International Journal of Current Science Research and Review
ISSN: 2581-8341
Volume 05 Issue 12 December 2022
DOI: 10.47191/ijcsrr/V5-i12-19, Impact Factor: 5.995
IJCSRR @ 2022
www.ijcsrr.org

A Brief Review on The Common Defects in Wire Arc Additive Manufacturing (Review Paper)

Abdulaziz I. Albannai
Department of Manufacturing Engineering Technology, College of Technological Studies, Public Authority for Applied Education & Training, Kuwait.

ABSTRACT: Wire arc additive manufacturing (WAAM) process, which depends on conventional welding arc processes, is a promising option for industries when compared to typical manufacturing processes for assembling large and complicated products. WAAM process attracting manufacturing industries due to its potential to make large and complicated components with real sharp production run time with almost single step process. The process represents greater material savings, higher material buildup rate and speed, cost savings, lower cycle time, less impact on the environment, and capability of producing large size parts when evaluated with other fabrication methods. This paper focuses on WAAM process and reviews some of the common possible process defects found in variety of studies made previously to summaries a guideline for the causes of such defects and provides some prevention methods found by those studies. Of these common possible defects found in researchers works and reviewed in this work are pores, lack of fusion, cracks, and residual stress.

KEYWORDS: Additive manufacturing; Arc welding defects; Wire Arc Additive Manufacturing WAAM; WAAM defects review; Fusion welding defects.

INTRODUCTION

Additive manufacturing (AM) is one of the manufacturing processes and known as three-dimensional (3D) printing process, which allows assembly of structures by continually printing layer over layer guided by numerical 3D model [1-3]. American Society for Testing and Materials (ASTM) has defined "AM as a process of joining materials to make objects from 3D model data, usually layer upon layer" [4-6]. So, AM is a tool resource that allows engineers to generate custom or complicated models in a single step with no regular manufacturing limitations such as waste of material and energy, struggle to manufacture complicated structures, and specific and pricey tooling [1, 7]. In addition, AM would produce parts on demand, which enhances response time, reduces supply chain, lessen storage needs, eradicates delivery costs, and diminish lead-time for critical spare parts [4, 5, 8]. Therefore, AM is a groundbreaking manufacturing technique for producing near net shape of various materials (metallic and non-metallic materials), which is likely will reform the future of industries manufacturing system [1, 5, 9]. In metal AM, parts would be produced using layer upon layer with feedstock materials in the form of (powder, wire, or sheet) [10-14]. Depending on one of the energy sources such as electron beam, ultrasound, laser beam, or arc [1, 15].

AM process can be classified in three main categories depending on the raw material state fed to the system such as liquid, solid, and powder as can be seen in Fig. 1. [16]. A sub classification category for AM processes divided in to seven processes based on the ISO/ASTM 52900-15 standard [7, 17, 18]. These seven AM processes include powder bed fusion (PBF), vat photo-polymerization (VP), material jetting (MJ), sheet lamination (SL), binder jetting (BJ), material extrusion (ME), and directed energy deposition (DED) which are classified in Fig. 1. [7, 16, 17]. Fig. 2. & 3. showing the metal additive manufacturing market in 2020 and the industrial adoption of AM and applications [1]. However, AM process has some limitations regarding product size limitation, slow built rates, require additional process to improve quality, need of support structure for regions with overhang, drive researchers to develop new fabrication strategies, and one of the most concern drawbacks of AM process is the possible presence of undesired defects in the produced parts. Defects such as porosity, delamination, cracks, residual stresses, swilling, surface quality, and anisotropy and heterogeneity in microstructure are most found in AM process [10, 19-23]. The presence of one or more of the mentioned defects negatively influencing the mechanical strength and fatigue life of the AM produced product [24-27]. Wire arc additive manufacturing (WAAM) process, which depends on conventional welding arc machines and falls under the DED classification, is preferable because it offers greater material savings, higher material deposition rate and speed, cost savings, lower cycle time, less impact on the environment, and capability of large size parts production when compared with other AM processes [17, 27-31]. WAAM has low capital costs which allow it to be used in small machine shops for manufacturing and repair activities [16, 32, 33]. Additionally, metal wires are freely available at a minor cost and are very easy to handle in comparison to metal powders [16]. Wire based system has a greater deposition rate and less environmental impact than other MA processes [16, 34-37]. WAAM is also considered to be plainer in setup operation and lower energy consumption than other MA processes [38-40]. Therefore, WAAM seems to be more economical (low bay-to-fly ratio) and great viable alternative manufacturing technique for metal parts [17, 41]. Thus, the technique found early by Baker patent in 1296 applying of electric arc as the source of heat to produce bulk objects by spraying molten metal into the deposited layers [7, 42]. In 1983 Kussmaul used the WAAM technique to manufacture large-scale products from high strength 20MnMoNi5 steel of 79ton weight [42]. Since late 1920s up to date, WAAM has been applied in nuclear energy, marine, aerospace, and building industries [7, 19]. Even though, WAAM showed production of similar microstructure and mechanical strength in manufactured parts when compared with other produced by powder-based AM processes, WAAM has its own drawbacks [43-46]. WAAM is a welding process that uses different weld parameters to buildup and join a layer upon another layer by melting and solidifying a feeding metal wire with the previous layer when applying the arc as fusion heat source passes on to produce and form 3D shape [17, 47]. Thus, welding principles are very important in WAAM process, which means the possible weld defects are applicable in this process [27, 48, 49]. There are three main weld processes mostly used and can transferred in WAAM process with certain additions like a computer numerical control (CNC) or a robotic system. These weld processes are gas tungsten arc welding (GTAW), gas metal arc welding (GMAW), and plasma arc welding (PAW) [41, 50-53]. Moreover, a wire feeder system should be added and controlled to complete the WAAM process [48, 54]. Over last 15 years, WAAM process has attracted significant interests, due to its high deposition rate, unlimited build envelops, efficient use of materials, and fabricating medium to large sized components. Thus, WAAM been used for various alloys as they proposed in Table 1. [55]. On the other hand, most defects of the mentioned weld processes are possible to be found in parts produced by WAAM process and can be blended with the mentioned earlier AM defects [14, 19, 56, 57]. So, WAAM can produce parts with larger window of defects when compared with other AM processes [58]. Additional to the AM process defects, WAAM process is attended by serial melting and solidifying of the buildup material, making the process prone to the formation of solidification limitations, including discontinuities, such as pores, hot cracks, and lack of fusions, as well as microstructural inhomogeneity and imperfection, such as grain coarsening or creation of contrasting phases with brittle nature in the heat-affected zone (HAZ) [19, 27, 59]. The aim of this work is to study and review some significant studies made from respectful effort of other researchers on WAAM processes, to build up a summarized review about some of WAAM common defects and their causes by creating a helpful prevention guide for those defects.

Table 1. Various alloys used with different WAAM processes along with the references

Alloys/WAAM process	**GMAW**	**GTAW**	**PAW**
Titanium Alloys	[60, 61]	[62-64]	[65-67]
Aluminum Alloys	[60, 68, 69]	[70-72]	[72, 73]
Nickle Alloys	[70, 74]	[70, 75]	[76, 77]
Steel Alloys	[78-80]	[50, 78]	[50, 72]
Bronze Alloys	[55, 81]	[55, 82]	[39, 83]
Intermetallic Alloys	[19, 84]	[83, 84]	[83, 85]

International Journal of Current Science Research and Review
ISSN: 2581-8341
Volume 05 Issue 12 December 2022
DOI: 10.47191/ijcsrr/V5-i12-19, Impact Factor: 5.995
IJCSRR @ 2022
www.ijcsrr.org

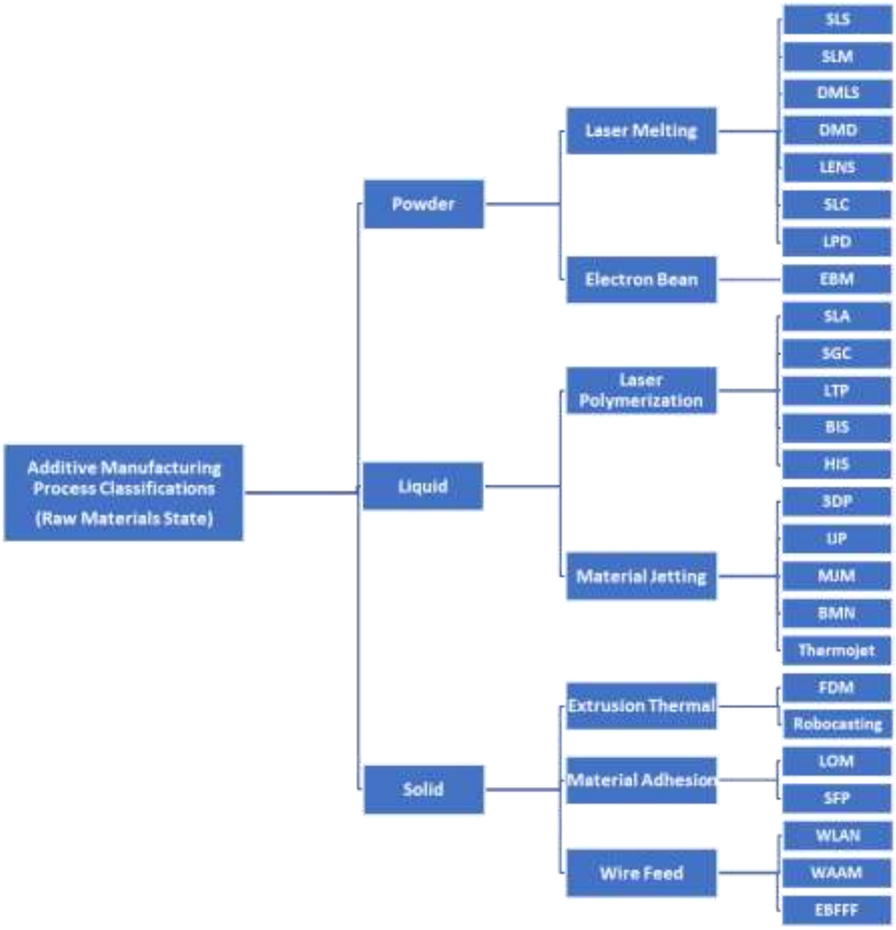

Figure 1. AM process classification depending on the raw material state fed to the system [16].

