaffrath, Markus Feldmann (2021)	Steel; filler metal: G3Si1	Wire Arc Additive Manufacturing (WAAM); EN 1993-1-9 fatigue test; Numerical simulation; 255A; 27V; WFR 4 m/min; melting rate 4.26 kg/h	Maximum number of cycles to fatigue; L3 (long sample) failure region- edge in centred WAAM region; 1,251,878 cycles; Max roughness (mm) single wire tech- 0.610 and multi wire tech- 2.112.	Water jet cut samples are taken for fatigue tests and SN curves are obtained. Surface of single and multiple-wire (three-wire) technology was compared and the later was found to have higher mean roughness and waviness. Numerical simulations were carried out to find out the dependence of fatigue strength on surface roughness. An exponential trend was observed. As the surface roughness increased, the fatigue strength decreased.
12	Ruwei Geng, Jun Du, Zhengying Wei, Siyuan Xu, Ninshu Ma (2021)	ER2319 Al alloy; 2024 Al alloy substrates	GTAW; Numerical simulation; 180, 200, 220A; WFR 180 cm/min; substrate speed 3, 4, 5 mm/s; shielding flow rate 15 L/min	Substrate-speeds of 3mm/s, 4mm/s, and 5mm/s, the avg. PDAS of the works were 5.2 µm, 7 µm, and 9.42 µm, respectively.	For WAAM characteristics like as heat source electricity and substrate-speed, a 3D method was created to analyse structure development and temperature gradients. The results revealed that the height of the deposition layer was inversely proportional to the parameters in question. The experimental results also supported the computational results, which help determine that PDAS reduced with increased substrate speed and increased with increased heat source power.
13	M. Bambach, I. Sizovaa, B. Sydowa, S. Hemesb, F. Meinersc (2020)	Ti–6Al–4 V	WAAM; Forging; 120A; 14V; WFR 10 m/min; argon flow rate 15 L/min	UTS in the transverse direction is of about 945MPa, in the vertical direction 940 MPa and at the 45° to build direction 954MPa. YS is 850 MPa; forged Ti-6Al-4 V material (YS > 830 MPa and UTS > 900 MPa).	The conventional forging of a Ti–6Al–4 V component is compared to two distinct approaches: First, a WAAM-prepared sample is forged; second, the WAAM method is employed to add structural elements to a forged preform sample. Different regions' mechanical and microstructural qualities were investigated and compared. The first method had improved mechanical characteristics and a comparable microstructure to conventionally forged pieces. The second hybrid process yielded encouraging results, with mechanical characteristics equivalent to poured and welded Ti–6Al–4 V.
14	Philipp Henckell, Karsten Günther, Yarop Ali, Jean Pierre Bergmann,	S355 steel; Wire: G4Si1;	WAAM; GMAW; 19V; welding velocity 0.3 m/min; WFR 6 m/min; shielding gas flow rate 15 L/min; Cooling gar rate 30	Hardness average value of 160 HV1 with strongly varying values up to 50 HV1 without using cooling gas. With cooling gas homogeneous value of	A novel method of inputting additional cooling gas during the WAAM process was developed. Three gases (Nitrogen, Argon and Hydrogen) were used and gas nozzles at different positions with respect to the

