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A review of the wire arc additive manufacturing of metals: properties, defects and quality improvement

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ABSTRACT

Due to the feasibility of economically producing large-scale metal components with relatively high deposition rates, significant progress has been made in the understanding of the Wire Arc Additive Manufacturing (WAAM) process, as well as the microstructure and mechanical properties of the fabricated components. As WAAM has evolved, a wide range of materials have become associated with the process and its applications.

This article reviews the emerging research on WAAM techniques and the commonly used metallic feedstock materials, and also provides a comprehensive over view of the metallurgical and material properties of the deposited parts. Common defects produced in WAAM components using different alloys are described, including deformation, porosity, and cracking. Methods for improving the fabrication quality of the additively manufactured components are discussed, taking into account the requirements of the various alloys. This paper concludes that the wide application of WAAM still presents many challenges, and these may need to be addressed in specific ways for different materials in order to achieve an operational system in an acceptable time frame. The integration of materials and manufacturing process to produce defect-free and structurally-sound deposited parts remains a crucial effort into the future.

1. Introduction

In recent years, wire arc additive manufacturing (WAAM) has increasingly attracted attention from the industrial manufacturing sector due to its ability to create large metal components with high deposition rate, low equipment cost, high material utilization, and consequent environmental friendliness. The origin of the WAAM process can be traced back to the 1925s when Baker [1] proposed to use an electric arc as the heat source with filler wires as feedstock materials to deposit metal ornaments. Since then, consistent progress has been made on the development of this technology, particularly in the last 10 years. The WAAM technique bears various nomenclatures by different research institutions worldwide [2–24], as shown in Fig.1. Today, WAAM has become a promising fabrication process for various engineering materials such as titanium, aluminium, nickel alloy and steel. Compared to traditional subtractive manufacturing, the WAAM system can reduce fabrication time by 40–60% and post-machining time by 15–20% depending on the component size [25]. For instance, recent breakthroughs in WAAM technology have made it possible to fabricate aircraft landing gear ribs with a saving of approximately 78% in raw material when compared with the traditional subtractive machining process [26].

Due to the highly complex nature of WAAM, many different aspects of the process need to be studied, including process development, material quality and performance, path design and programming, process modelling, process monitoring and online control [9]. Several WAAM review papers have been published by leaders in the field, covering state-of-the-art systems, design, usage, in-situ process monitoring, in-situ metrology and in-process control and sensing [26–31]. Nevertheless, there is still a need for a systematic review of the properties of various WAAM-processed materials, the defects associated with different alloys, and a summary of current and future research directions that are aimed at quality improvements for the alloy classes of interest.

This paper reviews the microstructure and mechanical properties of various metals, including titanium and its alloys, aluminum and its alloys, Ni-based alloy, steel and other intermetallic materials fabricated by the various WAAM processes. The common defects that have been found to occur for different materials are also summarized. The current methods for both in-process and post-process quality improvement and defect reduction are introduced. Finally, a discussion is given on

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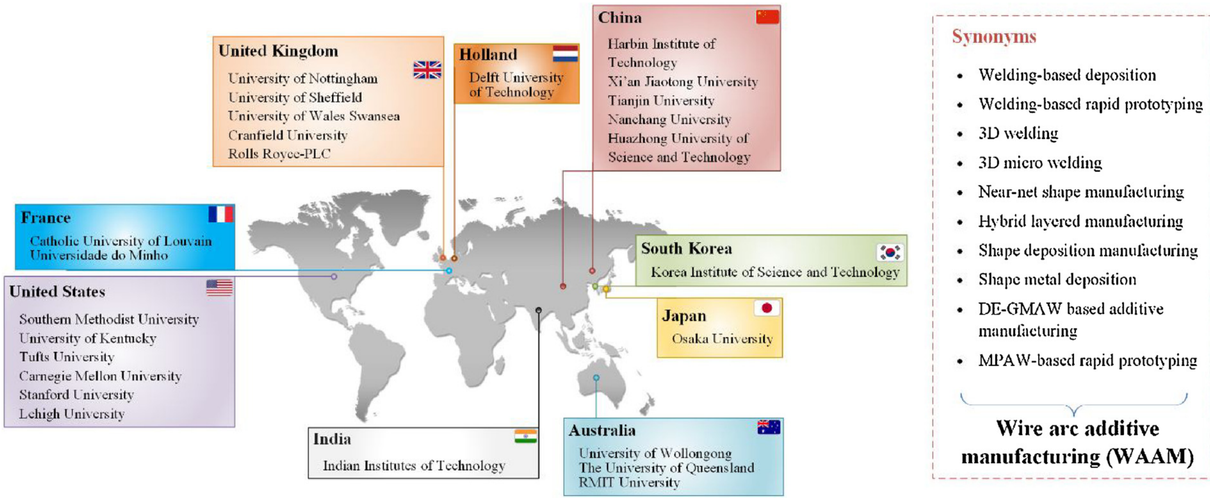