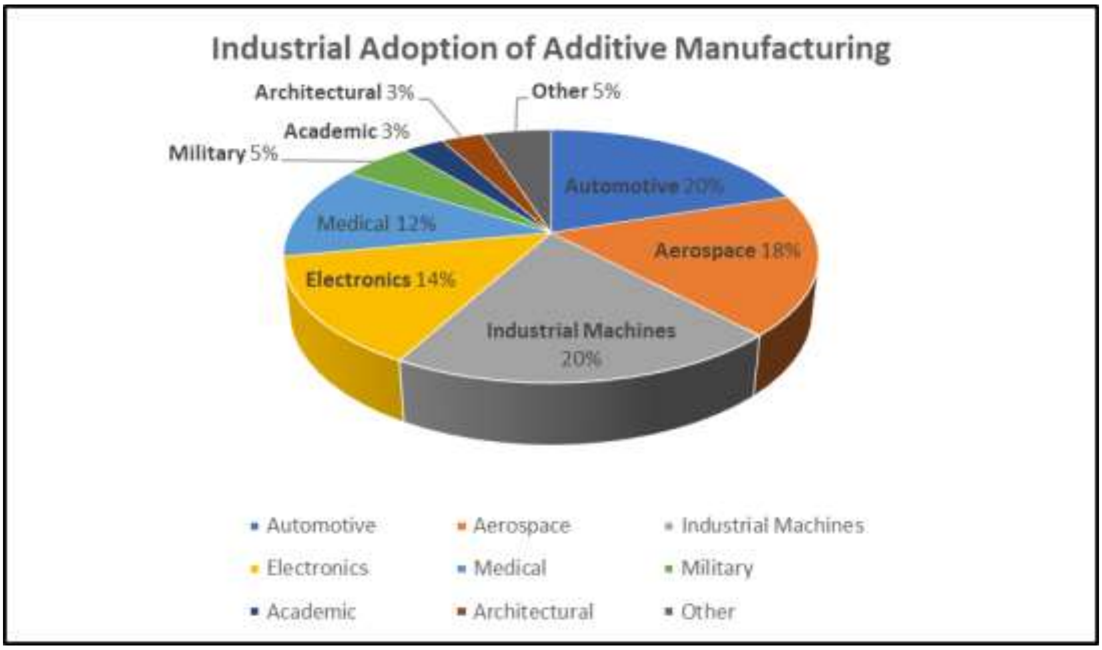

Figure 2. The industrial adoption of AM process in 2020 [1].

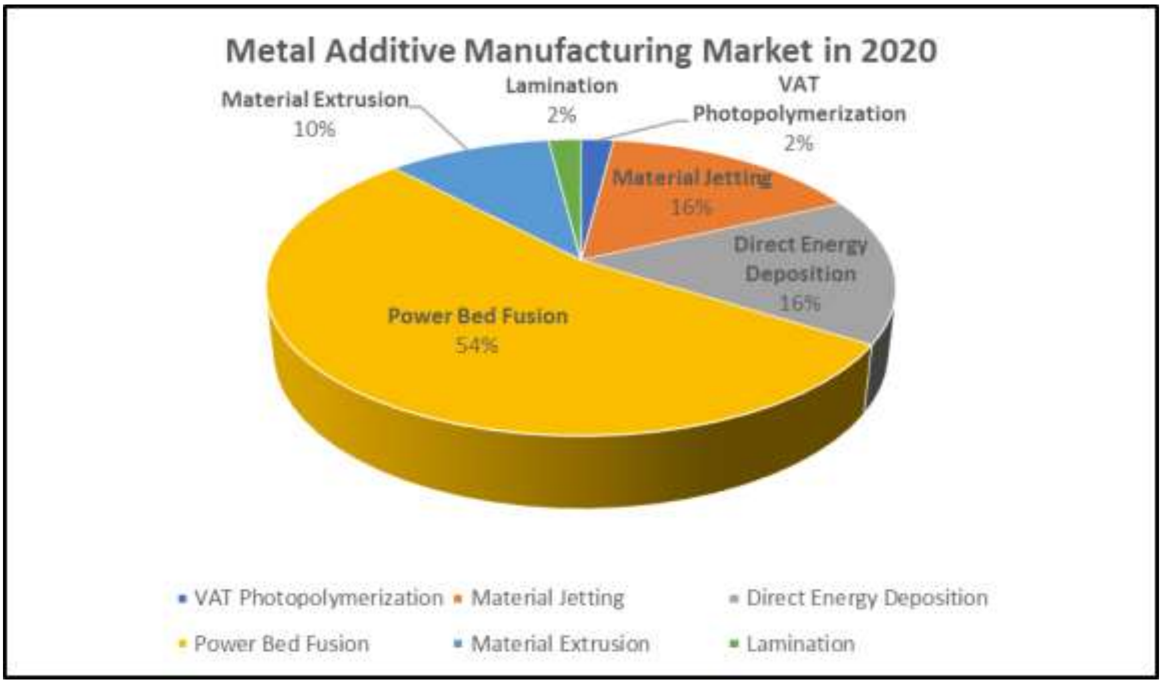

Figure 3. The market of metal additive manufacturing in 2020 [1].

1. PORES

Existence of Porosity is one of crucial troubles in WAAM process, which can reduce the overall density of the produced parts and thus severely harm the mechanical properties of the fabricated components [59, 86, 87]. Pores can be mainly sorted into small and homogenously distributed hydrogen pores, with a diameter size up to 100 µm, and into big and in homogeneously distributed process pores [87]. Porosity is generated by various reasons including type of the used arc welding process, process parameters, inter pass temperature, wire alloy composition and quality [59]. PN Anyalebechi [88], explained that gas porosity is usually caused by two concomitant mechanisms, namely, volumetric shrinkage and the change in the solubility and associated precipitation of hydrogen during solidification. Process related pores are distributed more inhomogeneously in aluminum and can be triggered by entrapment of shielding gas, air (oxygen and nitrogen), or other gases which cannot escape because of the rapid material solidification [87]. Fu Rui et al. [89] stated that Hydrogen is believed to be the main cause of the porosity in WAAM aluminum alloys. Moreover, J. Gu et al. [90], mentioned that many pre-occurrence imperfections in the wires such as impurities, supersaturated hydrogen and segregation of composition etc. will be transferred into the molten pool, which could employ harmful effects on the mechanical strength of the produced WAAM alloys. Also, Ryan et al. [91] showed that the quality and batch-to-batch irregularity in feedstock wire had a considerable influence on the porosity appearance, volume, and distribution. M.C. Brennan et al. [25], declared that gas entrapped pores in parts produced with DED are characteristically larger in size than those produced by other AM process. The research team added that, high solidification rates and high gas flow in the weld pool led to rise pore concentrations in the produced metal alloys. J. Gu et al. [92], stated that the major hydrogen sources can be the moisture, grease, and hydrocarbon impurities on the wire surface, which easily can be vaporized in the arc, and converted into atomic hydrogen and then absorbed into the molten pool to be trapped after solidification. Artur I. Kurakin et al. [93], studied Al-Mg alloy and the influence of surfacing modes on the formation of pores in the deposited metal produced by WAAM. They have found that increasing both process arc instability and rate of energy input, resulted in larger pore size formation in the produced part. Moreover, Tao Lu et al. [94], in their study about “hot-wire arc additive manufacturing Ti–6.5Al–2Zr–1Mo–1V titanium alloy”, they stated that spherical trapped gas pores can be form by hydrogen rejection, while large and irregular or flat pore shape generated by lack of fusion defect, and as can be seen in Fig. 4. which presented by M.C. Brennan et al. [25] in their great work. While clear round trapped pores in aluminum alloy with different sizes can be seen in Fig. 5. as been presented by Ana Lopez et al. [57]. Also, René Winterkorn et al. [95] declared in their work, which was titled by “Wire Arc Additive Manufacturing with Novel Al-Mg-Si Filler Wire—Assessment of Weld Quality and Mechanical Properties” the risk of pore existence depending on the high solubility and entrapment of gases, such as Hydrogen and the heterogeneous microstructure. Therefore, the presence of Hydrogen around the weld pool can considerably be the primary reason of pores formation in the fabricated parts as mentioned in most of the previous studies. Even though, the primary cause of pores is the appearance of Hydrogen around the weld pool, it should be noted that there are other factors can contribute the presence of Hydrogen as well as formation of pores. For instance, Maider Arana et al. in their study [59], concluded that factors like type of material used, buildup sequence strategy, shielding gas type, and gas flow rate promptly impact the porosity noted in AA5356 WAAM built walls by cold metal transfer (CMT) arc mod. Also, W. J. Sames et al. in their work [10] stated that pores which formed by processing technique, known as process-induced porosity, are existed when the applied energy is insufficient for complete melting or spatter ejection occurs. These pores are typically non-spherical and has in a variety of sizes. Bintao Wu et al [19], also stated that pores defects generally are mainly classified as either raw material-induced or process-induced.

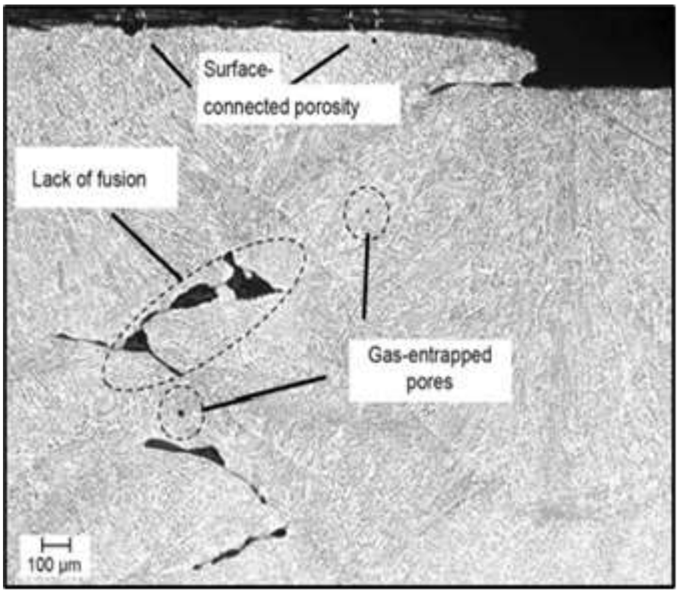

Figure 4. A great combination of defects figure, found in DED processed stainless steel indicating instances of lack of fusion, gas-entrapped pores, and surface-conducted porosity. which was presented in a study made by M.C. Brennan et al. [25].

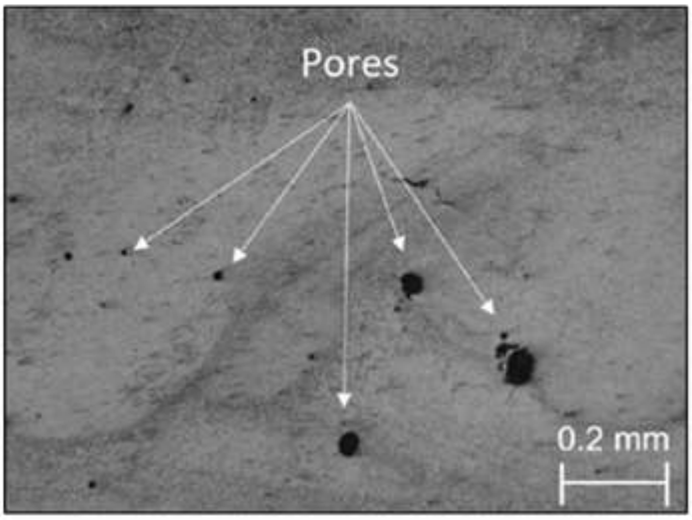

Figure 5. Pores on aluminum sample of about 5-50 µm dimension, as been presented in Ana Lopez et al. research paper [57].

