WIRE AND ARC ADDITIVE MANUFACTURING OF INCONEL ALLOYS: A REVIEW ON MICROSTRUCTURES, MECHANICAL PROPERTIES, AND COMMON DEFECTS

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ABSTRACT

Wire and arc additive manufacturing (WAAM) has increasingly attracted much attention from scientists worldwide due to its ability to produce medium to huge metallic parts with elevated material deposition rate, high material usage efficiency, less environmental effect, and low equipment costs. Nickel-based superalloys, especially Inconel 625 and 718, are the most popularly studied by the additive manufacturing (AM) research community because of their superior strength, good oxidation, and corrosion resistance. This paper provides a comprehensive review and the internal qualities (i.e., microstructure and mechanical characteristics) of Inconel alloys fabricated by WAAM technologies. Common defects of as-built parts, such as cracks, porosity, deformation, residual stress, and delamination phenomenon, which occur during the WAAM process, and feasible methods to improve the quality of the as-built parts were also discussed. This review paper contributes to a better understanding of the WAAM processes of Inconel alloys.

Keywords: *WAAM, Inconel superalloys, mechanical properties, microstructures, defects.*

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1. INTRODUCTION

Additive manufacturing (AM) is an advanced production process that enables the manufacture of near-net-shape components directly from a 3D CAD model without utilizing any specialized cutting tools, molds and dies as in traditional manufacturing processes. With the layer-by-layer manufacturing principle, metallic AM has proven to be an efficient method for saving production costs of high-strength and hard-to-machine materials in various industrial fields, such as biomedicine, defense, automobile, aerospace, transportation, and nuclear construction.

Based on the energy sources, metallic AM can be classified into 3 types, including electron beam, laser beam, and plasma/electric arc-based AM. Among these technologies, wire and arc additive manufacturing (WAAM) is an advanced technology for producing large-scale parts with medium accuracy. This process utilizes a metallic wire and an electric arc as the raw material and the energy source, respectively [1]. Compared to other metallic AM technologies, WAAM features higher material deposition rate, low equipment costs, and less environmental impact.

In WAAM, the welding sources - Gas Tungsten Arc Welding (GTAW or TIG), Gas Metal Arc Welding (GMAW or MIG), and Plasma Arc Welding (PAW) can be utilized. Compared to GTAW and PAW, GMAW shows a significantly higher deposition rate [2]. Especially, Cold Metal Transfer (CMT) - a variation of GMAW has broadly applied in WAAM because of its superior advantages such as reducing heat input and splash disturbances phenomenon, better quality, and high production rate [3].

Nickel-based superalloys, particularly Inconel 625 and 718 alloys with outstanding mechanical properties are applied in many industrial fields. However, they are costly and difficult to machine by turning and milling processes. Therefore, the machining processes are unsuitable for producing Inconel components in terms of reducing production costs, tool wear, and material waste. To deal with this challenge, metallic AM technologies have become an effective solution. Therefore, Inconel 625 and 718 alloys have been widely studied by researchers in AM and WAAM after titanium superalloys [11].

This paper aims to review the WAAM process of Inconel 625 and 718 alloys regarding microstructures, mechanical properties, and defects. The typical defects such as crack, porosity, deformation, residual stress, and delamination were summarized. The methods to enhance the part quality are also discussed.

2. METALLURGICAL PROPERTIES OF WAAMED INCONEL ALLOYS

2.1. WAAM of Inconel 625

Inconel 625 is the most popular in the group of nickel-based alloys with more iron elements added than Inconel 718. Its composition includes 58% Ni, 20 - 23% Cr, 3.15 -

4.15% Nb, 8 - 10% Mo, max 0.4% Ti/Al/Mn/C, and balanced Fe.

Typically, the microstructure of Inconel 625 fabricated by WAAM composes of columnar dendrites with many Laves phases, MC carbides, and Ni_3Nb, as shown in Fig. 1 [5]. The post-processing methods such as heat treatment are recommended to refine the microstructure and minimize the spacing of dendritic arms, discontinuous Laves phases, and Niobium segregation in the inter-dendritic regions. As a result, the mechanical strength is significantly enhanced.

