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Investigation of Robotic Transverse Twin-Wire GMAW for Large-Scale Wire-Arc Additive Manufacturing Applications

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Abstract

Bulk metal additive manufacturing using wire-arc processes has gained significant attention for fabricating large-scale engineering components due to their high deposition rate and material efficiency. In this study, the feasibility and performance of robotic transverse twin-wire gas metal arc welding (GMAW) for bulk wire-arc additive manufacturing (WAAM) is systematically assessed. The research focuses on understanding arc stability, weld bead characteristics, and process–product relationships under high-deposition conditions. Welding current signals from both primary and secondary electrodes are analyzed to evaluate arc interactions and stability, while the influence of torch orientation and process parameters on bead geometry, penetration, and heat-affected zone characteristics is examined. Experimental investigations reveal that transverse twin-wire configuration improves arc stability and enables wider, more uniform weld beads compared to conventional tandem arrangements, making it suitable for additive manufacturing applications. An asymmetric weld bead model is developed and validated to predict bead geometry and overlapping behavior, which is critical for achieving dimensional accuracy in multi-pass, multi-layer deposition. The integration of process models with component-level design demonstrates improved material utilization and reduced post-machining requirements. The outcomes of this work establish robotic transverse twin-wire GMAW as a viable and efficient approach for large-scale WAAM, offering enhanced control over deposition quality and mechanical consistency.

Keywords: Wire-arc additive manufacturing, twin-wire GMAW, robotic welding, bulk additive manufacturing, arc stability, weld bead modeling

INTRODUCTION

Metallic additive manufacturing (AM) is often considered a prototyping tool and used to produce one-off components or mold tooling to offer a shorter time to market in the industries [1–19]. These often are manufacturers of small, complex high-value components on short lead times for the medical, dental, motorsports, marine, or aviation industries [20–22]. The metallic AM processes are competent in fabricating material equivalent to wrought product [23, 24] and often superior to that manufactured by casting or hot isostatic pressing (HIP) [23]. Mechanical properties seem to be almost equal to or superior to those of the same material processed by more conventional routes (cast or HIP) [24–26]. The metallic AM carries certain advantages to the manufacturing of components. A layer-by-layer deposition allows

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significant liberty in the geometry, which can be achieved, removing various traditional limits on the production of shapes and features, though imposing certain limitations of its own [27]. The intricate lattice structures, internal cavities, and fluid flow channels or internally routed pressure tapings are feasible; however, overhanging below a critical angle require support structures. The surface roughness of components is affected by both layer thickness and the processing parameters of the energy source. In contrast, sidewall surface roughness is regulated predominantly by the layer thickness and surface orientation [28]. The process of quality control in the area of metallic AM is very critical to enable it to produce defect-free parts or components. In the case of wire-arc additive manufacturing (WAAM), passive machine vision systems can ensure a constant torch offset distance, as well as weld bead width during thin wall deposition [29–32]. A line or area scanning infrared pyrometer can be used to monitor the thermal profile surrounding the solidified weld bead and provide feedback information in WAAM processes [32, 33]. Most research into WAAM techniques has so far been based on the basis of gas metal arc welding (GMAW) due to its pervasive availability and presence of substantial knowledge and equipment solutions in the welding industry.

WELDING-BASED ADDITIVE MANUFACTURING TECHNIQUES

Some metallic components produced by welding-based AM processes, such as WAAM, laser additive manufacturing (LAM), and electron beam additive manufacturing (EBAM), are shown in Figure 1. Wire arc manufacturing (WAM) can be classified based on the motion controller, raw material, and heat source, as shown in Figure 2. The way the raw material is used (i.e., in powder or wire form) is the primary attribute of the AM technology that is supported by the heat source and motion control [34–40].

Powder-Based AM Technology

Powder-based AM is of two types: powder bed and powder feed, as shown in Figure 3. In the former, the powder is spread in the powder bed system and then selectively melted, whereas in the latter, the powder is fed in the presence of a heat source that melts and deposits the metal. Powder bed AM, also known as powder bed fusion (PBF), consists of a roller or blade to spread powder to form a layer of thickness up to 20–100 μm depending on the process and particle size of the powder [35].

