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A review of present status and challenges of using additive manufacturing technology for offshore wind applications

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Abstract

Offshore wind is an efficient sustainable source of energy, which is a preferable alternative to burning fossil fuels in Europe and worldwide. About 85% of existing offshore wind turbines are supported using monopile foundations, which are made of large welded plates. The locked in residual stresses in a monopile structure have a great impact on its fatigue life. The new emerged technology of additive manufacturing (AM), which is widely used in other industries such as aerospace and automotive, has the potential to significantly improve a lifespan of the structure by managing the residual stress fields and microstructure in the future monopiles, and moreover reduce the manufacturing cost. In order to achieve this goal, new materials that are used for additive manufacturing parts fabrication and their behaviour in the harsh marine environment and under operational loading conditions need to be understood. Also purely welding fabrication technique employed during AM process is likely to significantly affect crack growth behaviour in air as well as in seawater. This paper presents a review of additive manufacturing technology and suitable techniques for offshore structures. Existing literature that reports current data on fracture toughness and fatigue crack growth tests conducted on AM parts is summarised and analysed, highlighting different steel grades and applications, with the view to illustrating the requirements for the new optimised functionally graded structures in offshore wind structures by means of AM technique.

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Keywords: Offshore wind; Additive manufacturing; Fatigue crack growth.

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1. Introduction

The urge for the renewable energy source is dramatically increasing the number of wind farm installations worldwide. Offshore wind energy is attracting more interest in recent years due to constrains of suitable onshore space and reducing trend in the levelised cost of offshore wind energy. Offshore sites ensure larger space and better wind potential, hence more efficient energy outcome, but at relatively higher cost.

The majority of the existing offshore wind farms are located in shallow waters with maximum depth of 30 m and about 85% of them are supported by monopile structures, due to design simplicity and cost effectiveness. Monopiles are fabricated out of thick plates of new grades of steel such as S355, and comprise of several cylindrical sections circumferentially welded together. Typical monopile dimensions range from 50 to 70 m in length, 3 to 10 m in diameter and 40 to 150 mm in wall thickness [1]. However, due to rapid development of the wind industry and increasing demand for more efficient wind turbines, the monopile structures may have to be increased, and this will significantly increase the associated production and installation costs. The installation phase is the most critical stage of commissioning an offshore wind turbine which is time consuming and involves the high capital cost [2, 3].

Monopiles are installed by placing them into the seabed. Thus the structure should withstand the hammering loads, which depend on the soil condition and vary from site to site. During operation, monopiles are subjected to wind, sea wave and current cyclic loads as well as static gravitational, hydrostatic and aerodynamic loads. Therefore they have to be designed against failure for a certain period of fatigue life and for corresponding magnitudes of static loads. Apart from the operational loads, monopile foundations are subjected to relatively harsh marine environment. Corrosion-fatigue is reported as the dominant mode of failure in monopiles across relatively narrow band of frequencies [4]. Moreover it has been presented in many researches that welding residual stresses alter the mean stresses under cyclic loading and consequently influence fatigue crack growth behaviour of materials [5, 6].

Emerging new materials and manufacturing techniques can be considered to address the current challenges of the renewable wind industry and future sustainable goals.

2. Additive Manufacturing Techniques

Nowadays additive manufacturing (AM) has gained considerable attention for industries that are targeting low volume production of highly customised parts for specific applications. The technology offers building the 3D model layer upon layer using additive process instead of conventional subtractive method, which can lead to waste reduction. This new manufacturing technology has opened new avenues for fabricating net-shaped structures and assemblies of complex geometries that traditional manufacturing is unable to provide [7, 8]. With less geometrical constrains AM provides benefits to industries for building lighter and cleaner products by establishing new design paradigms within shorter lead times and with lower cost [9, 10]. Moreover, AM allows the ability to remote manufacturing and repair upon request as well as manufacturing of functionally-graded components, which makes it beneficial and suitable for the offshore wind energy applications [11].