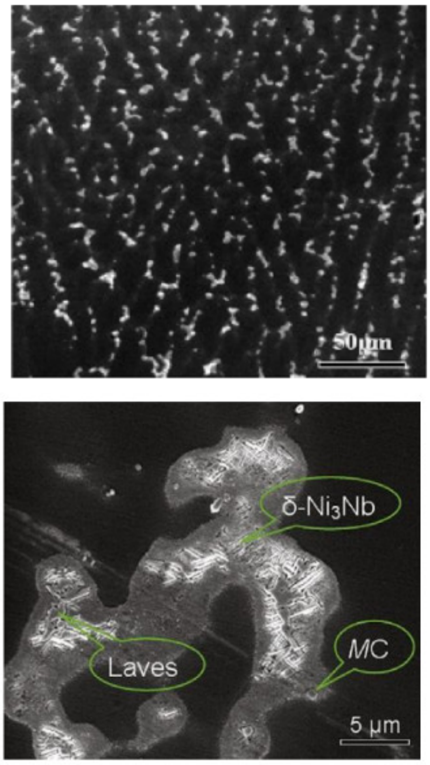
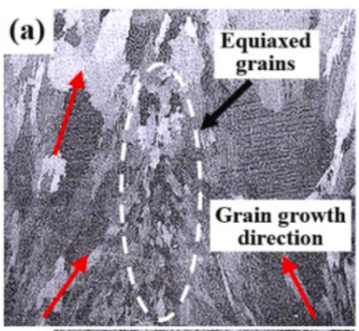


Fig. 1. The typical microstructure of Inconel 625 built by WAAM [5]

In addition, Chen et al. [4] reported that the microstructure of the as-deposited Inconel 625 wall shows epitaxial growth and columnar grains. The temperature gradient has a crucial role in their growth direction (Fig. 2). Moreover, equiaxial grains have been observed in the center region (Fig. 2a). The columnar grains tend to rise in the building direction. The angle development of columnar grains has been deflected when the heat emission process does not pass through the substrate, as displayed in Figs. 2b and 2c.



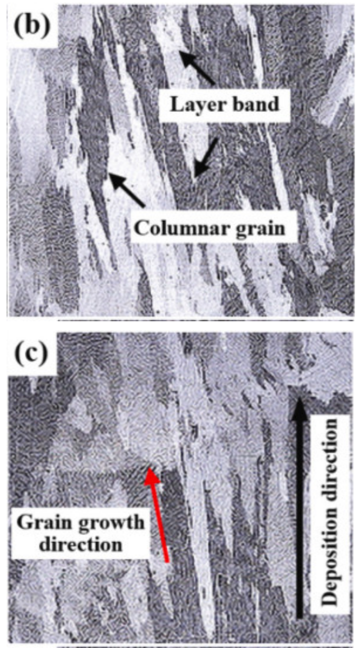
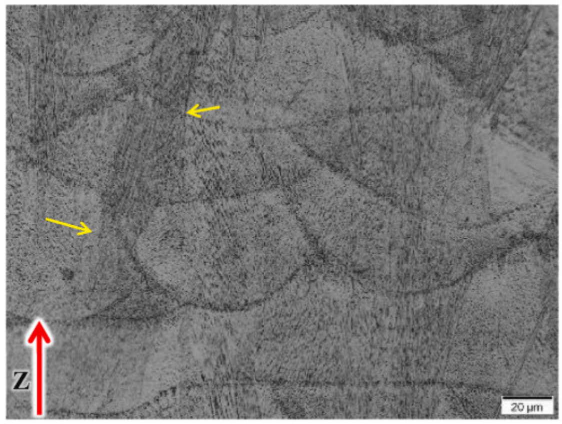
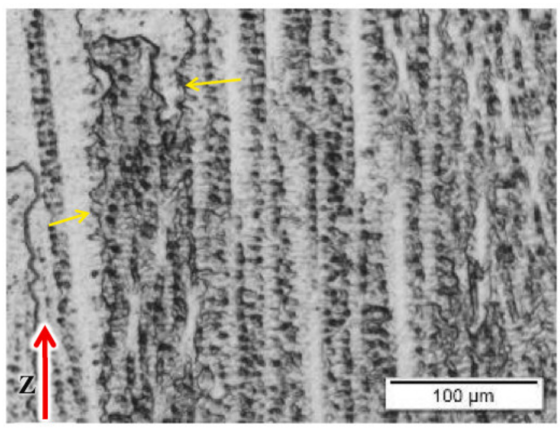


Fig. 2. Microstructures of WAAMed Inconel 625 in (a) the bottom, (b) the middle, and (c) the top of the wall [4]



