

Wire Arc Additive Manufacturing for Industrial Part Fabrication: A Short Review

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Abstract

The purpose of this review is to summarize the status of wire arc additive manufacturing (WAAM) in industrial parts and identify future research topics. First, a literature review of the results of studies on WAAM for industrial parts was conducted to summarize the current literature. Based on the study results obtained through the literature review, the main current issues are summarized. It was found that studies on WAAM have been conducted for a variety of industries, but not for all industries where arc welding, the basis of WAAM, is used. In addition, many studies have been conducted on steel, whereas no studies have been conducted on titanium or multi-materials. The study concluded that an effective means of expanding the industrial use of WAAM is to treat the uncovered topics.

Key Words : WAAM; Additive manufacturing; Industrial application; Fabrication process

1. Introduction

Additive manufacturing (AM) is a new fabrication technology that has been the focus of much attention recently in the industry [1]. AM has the potential to be a means of realizing structures that were not possible with traditional fabrication methods and solving social issues, such as reducing environmental burden. Research and development on various AM processes for diverse materials, such as metals, resins, and ceramics, as well as their application in industry, are in progress. This paper focuses on one of metal additive manufacturing technologies [2], wire arc additive manufacturing (WAAM) [3], which is based on arc welding, in which weld beads are stacked in multiple layers. Therefore, it is not suitable for microfabrication, such as extremely thin flow paths, but it is well suited for manufacturing medium- to large-sized parts. A large number of studies have also been conducted on WAAM, and a number of review papers summarizing the results of these studies on a variety of topics. Topics include mechanical properties [5], material micro-structures [6 7], heat input conditions [8], manufacturing systems [9], non-destructive testing [10], post-processing [11], artificial intelligence techniques [12], and repair [13]. These review papers make it possible to determine that the research results were obtained from multiple perspectives. On the other hand, most of these analyses were conducted using simple geometries, such as general-purpose specimens or walls. Analysis using simple geometries is important for fundamental engineering. However, to connect WAAM as a manufacturing technology to industrial applications, it is also necessary to conduct a comprehensive survey of various research results using actual part geometries used in industry as test pieces, although there are no review papers from this perspective.

The purpose of this paper is to further clarify the industrial application value of WAAM. First, a literature survey on research results on WAAM for industrial parts is conducted to summarize the current overall status of WAAM. Then, based on the research results obtained from the literature survey, the current issues are summarized. In addition, topics that should be treated to apply WAAM to various industries are discussed.

2. Literature Review Methods

The survey covers peer-reviewed original articles and proceedings written in English. In general, industrial outputs, such as products, are often applications of academic results that are created later in life. Therefore, when discussing the industrial potential of WAAM, it is better to analyse only the academic outputs that are created first, so that the prospects are clearer. It

was also intended to remove as much commercial bias as possible. For this reason, commercial information was treated as outside the scope of this study. commercial information means, for example, brochures, white papers, newspapers, websites, and commercial magazines. Furthermore, original articles, proceedings, and preprints that were not peer-reviewed were excluded from this survey because the reliability of their contents could not be determined. Books and review articles were also excluded from this survey because they are mainly secondary information.

In this study, a literature search by Google Scholar was conducted to conduct a wide-ranging study. Wire arc additive manufacturing and industry-related keywords were combined in the search, and the top 100 results sorted by relevance were reviewed for content and selected for inclusion in the study. The 16 industry-related keywords used here are aerospace, application, automobile, blade, bridge, civil, industry, machine, marine, pipe, railway, mold, ship, structure, turbomachinery, and vehicle. Since WAAM is an applied technology of arc welding; thus, keywords were planned so that a comprehensive list of industries where welding is commonly used could be extracted. The search results as of the end of November 2024 are used as the final literature list.

3. Results and Discussion

Table 1 lists the search results of the literature survey on WAAM for industrial parts. If the same literature was found in the survey when searching with different keywords, it was counted in each result. Duplicate literature was excluded during the final tally. After excluding duplicate literature, 18 papers were extracted that fit the research findings focused on in this study.