However, there are some metallurgical differences between conventional and AM built components, such as mechanical anisotropy, residual stress, and defects inherent in AM processes that must be addressed for critical applications, related to fatigue exposure in particular [12]. The behaviour of new materials used in AM needs to be understood with respect to the area of application. Also the new fabrication technique mostly consisting of welding process is likely to influence crack growth behaviour of the materials in air, as well as in sea water environments. This is caused due to changes in microstructure of the welded material and level of residual stresses accumulated during welding process [13]. Thus the new database on fracture toughness and air/corrosion fatigue crack growth tests needs to be generated for each new material and technique.

During AM process the feedstock material, such as powder or wire, is consolidated into a dense metallic part by melting and solidification by means of energy source such as laser, electron beam or electric arc [13]. The typical metal AM techniques can be divided into two main groups based on type of deposited material: powder bed fusion (PBF) and direct energy deposition (DED). Comparison of the main techniques' features is presented in Table 1.

Based on the comparative study and the scale of offshore wind turbine support structures, DED AM seems to be the most suitable technique to be considered for further analysis. DED represents such technologies as Laser Engineering Net Shape (LENS), Electron Beam Additive Manufacturing (EBAM) and Wire + Arc Additive Manufacturing (WAAM), which use of laser, electron beam and electric arc for fusion respectively.

Table 1 Comparison of PBF and DED AM techniques

AM technique	Advantages	Disadvantages
PBF	- High density parts - can achieve a density over 99%, hence properties similar to the bulk material - High geometrical accuracy of fabricated parts ±0.05 mm	- Time consuming, as the height of a powder layer is typically between a few tens of microns to just below 100 microns, depositing around 10 g/min - Fine powders as the starting material can pose health and safety concerns - Low availability and high cost of raw material, costly recycling - High porosity level, that reduces the fatigue life
DED	- Cheaper raw material (wire) and less waste, as up to 100% of the wire is deposited into component - Fast builds with rapid material deposition (330 g/min for steel) - Process allows parts repair	- Poor surface finish and less accuracy of wire process - Limited options of materials

3. Wire + Arc Additive Manufacturing

Wire + Arc Additive Manufacture (WAAM) is a promising DED technology for fabricating large components with moderate complexity from a variety of metallic alloys. WAAM is a direct feed process with an arc heat source and metallic wire as the feedstock. The component fabricated by WAAM consists of weld beads, deposited on top of each other. Due to high deposition rates, relatively low equipment and material cost and good structural integrity of built parts, WAAM is becoming a beneficial replacement for machining parts out of solid wrought material [14].

Essentially, WAAM technology divides the three-dimensional model into several two-dimensional layers with nominal height, where layer height is limited and depends on process setup [15]. Each layer is built by moving the torch along the required tool path. The quality of each layer affects the locked-in residual stresses, dimensional inaccuracies, defects, distortion, etc. Therefore, it is essential to select a building strategy which will result building a flat surface to be a good base for the following layers. The simplest strategy is a wall, when the thickness of the required product matches the thickness of the deposited material. In order to build wider walls, parallel or oscillation building strategies can be implemented [16]. For the first method wall layer is divided into several parallel weld beads, whereas for the second, oscillation manner is used (Figure 1**Error! Reference source not found.**).

Oscillation patterns offer several advantages compared to the parallel, such as flexibility of building various wall widths without continuous change of weld parameters. Therefore, it provides more accurate control of wall thickness. Also, oscillation strategy reduces the probability of fusion defects, since this process is warmer compared to the parallel deposition. Moreover, due to continuous deposition of one layer, this strategy is less time consuming [17].