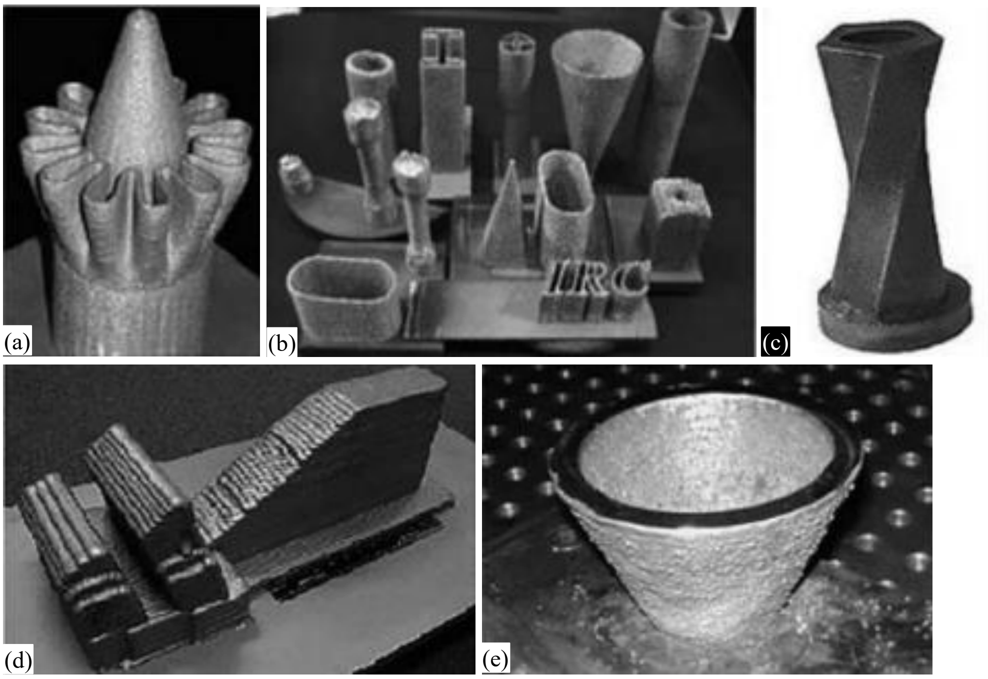

Figure 1. AM parts fabricated by (a) and (b) laser-based powder bed/feed, (c) electron beam-based, (d) laser-based wire-feed, and (e) arc-based [34].

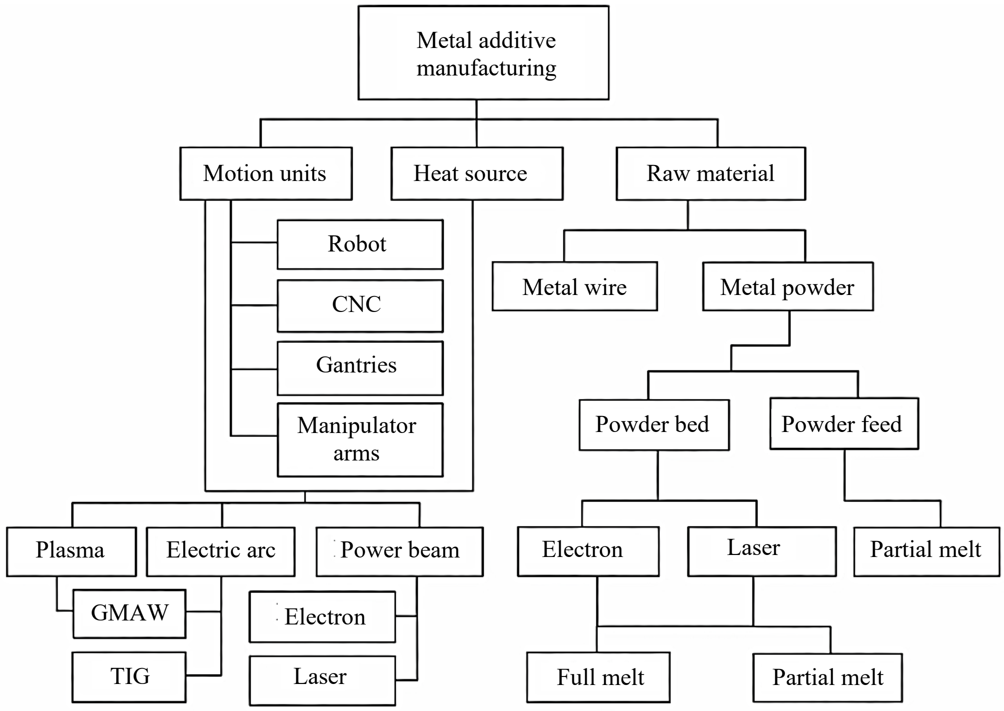

Figure 2. Classification of welding additive manufacturing.

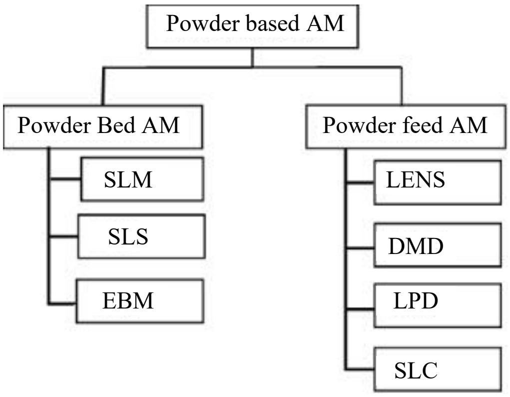

Figure 3. Powder-based additive manufacturing.