International Journal of Current Science Research and Review
ISSN: 2581-8341
Volume 05 Issue 12 December 2022
DOI: 10.47191/ijcsrr/V5-i12-19, Impact Factor: 5.995
IJCSRR @ 2022
www.ijcsrr.org

1.1. Influences of Pores Formation

The presence of pores has a significant impact on the overall mechanical properties, leading to a sharp drop in ductility and strength in the manufactured components [89]. Moreover, pores can become a primary source of stress concentration in the part and can lead to crack initiation or propagation and failure during processing, or even during part operation [96]. Thus, existence of porosity will produce a component with low mechanical strength by damage from micro-cracks, and mostly brings low fatigue property to deposition via spatially with different size and shape distribution [19]. Because pores facilitate crack propagation, aggravate the anisotropy and heterogeneity, and reduce the properties of the components. Hence, the quantitative determining of porosity and pore distribution are crucial for quality evaluation [94].

1.2. Prevention of Pores Formation

It is very important for industries to eliminate pores in order to produce high quality component when deploying WAAM process [97]. Therefore, WAAM process attracted the attention of both researchers and industries to improve the process and produce parts free of pores. Thus, various studies been published and proposing different significant factors involving in elimination of pores in the produced part when WAAM process is implemented. For example, Donghai Wang et al. in their study [98], concluded that coarse grains and gas pore are responsible for limiting the application of arc additive manufacturing for Al–Si alloys. They pointed that eliminating gas pores formation can be reached when gas pores get away from the molten pool if the cooling speed is slower than escape speed. So, they have shown using low process pulse frequency thus higher heat input loss produces smaller pores size in the samples. While, using high pulse frequency thus lower heat input loss, larger pores are formed. Donghai Wang and his research team, concluded that the pulse frequency can strongly influence the proportion of the formation and size of pores in WAAM process. In addition, Karan S. Derekar et al. [99], indicated that heat input, interlayer temperature, and interlayer dwell time also played a key role in pore formation and distribution in WAAM-produced aluminum 5183 alloy. So, they concluded that using Pulsed-MIG with process conditions of low heat input, low interlayer temperature and longer dwell time control methods produce higher total pore volume fraction than applying high heat input, high interlayer temperature and shorter dwell time. The reverse was true for CMT. Karan Derekar et al. [100], concluded in their study that sample with higher interpass temperature revealed less pore content dominated by small sized pores compared to lower interpass temperature sample that revealed presence of large size pores. Cong et al. [101] also found the key factors that prevent the porosity in Al-6.3%Cu alloy, which are the low energy input and effective oxide cleaning of the wire. They concluded that with proper control of the heat input the process may produce walls with no porosity, when WAAM process is applied using CMT with advanced pulse mode. Rui Fu et al. [89] concluded that porosity could be significantly reduced by the assistance of feeding hot-wire. Thus, the optimum density of the produced part could reach 99.646% when the hot-wire current was increased. They proved that by increase of hot-wire current, the total energy input per unit volume decreased greatly from 84.0 J/mm3 to 40.1 J/mm3 and less porosity were formed. J Bai et al. in their study [102], mentioned that aluminum alloys are the most susceptible to hydrogen pores due to the great difference in solubility between liquid and solid metal. Thus, using aluminum is a challenging process when WAAM is deployed, thus wide applications of aluminum alloys are restricted in WAAM process due to its hydrogen pores susceptibility [103]. Zhang et al. [104], verified that a vibrated workpiece during WAAM Al-Mg alloy, could significantly reduce the porosity from 6.66% to 1.52%, which attributed to a strong stir in the melt pool. Murav'ev, et al. [105], found higher quality wire significantly reduced porosity in the welded joint in welding of titanium alloys. Jianglong Gu et al. [86], supported that higher quality of feeding wire greatly reduced porosity in WAAM produced parts. Derekar, K. [106], revealed the presence of finer equiaxed grains, lower heat input, shallower penetration and alternating polarities producing oxide cleaning effect in CMT with advanced mode (a reversal of polarity of the welding current in the short circuit phase of the CMT cycle [91]) in WAAM process, significantly helped hydrogen to escape that revealed no pore with size larger than 50µm existed. Maider Arana et al. [59], stated that CMT technique can reduce arc energy compared to traditional GMAW, causing smaller, cooler, and faster cooling melt pool, which deliver pore content reduction when fabricating aluminium alloys. Moreover, an application of CMT mode and interlayer rolling have provided positive solutions to minimize and even eliminate the porosity has been reported by Karan Derekar et al. [100]. Hauser T. et al. [87], showed that lower flow rate of shielding gas can reduce the number of pores in aluminum parts, because in this case, the molten pool solidifies slower and helps the escape of gas inclusions. On the other hand, they concluded that higher shielding gas flow rates with higher velocities and higher dynamic gas pressure lead to more process related pores, probably because of increased turbulent mixing. M.C. Brennan et al. [25], declared that a higher likelihood of nucleating entrapped gas pores is apparent when the equilibrium pressure of a gas exceeds the combined hydrostatic, atmospheric, and capillary pressure. So, they added that when rapid

International Journal of Current Science Research and Review
ISSN: 2581-8341
Volume 05 Issue 12 December 2022
DOI: 10.47191/ijcsrr/V5-i12-19, Impact Factor: 5.995
IJCSRR @ 2022
www.ijcsrr.org

cooling takes place, pore nucleation sites are likely to become trapped in the molten pool. However, slower cooling and solidification rates allow these pores to grow and sometimes coalesce with neighboring pores. Wang, S., et al. [107], In their study "The Influence of Heat Input on the Microstructure and Properties of Wire-Arc-Additive-Manufactured Al-Cu-Sn Alloy Deposits" they proposed that if the heat input is greater than 90 J/mm, then the pore size in the bulk material can be greater than 50 µm, and the formed grains were primarily columnar in the as-built state. Nicolas Béraud et al. [108], Mentioned that the larger the volume of the melt pool, the higher the probability of trapping pore and thus the risk of increased porosity. E.M. Ryan [91], suggested that a larger weld bead size would limit the ability of hydrogen bubbles to escape to the surface, thus more pores can be formed. Karan Derekar [109], stated that Samples produced with CMT process showed smaller and lesser pores with reduced overall pore volume compared to samples from pulsed-MIG technique processed with similar conditions of heat input and temperature controls. Because of increased overall energy, hotter deposit, higher arc penetration and lower cooling and solidification rates that supported in increased hydrogen absorption, easy movement, and coalescence of atomic hydrogen. Maider Arana et al. [59], indicated that in a buildup layers WAAM process, the heat input of each new superposed layer can promote the growth of pore. Jianglong Gu et al. [110], declared that CMT-PADV process (where; "'P' refers to pulsing the current, 'ADV' involves a reversal of polarity of the welding current in the short circuit phase of the CMT cycle" [91]) is an efficient deposition process in terms of reducing and even eliminating the porosity, because of its lower heat input. Jianglong Gu et al. [86], proposed that unstable arcs are associated with porosity. Henckell, P., et al. [111], pointed that increasing the contact tube to work piece distance by offsetting the wire tip to the desired welding position in GMAW, leads to unstable arc behavior, increase spattering or weld seam irregularities. This can be resulted due to the spin of the electrode resulting from the wire spooling which limits the weld process. Therefore, from the previous mentioned studies we can conclude there are several factors preventing or reducing pore formation in WAAM process. These factors are slower cooling rate [98], low process pulse frequency [98], higher interpass temperature [99, 100], clean and high-quality wire [86, 101, 105], CMT technique [109] or CMT with advanced mode and pulsing current [101, 110], lower total energy input per unit volume [89], avoid using alloy composition with great difference in solubility between liquid and solid metal such as aluminum alloys [102, 103], vibrating workpiece [104], CMT mode combined with interlayer rolling [90], lower flow rate of shielding gas [87], equilibrium melt pool sounding pressure [25], equiaxed fine grain structure [106, 107], smaller weld pool or weld bead size [91, 108], stable or smooth arc [86], eliminate the existence of hydrogen around the weld pool as much as it is possible [92], and reducing the distance between the nozzle and workpiece during WAAM process [111].

2. LACK OF FUSION

Lack-of-fusion or lack of bonding defects are a consequence of insufficient overlap between passes, motivated by a mismatch in hatch-spacing parameters in DED as can be seen in Fig 4. & 6. [57]. These defects exist due to a polluted substrate and form deviations in the build-up process because of inadequate material deposition in the previous layer [112]. The incomplete melting phenomenon between layers will also result in lack of fusion defects [113]. Lack of fusion defects can be characterized with irregular and elongated shapes ranging from 50 µm to several millimeters in size [24, 25]. These defects are more dangerous than gas porosity in terms of increasing the local stress, and they can be located inside and between the deposited layers [20, 114].

2.1 Influences of Lack of Fusion

Lack of fusion is harmful to the mechanical properties of the component, and in extreme cases leads to direct part rejection [24]. The random distributions of lack of fusion defect in the manufactured part is responsible for the low fatigue resistance and shrinkage in fatigue life [115] and affect the mechanical tensile properties [116]. Lack of fusion defects will cause a remarkable drop in the toughness of the produced material about the defect, prompting its growth [27]. Moreover, lack of fusion is considerable weakening of the welded joint and causing of initiation structural failure [117, 118]. Therefore, such defects of the current deposition layer can likewise influence the quality of the following deposition layer and then the overall product because of the layer-upon-layer characteristic [113].

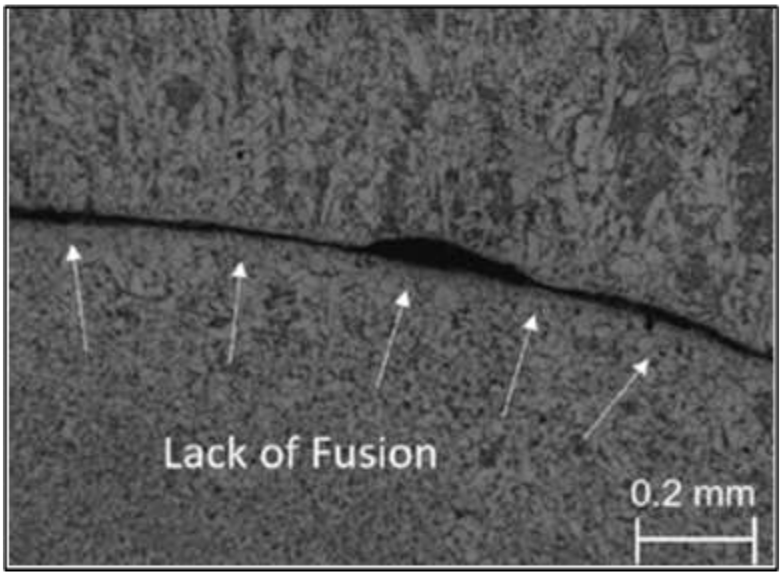

Figure 6. Lack of fusion on mild-steel sample (between layers) of about 20–30 µm, as been presented in Ana Lopez et al. research paper [57].