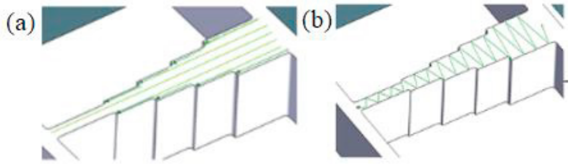

Figure 1 Geometric patterns for layer depositing: (a) parallel and (b) oscillation [17]

One of the major concerns in WAAM process is the control of residual stresses and distortions, especially for the large-scale parts fabrication, as it affects the tolerance and causes premature failure. The reason for thermally induced stresses in welding is thermally induced strains given by non-uniform expansion and contraction of material. Moreover, once the completed part is unclamped from the fabrication table, residual stresses are redistributed which may result in the distortion of the AM built component. Even though the residual stresses can be minimised by post processing techniques, the distortion due to the stresses can only be limited by controlling the residual stresses during the deposition [18].

4. Mechanical and Fatigue Properties of WAAM components

4.1. WAAM strategies

Different WAAM strategies have been investigated on thermal stresses, altering deposition patterns and sequences, reliable printing parameters, and adjusting the cooling time between layers. It was reported by Ding D. et al [18] that stresses across the deposited wall are typically uniform with little influence from the adjacent layers. Xiong et al. [19] worked on effective adjustment of the weld bead width. Later Xiang and Zhang [20] presented a control system for consistent nozzle height position. Meanwhile Ding J. et al. [21] developed a gas shielding device for WAAM system. Xiong et al. [22] have investigated a closed loop control process for metal deposition. Effects of deposition pattern, sequences on residual stress available in the literature mainly present two dimensional layers or thin wall structures. Thus, for real engineering applications, the optimum deposition strategy for reducing the residual stresses caused by WAAM are not yet defined.

4.2. Layer by layer material properties

The material properties of steel subjected to WAAM process are poorly characterised to date. Suryakumar et al. [23] reported that number of layers affects the hardness of the product; the layers on the top of the part experience fewer thermal cycles and this leads to improved hardness of the material (Figure 2). Also they revealed that residual effects do not propagate deeper than five layers.

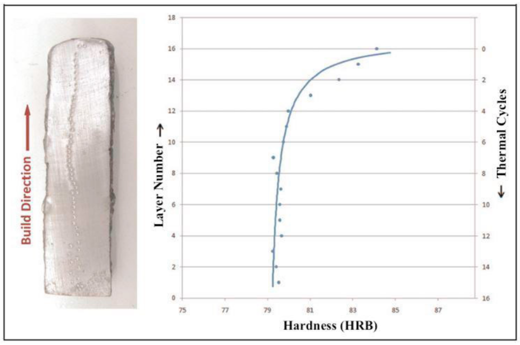

Figure 2 Hardness of WAAM wall against number of layers [23]

Ding et al. [21] developed a thermos-mechanical properties model to predict residual stresses in the fabricated part and associated distortions. It was stated by Colegrove et al. [24], that post processing treatment, such as rolling, can release the residual stresses and hence distortions, particularly in the layers close to the base plate. Moreover high-pressure rolling causes grain refinement and leads to improvement in microstructure of WAAM mild steels.

4.3. Yield and ultimate tensile strength variation

Mechanical properties of WAAM specimens have been extensively investigated by such research groups as [23, 25, 27, 30]. Haden et al. [25] have suggested that WAAM material properties can be controlled and designed by careful toolpath planning. Samples extracted from WAAM wall built out of ER70S-6 were investigated in their study and the effect of horizontal and vertical orientation on the test results was examined. A single line microhardness test was conducted to compare material strength of WAAM printed wall to wrought part. The results shown that the printed material has an average value between minimum and maximum values for bulk ASTM A36, composition of which is nearly identical to ER70S. Uniaxial tensile test of WAAM specimen (Figure 3a) revealed typical behaviour of wrought material for low carbon steels in [26]. The AM printed mild steel yield strength is also similar to characteristics of wrought A36 steel (Figure 3b). As it can be seen in Figure 3b that the orientation of specimen does not show significant difference in yield stress and the results from both orientations have shown similar ranges. Similar observation has been made in the ultimate tensile strength results obtained from samples with different orientations with about 5% difference between the two (Figure 3c). Similar results have been observed and reported by Lu et al. [27].