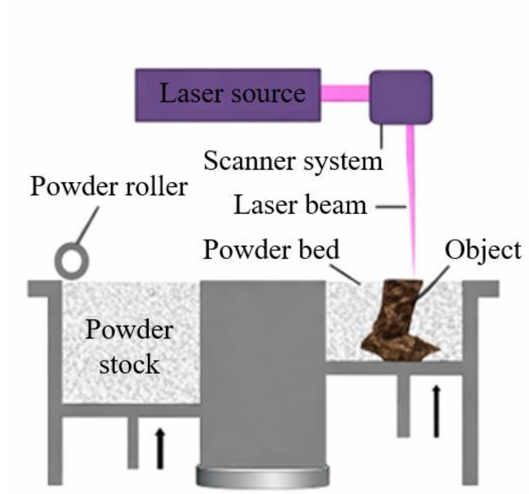

Figure 4. Laser beam-based powder bed AM

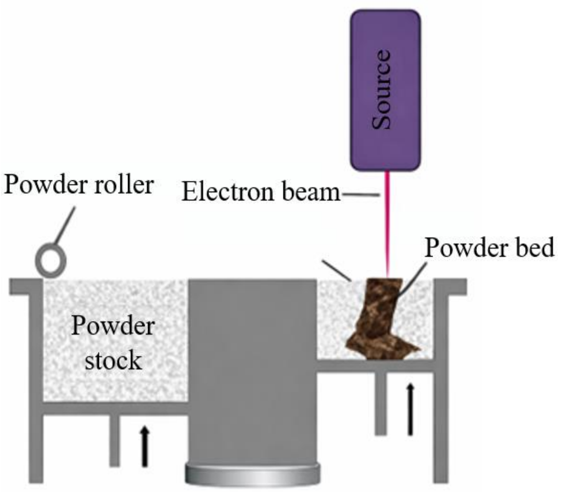

Figure 5. Electron beam-based powder bed AM

The requirements for powder precursor materials depend on the specific powder-based AM technology, as shown in Figure 4. The essential requisites of metal powders include grain size (nano, submicron, or micron powder), grain shape (spherical, irregular, or granulated), composition (pre-alloyed or blended), gas infusions, powder flowability, tendency to oxidize, and sintering/melting conditions. Figure 4 shows the typical powder grain size distribution required by different AM methods, with an example of titanium alloy powders [38].

EBM (electron beam melting) uses a nominal particle size distribution between 45 and 106 µm, while SLM (selective laser melting) / SLS (selective laser sintering) uses finer powders between 15 and 45 µm. Particle size distribution affects the capabilities of the corresponding AM technology Figure 5. Powders with finer grains provide better control of the layer thickness, print resolution, and printed roughness of the components [39].

In contrast, larger-sized grain powders possibly allow faster fabrication in thicker layer deposition. The distribution of finer powder fractions improves the packing density by filling the voids between larger fractions. Small powder particles (smaller than 10–15 µm) decrease the flowability of the powder and increase the risks during powder handling. Therefore, a trade-off in the particle size distribution is required to achieve a high packing density and good flow properties [40, 41]. High-density products are difficult to fabricate with powders that have irregular or large numbers of “satellites” (smaller particles fused with the main grain) Figure 6.

Therefore, a component with high porosity leads to the heterogeneity of the microstructure and even anisotropy of properties. Among the three versions, SLS is relatively slow and has a non-uniform temperature distribution that may lead to thermal distortion and cracks on the component. Despite this, SLS has a high degree of accuracy and surface quality. Hence, metal AM processes are widely used to fabricate porous materials. One of the prominent examples of powder-based AM is the first wall (FW) panel part of the International Thermonuclear Experimental Reactor (ITER), which is a very sophisticated design fabricated using SLM- and EB-based AM processes [42].

Powder feed AM includes several variants, such as laser engineering net shaping (LENS), laser powder deposition (LPD), direct metal deposition (DMD), and selective laser cladding (SLC). A typical LENS system is shown in Figure 7, where the powder nozzles and the head of the laser travel as an integral entity. The powder is injected or blown by gravity or pressurized gas into a laser-focused beam to create a molten pool. The component is fabricated by depositing the material, layer-by-layer. It is also used to repair parts but still requires post-production treatments [42–48].