2.2 Prevention of Lack of Fusion

Lack of fusion defects and their limited control is a key barrier for the application of AM technologies [119]. Therefore, significant volume of experimental data has been reported in the literatures about reducing or preventing lack of fusion defects in different alloy systems. Experimentally, lack of fusion defect was found to be reduced in produced parts with increasing the weld process power [120] for stainless steel [121], aluminum alloys [122], titanium alloys [123], and CoCrMo alloy [124]. T. Mukherjee and T. DebRoy in their study [120] titled by "Mitigation of lack of fusion defects in powder bed fusion additive manufacturing", declared that applying higher heat input per unit length results is larger liquid pool size and decrease occurrence of lack of fusion defects. Jovanovic, M. et al. [125], stated using high welding speed will provide lower energy input per unit of length of a welded joint, which will end with inappropriate melting of the parent metal, a risk of occurrence of lack of fusion, and unsound welds. In addition, they pointed that inappropriate weld joint preparation, incorrect torch inclination, and improper welding position are very important contributing factors for the existence of lack of fusion. Also, they added an important factor for preventing lack of fusion, which can be reached by proper mixing of the parent metal and filler material by controlling the droplet formation when welding speed is compatible with filler wire feed speed. Other factors such as stable melt pool dynamics, noncomplex thermal cycles, proper process setup parameters, and sufficient shielding gas are effective in preventing lack of fusion defects as proposed by Ghaffari, M., et al. [27]. Another study made by Jin, W., et al [7], and they summarized that accurate and proper control of heat input and thermal history, correct shielding gas, good quality feedstock, and clean substrate surfaces are beneficial to reduce lack of fusion defects in stainless steel when WAAM process is used. G. Marinelli et al. [126], studied the effect of wire feeding orientation on the occurrence of spatter and structural defects, such as pores and lack of fusion in high-purity tungsten structure. They concluded that the front wire feeding orientation has a good prevention of spatter and structural defects and a defect free tungsten structure was deposited. While, using side wire feeding lead to spatter and existence of lack of fusion and pores defects. Therefore, they shared that avoiding spatter is necessary in order to protect the structural integrity of the tungsten wall deposited via WAAM. In general, from the previous studies, we can conclude that increasing weld power and heat input [120], proper weld joint preparation, lower weld speed, correct torch inclination, suitable welding position, fitting of both weld speed and wire feed speed [125], stable melt pool dynamics, noncomplex thermal cycles, exact process setup parameters, sufficient shielding gas [27], high quality feedstock, clean substrate surfaces [7], front wire feeding orientation, and lower process spatter [126] are the recommended factors for preventing or reducing lack of fusion defects in WAAM process.

3. CRACKS

As mentioned earlier in the introduction section, WAAM process depends on traditional welding arc processes, thus unweldable alloys such as Al-Zn-Mg-Cu [127], AA7075 [128], AA7055 [129], AA2024 [130], and super alloys with overall Al and Ti content of more than 6% [131] are highly restricted due to their hot crack sensitivity behavior during a fusion weld process. Therefore, alloys attracted to hot cracking such the mentioned ones are unrecommended in WAAM due to their predisposition and ability of forming hot cracking at some point in the process and producing of unacceptable part. There are two possible types of hot cracking, one called solidification cracking (SC) and forms in the weld zone specifically, while the other one forms in HAZ and called liquation cracking (LC) [132]. SC forms and propagates through the solidification progress of the material at the trailing end of the moving weld pool in a mushy zone, where liquid is still present around the rising dendritic arms following the heat source [133]. The mechanically weak region namely mushy zone is always the trailing area behind the weld pool and the perfect location for forming SC, where interference occurs flanked by the solid and liquid phases due to opposing material ductility and the shrinkage rate of the solidification progression [134]. In contrast, LC can be found in HAZ in the partially melted zone (PMZ) during a fusion welding process. Due to existence of thermal stresses and liquation of partial phases in the PMZ, separation of the liquid stains can be formed under high stress concentration and leads to creation of LC [132]. Therefore, LC outcomes from liquation of low melting point constituents in the microstructure, and very likely to be found in WAAM due to reheating process of the deposited material [135]. Even though, LC always forms in PMZ of HAZ, it can extend and propagate inside the weld zone and transferring to a SC depending on the level of stress concentration around the tip of the existed crack as can be seen in Fig. 8.

3.1 Influences of Cracks

Cracking is a crucial issue in welding processes. If unobserved, the crack defect behaves as stress absorption sites and mostly lead to early failure through short fatigue life, as well as prepares satisfactory sites for other types of cracking such as hydrogen assisted cracking and stress corrosion cracking [136]. Thus, crack is the riskiest type of defects found in a welded part and must be eliminated and repaired. Cracks also known to be diminished the toughness of the welded part due to the drop in the cross-section area, which can easily proliferate out of stress concentration at the tip of the crack and weaken the fabricated part and make it improper product.

3.2 Prevention of Cracks

Cracks can be formed simply when fusion welding process is applied on alloys has high potential to cracking behavior. Thus, it is highly recommended to avoid using WAAM on unweldable alloys such as AA2024, AA7075, AA7055, Al-Zn-Mg-Cu, and super alloys with overall Al and Ti content of more than 6%. In addition, welding alloys with high solidification range can produce parts with high possibility of SC formation due to appearance of liquid films on the grain boundaries for longer time under surrounding thermal and/or mechanical stresses. In general, prevention of SC can be achieved by reducing all affecting factors such as thermal and/or mechanical stresses, weld speed, heat input, solidification range, grain size, and mushy zone size [133]. Moreover, cracking take place if the tensile stresses surpass the tensile strength of the welded material at the given temperature. Thus, controlling the shrinkage of the welded material can prevent cracking during the solidification progress. Also, in WAAM process a clean, dry, and good wire surface quality a key to produce parts free of hydrogen and avoids hydrogen induced cracking [137]. Furthermore, the chemical composition of welded material can be improved by adding a sufficient filler wire, in arc welding processes to degrade SC [138]. Additionally, It has been shown that modifying the microstructure by welding arc oscillation (weave weld pool motion) hindered SC when compared with straight weld pool motion [139, 140]. As well, the microstructure mood resulted during the weld solidification process has a significant impact on cracking resistivity. Thus, forming equiaxed grain structures in weld zone area are more preferable and resistant to hot cracking than columnar dendritic [141]. Besides, increasing the size of HAZ which is usually resulted from applying higher amount of heat input, therefore regions that susceptible to LC is extended as a result, poor LC resistivity regions will be existed [142]. Additionally, increasing the deposition layers lead to increase the partial melting zone of the solidified deposited parts and the stress along that zone, which will result in LC, which can form clear macrocracks as can be seen in Fig. 7. [143].

Figure 7. Shows different macrocracks directions on a part of Ale6.6Zne2.6Mge2.6Cu alloy produced by WAAM with single-pass multilayers, as presented by Chen, S., et al. [143].

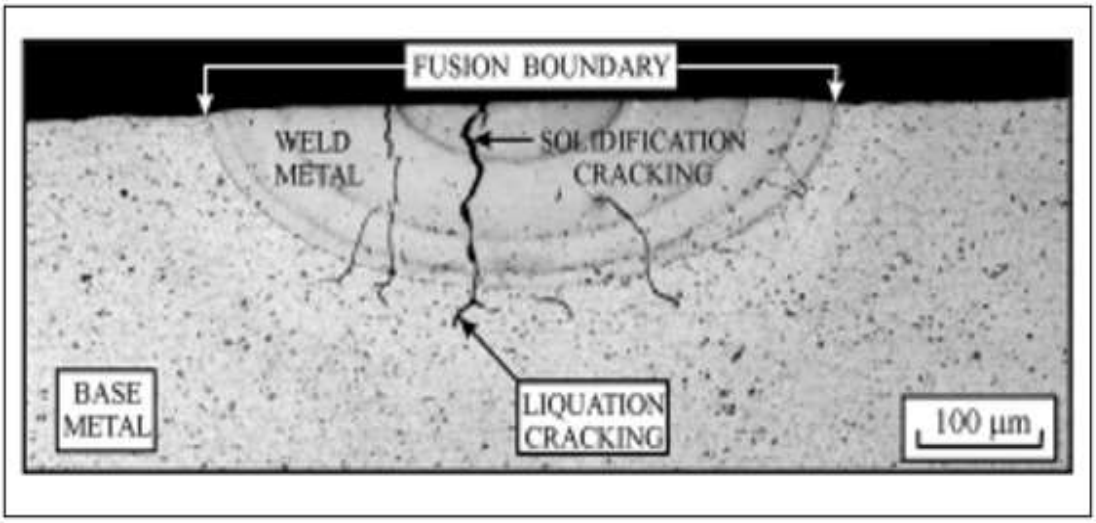

Figure 8. Shows the locations of both solidification and liquation cracking in an Aluminum welded part with a linking crack, as been presented by Zhang, J et al. [144].

4. RESIDUAL STRESS

Residual stress is the stress that stays inside the material when all exterior loading eliminated. If the residual stress is high enough, it will be a dangerous influential factor for the material mechanical strengths and fatigue life of the fabricated part [19]. In WAAM, shrinkage of the weld pool through solidification progress and repetitive heating and cooling process can result in high rate of residual stresses and distortion in the deposited part [145]. The frequent remelting and solidifying can trigger thermal expansion and shrinkage of the deployed part, causing undesirable distortion or weakening material's mechanical strength, particularly in large thin-walled part [146]. Thus, thermal history of the deposited layers is responsible for creating residual stresses in the buildup deposits, which means the morphology of deposition paths in WAAM production may or may not promote residual stresses and distortion [147]. Fig. 9. shows how can thermal history of the deposited paths and sequence of layers affect the buildup heat and change the deposited microstructure. Therefore, thermal contraction after the deposition may grows high quantity of tensile residual stresses in the

International Journal of Current Science Research and Review
ISSN: 2581-8341
Volume 05 Issue 12 December 2022
DOI: 10.47191/ijcsrr/V5-i12-19, Impact Factor: 5.995
IJCSRR @ 2022
www.ijcsrr.org

longitudinal direction. These stresses can trigger terrible deformation and/or rash malfunction during deposition process or service life [148]. So, residual stress in welding is a serious issue that must be addressed and removed immediately to avoid its important consequences on the performance of engineering components [149].

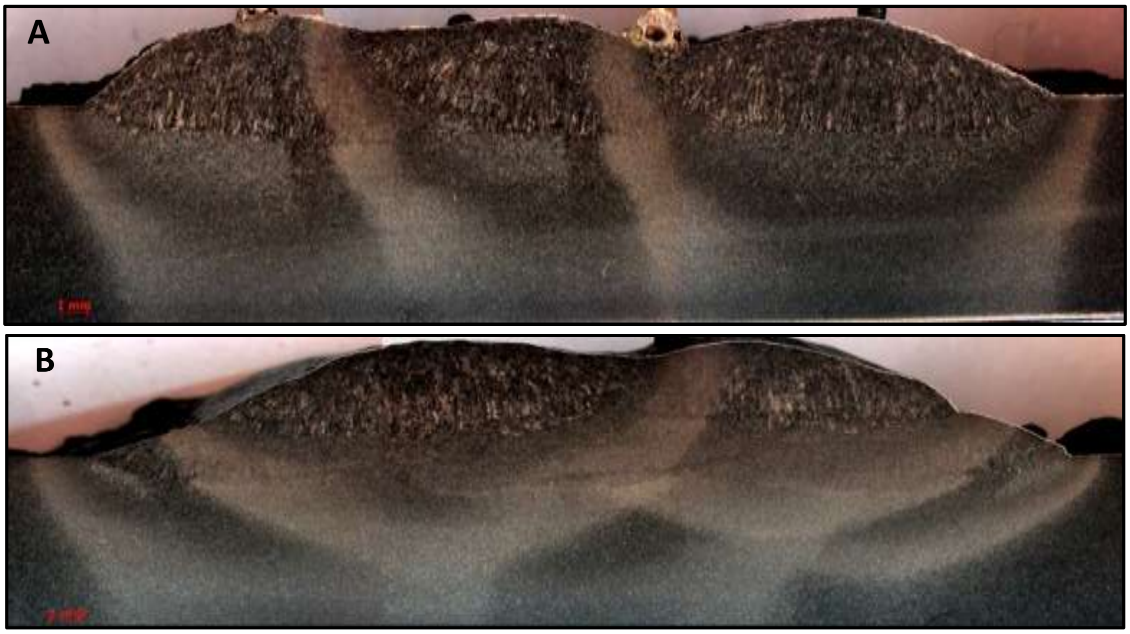

Figure 9. Two different macrostructures showing; **a)** three welded beads beside each other, and the sequence of the weld was from left to right where the last deposited bead on the right has its full and clear weld profile showing, but the other two beads are not and they are influenced by neighbor, since they were deployed earlier. **b)** showing more complicated heat spread history, the welded beads for the first layer consist of three welded beads beside each other and the sequence was from right to lift, then a second layer of two beads was deployed upon those three beads from right to left, and it is showing that almost the first layer weld profile has been completely changed.