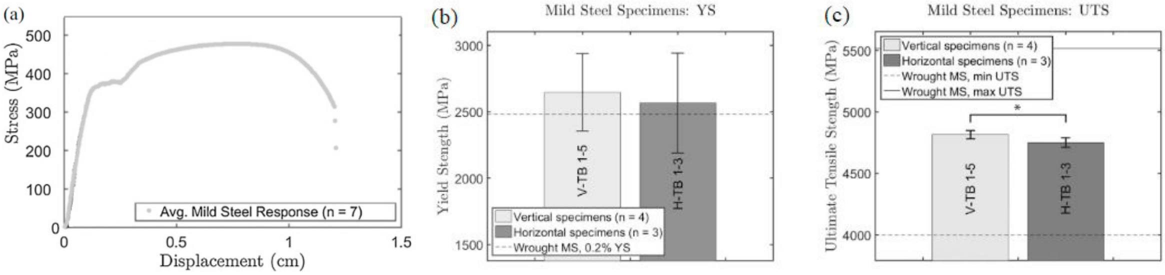

Figure 3 ER70S-6 material characteristics (a) stress-displacement curve (b) yield strength (c) ultimate tensile strength [25]

Suryakumar et al. [23] investigated all three orientations of ER70S samples, adding a stepover direction – perpendicular to the torch direction in XY plane. It was found in their study that ultimate strength in the stepover direction shown the best result. However variations of yield and ultimate strength between torch and stepover directions is within 7.6% and 4.8% respectively, whereas the difference between XY plane and vertical direction is more significant: 10.6% and 10.8%. Moreover, it was observed in their study that the tensile strength can be further improved by increasing the current of welding arc.

4.4. Charpy impact tests

Charpy impact tests were conducted by Waqas et al. [28] on sub-size specimens made of ER70S-6 steel. It was concluded that the impact toughness of printed steel is higher than the wrought low carbon steel with comparable hardness. Parallel and perpendicular orientations of the samples did not show significant difference of results (within 10%) indicating relatively homogenous properties with ductile behaviour across the volume of the AM build component.

4.5. Fracture toughness analysis

Fracture toughness tests were performed on the standard Compact Tension (C(T)) specimens printed by WAAM technique from Ti-6Al-4V wire by Zhang et al. [29]. It was observed that fracture toughness of such specimens is comparable or greater than properties of wrought titanium material. Also it was found that fracture toughness results depend on orientation of the sample and is higher when crack propagates perpendicular to the additive layers.

4.6. S-N Characterisation

Flat dog-bone specimens for this research by Gordon et al. [30] were extracted from single bead WAAM walls fabricated from 304L stainless steel. The experimental S-N curves can be seen in Figure 4, summarising the mean values for horizontal and vertical WAAM specimens fatigue data. The graph shows that build orientation also affects fatigue life of WAAM samples, and for vertical specimens the fatigue life is longer. Additionally AM samples have greater median number of cycles to failure than conventionally built samples.

4.7. Fatigue analysis

There are limited studies on the fatigue crack initiation and propagation in WAAM steels available in the literature. Fatigue crack growth of WAAM fabricated components using 304L stainless steel was investigated by Gordon et al. [31] and their observations were explained in terms of the microstructure, texture and locked-in residual stresses in the specimens. The fatigue crack growth behaviour of the Paris region of the WAAM samples have shown better results compared to conventional wrought stainless steel (Figure 5), as WAAM printed material provides improved fatigue crack growth resistance and monotonic properties. Different fatigue crack growth rates for vertical and horizontal specimens can be justified by presence of long columnar grains and stronger texture in build direction. Moreover, it was observed that retained residual stresses positively affect fatigue crack growth for specimens in both orientations when the test results from as-printed samples were compared with stress relieved specimens.