	Jürgen Scholz and Pierre Forêt (2017)		L/min; position of additional nozzles (90°, 180°, 270°)	150 HV1.	rotating GMAW torch were tested and analyzed. Nitrogen and 5% hydrogen cooling gas gave best results with respect to neat geometry and desirable cooling which lead to fine and homogeneous microstructure.
15	A. Horgar, H. Fostervoll, B. Nyhus, X. Ren, M. Eriksson, O.M. Akselsen (2018)	AA5183 wire; AA 6082-T6 support plate	WAAM; GMAW; 230-240, 120-130 A; 32-33, 28-30 V; WFR 15, 10 m/min; travel speed 12, 22 mm/s; argon flow rate 30 L/min	Mean YS 145 MPa; Mean UTS 293 MPa; Hardness measurements in horizontal direction gave HV1 of around 75 kg/mm2, while 70–75 kg/mm2 in the vertical direction.	They looked at the structure and elastic modulus of AA5183 wire generated using wire arc additive manufacturing (WAAM). To evaluate the characteristics of tensile samples collected from different orientations to respect to the AA6082-T6 support plate, They discovered that the specimens' ductility was high in both parallel and perpendicular directions to the weld feed direction.
16	Zeqi Hu, Xunpeng Qin, Tan Shao, Huaming Liu (2017)	ER70S-6 copper-coated solid wire; mild steel substrate	GMAW; CFD; FEA; 200,250,300,350 A; 20.7,23.2,25,27.8 V; Travel speed 300, 500, 700,1100,1500 mm/min	Max temperature of weld pool 1790 K. Length of bead was measured with a different combination of parameters.	A 3D simulation model was created to analyze thermal contour and weld pool dynamics and geometry. High travel speed of weld torch and low current produced better and consistent beads. The simulation results were validated with experimentation. Altering direction (zig-zag) motion of torch provided with best surface quality for open path parts.
17	Donghong Ding, Zengxi Pan, Stephen van Duin, Huijun Li and Chen Shen (2016)	NiAl Bronze alloy; CuAl8Ni6 welding wire	WAAM; GMAW; 175.5, 218.3, 256.1 A; 24.8, 26.7, 29.0 V; WFR 5.4, 6.7, 8 m/min; Travel speed 400 mm/min	BM YS 322 MPa; UTS 689 MPa; WM YS 339-342 MPa; UTS 630-653 MPa.	To manufacture NAB alloy utilising WAAM, experimental investigation with various welding conditions was carried out. With and without post-weld heat treatment, mechanical and microstructural characteristics were examined. WAAM's portion had a fine microstructure and elastic modulus that were equivalent to those of the as-cast alloy. PWHT, on the other hand, improved in all areas, including hardness.
18	Jing Guo, Yong Zhou, Changmeng Liu, Qianru Wu , Xianping Chen and Jiping Lu (2016)	AZ31 magnesium alloy	WAAM; GTAW; EP 136 A; EN 91 A; Pulse frequency 1, 2, 5, 10, 100 and 500 Hz; WFR 2 m/min; Deposition rate 200 mm/min; Shield gas flow rate 20 L/min	UTS 258 MPa, 100MPa MPa at 5 Hz; 21 micrometre equiaxed grain at 5 and 10 Hz.	The study addresses the effect of frequency of pulses of deposition on the structure and strength. The experimental work showed that the grain fineness and tensile strength first increases and then decreases with pulse frequency. The finest grain structure is produced at 5-10 Hz frequency which is the natural frequency of weld pool i.e. resonance occurs. The magnesium alloy produced had no pore defect and were fully dense. The alloy created at 5-10

					Hz showed greater yield strength and UTS than a conventional forged magnesium alloy.
19	Chen Shen, Zengxi Pan, Yan Ma, Dominic Cuiuri, Huijun Li (2015)	Fe-Al intermetallic	WAAM; GTAW; 140 A; 12.7 V; travel speed 100 mm/min; WFR Al 695 mm/min, Fe 1000 mm/min; Deposition rate 6 g/min.	Average UTS 944.3 MPa; Average YS 847.7 MPa; Elongation 3.27%.	WAAM is used to produce fully dense iron rich Fe-Al intermetallic alloy and compared with conventional powder metallurgy parts. Microstructure, hardness and tensile strength at room temperature is analyzed. The results show that yield strength is increased by about 50MPa compared to cast alloy. Optical microstructure analysis and electron dispersive spectroscopy reveal the presence of columnar Fe3Al in most parts and carbide formation in the lower part because of steel substrate.
20	Bintao Wu, Donghong Ding, Zengxi Pan, Dominic Cuiuri, Huijun Li, Jian Han, Zhenyu Fei (2017)	Ti6Al4V	WAAM; GTAW; 110 A; 12 V; Travel speed 95 mm/min; WFR 1000 mm/min; Argon flow rate 10 L/min.	Max interpass temperature reaches upto 300 °C.	The Ti6Al4V alloy was created using the GT-WAAM method. An infrared pyrometer was used to determine the heat of the deposition layer and substrate. According to the data, the heat rose for the first 5 levels, then remained practically constant for the next 10 layers. High speed cameras revealed that oxidation was occurring on the top layer rather than the bottom layer due to the constant increase in interpass temperature due to heat accumulation.
21	Bintao Wu, Zengxi Pan, Donghong Ding, Dominic Cuiuri, Huijun Li (2018)	Ti6Al4V alloy	WAAM; GTAW; 110 A; 12 V; Travel speed 95 mm/min; WFR 1000 mm/min; Argon flow rate 10 L/min.	Average width of α lamellae at diff height samples were about 1.89 µm, 1.80 µm and 0.89 µm; YS range 892MPa and 844 MPa; UTS range 958MPa and 1049MPa.	Wu et al. expanded on their previous work by looking at the influence of temperature buildup on structure and, as a result, physical characteristics. The findings reveal that coarse colony structures form as a result of localised gas shielding and high heat buildup, and that oxidation occurs on the top deposited layer. They also came to the conclusion that the interpass temperature should be kept below 200°C in order to achieve good mechanical qualities.
22	Wang Yangfan, Chen Xizhang, Su Chuanchu (2019)	Inconel 625 alloy; ERNiCrMo-3 AMS 5837 wire; Q235 steel Base metal	CMT WAAM; 148 A; 14.6 V; Torch speed 8,9,10 mm/s; WFR 6.5 m/min.	YS between 376.9 MPa to 400.8 MPa; UTS between 647.9 MPa to 687.7 MPa; Average micro-hardness of near-substrate region 264.4 HV; 246 HV average hardness at top region.	Cold Metal Transfer (CMT) WAAM was used to prepare Inconel 625 alloy specimens and compare it with alloy produced using casting on the basis of physical performance and microstructure qualities. The effect of torch travel speed was analyzed and the results showed that with the increase of travel

