

Effect of location on microstructure and mechanical properties of additive layer manufactured Inconel 625 using gas tungsten arc welding

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ABSTRACT

Additive layer manufacturing (ALM), using gas tungsten arc welding (GTAW) as heat source, is a promising technology in producing Inconel 625 components due to significant cost savings, high deposition rate and convenience of processing. With the purpose of revealing how microstructure and mechanical properties are affected by the location within the manufactured wall component, the present study has been carried out. The manufactured Inconel 625 consists of cellular grains without secondary dendrites in the near-substrate region, columnar dendrites structure oriented upwards in the layer bands, followed by the transition from directional dendrites to equiaxed grain in the top region. With the increase in deposited height, segregation behavior of alloying elements Nb and Mo constantly strengthens with maximal evolution in the top region. The primary dendrite arm spacing has a well coherence with the content of Laves phase. The microhardness and tensile strength show obvious variation in different regions. The microhardness and tensile strength of near-substrate region are superior to that of layer bands and top region. The results are further explained in detail through the weld pool behavior and temperature field measurement.

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1. Introduction

Ni-based superalloy Inconel 625 has been widely used in aerospace, petrochemical, chemical and marine applications due to their attractive combination of high tensile strength, excellent corrosion resistance and fatigue strength in aggressive environments [1–3]. These excellent properties have made Inconel 625 the choice for diverse applications over a wide temperature range from cryogenic conditions to elevated temperature environments [4]. However, the production of Inconel 625 components is still challenging for further application owing to highly complex shapes and overall production cost [5,6]. Many works have been carried out to produce Inconel 625 components, and industrial scale processing methods include casting, powder metallurgy or wrought [7,8]. Although these methods are capable of producing acceptable components, high production costs and complex geometries are recognized as the limiting factors of Inconel 625 components to successfully reach the market for many commercial

exploitation. Fortunately, additive manufacturing (AM) techniques allow a feasible and economical alternative to traditional manufacturing methods [9–11].

According to the American Society for Testing and Materials (ASTM), AM is defined as “processes of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing fabrication methodologies” [12,13]. The ASTM F42 committee classifies the AM processes into seven categories: (1) Vat photopolymerization (e.g., stereolithography); (2) Material jetting (e.g., Polyjet); (3) Binder jetting (e.g., some 3D printers by powder and binder); (4) Material extrusion (e.g., fused deposition modeling, FDM); (5) Powder bed fusion (e.g., selective laser sintering, SLS); (6) Sheet lamination (e.g., Ultrasonic Consolidation); (7) Directed energy deposition (e.g., additive layer manufacturing) [14]. Each technique has its own advantages and drawbacks, and the main considerations for choosing a technique depend on the required deposition velocity, surface quality, manufacturing costs, material compatibility as well as its applicability considering the complexity of the technique and the necessary atmosphere [15].

For example, in the case of directed energy deposition (DED), parts are fabricated via the in situ delivery of powder (or wire) producing fully dense parts [16]. However, compared to DED

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which utilizes injected powder, powder bed fusion (PBF) utilizes pre-deposited powders and the parts with complex features are more easily obtained, but the build volumes are still prohibitive due to the size of the powder bed [17]. Besides, material jetting and binder jetting followed by heat treatment can produce high fidelity of the parts. Usually, the production of fully dense and excellent property parts is not as good as for other process [18]. By contrast, ultrasonic additive manufacturing (UAM) is a solid state manufacturing technique that produces three dimensional metal parts at low temperatures. The process can produce a scrubbing action at the mating interface of thin metal foils, however voids and poor mechanical properties may occur under certain process conditions [19,20].

In additive layer manufacturing (ALM) of metallic alloys, many successive layers are deposited onto a substrate using wire or powder in a protected atmosphere and realized via a computer aided design model. ALM techniques aim towards zero waste manufacturing to produce near-net-shape metal components with minimum finishing operations. Based on the difference in the heat source, the typical ALM techniques include electron beam melting (EBM) [21–23], laser beam deposition (LBD) [24–27], plasma arc additive manufacturing (PAM) [28–30], gas tungsten arc welding (GTAW) deposition [16,31–33] and gas metal arc welding (GMAW) deposition [34–36]. A certain manufacturing technique can be complementary and selected for a specific component depending on the required production quantity and cost, geometrical complexity and mechanical properties. Both of EBM and LBD processes are especially suitable for precise parts or miniature sized deposition in virtue of fine structure and better mechanical characteristics [37]. However, production quantity [29], energy consumption [30] and deposition rate [38] are the major issues for the two processes. It has been demonstrated that arc-based ALM techniques are preferred for high volume manufacturing and deposition rate [16,28–36]. Generally, the accuracy and surface quality of arc-based ALM are inferior to that of both laser and electron beam processes. Considering its high deposition rate and cost-savings deposited layer by layer, additive layer manufacturing by gas tungsten arc welding (GTAW-ALM) is an appealing option for fabricating large parts production.