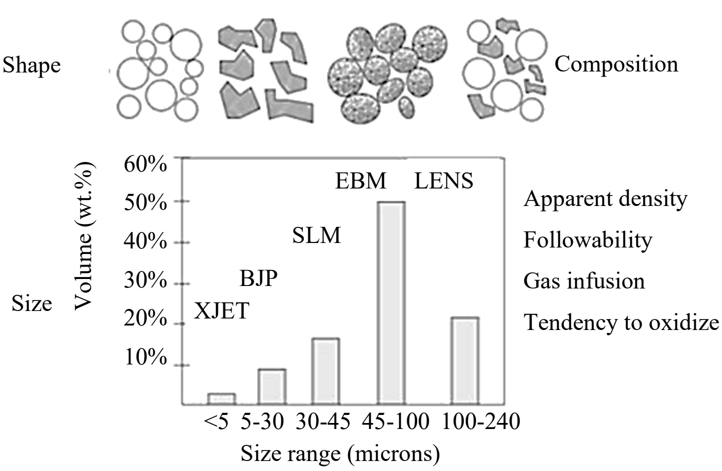

Figure 6. Powder bed MAM [36] and powder characteristics in AM [37].

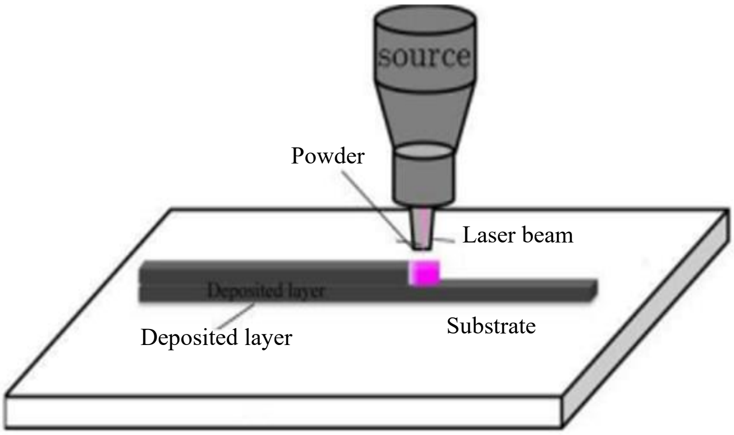

Figure 7. Powder feed system [36].

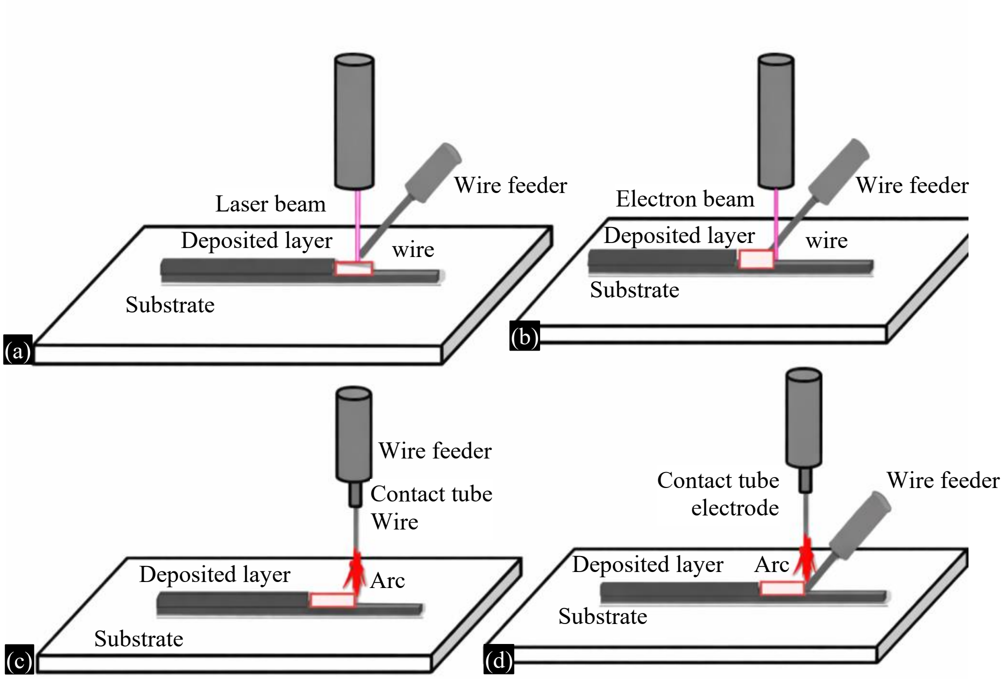

Figure 8. Wire-feed additive manufacturing (a) laser-based, (b) electron beam-based, (c) arc-based Gas metal arc welding (GMAW), and (d) arc-based gas tungsten arc welding (GTAW) techniques for additive manufacturing.

Wire-Feed AM Technology

Wire-feed WAM comprises a wire feeder, heat source, and motion control unit. In this process, the wire melts and creates a weld pool using a heat source (e.g., laser, electron beam, plasma, or arc) to manufacture the components. The material usage efficiency of wire-feed-based WAM is very high and even reaches 100 % without exposing operators to the hazardous powder environment, making it environmentally friendly [44].