The examination of fatigue crack growth of WAAM titanium samples has been extensively investigated by other researchers such as [29, 32]. For example, analysis of WAAM Ti-6Al-4V specimens by Zhang et al. [29] shown that fatigue crack growth rate is considerably lower than in the wrought alloy. Moreover it was observed that the rate is slightly faster (within the range of data scatter) when the crack propagates through AM layers, this indicates that WAAM material can be considered to have isotropic fatigue crack growth rate. The effect of microstructure and residual stress on fatigue crack growth behaviour was studied by Zhang et al. [32]. Where the Ti-6Al-4V specimens contain a combination of WAAM and wrought material in different orientations. Conclusion was made that crack propagation rate in WAAM material is lower, due to tortuous path in lamellar structure of WAAM alloy.

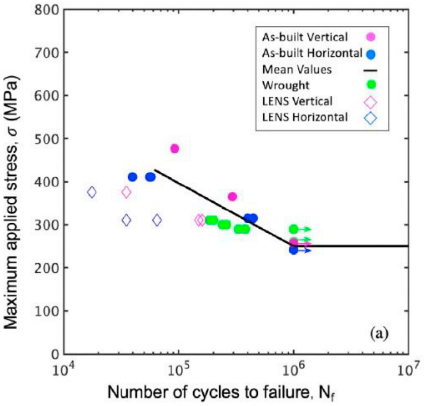

Figure 4 S-N curve for printed WAAM and wrought 304L steel [30]

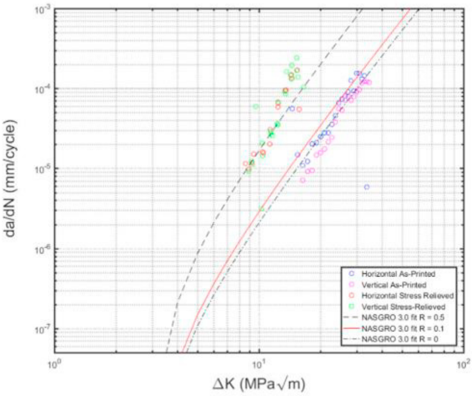

Figure 5 Comparison of fatigue crack growth rate of WAAM as-build and heat treated specimens to wrought material (NASGRO model) [31]

The limited results available in the literature suggest that AM process significantly affects the corrosion performance of materials, however more studies need to be performed to achieve solid conclusions, especially to examine corrosion damage in WAAM steels for which no data has been found in the literature. Some beneficial effects in corrosion resistance have been reported by Ganesh et al. [33], showing that corrosion pitting resistance behaviour was found in austenitic stainless steel specimens fabricated by direct laser deposition AM method. The influence of inclusions in high temperature water (288^{0}C) was investigated by Lou et al. [34] on stainless steel specimens fabricated by means of AM selective laser melting (SLM) method. The printed samples shown better corrosion resistance compared to the wrought stainless steel specimens. Corrosion-fatigue crack growth was analysed by Lou et al. [35] in hot pressurised waterer 288^{0}C. Samples were SLM printed using stainless steel material and test specimens were examined in two different orientations. Specimens extracted from X-Z plane (load applied in X direction and crack growth along Z direction) presented higher crack growth rate. It was also observed that in both specimen orientations, a lower resistance to fatigue crack growth was observed compared to wrought stainless steel (Figure 6), though the stress intensity range and load ratio during tests were not identical. Similar specimens were utilised for another study on corrosion-fatigue crack growth in pure water at 288^{0}C by Lou et al. [36]. It was observed that longer cracks appeared in X-Z samples – along direction of the build. Corrosion fatigue crack growth rate of the AM specimens was found higher than for the wrought counterpart (Figure 7). A study conducted by GE Global Research [37], has shown that fatigue and corrosion-fatigue crack growth rates in air and hot water are similar for wrought and PBF AM stainless steel specimens.