To date, research into the subject of Inconel 625 components manufactured by GTAW-ALM has been limited. Thivillon et al. studied the difference of microstructure of Inconel 625 components produced by LBD and GTAW [39]. The effect of post-weld heat treatment on the microstructure of Inconel 625 deposited metal has also been evaluated [40]. No previous literature has

been reported on mechanical properties of Inconel 625 components produced by GTAW-ALM process. Given the increasing interest in the manufactured Inconel 625, it is essential that further research be completed by GTAW-ALM technique. Furthermore, the solidification process of welded Inconel 625 is accompanied by segregation of high concentration alloying elements, such as Nb and Mo [41]. Consequently, Laves phase, which is reported to deteriorate the mechanical properties, is precipitated in the interdendritic regions [42]. The morphology and content of Laves phase is strongly dependent on the temperature gradient and cooling rate during solidification [43]. However, the GTAW-ALM process has more complex thermal cycles than welding. Significant research efforts are still required to focus on the degree of phase segregation within one build.

Further, in order to produce the components endowed with acceptable quality, reproducibility, and repeatability, it is also important to explore the variation in microstructure and mechanical properties within the manufactured component. Considerable investigations have been carried out on microstructure and mechanical properties of Inconel 625 components produced by EBM [44], LBD [3,5,27], and PAM [29,45]. However, no information can be found to specifically study the effect of location on additive manufactured Inconel 625 produced by GTAW-ALM in the open literature. In this paper, microstructure and mechanical properties of the manufactured components are made as a function of location. The variation of microstructure and mechanical properties in different regions is further explained through the weld pool behavior and temperature field measurement. These results help understand the effectiveness of GTAW-ALM process in producing Inconel 625 components.

2. Experimental procedure

The Inconel 625 deposited sample was fabricated by the GTAW-ALD technique. Fig. 1a shows the schematic representation of the manufacturing process. Commercially available Inconel 625 welding wire (ERNiCrMo-3) with 1.2 mm diameter was used as filler metal, of which the nominal chemical composition was 64.24 Ni, 22.65 Cr, 8.73 Mo, 3.53 Nb, 0.16 Al, 0.32 Fe and 0.2 Ti (in wt%). The substrate in the present work was a Q235 plate with dimensions of $200 \times 100 \times 7$ mm. The substrate surface were cleaned to remove the grease or oil with acetone before the deposited process. Inconel 625 welding wire was fed into a weld pool produced by GTAW, and rapidly solidified onto the substrate or the pre-

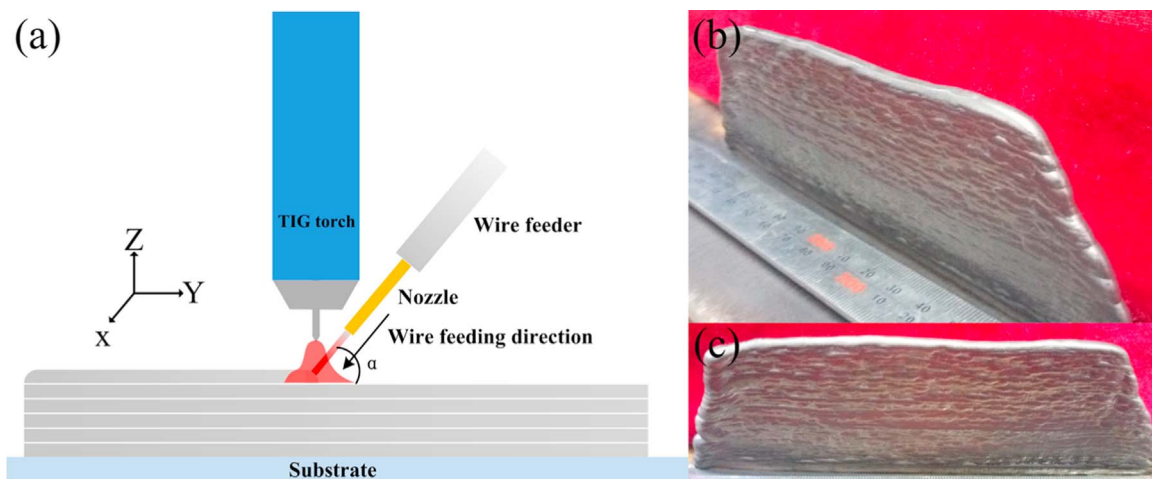


Fig. 1. Experimental setup of the GTAW-ALM process and the typical wall components: (a) schematic representation of the manufacturing process, (b) and (c) examples of Inconel 625 components.

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