Wire-feed-based WAM processes are designated based on heat sources, e.g., EBF3 (electron beam freeform fabrication), wire and laser additive manufacturing (WLAM), and WAAM.

Laser, electron beam, and plasma are primarily used to fabricate small components owing to their low deposition rate and energy efficiency, whereas arc (gas tungsten arc welding (GTAW) or gas metal arc welding (GMAW)) is used to produce comparatively large components with moderate complexity. A schematic of the WLAM, EBF3, and WAAM processes is shown in Figure 8.

RESEARCH METHODOLOGY

Path Planning

Path planning is primarily the ability to automatically produce sensible paths for depositing various geometries with minimum residual stress and distortion [46]. The layers can be deposited through several tool paths, which involve a single start and stop for continuous material deposition. Geometrical features, thermal effects, and process capability limitations are essential aspects that must be considered in the decision-making process of path planning. Various tool path planning approaches have been developed in WAM processes over the years to meet these requirements, some of which are shown in Figure 9. The raster tool path fills the area linearly in a particular direction, as shown in Figure 9(a). It starts and frequently stops owing to the presence of discontinuous paths, which is undesirable for WAAM because of instability during the start and end of the process.

The raster produces a non-uniform deposition of material that has no resemblance to the ideal bead obtained under steady-state conditions. Zigzag tool path generation is applied to overcome this problem by combining the separate parallel lines into a single continuous pass, as shown in Figure 9(b). However, the discretization errors in both raster and zigzag may lead to an accuracy reduction on the boundary of the component if the tool motion direction is not parallel to the edge. The accumulation of heat also occurs in certain regions owing to the involvement of highly convoluted paths in a zigzag pattern. The spiral tool path is another technique used to resolve the zigzag path complications in the WAM process, as shown in Figure 9(c) and (d); however, it is appropriate only for particular geometrical models.

The contour tool path shown in Figure 9 offsets parallel to the boundary of the component recursively and can thus effectively address the issue of a geometrical feature in raster and zigzag. It reduces distortion and anisotropy by regularly altering the path direction along the boundary [47]. It is often preferred in wire-feed AM deposition over raster and zigzag for constant wall thickness. The limitations of the aforementioned tool paths for complex geometries are overcome by algorithmic path plans such as the medial axis transformation (MAT) and adaptive path planning (APP).

The medial axis is the locus of the centers of circles (spheres) of different radii that touch or are close to at least one point on the surface of the object. The contour and MAT paths have constant step-over distances that may lead to unfilled or overfilled areas, as shown in Figure 10. The contour path plan shown in Figure 10(a) generates several closed paths by offsetting the boundary curves toward the interior. In the case of WAAM, where the step-over distance is large, the contour path may leave a gap, as shown in Figure 10(b).

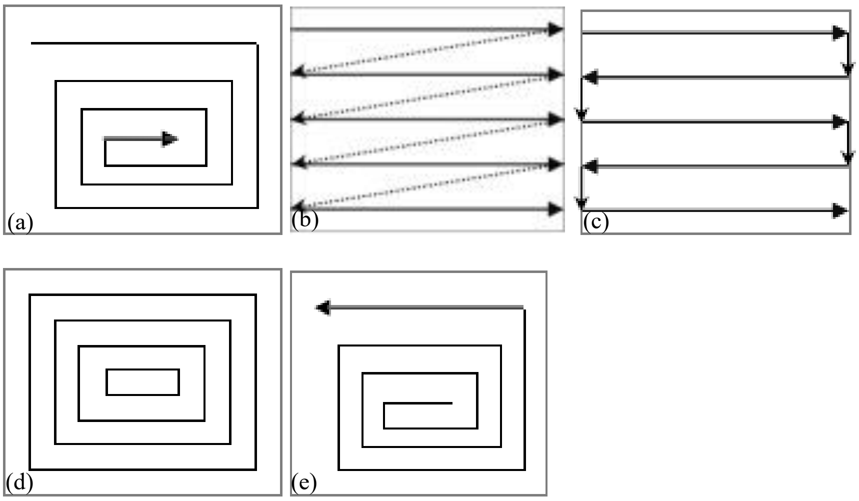

Figure 9. Typical path planning of additive manufacturing: (a) raster, (b) zigzag, (c) spiral-in, (d) spiral-out, and (e) contour.

The MAT path shown in Figure 10(c) generates a void-free deposition, as shown in Figure 10(d), but deposits extra material at the boundary. Post-processing, such as machining, removes these extra materials to enhance accuracy at the cost of material and energy wastage. The limitations of the contour and MAT paths are overcome by APP, wherein the voids and excess material are avoided by continuously varying the step-over distances through adjustment of the process parameters [48], as shown in Figure 10(e) and (f). WAAM is specially equipped for APP because different widths within a layer can be achieved by changing the welding speed and wire feed.