Table 1. Literature search results using WAAM and industrial keywords.

Searched industrial keyword	Target papers	Non-target papers
Aerospace	3	97
Application	0	100
Automobile	1	99
Blade	3	97
Bridge	1	99
Civil	0	100
Industry	2	98
Machine	0	100
Marine	3	97
Pipe	3	97
Railway	0	100
Mold	1	99
Ship	2	98
Structure	2	98
Turbomachinery	2	98
Vehicle	2	98
Total target papers	18 (duplication: 7)	

The following summarizes of the research findings presented in the 18 references obtained through the literature survey. Shen C., et al. [14] fabricated a nickel-aluminum bronze (NAB) alloy component for the marine industry using WAAM. To further investigate the effects of anisotropy, components fabricated by WAAM with different post-manufacturing heat treatments were characterized. The results show that quenching and tempering heat treatments can effectively correct the anisotropy of additively manufactured alloys. Dai F., et al. [15] proposed a method for easily and accurately generating toolpaths on cylindrical or conical surfaces and planning the welding process on these deployable surfaces. The objective is to fabricate large metal parts with overhangs on cylindrical or conical surfaces with high dimensional accuracy. A stainless steel underwater thruster was fabricated to validate of the proposed method. Tianying H., et al. [16] fabricated a marine steel propeller bracket

using a 3D scanner and a program created in Matlab to obtain the center displacement of the deposition layer and adjust the fabricating path in real time to obtain high forming accuracy. The offset filling method was used to fabricate the hubs, and the scanning filling method was used to fabricate the supports and crossarms to improve the forming accuracy of the brackets. Ya W., et al. [17] studied how spare parts in the marine industry can be manufactured on demand by WAAM. Using a steel propeller, which is a familiar object in the marine industry, as a case study, they identified development time and cost savings by manufacturing parts on a need basis close to where they are needed. Ejiri S. [18] fabricated a stainless steel axial flow impeller, called a fan-type inducer, using WAAM. Based on the fabricated information, the advantages of this method over traditional methods regarding the number of chips are discussed. Furthermore, the fabricated fan-type inducer was attached to a centrifugal pump for operation, and pump performance was measured to confirm that the fabricated fan-type inducer can function as a pump impeller. Ejiri S. [19] also fabricated an axial-flow impeller by additively manufacturing Inconel 718 by WAAM on a stainless steel round bar. The analysis of the fabrication process shows that the applying WAAM to parts made of difficult-to-machine materials can improve not only the machining time but also the number of tool changes. Kulikov A. A., et al. [20] customized an industrial robot combined with a welding machine for the 3D printing by WAAM. A steel open impeller for a compressor was fabricated and the process from 3D modeling to 3D printing using WAAM is presented. Zhang W., et al. [21] fabricated an aluminum alloy Ultra High Frequency (UHF) antenna feed as a case study of a large product using a hybrid process combining WAAM and milling. Compared with the conventional subtractive process, only 1/6 of the material was used in this hybrid process, and the machining cycle was reduced from 2 months to 25 days. Ding D., et al. [22] developed a fully automated system robot gas additive manufacturing of metal parts using arc welding. The system includes several modules, including bead modeling, slicing, weld path planning, weld setting, and post-process machining. The developed system has a user-friendly interface that allows non-experts to operate the system and automatically fabricate thin-walled aluminum structures for aeronautical applications. Zhang X., et al. [23] proposed a design method for reinforced structures with controlled structural connectivity based on the Moving Morphable Components (MMC) method, which uses reinforced members with explicit geo-metric parameters as primitives for topology optimization. A core load-bearing structure for a large satellite, a 3.5 m tank support structure, was designed using the proposed method and fabricated using WAAM. The structure passed the mechanical tests, and a final weight reduction of 31.6% was achieved. Zhong Y., et al. [24] deposited a stainless steel nuclear nozzle directly on a large curvature Pressurized Water Reactor (PWR) main pipe using a spatial scanning path designed based on an originally developed slicing algorithm for 3D models in a process using WAAM. In addition, comprehensive and systematic microstructural and mechanical data on the process are presented. Rafferty G. J., et al. [25] fabricated a steel elbow prototype to establish disruptive capabilities in advanced manufacturing for the supply of metal components in the oil and gas sector. The results indicate that the proposed work will directly contribute to a new roadmap for the advanced manufacturing of metal components in the oil and gas sector. Yili D., et al. [26] fabricated a complex structure, a steel 10-way pipe joint, using WAAM. To fabricate this complex intersecting structure, they proposed a spatial surface slicing method, which slices the formed pipe using the outer sleeve of the main pipe to form a deposition path along the spatial surface. Plangger J., et al. [27] investigated the feasibility of manufacturing near-net-shape crane mountings directly on subassemblies without any post-processing to apply WAAM to crane construction. Although initial attempts were made to establish a stable process to produce the specified shape of the part, further re-search was shown to be necessary to optimize this process. Greer C., et al. [28] fabricated a steel excavator arm using topology optimization as a case study for a metal additive manufacturing process called metal Big Area Additive Manufacturing (mBAAM). In this study, it showed how mBAAM design rules, such as overhang constraints, large weld bead thicknesses, and support structures, interact. Josten A., et al. [29] fabricated steel gusset plates added by WAAM to galvanized car body parts to reinforce formed thin steel sheets in automotive engineering manufacturing. Furthermore, to confirm that depositing the weld metal as a grid increases the bending stiffness of the sheets, bending tests of the thin plates showed an increase in the bending stiffness compared with the base metal. Gardner L., et al. [30] studied a 10.5 m span stainless steel pedestrian bridge fabricated by MX3D [31]. Results are presented for this bridge and its components, including advanced geometric analysis, material testing, cross-sections compression testing, and full-scale load testing of the bridge at various stages during and after construction. Casuso M., et al. [32] applied WAAM to fabricate thin-walled steel molds.