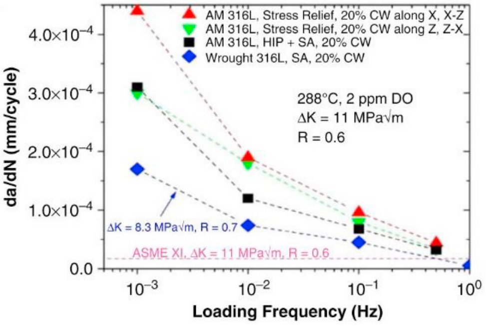

Figure 6 Corrosion fatigue crack growth of AM and wrought stainless steel in hot water [35]

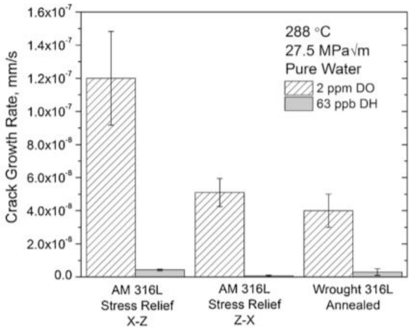

Figure 7 Comparison of crack growth rate of SLM and wrought stainless steel [36]

5. Conclusion and future work

Additive manufacturing has been rapidly developed for the past decade providing capability of complex shapes fabrication with less material waste and at lower cost and shorter lead times. As shown in the present literature review, printed WAAM mild steel parts have displayed similar yield and ultimate tensile strength compared with wrought material. Also, higher Charpy impact test results have been found in WAAM steel specimens compared to the wrought steel. Moreover, material properties of WAAM specimens were concluded to be relatively uniform. It was reported that fracture toughness of WAAM Ti-6Al-4V specimens is comparable or greater compared with wrought material. The experimental S-N curves for WAAM 304L stainless steel samples presented greater median number of cycles to failure than conventionally built samples. Fatigue crack growth analysis of stainless steel samples built using the WAAM technique have shown improved fatigue crack growth resistance of the novel material compared to the conventional material. Retained residual stress was reported to influence the fatigue crack growth of the material. Extensive fatigue crack growth analysis of WAAM Ti-6Al-4V shown that fatigue crack growth rate is considerably slower than in counterpart samples. Moreover based on examination of results for different orientation samples, the conclusion was drawn that WAAM material has isotropic fatigue crack growth rate. It has been found that AM process significantly affects the corrosion performance of the material, however very limited information is available in literature on this topic, especially for WAAM steels. The limited results in the literature on stainless steel parts built by direct laser deposition have shown better corrosion resistance in hot water, compared with wrought samples. However some studies on similar WAAM steel samples, present higher corrosion fatigue crack growth rate compared to counterparts. Although AM shows tremendous potential for application in offshore wind industry, the amount of data available to better characterise and implement the AM components in a new industry are very limited. A better metallurgical knowledge of AM parts needs to be developed, which requires specific and systematic experimental and numerical studies. Therefore, it is proposed to investigate in future work the fatigue crack growth behaviour of WAAM components in air and seawater to examine the applicability of WAAM technique for building structures to operate in the harsh offshore environment. It is also proposed to consider different grades of mild steel in future study and more importantly to characterise residual stresses and surface treatment effects on the fatigue performance of WAAM built components.

References

[1] Jacob, A., Oliveira, J., Mehmanparast, A., Hosseinzadeh, F., Kelleher, J., Berto, F. 2018. Residual stress measurements in offshore wind monopile weldments using neutron diffraction technique and contour method. Theoretical and Applied Fracture Mechanics 96 (2018), 418-427

[2] Sarker, B.R., Faiz, T.I. 2017. Minimising transportation and installation costs for turbines in offshore wind farms. Renewable Energy 101 (2017), 667-679.

[3] Adedipe, O., Brennan, F., Kolios, A. 2016. Review of corrosion fatigue in offshore structures: Present status and challenges in the offshore wind sector. Renewable and Sustainable Energy Reviews 61 (2016), 141-154.

[4]Adedipe, O., Brennan, F., Kolios, A. 2015. Corrosion fatigue load frequency sensitivity analysis. Marine Structures 42 (2015), 115-136.