Overhanging Feature in WAM

Overhanging features are indispensable in AM. Unlike polymer 3D printing, detachable support structures are not always possible in WAM.

On the bottom side during fabrication, the molten metal may crossflow and deform. In order to prevent deformation, the support structures are fixed to the fabricating platform through which excess heat is conducted away from the component. The presence of the support structures increases the difficulty of post-processing operations. Therefore, the geometrical design and optimization of the support structures are essential to improve the sustainability and efficiency of a metallic object fabricated by the AM. The overhanging features cannot always be avoided but can be minimized only by selecting an appropriate orientation.

The feature of the part, whether it is overhanging or not, is determined by the orientation of the component during manufacturing. The surface area of the support structure depends on the built orientation of the part. The best orientation in the manufacturing of a component with minimal support structures is selected from a list of the candidate orientations. In case the support structures required for two orientations are equal, the orientation having a lower center of mass is selected. In the powder-bed-based AM process, the melt pool is created by the heat source that is supported by a bed of powder particles. The heat is conducted by two different zones (i.e., solid-supported and powder-supported) wherein one has a higher heat conduction rate while the other is much lower. This makes the melt pool, when supported by powder, large and deep, which sinks into the powder due to gravitational and capillary forces. The melting penetration of the melt into the powder bed is caused by the Rayleigh–Taylor instability in the gravity field. The heat of the melt pool causes unintentional sintering of the supporting powder particles to form dross, which lowers the dimensional accuracy (Figure 11).

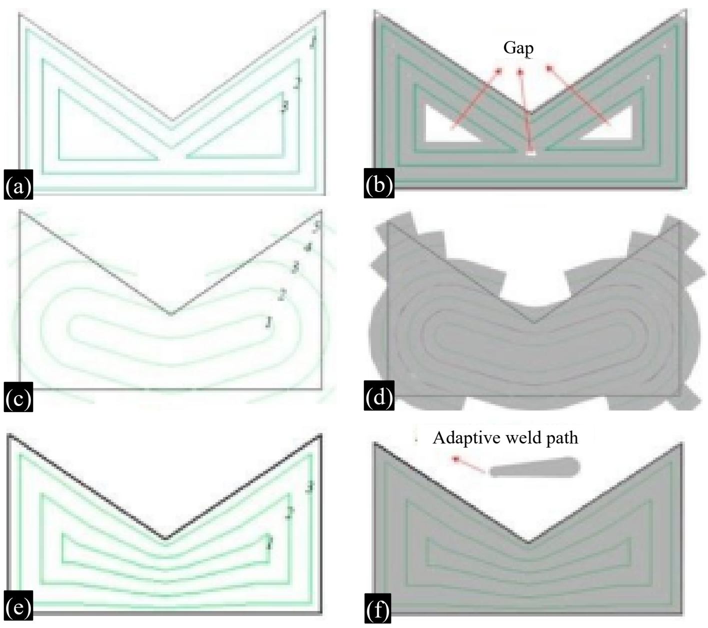

Figure 10. (a) and (b) Effect of contour, (c) and (d) Medial axis transformation (MAT), and (e) and (f) adaptive path planning [48].

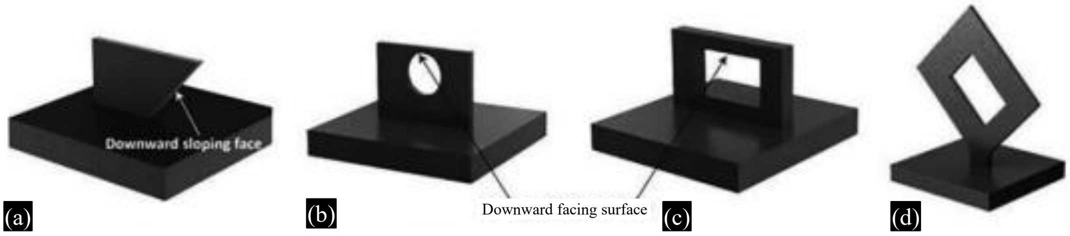

Figure 11. Overhanging structures: (a) downward sloping face, (b) and (c) downward-facing surfaces, and (d) downward sloping faces obtained by orientation in the building platform.

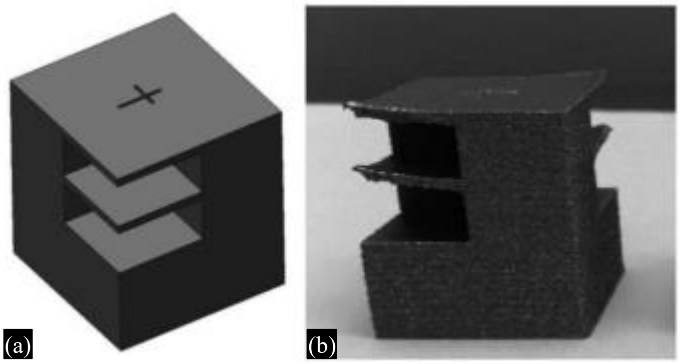

Figure 12. Overhanging features: (a) CAD model, and (b) warping of an overhanging feature in the fabrication of powder bed AM.