					speed microhardness increased by a small amount. The yield strength and % elongation also increased as well. Helium-Argon gas was used for cooling and preventing interpass temperature exceeding 400℃.
23	Xiaoyu Cai, Bolun Dong, Xianlai Yin, Sanbao Lin, Chenglei Fan, Chunli Yang (2020)	TiAl alloy; Ti6Al4V wire and pure Al wire;	WAAM; TIG; 120 A; 9-10 V; WFR Al 480, 600, 760 mm/min; WFR Ti6Al4V 700, 800 mm/min.	Top region microstructure composition 55.21 Ti; 43.29 Al; 1.49 V. Vickers hardness is about 350 HV to 580 HV.	there are 2 wires The TiAl alloy was created via TOP-TIG manufacturing processes. However, traditional TIG welding makes it difficult to achieve the appropriate microstructure and homogenous composition of the two metals. As a result, the Al wire was fed in front of the liquid metal (as is customary), whereas the Ti6Al4V wire was fed behind it. For various wire input rates, the structure and physical characteristics were researched. The output indicated that the intermediate layer had the least amount of Al, suggesting that it was harder.
24	Lei Yuan, Zengxi Pan, Donghong Ding, Fengyang He, Stephen van Duin, Huijun Li, Weihua Li (2019)	plain carbon steel ER70S-6 filler wire; Q235 plates	WAAM; GMAW/CMT; WAAM; GTAW; 35-100 A; 12.1-13.8 V; Travel speed 100-500 mm/min; WFR 1-5 m/min; Argon flow rate 25 L/min.	Molten pool dimension are studied.	The WAAM technique, which is multi-directional and multi-axis, is a very versatile way to build medium to large sized objects. However, because to the humping phenomena, beadlike protuberances occur occasionally while conducting overhanging or downhand welding. It can be explained by the reverse material flow caused by gravity's action. The torch travel speed and a well-defined robot trajectory were indicated as crucial elements for a better finish by the researchers.
25	Bosheng Dong, Zengxi Pan, Chen Shen, Yan Ma, And Huijun Li (2017)	Cu-9 at. pct Al; Cu and Al wire; Pure Cu plate substrate	WAAM; 160 A; WFR Cu 1300 mm/min; WFR Al 311 mm/min; Travel speed 95 mm/min.	UTS (MPa) 231 ± 2.5; 0.2 Pct YS (MPa) 63 ± 2.1; Elongation (Pct) 63 ± 4.0%; Grain size 302-949 micrometre.	Cu-Al alloy was fabricated using GT-WAAM. Two wire feed technology was used with pure Copper substrate. Interpass temperature was set at 400℃ and suitable feed rate for Al wire was selected. The obtained alloy contained precipitate phases which were reduced using annealing. The mechanical properties of parts before and after annealing at 900℃ were compared. The results showed increased homogenisation of microstructure and improved yield strength, hardness and UTS.

3. CONCLUSION:

The FMS is an efficient and effective instrument in terms of its merits and uses in the current business climate and competitive landscape amongst numerous manufacturing firms in order to attain increased productivity and good quality at low price as per customers' demands. The deconstruction of CNC systems enables the creation of a matrix of solutions for controlling various processing technologies. WAAM is evolving and is a process with great scope of improvement. Its integration in flexible manufacturing systems can provide a huge versatility advantage to OEMs and an edge for firms over their competitors.

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5. DECLARATION OF COMPETING INTEREST:

The authors declare that they have no known competing financial or personal interests that could have appeared to influence the work reported in this paper.

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