This study demonstrated that a simulation model that predicts deformation in the final shape can be used to qualitatively estimate the deformation mode of the part.

Key information from these papers is summarized below. The results of summarizing the 1st author's affiliation are shown in Figure 1. In addition, Figure 2 presents the results of summarizing the affiliations of all authors, including co-authors. This section is broadly categorized as either academia or industry. If authors belonged to more than one organization, they were classified as academia and industry. The results confirm that re-search on WAAM is being conducted not only in academia but also in industry. In some cases, research is conducted solely in industry, whereas in other cases, it is conducted through industry-academia collaboration. Figure 3 presents a summary of the publication years of the papers obtained from the survey. The oldest literature extracted in this survey was in 2016, and although we could not find only literature published in 2022, it can be confirmed that research using industrial parts as test pieces is being conducted continuously until 2024. The results summarizing the countries to which the 1st author belongs are shown in Figure 4. It can be seen that the studies are conducted in various countries. However, while countries included in the regions of Asia, Europe, North America, and Oceania were included in the findings, the study did not find any research results for countries in the regions of South America and Africa. The industries of the parts used as test pieces are summarized in Figure 5. Studies targeting various industries have been conducted. This can be attributed to the fact that many industries have high expectations for the manufacturing technology by WAAM. However, the results did not indicate that industrial application of WAAM have been conducted in all industries. For example, no research results were found targeting railroads [33], where arc welding is generally used. WAAM is an applied technology for arc welding; therefore, future studies are expected, as there is good potential for WAAM application in industries where arc welding is traditionally used. The results of the test piece materials are shown in Figure 6. More than half of the studies targeted steel, and only one study was found targeting WAAM with a single material. This indicates that research on WAAM for industrial parts only deals with a subset of research on WAAM using simple geometric specimens. Although studies on WAAM have been conducted on titanium [34] and multi-materials [35 36], no studies on industrial parts using these materials were found in this survey.