Dross formation is unavoidable when fabricating overhanging surfaces using PBF. The dross can be minimized by selecting proper process conditions through investigating the thermophysical mechanism using numerical simulation; for example, both high and low laser volume energy densities result in an inferior quality of the downward-facing surface. A relatively smooth downward-facing surface was obtained at the optimal processing parameter owing to the sound melt pool dimension and steady melt flow behavior. Warping is another effect caused by the difference in thermal conductivity, as shown in Figure 12. This is because the thermal conductivity of a powder bed is approximately 100 times lower than that of a bulk solid. Therefore, support structures are often required to aid heat dissipation, particularly at overhanging features.

The finite-element method (FEM) is used to simulate the thermally induced deformation for different overhanging support patterns such as overhang length, the support column, and the gap between solid pieces. The longer overhang length causes a more extensive deformation, whereas even a thin support column can prevent overhang curling. Support cannot be avoided, and its utilization becomes mandatory in some cases. The removal of support during the post-processing phase is a tedious task for delicate parts, may cause the breakdown of a small piece, and adversely affects the surface quality, which partially limits the freedom of design. Therefore, the focus in powder bed AM is to reduce the number of supporting surfaces for improving sustainability and process efficiency without compromising the quality through the optimization and geometrical design of the support structures. The conventional support has straight rectangular solid walls in the form of a grid of x and y lines, which are separated at a certain distance (x hatching and y hatching) or blocks that should be strong enough to bear both the vertical weight and other horizontal instabilities. The selection of hatching depends on the surface area. The problem associated with this kind of support is trapping of the loose powder inside the support structures during the fabrication, which becomes unsuitable for recovery, especially when trapped raw powders wash away during removal by EDM-wire cutting. The support structures are not used in the manufacturing of the overhang features in wire- feed AM. Torch orientation and table orientation in the following manners facilitate overhang feature fabrication: (a) flat table and vertical torch position, (b) flat table and inclined torch position, (c) rotating table and vertical torch position, and (d) rotating table and inclined torch position, which are shown in Figure 13.

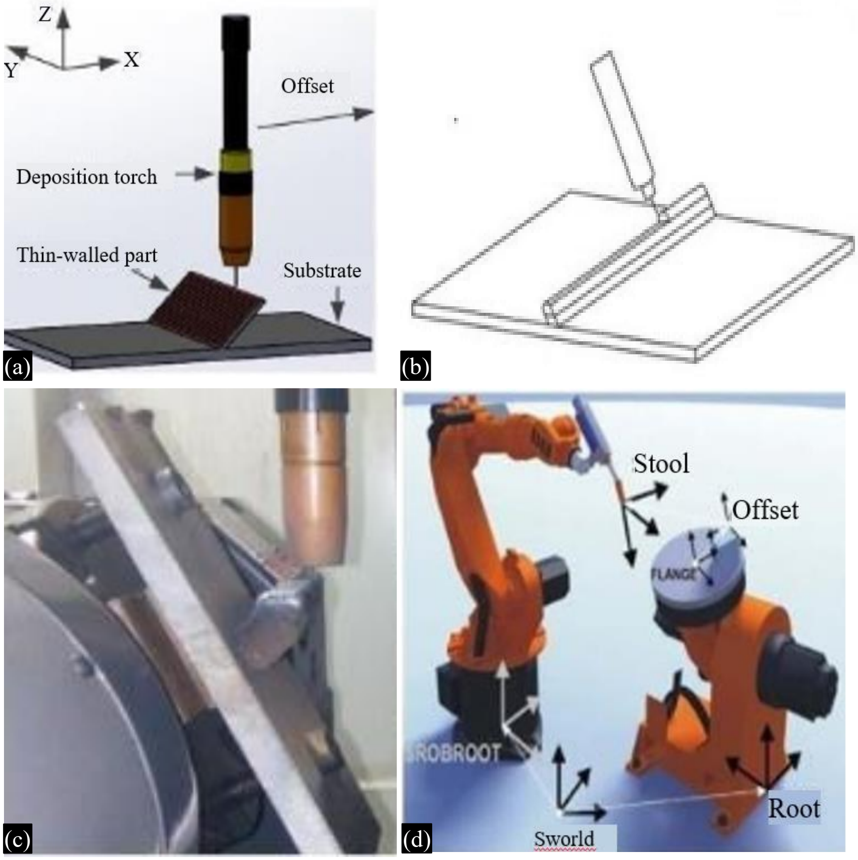

Figure 13. Method for fabricating overhanging features: (a) flat table and vertical torch, (b) flat table and inclined torch, (c) rotational table and vertical torch, and (d) rotational table and inclined torch position.