(a) Laser Powder Bed Fusion



(b) WAAM

Fig. 3. Microstructures of AM Inconel 625 parts in the build direction Z [6]

Wang et al. [7] considered the microstructure in various regions of GTAW-WAAM as-deposited part made from Inconel 625 material. The dendrite arm spacing was measured by 13μm, 23μm, and 25μm, in the bottom, layer bands, and the top, respectively. In the middle bands, columnar dendrites developed along the deposition direction, which is a primary feature. During the growing process, the separation phenomenon constantly strengthens and reaches the maximal value at the end of the deposition process. Regarding mechanical properties, the average UTS value of the as-fabricated samples according to travel direction and construction direction were 722MPa and 684MPa, respectively, which is much lower than the wrought standard (1103MPa and 758MPa) [7].

Besides, the average elongation of the samples was 42.7% and 40.13% in the travel and construction directions, respectively. They are much higher than those achieved by the wrought standard (27%) [7]. Moreover, the UTS and micro-hardness showed the highest value at the top region of the deposited part. This inhomogeneity phenomena in mechanical properties along the build direction can be explained by the variation of the temperature cycle and cooling rate during the deposition.

Compared to Laser Powder Bed Fusion (LPBF) processes, the WAAM produced larger columnar grain size in microstructures (Fig. 3). Therefore, the microhardness of the material deposited by WAAM is lower than that produced by LPBF (228 vs. 304HV) [6].

2.2. WAAM of Inconel 718

The Inconel 718 is mostly used in modern airplane engines. Its composition includes 50 - 55% Ni, 4.8 - 5.5% Nb, 17 - 21% Cr, 0.65 - 1.15% Ti, 2.8 - 3% Mo, 1% Co, 0.2 - 0.8 % Al, 18%Fe. The as-deposited Inconel 718 parts by WAAM expose dendritic microstructures containing Laves phases, carbides NbC/TiN, and some δ phases Ni_3Nb. They are normally considered harmful for mechanical properties. The reason is that δ phases explode the matrix of Nb for γ"-Ni3Nb precipitation and badly affect the material [9]. Fig. 4 shows some dendrites, and their lengths are several millimeters. They tend to rise across interlayer boundaries which are observed according to the differences in dendrite patterns.

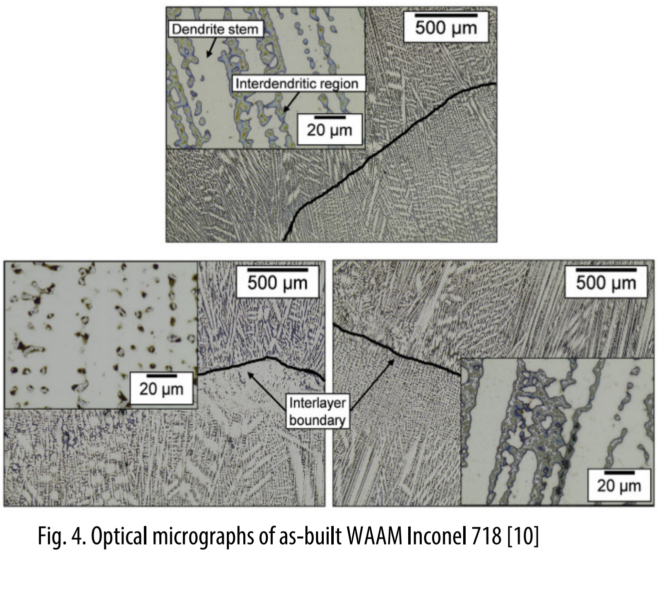


Fig. 4. Optical micrographs of as-built WAAM Inconel 718 [10]

Like Inconel 625, the representative microstructure of as-deposited Inconel 718 by WAAM consists of columnar grains and crystal texture and has higher anisotropy compared to the wrought material. However, their anisotropic relevance and relationship to the anisotropic grain structure have not been clearly investigated [10].

Xu et al. [11] apply the in-process thermo-mechanical method to enhance the mechanical properties of PAW as-built Inconel 718. The microstructure and mechanical characteristics under different conditions, including before and after using interpass cold rolling, were examined. Without using the interpass cold rolling, the average UTS and YS values of the as-fabricated samples are 793MPa and 516MPa, respectively, which is much lower than the wrought standard (1276MPa and 1034MPa). Besides, the average elongation of the samples is 30,6%, so it is much higher in comparison with the wrought standard (12%).