[5] Nelson, D.V. 1982. Effect of residual stress on fatigue crack propagation, Residual stress effects in fatigue.

[6] Baumgartner, J. 2016. Enhancement of the fatigue strength assessment of welded components by consideration of mean and residual stresses in the crack initiation and propagation phases. Welding in the World 60 (3), 547–558.

[7] Lott, P., Schleifenbaum, H., Meiners, W., Wissenbach, K., Hinke, C. and Bültmann, J. 2011. Design of an Optical system for the In Situ

Process Monitoring of Selective Laser Melting (SLM). Physics Procedia, 12, pp.683-690.
[8] Emelogu, A., Marufuzzaman, M., Thompson, S., Shamsaei, N. and Bian, L. 2016. Additive manufacturing of biomedical implants: A feasibility assessment via supply-chain cost analysis. Additive Manufacturing, 11, pp.97-113.
[9] Frazier, W.E. 2014. Metal additive manufacturing: a review. Journal of Materials Engineering and Performance 23, 1917–1928.
[10] Levy, G., Schindel, R. and Kruth, J. 2003. Rapid Manufacturing and Rapid Tooling With Layer Manufacturing (LM) Technologies, State of the Art and Future Perspectives. CIRP Annals, 52(2), pp.589-609.
[11] Shamsaei, N., Yadollahi, A., Bian, L. and Thompson, S. 2015. An overview of Direct Laser Deposition for additive manufacturing; Part II: Mechanical behavior, process parameter optimization and control. Additive Manufacturing, 8, pp.12-35.
[12] Milewski, J.O. 2017. Additive manufacturing of metals. Springer series in materials science, vol. 258. Springer.
[13] DebRoy, T., Wei, H.L., Zuback, J.S., Mukherjee, T., Elmer, J.W., Milewski, J.O., Beese, A.M., Wilson-Heid, A., De, A., Zhang, W. 2018. Additive manufacturing of metallic components – Process, structure and properties. Progress in Material Science 92 (2018), 112-224.
[14] Williams, S. W., Martina, F., Addison, A. C., Ding, J., Pardal, G., Colegrove, P. 2015. Wire+Arc Additive Manufacturing. Material Science and Technology 23, 73–80.
[15] Martina, F., Mehnen, J., Williams, S. W., Colegrove, P., Wang, F. 2012. Investigation of the benefits of plasma deposition for the additive layer manufacture of Ti–6Al–4V. Journal of Materials Processing Technology 212(6), 1377–1386.
[16] Leinonen, M. 2011. Additive-Layer-Manufacturing by CMT using Cu97Si3 wire on steel.
[17] Bandari, Y.K., Charrett, T.O.H., Michel, F., Ding, J., Williams, S.W., Tatam, R.P. 2016. Compensation strategies for robotic motion errors for additive manufacturing. Proceedings of 27th Annual International Solid Freeform Fabrication Symposium. 8-10 August 2016, Austin, Texas, USA.
[18] Ding, D., Pan, Z., Cuiurim D., Li, H. 2015. Wire-feed additive manufacturing of metal components: technologies, developments and future interests. The International Journal of Advanced Manufacturing Technology 81, 465-481.
[19] Xiong, J., Zhang, G., Qiu, Z., Li, Y. 2013. Vision-sensing and bead width control of a single-bead multi-layer part: material and energy savings in GMAW-based rapid manufacturing. Journal of Cleaner Production 41, 82-88.
[20] Xiong, J., Zhang, G. 2014. Adaptive control of deposited height in GMAW-based layer additive manufacturing. Journal of Materials Processing Technology 214 (4), 962–968.
[21] Ding, J., Colegrove, P., Martina, F., Williams, S., Wiktorowicz, R., Palt, M.R. 2015. Development of a laminar flow local shielding device for wire + arc additive manufacture, Journal of Materials Processing Technology 226, 99–105.