4.1 Influences of Residual Stress

Largest stresses in WAAM are always observed in the region between the substrate and the buildup wall. These stresses which known as residual stresses can have a significant impact on mechanical properties of the fabricated structures. Moreover, If the residual stress exceeds the regional ultimate tensile strength (UTS) of the material, cracking will take place, while if it is higher than the local yield strength (YS) but lower than UTS, warping or plastic deformation will occur [7, 150]. Thus, residual stress can produce deformation, decrease in dimensional accuracy, defects, as well as deterioration of mechanical properties of the components as can be seen in Fig. 10. & 11. [17, 151, 152]. Therefore, residual stress in WAAM process should be consider as one of the most potential defects that need to be removed or solved to guarantee the quality of the produced part.

4.2 Prevention of Residual Stress

Residual stresses depend more on the thermomechanical behavior of the entire fabricated part likened to the localized solidification shrinkage of the molten pool. Therefore, the pool size is less influential on residual stresses compared to the variance between solidus and preheat temperature. Thus, Residual stresses depend on the net heat content in the system, which contains both the heat input from the arc source as well as the heat from the preheating. Hence, to prevent residual stress and distortions, one must know that residual stress and distortion are correlated to process parameters, such as welding current, welding voltage, wire feeding speed, heat input, shielding gas and flow rate, etc [153]. Generally, residual stresses and distortions in WAAM are highly possible due to the excessive heat input and inspired by process parameters such as arc power, scanning speed, wire-feed rate, deposition pattern and deposition sequences, substrate preheat temperature and substrate thickness as well as alloy properties [35]. As mentioned earlier, if the residual stress exceeds the local YS and inferior to local UTS, then distortion will occur, and if the build-up of residual stresses higher and exceeding local UTS cracking will form. Therefore, best way to regulate distortions is to monitor the build-up of residual stresses through the deposition process. Thus, preventing build-up of residual stresses can be obtained by applying interpass cooling to avoid extreme heating and maintaining enough preheating to moderate deformation [151, 154]. Also, uniform substrate preheating reduces residual stresses and deformation. Yet, continuous buildup may produce excessive heat input in a localized region, delivering high temperature gradients and large remelting of the substrate, which produces poor dimensional tolerances and surface finish [35]. On the other hand, by varying the rate of heating and cooling during the deposition process, which causes differential rates of expansion and shrinkage in the build structure, causing it to deform and develop serious residual values of stress [155]. Moreover, the greatest stresses are always found at the last deposition rows, since later deposition is a reheating process which relaxes the stresses in the former deposits. However, applying sufficient interpass cooling, the residual stress separation turns into independent to the deposition sequence as each deposition sequence does not deliver any preheating influences the next sequence [35]. In addition, many studies been made to avoid or decrease residual stresses and stated some significant factors to reduce residual stresses in the fabricated part, and these factors are controlling the preheating temperature [156], appropriate process parameter to control the heat input [120, 157], using cold metal transfer technique [70, 158], applying interpass rolling process [159, 160], post laser shock penning [161], proper heat treatment [152, 162], enough interpass cooling [35, 151], and adequate deposition paths [38, 147].

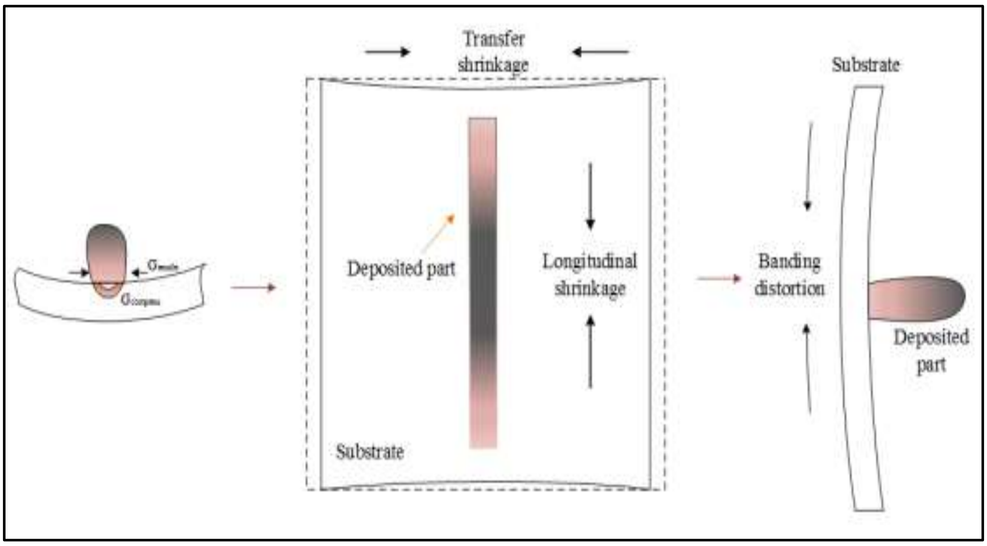

Figure 10. Distortion form in WAAM-produced component experiences non-uniform thermal expansion and contraction under alternate re-heating and re-cooling cycles during deposition layers, as been presented by Wu, B., et al. [151].

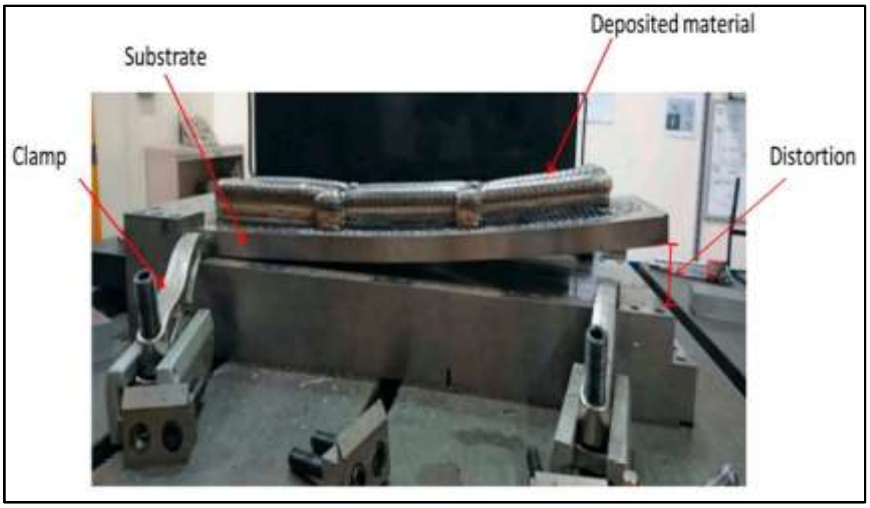

Figure 11. Structural distortion of a WAAM part, as been presented by Xu, F., et al. [17].

Table 2. WAAM common defects, their possible causes, & prevention

Type of Defect	Possible Causes	Prevention or Reduction	References
Pores	• Improper process parameters • Improper inter pass layer temperature • Bad wire quality • Insufficient alloy composition • High cooling rate • presence of Hydrogen.	• Low process pulse frequency • High heat input • High interpass layer temperature • High wire surface quality • Hot wire feeding • Vibrating workpiece • Avoid using AL Alloy	[59, 89, 98-100, 102, 103]
Lack of Fusion	• Low energy and heat input • Improper torch angle • Improper joint edge preparation • Inappropriate weld position • Insufficient filler wire material • Inappropriate weld speed with wire feed speed • Unstable weld pool dynamic • Complex thermal cycle • Inappropriate weld setup • High process weld spatter • In sufficient shielding gas	• Sufficient energy and heat input • Proper torch angle and weld joint preparations • Appropriate weld position • Sufficient filler wire material • A compatible weld speed with wire feed speed • Clean substrate surface and good wire feed quality • Stable weld pool dynamic and non-complex thermal cycle • Appropriate shielding gas and prevention weld spatter	[7, 27, 120, 125, 126]
Cracks	• Un-weldable alloy • Alloy with high solidification range • High thermal and/or mechanical stresses • High heat input • Columnar grain type and large grain size formation • Large mushy zone size • Large HAZ size • Presence of Hydrogen gas around the weld pool • Insufficient filler wire material and quality • In appropriate weld pool motion	• Weldable alloy • Avoiding alloys with large solidification range • Low thermal and/or mechanical stresses • Low heat input • Equiaxed grain type and small grain size formation • Small mushy zone • Small HAZ size • Avoid presence of Hydrogen around weld pool • Sufficient filler material and quality • Weave weld pool motion	[130, 131, 133, 137-142]
Residual Stresses & Distortion	• Insufficient weld process parameters • Complex thermal cycle • Extreme heat input • Inappropriate preheating temperature • Insufficient heat treatment or inter pass cooling • Inadequate deposition path	• Proper weld process parameters • Controlling thermal cycle • Sufficient heat input • Appropriate heat treatment or inter pass cooling • Adequate process deposition path • Applying CMT • Applying inter pass rolling process	[35, 70, 151, 157-162]

SUMMARY & CONCLUSION

Based on many recent respectful study articles published in the field of wire arc additive manufacturing, this review work delivers an inclusive view of the progress made and valuable knowledge to researchers around the world who seek new findings and make a difference to increase the acceptability and the applicability of the WAAM process. This review focused on the common defects that are highly possible in fabricated components during WAAM process. Despite WAAM process advantages and superiority, if wrong process preparation and/or incorrect WAAM process parameters used, then serious issues can be found in the manufactured components and alter the final product quality. Defects such as Pores, cracks, lack of fusion, residual stresses and distortions are the most common and serious defects can be produced when WAAM process is applied. Hence, the cause and prevention of these defects in WAAM process and the effort of all mentioned researchers and their work results are summarized in the previous Table 2. On the other hand, this review work does not focus on the defect's evaluation and inspection techniques, but it does summarize the common types of defects, causes, and prevention ways.