The results of the survey indicate that the study of the industrial applications of WAAM is incomplete in some aspects that require further research. Arc welding, which is the basis of WAAM, is an important technology that supports social infrastructure and is used in various industries. The advancement of WAAM has the potential to contribute to these industries; thus, there is sufficient social value for continuing the research. The geometry of parts used in machinery is not always simple, and there are many cases of complex shapes, such as curved surfaces. Therefore, it is important to continue not only fundamental evaluation of WAAM components but also to conduct evaluation of actual part geometries for industrial use as one of the future research activities related to WAAM. In other words, in industrial applications, unless the intended shape can be manufactured additionally, it cannot be used as a manufacturing technology, which means that it will not lead to the creation of new value.

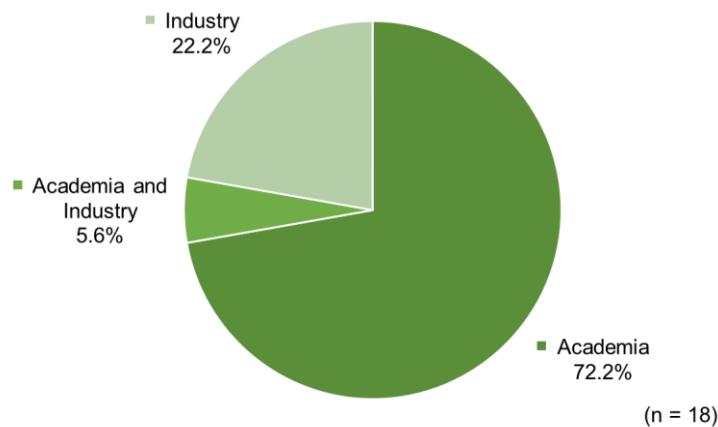


Figure 1. Literature review summary for 1st author affiliation.

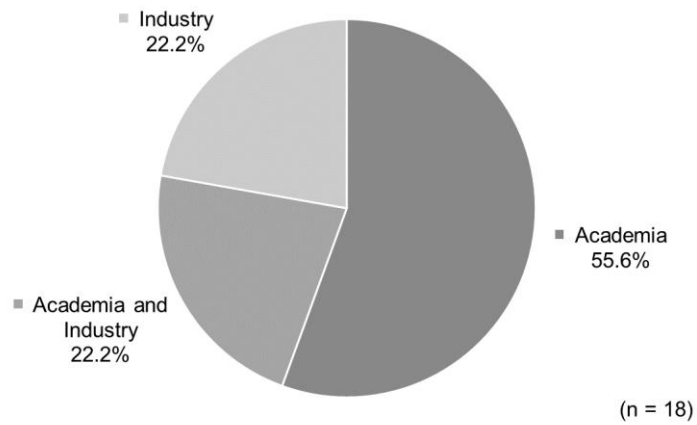


Figure 2. Literature review summary for authors affiliation.

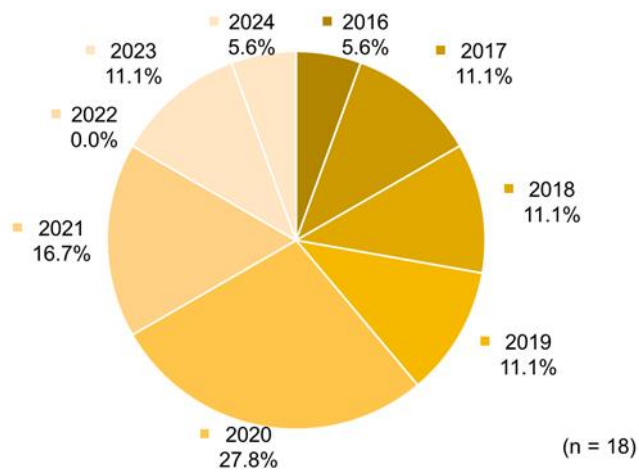


Figure 3. Literature review summary for paper published year.