3. DEFECTS AND QUALITY IMPROVEMENT METHODS

3.1. Common defects

Common defects of the WAAM as-fabricated parts include cracks, residual stress, porosity, and delamination. The main reason is the repeated continuously melting and cooling during printed processes.

Crack is a common defect often observed in the WAAM fabricated parts. The main reasons causing the crack include the blockage of solidified grain flow and high strain in the melting pool during the process. Delamination defects occur because of some reasons such as insufficient re-melting or incomplete melting of the underlying solid between layers. The post-process treatment is typically ineffective in mitigating this defect. Instead of this, the pre-heating of the substrate has been proven as an effective method to prevent cracks [11].

Porosity leads to a reduction in mechanical properties of as-built parts, for example, low fatigue strength. In general, porosity is primarily sorted into two types: raw material-induced and process-induced [12, 13]. The first one is because the surface is contaminated, which will easily mix into the melting pool, creating pores during solidification. On the other hand, the remaining reason is inappropriate toolpath generation or an unstable deposition process, which produces insufficient fusion or splash, leading to gaps and voids in as-deposited components.

Distortions and residual stress phenomena are inborn defects of the WAAM process, so they cannot be removed completely. The residual stress leads to some serious negative effects on the quality of the fabricated parts, for example, delamination of layers during deposition, loss of geometric tolerance, distortion of the part, degradation of fatigue strength and fracture resistance. Thus, controlling and minimizing these defects are essential, contributing to reducing the mentioned phenomena above. Numerous kinds of deformation occur in the parts, including longitudinal and transverse shrinkage and distortion [14].

3.2. Feasible methods for quality improvement of the WAAM-fabricated parts

One of the biggest disadvantages of WAAM technology is the time-consuming precision forming. Therefore, a hybrid additive-subtractive technique is chosen to overcome this drawback. Firstly, using WAAM to produce near-net-shape raw parts. Secondly, subtractive processes such as milling and turning techniques, which modify the parts, follow a given suitable machining strategy to obtain the desired accuracy and quality [15].

Post-processing methods are clearly proven as common technologies to improve the quality of WAAM as-built components. They can be classified into various types, including heat treatment, interpass cooling, interpass cold rolling, hot forging, ultrasonic needle peening, interlayer hammering and so on. The heat treatment method is broadly applied to decrease residual stress phenomenon, improve mechanical properties, refine microstructures, and refine grain (typically for WAAM as-deposited Inconel alloy [16]), and it is also known as an essential method to control the final hardness of as-built parts.

The interpass cold rolling method based on plastic deformation theory is a valuable method to reduce microstructural anisotropy significantly. This improvement method also helps to lower the residual stresses and distortion and improve the surface roughness of the fabricated parts. On the other hand, beneficial grain refinement occurs by heating the rolled layer in the subsequent layer deposition.

Interpass cooling is recently adopted to improve microstructure and mechanical characteristics of as-deposited components by using argon, nitrogen or CO_2 gas through moveable gas nozzles. This method provides an active or passive cooling process during and after the deposition of each layer. Interpass cooling was reported to produce better results than components manufactured without active cooling, which are refined microstructure, less surface oxidation, higher hardness, and enhanced tensile strength. Furthermore, interpass cooling also helps improve manufacturing efficiency by reducing dwell time between deposited layers.

In-situ monitoring and Artificial Intelligence (AI) are well-known as great thinkable solutions to enhance the quality of WAAM as-deposited parts because of its ability to detect defects, optimize input technological parameters to predict quality, and control closed-loop data. Recent studies using traditional optimization techniques (design of experiment) have only focused on some parameters simultaneously. The reason is the cause of lacking enough understanding of the complex relationship between investigated input parameters. On the other hand, this work is costly, time-consuming, and nearly impossible to effectively apply simultaneously in case of large quantities without using AI.

4. CONCLUSIONS

The microstructures and mechanical properties of Nickel-based superalloys (Inconel 625 and Inconel 718) produced by WAAM technologies were reviewed in this paper. Common defects of as-built components occurring in the WAAM process, including crack, porosity, deformation, residual stress, and delamination phenomenon are deeply discussed. To improve the final quality of the as-deposited parts, various feasible methods are pointed out and proposed. This review paper provides a useful document related to numerous aspects of WAAM Inconel as-deposited components, particularly the possible research directions in future.

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