ACKNOWLEDGEMENT

The author sends special and grateful thanks to all mentioned researchers for their wonderful work and rich information, which has been gathered to assist and help in delivering this review study and building up defect prevention guidance to WAAM process operators.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

1. Vafadar, A., et al., *Advances in metal additive manufacturing: a review of common processes, industrial applications, and current challenges.* Applied Sciences, 2021. **11**(3): p. 1213.
2. Citarella, R. and V. Giannella, *Additive Manufacturing in Industry*. 2021, Multidisciplinary Digital Publishing Institute. p. 840.
3. Paul, A., et al. *A real-time iterative machine learning approach for temperature profile prediction in additive manufacturing processes*. in *2019 IEEE International Conference on Data Science and Advanced Analytics (DSAA)*. 2019. IEEE.
4. Kim, F.H., F.H. Kim, and S.P. Moylan, *Literature review of metal additive manufacturing defects*. 2018: US Department of Commerce, National Institute of Standards and Technology ….
5. Athaib, N.H., A.H. Haleem, and B. Al-Zubaidy. *A review of Wire Arc Additive Manufacturing (WAAM) of Aluminium Composite, Process, Classification, Advantages, Challenges, and Application*. in *Journal of Physics: Conference Series*. 2021. IOP Publishing.
6. Standard, A., *Standard terminology for additive manufacturing technologies.* ASTM International F2792-12a, 2012.
7. Jin, W., et al., *Wire arc additive manufacturing of stainless steels: a review.* Applied sciences, 2020. **10**(5): p. 1563.
8. Liu, P., et al., *The impact of additive manufacturing in the aircraft spare parts supply chain: supply chain operation reference (scor) model based analysis.* Production Planning & Control, 2014. **25**(13-14): p. 1169-1181.
9. Frazier, W.E., *Metal additive manufacturing: a review.* Journal of Materials Engineering and performance, 2014. **23**(6): p. 1917-1928.
10. Sames, W.J., et al., *The metallurgy and processing science of metal additive manufacturing.* International materials reviews, 2016. **61**(5): p. 315-360.
11. Das, S., D.L. Bourell, and S. Babu, *Metallic materials for 3D printing.* Mrs Bulletin, 2016. **41**(10): p. 729-741.
12. Gokuldoss, P.K., S. Kolla, and J. Eckert, *Additive manufacturing processes: Selective laser melting, electron beam melting and binder jetting—Selection guidelines.* materials, 2017. **10**(6): p. 672.
13. Gibson, I., et al., *Materials for additive manufacturing*, in *Additive Manufacturing Technologies*. 2021, Springer. p. 379-428.
14. Thapliyal, S., *Challenges associated with the wire arc additive manufacturing (WAAM) of aluminum alloys.* Materials Research Express, 2019. **6**(11): p. 112006.

15. Yilmaz, O. and A.A. Ugla, *Shaped metal deposition technique in additive manufacturing: A review.* Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 2016. **230**(10): p. 1781-1798.
16. Warsi, R., K.H. Kazmi, and M. Chandra, *Mechanical properties of wire and arc additive manufactured component deposited by a CNC controlled GMAW.* Materials Today: Proceedings, 2021.
17. Xu, F., et al., *Realisation of a multi-sensor framework for process monitoring of the wire arc additive manufacturing in producing Ti-6Al-4V parts.* International Journal of Computer Integrated Manufacturing, 2018. **31**(8): p. 785-798.
18. Rabbi, M.S., et al., *ADDITIVE MANUFACTURING TECHNOLOGY-CHALLENGES AND OPPORTUNITIES IN COVID-19 PANDEMIC TIMES.* HUMANIDADES E TECNOLOGIA (FINOM), 2020. **25**(1): p. 185-199.
19. Wu, B., et al., *A review of the wire arc additive manufacturing of metals: properties, defects and quality improvement.* Journal of Manufacturing Processes, 2018. **35**: p. 127-139.
20. Kok, Y., et al., *Anisotropy and heterogeneity of microstructure and mechanical properties in metal additive manufacturing: A critical review.* Materials & Design, 2018. **139**: p. 565-586.
21. Singh, P., et al., *Additive manufacturing of Ti-6Al-4V alloy by metal fused filament fabrication (MF3): Producing parts comparable to that of metal injection molding.* Progress in additive manufacturing, 2021. **6**(4): p. 593-606.
22. Simpson, J., et al., *Considerations for application of additive manufacturing to nuclear reactor core components*. 2019, Oak Ridge National Lab.(ORNL), Oak Ridge, TN (United States).
23. Han, C., et al., *Recent advances on high-entropy alloys for 3D printing.* Advanced Materials, 2020. **32**(26): p. 1903855.
24. Du Plessis, A., I. Yadroitsava, and I. Yadroitsev, *Effects of defects on mechanical properties in metal additive manufacturing: A review focusing on X-ray tomography insights.* Materials & Design, 2020. **187**: p. 108385.
25. Brennan, M., J. Keist, and T. Palmer, *Defects in Metal Additive Manufacturing Processes.* Journal of Materials Engineering and Performance, 2021. **30**(7): p. 4808-4818.
26. Belotti, L.P., et al., *Microstructural characterisation of thick-walled wire arc additively manufactured stainless steel.* Journal of Materials Processing Technology, 2022. **299**: p. 117373.
27. Ghaffari, M., et al., *Effect of solidification defects and HAZ softening on the anisotropic mechanical properties of a wire arc additive-manufactured low-carbon low-alloy steel part.* Jom, 2019. **71**(11): p. 4215-4224.
28. Li, B., et al., *Low-Roughness-Surface Additive Manufacturing of Metal-Wire Feeding with Small Power.* Materials, 2021. **14**(15): p. 4265.
29. Guessasma, S., et al., *Challenges of additive manufacturing technologies from an optimisation perspective.* International Journal for Simulation and Multidisciplinary Design Optimization, 2015. **6**: p. A9.
30. Dhinakaran, V., et al., *Wire Arc Additive Manufacturing (WAAM) process of nickel based superalloys–A review.* Materials Today: Proceedings, 2020. **21**: p. 920-925.
31. Benakis, M., D. Costanzo, and A. Patran, *Current mode effects on weld bead geometry and heat affected zone in pulsed wire arc additive manufacturing of Ti-6-4 and Inconel 718.* Journal of Manufacturing Processes, 2020. **60**: p. 61-74.
32. Dinovitzer, M., et al., *Effect of wire and arc additive manufacturing (WAAM) process parameters on bead geometry and microstructure.* Additive Manufacturing, 2019. **26**: p. 138-146.
33. Gu, W., E. Styger, and D.H. Warner, *Assessment of Additive Manufacturing for Increasing Sustainability and Productivity of Smallholder Agriculture.* 3D Printing and Additive Manufacturing, 2020. **7**(6): p. 300-310.
34. Jackson, M.A., et al., *Energy consumption model for additive-subtractive manufacturing processes with case study.* International Journal of Precision Engineering and Manufacturing-Green Technology, 2018. **5**(4): p. 459-466.
35. Ding, D., et al., *Wire-feed additive manufacturing of metal components: technologies, developments and future interests.* The International Journal of Advanced Manufacturing Technology, 2015. **81**(1): p. 465-481.
36. Jackson, M.A., et al., *A comparison of energy consumption in wire-based and powder-based additive-subtractive manufacturing.* Procedia Manufacturing, 2016. **5**: p. 989-1005.
37. Singh, S.R. and P. Khanna, *Wire arc additive manufacturing (WAAM): A new process to shape engineering materials.* Materials Today: Proceedings, 2021. **44**: p. 118-128.
38. Jafari, D., T.H. Vaneker, and I. Gibson, *Wire and arc additive manufacturing: Opportunities and challenges to control the quality and accuracy of manufactured parts.* Materials & Design, 2021. **202**: p. 109471.

39. Singh, S., S. kumar Sharma, and D.W. Rathod, *A review on process planning strategies and challenges of WAAM.* Materials Today: Proceedings, 2021. **47**: p. 6564-6575.
40. Rodrigues, T.A., et al., *Current status and perspectives on wire and arc additive manufacturing (WAAM).* Materials, 2019. **12**(7): p. 1121.
41. Busachi, A., et al. *Modelling applications of additive manufacturing in defence support services: introducing the AM–decision support system*. in *NATO STO Meeting Proceedings STO-MPAVT-267-3B*. 2018.
42. Korzhyk, V., et al. *Welding technology in additive manufacturing processes of 3D objects*. in *Materials Science Forum*. 2017. Trans Tech Publ.
43. Venturini, G., et al., *Optimization of WAAM deposition patterns for T-crossing features.* Procedia Cirp, 2016. **55**: p. 95-100.
44. Klobcara, D., et al., *WAAM and Other Unconventional Metal Additive Manufacturing Technologies.* Adv. Technol. Mater, 2020. **45**: p. 1-9.
45. Rodrigues, T.A., et al., *Ultracold-Wire and arc additive manufacturing (UC-WAAM).* Journal of Materials Processing Technology, 2021. **296**: p. 117196.
46. Lin, Z., et al., *Microstructure and mechanical properties of medium carbon steel deposits obtained via wire and arc additive manufacturing using metal-cored wire.* Metals, 2019. **9**(6): p. 673.
47. Srivastava, S., et al., *Measurement and mitigation of residual stress in wire-arc additive manufacturing: A review of macro-scale continuum modelling approach.* Archives of Computational Methods in Engineering, 2021. **28**(5): p. 3491-3515.
48. Xia, C., et al., *A review on wire arc additive manufacturing: Monitoring, control and a framework of automated system.* Journal of Manufacturing Systems, 2020. **57**: p. 31-45.
49. Norrish, J., J. Polden, and I.M. Richardson, *A Review of Wire Arc Additive manufacturing: Development, Principles, Process Physics, Implementation and Current Status.* Journal of Physics D: Applied Physics, 2021.
50. Paskual, A., P. Álvarez, and A. Suárez, *Study on arc welding processes for high deposition rate additive manufacturing.* Procedia Cirp, 2018. **68**: p. 358-362.
51. Li, J.Z., et al., *Review of wire arc additive manufacturing for 3D metal printing.* International Journal of Automation Technology, 2019. **13**(3): p. 346-353.
52. Artaza, T., et al., *Wire arc additive manufacturing Ti6Al4V aeronautical parts using plasma arc welding: Analysis of heat-treatment processes in different atmospheres.* Journal of Materials Research and Technology, 2020. **9**(6): p. 15454-15466.
53. Li, N., et al., *Self-adaptive control system for additive manufacturing using double electrode micro plasma arc welding.* Chinese Journal of Mechanical Engineering, 2021. **34**(1): p. 1-14.
54. Busachi, A., et al., *Designing a WAAM based manufacturing system for defence applications.* Procedia Cirp, 2015. **37**: p. 48-53.
55. Pan, Z., et al., *Arc welding processes for additive manufacturing: a review.* Transactions on intelligent welding manufacturing, 2018: p. 3-24.
56. Lopez, A.B., et al., *Phased array ultrasonic inspection of metal additive manufacturing parts.* Journal of Nondestructive Evaluation, 2019. **38**(3): p. 1-11.
57. Lopez, A., et al., *Non-destructive testing application of radiography and ultrasound for wire and arc additive manufacturing.* Additive Manufacturing, 2018. **21**: p. 298-306.
58. Li, Y., et al., *A defect detection system for wire arc additive manufacturing using incremental learning.* Journal of Industrial Information Integration, 2021: p. 100291.
59. Arana, M., et al., *Strategies to reduce porosity in Al-Mg WAAM parts and their impact on mechanical properties.* Metals, 2021. **11**(3): p. 524.
60. Gierth, M., et al., *Wire arc additive manufacturing (WAAM) of aluminum alloy AlMg5Mn with energy-reduced gas metal arc welding (GMAW).* Materials, 2020. **13**(12): p. 2671.
61. Panchenko, O., et al., *Gas Metal Arc Welding Modes in Wire Arc Additive Manufacturing of Ti-6Al-4V.* Materials, 2021. **14**(9): p. 2457.
62. Baufeld, B., O. Van der Biest, and R. Gault, *Additive manufacturing of Ti–6Al–4V components by shaped metal deposition: microstructure and mechanical properties.* Materials & Design, 2010. **31**: p. S106-S111.