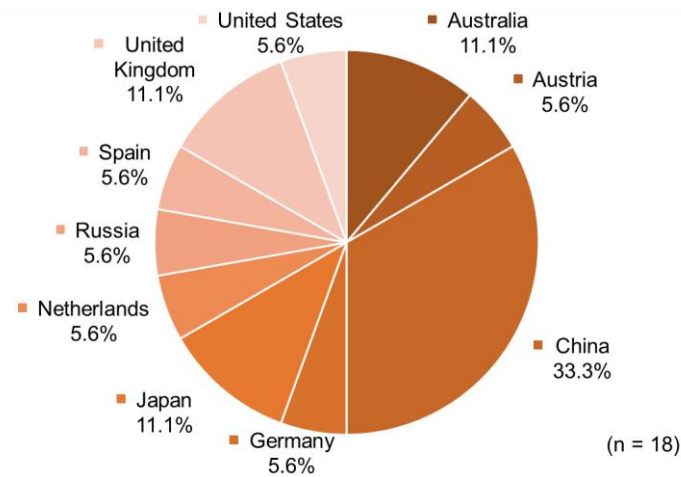


Figure 4. Literature review summary for country of 1st author affiliation.

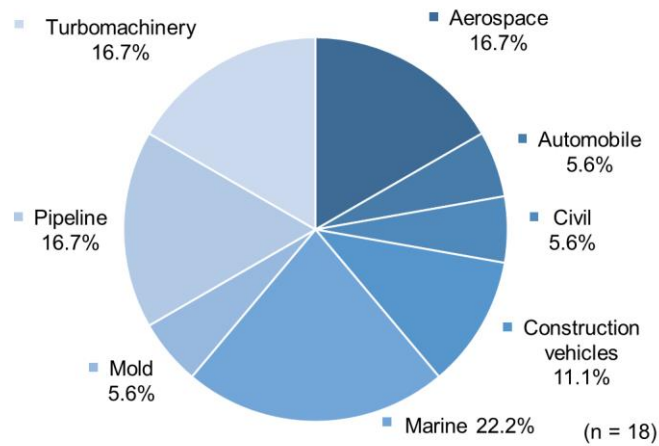


Figure 5. Literature review summary for applicable industry.

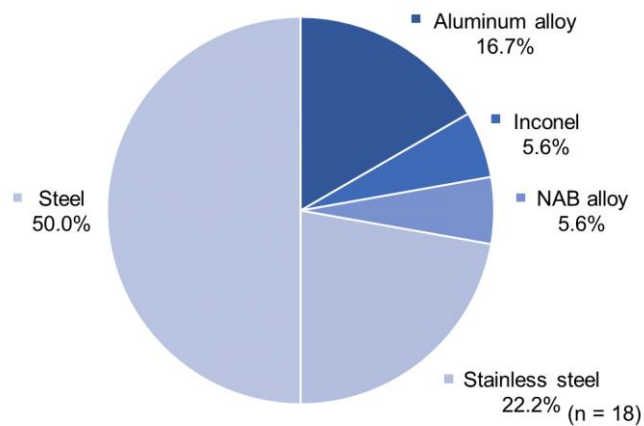


Figure 6. Literature review summary for test material.

4. Conclusions

A literature review of peer-reviewed original articles and proceedings was conducted on study for WAAM using industrial parts as test pieces. It was found that studies have been conducted targeting a variety of industries; however, it was also clear that studies have not been conducted for all industries that use arc welding as the basis for WAAM. Many studies targeted steel, whereas others targeted aluminium alloys, Inconel, NAB alloys, and stainless steels. On the other hand, it also became clear that studies using test pieces of industrial parts only treated a subset of the topics that could be treated by WAAM, since fundamental studies using simple geometry specimens also were conducted on titanium and multi-materials. It is possible that treating the topics clarified in this study could lead to an expansion of the industrial use of WAAM.

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