[22] Xiong, J., Yin, Z., Zhang, W. 2016. Closed-loop control of variable layer width for thin-walled parts in wire and arc additive manufacturing. Journal of Materials Processing Technology 233, 100–106.
[23] Suryakumar, S., Karunakaran, K.P., Chandrasekhar, U., Somashekara, M.A. 2013. A study of the mechanical properties of objects built through weld-deposition. Journal of Engineering Manufacure 227(8), 1138-1147.
[24] Colegrove, P., Coules, H.E., Fairman, J., Martina, F., Kashoob, T., Mamash, H. and Cozzolino, L.D. 2013. Microstructure and residual stress improvement in wire and arc additively manufactured parts through high-pressure rolling. Journal of Materials Processing Technology 213(10), 1782–1791.
[25] Haden, C.V., Zeng, G., Carter III, F.M., Ruhl, C., Krick, B.A., Harlow, D.G. 2017. Wire and arc additive manufactured steel: Tensile and wear properties. Additive Manufacturing 16, 115-123.
[26] Young, C.M., Walser, B., Abrahamson, E.P., Sherby, O.D. 1975. Elimination of yield point phenomenon in mild steel by warm working. Scripta Metallurgica 9 (1), 35–38.
[27] Lu, X., Zhou, Y.F., Xing, X.L., Shao,L.Y., Yang, Q.X., Gao, S.Y. 2017. Open-source wire and arc additive manufacturing system: formability, microstructures, and mechanical properties. International Journal of Advanced Manufacturing Technology 93, 2145-2154.
[28] Waqas, A., Xiansheng, Q., Jiangtao, X., Chaoran, Y., Fan, L. 2018. Impact toughness of components made by GMAW based additive manufacturing. Procedia Structural Integrity 13, 2065-2070.
[29] Zhang, X., Martina, F., Ding, J., Wang, X., Williams, S.W. 2017. Fracture toughness and fatigue crack growth rate properties in wire + arc additive manufactured Ti-6Al-4V. Fatigue & Fracture of Engineering Materials & Structures 40(5), 790-803.
[30] Gordon, J., Hochhalter, J., Haden, C., Harlow, D.G. 2019. Enhancement in fatigue performance of metastable austentic stainless steel through directed energy deposition additive manufacturing. Materials and Design 168, 1-10.
[31] Gordon, J.V., Haden, C.V., Nied, H.F., Vinci, R.P., Harlow, D.G. 2018. Fatigue crack growth anisotropy, texture and residual stress in austentic steel made by wire and arc additive manufacturing. Material Science & Engineering A 724, 431-438.
[32] Zhang, J., Wang, X., Paddea, S., Zhang, X. 2016. Fatigue crack propagation behaviour in wire + arc additive manufactured Ti-6Al-4V: Effects of microstructure and residual stress. Materials and Design 90, 551-561.
[33] Ganesh, P., Giri, R., Kaul, R., Ram Sankar, P., Tiwari, P., Atulkar, A., Porwal, R.K., Dayal, R.K., Kukreja, L.M. 2012. Studies on pitting corrosion and sensitisation in laser rapid manufactured specimens of type 316L stainless steel. Materials and Design 39, 509-521.
[34] Lou, X., Andresen, P.L., Rebak, R.B. 2018. Oxide inclusions in laser additive manufactured stainless steel and their effects on impact toughness and stress corrosion cracking behaviour. Journal of Nuclear Materials 499, 182-190.
[35] Lou, X., Othon, M.A., Rebak, R.B. 2017. Corrosion fatigue crack growth of laser additively manufactured 316L stainless steel in high temperature water. Corrosion Science 127, 120-130.
[36] Lou, X., Song, M., Emigh, P.W., Othon, M.A., Andresen, P.L. 2017. On the stress corrosion crack growth behaviour in high temperature water of 316L stainless steel made by laser powder bed fusion additive manufacturing. Corrosion Science 128, 140-153.
[37] GE Global Research. 2018. Environmental and Irradiation Resistant Stainless Steels by Additive Manufacturing. Schenectady: 1 Research Circle.