63. Tian, Y., et al., *Microstructure and mechanical properties of wire and arc additive manufactured Ti-6Al-4V and AlSi5 dissimilar alloys using cold metal transfer welding.* Journal of Manufacturing Processes, 2019. **46**: p. 337-344.
64. Brandl, E., et al., *Additive manufactured Ti-6Al-4V using welding wire: comparison of laser and arc beam deposition and evaluation with respect to aerospace material specifications.* Phys. Procedia, 2010. **5**(Pt 2): p. 595-606.
65. Martina, F., et al., *Investigation of the benefits of plasma deposition for the additive layer manufacture of Ti–6Al–4V.* Journal of Materials Processing Technology, 2012. **212**(6): p. 1377-1386.
66. Lin, J., et al., *Heterogeneous microstructure evolution in Ti-6Al-4V alloy thin-wall components deposited by plasma arc additive manufacturing.* Materials & Design, 2018. **157**: p. 200-210.
67. Wang, K., et al., *Microstructural evolution and mechanical properties of Inconel 718 superalloy thin wall fabricated by pulsed plasma arc additive manufacturing.* Journal of Alloys and Compounds, 2020. **819**: p. 152936.
68. Gu, J., et al., *The strengthening effect of inter-layer cold working and post-deposition heat treatment on the additively manufactured Al–6.3 Cu alloy.* Materials Science and Engineering: A, 2016. **651**: p. 18-26.
69. Patel, M., et al., *Development and implementation of wire arc additive manufacturing (WAAM) based on pulse spray GMAW for aluminum alloy (AlSi7Mg).* Transactions of the Indian Institute of Metals, 2021. **74**(5): p. 1129-1140.
70. Vimal, K., M.N. Srinivas, and S. Rajak, *Wire arc additive manufacturing of aluminium alloys: a review.* Materials Today: Proceedings, 2021. **41**: p. 1139-1145.
71. Dong, B., et al., *Fabrication of copper-rich Cu-Al alloy using the wire-arc additive manufacturing process.* Metallurgical and Materials Transactions B, 2017. **48**(6): p. 3143-3151.
72. Zeli, W. and Y. Zhang, *A review of aluminum alloy fabricated by different processes of wire arc additive manufacturing.* Materials Science, 2021. **27**(1): p. 18-26.
73. Çam, G., *Prospects of producing aluminum parts by wire arc additive manufacturing (WAAM).* Materials Today: Proceedings, 2022.
74. Queguineur, A., et al., *Evaluation of tandem controlled short-circuit GMAW for improved deposition in additive manufacture of large Nickel Aluminium Bronze naval components.* Welding in the World, 2020. **64**(8): p. 1389-1395.
75. Antonello, M.G., et al., *Effect of electromagnetic arc constriction applied in GTAW-based wire arc additive manufacturing on walls' geometry and microstructure.* Journal of Manufacturing Processes, 2021. **71**: p. 156-167.
76. Artaza, T., et al., *Influence of heat input on the formation of laves phases and hot cracking in plasma arc welding (PAW) additive manufacturing of inconel 718.* Metals, 2020. **10**(6): p. 771.
77. Bhujangrao, T., et al., *High-temperature mechanical properties of IN718 alloy: comparison of additive manufactured and wrought samples.* Crystals, 2020. **10**(8): p. 689.
78. Tripathi, U., et al., *Effect of build direction on the microstructure evolution and their mechanical properties using GTAW based wire arc additive manufacturing.* CIRP Journal of Manufacturing Science and Technology, 2022. **37**: p. 103-109.
79. Manurung, Y.H., et al., *Analysis of material property models on WAAM distortion using nonlinear numerical computation and experimental verification with P-GMAW.* Archives of Civil and Mechanical Engineering, 2021. **21**(1): p. 1-13.
80. Srivastava, M., et al., *Analysis of Temperature Concentration During Single Layer Metal Deposition Using GMAW-WAAM: A Case Study*, in *High-Performance Composite Structures*. 2022, Springer. p. 179-189.
81. Kim, J., et al., *Effect of filler metal type on microstructure and mechanical properties of fabricated nial bronze alloy using wire arc additive manufacturing system.* Metals, 2021. **11**(3): p. 513.
82. Gu, J., et al., *Deformation microstructures and strengthening mechanisms for the wire+ arc additively manufactured Al-Mg4. 5Mn alloy with inter-layer rolling.* Materials Science and Engineering: A, 2018. **712**: p. 292-301.
83. Dharmendra, C., et al., *Microstructural evolution and mechanical behavior of nickel aluminum bronze Cu-9Al-4Fe-4Ni-1Mn fabricated through wire-arc additive manufacturing.* Additive Manufacturing, 2019. **30**: p. 100872.
84. Shen, C., et al., *Fabrication of iron-rich Fe–Al intermetallics using the wire-arc additive manufacturing process.* Additive Manufacturing, 2015. **7**: p. 20-26.
85. Wang, L., et al., *Fabrication of γ-TiAl intermetallic alloy using the twin-wire plasma arc additive manufacturing process: microstructure evolution and mechanical properties.* Materials Science and Engineering: A, 2021. **812**: p. 141056.
86. Gu, J.L., et al. *The influence of wire properties on the quality and performance of wire+ arc additive manufactured*

aluminium parts. in *Advanced Materials Research*. 2015. Trans Tech Publ.
87. Hauser, T., et al., *Porosity in wire arc additive manufacturing of aluminium alloys.* Additive Manufacturing, 2021. **41**: p. 101993.
88. Anyalebechi, P.N., *Hydrogen-induced gas porosity formation in Al–4.5 wt% Cu–1.4 wt% Mg alloy.* Journal of Materials Science, 2013. **48**(15): p. 5342-5353.
89. Fu, R., et al., *Hot-wire arc additive manufacturing of aluminum alloy with reduced porosity and high deposition rate.* Materials & Design, 2021. **199**: p. 109370.
90. Gu, J., et al., *Micropore evolution in additively manufactured aluminum alloys under heat treatment and inter-layer rolling.* Materials & Design, 2020. **186**: p. 108288.
91. Ryan, E., et al., *The influence of build parameters and wire batch on porosity of wire and arc additive manufactured aluminium alloy 2319.* Journal of Materials Processing Technology, 2018. **262**: p. 577-584.
92. Gu, J., et al., *The effect of inter-layer cold working and post-deposition heat treatment on porosity in additively manufactured aluminum alloys.* Journal of materials processing technology, 2016. **230**: p. 26-34.
93. Kurakin, A.I., et al. *Influence of Surfacing Modes on the Formation of Pores in the Deposited Metal Produced by Wire Arc Additive Method (WAAM) Using Al-Mg Alloy*. in *Materials Science Forum*. 2021. Trans Tech Publ.
94. Lu, T., et al., *Hot-wire arc additive manufacturing Ti–6.5 Al–2Zr–1Mo–1V titanium alloy: Pore characterization, microstructural evolution, and mechanical properties.* Journal of Alloys and Compounds, 2020. **817**: p. 153334.
95. Winterkorn, R., A. Pittner, and M. Rethmeier, *Wire Arc Additive Manufacturing with Novel Al-Mg-Si Filler Wire—Assessment of Weld Quality and Mechanical Properties.* Metals, 2021. **11**(8): p. 1243.
96. Bandyopadhyay, A. and K.D. Traxel, *Invited review article: Metal-additive manufacturing—Modeling strategies for application-optimized designs.* Additive manufacturing, 2018. **22**: p. 758-774.
97. Cunningham, C., et al., *Invited review article: Strategies and processes for high quality wire arc additive manufacturing.* Additive Manufacturing, 2018. **22**: p. 672-686.
98. Wang, D., et al., *Reducing porosity and refining grains for arc additive manufacturing aluminum alloy by adjusting arc pulse frequency and current.* Materials, 2018. **11**(8): p. 1344.
99. Derekar, K.S., et al., *Effect of pulsed metal inert gas (pulsed-MIG) and cold metal transfer (CMT) techniques on hydrogen dissolution in wire arc additive manufacturing (WAAM) of aluminium.* The International Journal of Advanced Manufacturing Technology, 2020. **107**(1): p. 311-331.
100. Derekar, K., et al. *Influence of interpass temperature on wire arc additive manufacturing (WAAM) of aluminium alloy components*. in *MATEC Web of Conferences*. 2019. EDP Sciences.
101. Cong, B., J. Ding, and S. Williams, *Effect of arc mode in cold metal transfer process on porosity of additively manufactured Al-6.3% Cu alloy.* The International Journal of Advanced Manufacturing Technology, 2015. **76**(9): p. 1593-1606.
102. Bai, J., et al. *Porosity evolution in additively manufactured aluminium alloy during high temperature exposure*. in *IOP Conference Series: Materials Science and Engineering*. 2017. IOP Publishing.
103. Fang, X., et al., *Microstructure evolution of wire-arc additively manufactured 2319 aluminum alloy with interlayer hammering.* Materials Science and Engineering: A, 2021. **800**: p. 140168.
104. Zhang, C., M. Gao, and X. Zeng, *Workpiece vibration augmented wire arc additive manufacturing of high strength aluminum alloy.* Journal of Materials Processing Technology, 2019. **271**: p. 85-92.
105. Murav'ev, V., et al., *Effect of the quality of filler wire on the formation of pores in welding of titanium alloys.* Welding International, 2008. **22**(12): p. 853-858.
106. Derekar, K., *A review of wire arc additive manufacturing and advances in wire arc additive manufacturing of aluminium.* Materials science and technology, 2018. **34**(8): p. 895-916.
107. Wang, S., et al., *The influence of heat input on the microstructure and properties of wire-arc-additive-manufactured Al-Cu-Sn alloy deposits.* Metals, 2020. **10**(1): p. 79.
108. Béraud, N., et al., *An indicator of porosity through simulation of melt pool volume in aluminum wire arc additive manufacturing.* Mechanics & Industry, 2022. **23**: p. 1.
109. Derekar, K., *Aspects of Wire Arc Additive Manufacturing (WAAM) of Alumnium Alloy 5183*. 2020, Coventry University.