Fig. 1. The distribution of main WAAM research groups.

improving quality of WAAM fabricated parts through process selection, feedstock optimization, process monitoring and control and post-process, including proposals for future research directions.

2. Wire arc additive manufacturing (WAAM) systems

2.1. Classification of WAAM process

Depending on the nature of the heat source, there are commonly three types of WAAM processes: Gas Metal Arc Welding (GMAW)-based [32], Gas Tungsten Arc Welding (GTAW)-based [2] and Plasma Arc Welding (PAW)-based [3]. As listed in Table 1, specific class of WAAM techniques exhibit specific features. The deposition rate of GMAW-based WAAM is 2–3 times higher than that of GTAW-based or PAW-based methods. However, the GMAW-based WAAM is less stable and generates more weld fume and spatter due to the electric current acting directly on the feedstock. The choice of WAAM technique directly influences the processing conditions and production rate for a target component.

2.2. Robotic WAAM system

Most WAAM systems use an articulated industrial robot as the motion mechanism. Two different system designs are available. The first design uses an enclosed chamber to provide a good inert gas shielding environment, similar to laser Power-Bed Fusion (PBF) systems. The second design uses existing or specially designed local gas shielding mechanisms, with the robot positioned on a linear rail to increase the overall working envelop. It is capable of fabricating very large metal structures up to several a meters in dimension. Fig. 2 shows an example of this design of WAAM system, used for the research and development at the University of Wollongong (UOW).

Fabricating a part using WAAM involves three main steps: process planning, deposition, and post processing. For a given CAD model, 3D slicing and programming software generates the desired robot motions and welding parameters for the deposition process, aimed at producing defect-free fabrication with high geometrical accuracy [22,23,33]. Based on the welding deposition model for the specific material being used to fabricate the component, the 3D slicing and programming software offer automated path planning and process optimization to avoid potential process-induced defects [34–37]. During fabrication, the robot and external axis provide accurate motion for the welding torch to build up the component in a layer-by-layer fashion. Advanced WAAM systems can be equipped with various sensors to measure welding signals [38], deposited bead geometry [39], metal transfer behaviour [40] and interpass temperature [32,41,42], thereby supporting in-process monitoring and control to achieve higher product quality. This is an area of current and future research interest, with the potential for significantly improving WAAM process performance.

Table 1
Comparison of various WAAM techniques.

WAAM	Energy source	Features
GTAW-based	GTAW	Non-consumable electrode; Separate wire feed process; Typical deposition rate: 1-2 kg/hour; Wire and torch rotation are needed;
GMAW-based	GMAW	Consumable wire electrode; Typical deposition rate 3-4 kg/hour; Poor arc stability, spatter;
	Cold metal transfer (CMT)	Reciprocating consumable wire electrode; Typical deposition rate: 2-3 kg/hour; Low heat input process with zero spatter, high process tolerance;
	Tandem GMAW	Two consumable wires electrodes; Typical deposition: 6-8 kg/hour; Easy mixing to control composition for intermetallic materials manufacturing ;
PAW-based	Plasma	Non-consumable electrode; Separate wire feed process; Typical deposition rate 2-4 kg/hour; Wire and torch rotation are needed;

3. Metals used in WAAM process

WAAM processes use commercially available wires which are produced for the welding industry and available in spooled form and in a wide range of alloys as feedstock materials. Table 2 indicates the commonly used alloys and their various applications in WAAM. Manufacture of a structurally sound, defect free, reliable part requires an understanding of the available process options, their underlying physical processes, feedstock materials, process control methods and an appreciation of the causes of the various common defects and their remedies. This section reviews the metals that are commonly used in WAAM, with a particular emphasis on the microstructure and mechanical properties of the additively manufactured alloys.

3.1. Titanium alloys

Titanium alloys have been widely studied for application of additive manufacturing in aerospace components due to their high strength-to-weight ratio and inherently high material cost. There are increasing