110. Gu, J., et al. *Wire+ arc additive manufacturing of aluminum*. in *2014 International Solid Freeform Fabrication Symposium*. 2014. University of Texas at Austin.
111. Henckell, P., et al., *Reduction of energy input in wire arc additive manufacturing (WAAM) with gas metal arc welding (GMAW).* Materials, 2020. **13**(11): p. 2491.
112. Reisch, R., et al. *Distance-based multivariate anomaly detection in wire arc additive manufacturing*. in *2020 19th IEEE International Conference on Machine Learning and Applications (ICMLA)*. 2020. IEEE.
113. Chen, X., et al., *A review on wire-arc additive manufacturing: typical defects, detection approaches, and multisensor data fusion-based model.* The International Journal of Advanced Manufacturing Technology, 2021. **117**(3): p. 707-727.
114. Xie, C., et al., *Defect-correlated fatigue resistance of additively manufactured Al-Mg4. 5Mn alloy with in situ micro-rolling.* Journal of Materials Processing Technology, 2021. **291**: p. 117039.
115. Hu, Y., et al., *The effect of manufacturing defects on the fatigue life of selective laser melted Ti-6Al-4V structures.* Materials & Design, 2020. **192**: p. 108708.
116. Gong, H., et al., *Influence of defects on mechanical properties of Ti–6Al–4 V components produced by selective laser melting and electron beam melting.* Materials & Design, 2015. **86**: p. 545-554.
117. Rihar, G. and M. Uran, *Lack of fusion characterisation of indications.* Welding in the World, 2006. **50**(1): p. 35-39.
118. Saresh, N., M.G. Pillai, and J. Mathew, *Investigations into the effects of electron beam welding on thick Ti–6Al–4V titanium alloy.* Journal of Materials Processing Technology, 2007. **192**: p. 83-88.
119. Everton, S.K., et al., *Review of in-situ process monitoring and in-situ metrology for metal additive manufacturing.* Materials & Design, 2016. **95**: p. 431-445.
120. Mukherjee, T. and T. DebRoy, *Mitigation of lack of fusion defects in powder bed fusion additive manufacturing.* Journal of Manufacturing Processes, 2018. **36**: p. 442-449.
121. Di, W., et al., *Study on energy input and its influences on single-track, multi-track, and multi-layer in SLM.* The International Journal of Advanced Manufacturing Technology, 2012. **58**(9): p. 1189-1199.
122. Buchbinder, D., et al., *High power selective laser melting (HP SLM) of aluminum parts.* Physics Procedia, 2011. **12**: p. 271-278.
123. Tammas-Williams, S., et al., *XCT analysis of the influence of melt strategies on defect population in Ti–6Al–4V components manufactured by Selective Electron Beam Melting.* Materials Characterization, 2015. **102**: p. 47-61.
124. Darvish, K., Z. Chen, and T. Pasang, *Reducing lack of fusion during selective laser melting of CoCrMo alloy: Effect of laser power on geometrical features of tracks.* Materials & Design, 2016. **112**: p. 357-366.
125. Jovanovic, M., J. Grum, and M. Uran. *Influence of lack-of-fusion defects on load capacity of MAG welded joints*. in *17th World Conference on Nondestructive Testing, Shanghai-China*. 2008. Citeseer.
126. Marinelli, G., et al., *Development of Wire+ Arc Additive Manufacturing for the production of large-scale unalloyed tungsten components, ArXiv. Org.(2019)*. 1902.
127. Cheng, Y., et al., *Effect of TiC/TiC–TiB2 on microstructure and mechanical properties of spray formed 7055 aluminum alloy TIG welded joints.* Journal of Materials Research and Technology, 2021. **15**: p. 1667-1677.
128. Sokoluk, M., et al., *Nanoparticle-enabled phase control for arc welding of unweldable aluminum alloy 7075.* Nature communications, 2019. **10**(1): p. 1-8.
129. Huang, T., et al., *Appropriate amount of TiB2 particles causes the ductile fracture of the un-weldable spray-formed 7055 aluminium alloy TIG-welded joint.* Materials Research Express, 2021. **8**(9): p. 096512.
130. Murali, N., et al., *Gas-Tungsten Arc welding of dissimilar aluminum alloys with Nano-Treated filler.* Journal of Manufacturing Science and Engineering, 2021. **143**(8).
131. Zhang, G., C. Xiao, and M. Taheri, *Effect of Nd: YAG pulsed laser welding process on the liquation and strain-age cracking in GTD-111 superalloy.* Journal of Manufacturing Processes, 2020. **52**: p. 66-78.
132. Taheri, M., et al., *Relationship between solidification and liquation cracks in the joining of GTD-111 nickel-based superalloy by Nd: YAG pulsed-laser welding.* Journal of Materials Research and Technology, 2021. **15**: p. 5635-5649.
133. Albannai, A., et al., *Effects of tandem side-by-side GTAW welds on centerline solidification cracking of AA2024.* Manufacturing Technology, 2021. **21**(2): p. 151-163.

134. Agarwal, G., et al., *Evaluation of solidification cracking susceptibility during laser welding in advanced high strength automotive steels.* Materials & Design, 2019. **183**: p. 108104.
135. Seow, C.E., et al., *Effect of crack-like defects on the fracture behaviour of Wire+ Arc Additively Manufactured nickel-base Alloy 718.* Additive Manufacturing, 2020. **36**: p. 101578.
136. Aucott, L., et al., *Initiation and growth kinetics of solidification cracking during welding of steel.* Scientific reports, 2017. **7**(1): p. 1-10.
137. Langelandsvik, G., et al., *Review of Aluminum Alloy Development for Wire Arc Additive Manufacturing.* Materials, 2021. **14**(18): p. 5370.
138. Kang, M., H.N. Han, and C. Kim, *Microstructure and solidification crack susceptibility of Al 6014 molten alloy subjected to a spatially oscillated laser beam.* Materials, 2018. **11**(4): p. 648.
139. Kou, S. and Y. Le, *Grain structure and solidification cracking in oscillated arc welds of 5052 aluminum alloy.* Metallurgical Transactions A, 1985. **16**(7): p. 1345-1352.
140. Albannai, A.I., et al., *Improving Centerline Solidification Crack Resistivity of AA 2024 Using Tandem Side-by-Side GTAW Technique.* Materials Performance and Characterization, 2019. **8**(4): p. 541-554.
141. Yu, P., J. Morrow, and S. Kou, *Resistance of austenitic stainless steels to ductility-Dip cracking: mechanisms.* Weld J, 2021. **100**: p. 291s-301s.
142. Chen, Y., et al., *Characterization of heat affected zone liquation cracking in laser additive manufacturing of Inconel 718.* Materials & Design, 2016. **90**: p. 586-594.
143. Chen, S., et al., *Thermal–microstructural analysis of the mechanism of liquation cracks in wire-arc additive manufacturing of Al–Zn–Mg–Cu alloy.* Journal of Materials Research and Technology, 2022. **16**: p. 1260-1271.
144. Zhang, J., D. Weckman, and Y. Zhou, *Effects of temporal pulse shaping on cracking susceptibility of 6061-T6 aluminum Nd: YAG laser welds.* WELDING JOURNAL-NEW YORK-, 2008. **87**(1): p. 18.
145. DebRoy, T., et al., *Additive manufacturing of metallic components–process, structure and properties.* Progress in Materials Science, 2018. **92**: p. 112-224.
146. Colegrove, P.A., et al., *Microstructure and residual stress improvement in wire and arc additively manufactured parts through high-pressure rolling.* Journal of Materials Processing Technology, 2013. **213**(10): p. 1782-1791.
147. Lee, Y., et al., *Effect of interlayer cooling time, constraint and tool path strategy on deformation of large components made by laser metal deposition with wire.* Applied Sciences, 2019. **9**(23): p. 5115.
148. Abbaszadeh, M., et al., *Numerical investigation of the effect of rolling on the localized stress and strain induction for wire+ arc additive manufactured structures.* Journal of Materials Engineering and Performance, 2019. **28**(8): p. 4931-4942.
149. Price, J.W., et al., *Comparison of experimental and theoretical residual stresses in welds: The issue of gauge volume.* International Journal of Mechanical Sciences, 2008. **50**(3): p. 513-521.
150. Herzog, D., et al., *Additive manufacturing of metals.* Acta Materialia, 2016. **117**: p. 371-392.
151. Wu, B., et al., *Mitigation of thermal distortion in wire arc additively manufactured Ti6Al4V part using active interpass cooling.* Science and Technology of Welding and Joining, 2019. **24**(5): p. 484-494.
152. Bermingham, M., et al., *Optimising the mechanical properties of Ti-6Al-4V components produced by wire+ arc additive manufacturing with post-process heat treatments.* Journal of Alloys and Compounds, 2018. **753**: p. 247-255.
153. Wu, Q., et al., *Residual stresses in wire-arc additive manufacturing–Hierarchy of influential variables.* Additive Manufacturing, 2020. **35**: p. 101355.
154. Chaturvedi, M., et al., *Wire arc additive manufacturing: Review on recent findings and challenges in industrial applications and materials characterization.* Metals, 2021. **11**(6): p. 939.
155. Panicker, C.J., K.R. Surya, and V. Senthilkumar, *Novel process parameters based approach for reducing residual stresses in WAAM.* Materials Today: Proceedings, 2022.
156. Zhang, C., et al., *Influence of wire-arc additive manufacturing path planning strategy on the residual stress status in one single buildup layer.* The International Journal of Advanced Manufacturing Technology, 2020. **111**(3): p. 797-806.
157. Ravisankar, A., et al., *Influence of welding speed and power on residual stress during gas tungsten arc welding (GTAW) of thin sections with constant heat input: a study using numerical simulation and experimental validation.* Journal of

ISSN: 2581-8341
Volume 05 Issue 12 December 2022
DOI: 10.47191/ijcsrr/V5-i12-19, Impact Factor: 5.995
IJCSRR @ 2022
www.ijcsrr.org

Manufacturing Processes, 2014. **16**(2): p. 200-211.

158. Vazquez, L., et al., *Influence of Post-Deposition Heat Treatments on the Microstructure and Tensile Properties of Ti-6Al-4V Parts Manufactured by CMT-WAAM.* Metals, 2021. **11**(8): p. 1161.

159. Martina, F., et al. *Residual stress reduction in high pressure interpass rolled wire+ arc additive manufacturing Ti-6Al-4V components*. in *2014 International Solid Freeform Fabrication Symposium*. 2014. University of Texas at Austin.

160. Hönnige, J., et al., *Control of residual stress and distortion in aluminium wire+ arc additive manufacture with rolling.* Additive Manufacturing, 2018. **22**: p. 775-783.

161. Sun, R., et al., *Microstructure, residual stress and tensile properties control of wire-arc additive manufactured 2319 aluminum alloy with laser shock peening.* Journal of Alloys and Compounds, 2018. **747**: p. 255-265.

162. Shen, C., et al., *Neutron diffraction residual stress determinations in Fe3Al based iron aluminide components fabricated using wire-arc additive manufacturing (WAAM).* Additive Manufacturing, 2019. **29**: p. 100774.

Cite this Article: Abdulaziz I. Albannai (2022). A Brief Review on The Common Defects in Wire Arc Additive Manufacturing (Review Paper). International Journal of Current Science Research and Review, 5(12), 4556-4576