Hybrid WAAM Processes

The WAAM process has been hybridized with other fabrication operations to improve its efficacy. In milling-assisted WAM, the parts are milled after full deposition or immediately after each layer deposition. The latter reduces the manufacturing efficiency because of the time consumption in shifting the workpiece between the deposition and milling processes; however, it helps maintain accuracy. Milling-assisted WAM enhances dimensional accuracy and surface quality, creating a balance between product quality and fabrication time.

The milling-assisted WAAM process has recently become commercially available. Earlier, the welding gun was mounted on a vertical milling center to realize milling-assisted WAAM. In milling-assisted WAAM, after the deposition of each layer, the surface is face-milled to compensate for the variation in thickness owing to the irregular weld surface. The complex geometry of the injection mold with core and cavity (Figure 14) was fabricated by milling-assisted WAAM.

Milling-assisted WAAM provides better economic and manufacturing time viability than computer numerical control (CNC) machining. The hybridization of SLM and WAAM has also been reported in the literature. The fabrication of large and complex components by SLM and higher accuracy with WAAM are yet to be achieved. The hybridization of SLM and WAAM can fabricate large and complex components economically. The parts fabricated by this process are decomposed into complicated and simple parts, which are generated using SLM and WAAM, respectively. However, the inconsistency in mechanical properties is an unresolved issue; for example, tensile fractures occurring in the WAAM zone.

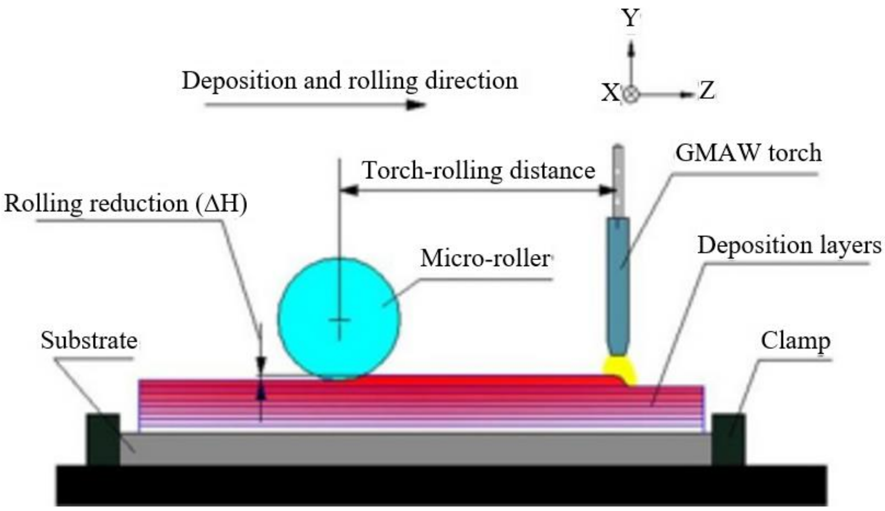

Figure 14. Schematic diagram of rolling on weld bead in rolling-assisted WAAM.

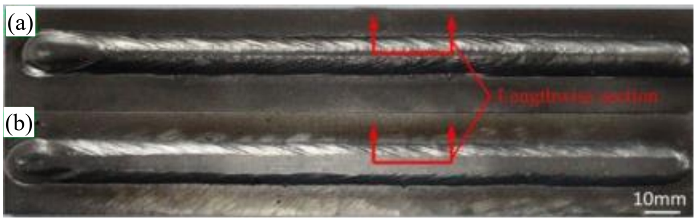

Figure 15. (a), (b) Effect of the roller on the weld bead in rolling-assisted WAAM.

Rolling-Assisted AM

The top surface of the bead in WAAM is convex and non-smooth, which causes the flow of molten material and yields a difference in theoretical and actual thicknesses, resulting in a cumulative error in the built-up height direction. The in-situ rolling or intermediate rolling after each layer or layers makes the top surface almost smooth and flat and alleviates the abovementioned effect.

In-situ rolling controls the deposition layer thickness and improves the deposition efficiency. The position of the roller during in-situ rolling is crucial because a roller that is too close damages the bead, whereas one that is too far has under-deformation, and an appropriate roller distance produces the desired effect. The weld beads with and without rolling are shown in 12 (a and b, respectively) are shown in Figure 14.

Uncertainty in Metallic AM Processes

One of the major problems that obstructs the insight into the significant potential of metal-based AM techniques is the variation in the quality of the manufactured parts. Compared to other manufacturing process-sensitive technologies, the various features of metallic AM have greater unpredictability and make its control challenging. Build parameters are tightly coupled in MAM; however, with the present state of the technology, no one can merely change one of them to attain predictable behavior (Figure 15).

Altering the product geometry or orientation in the fabrication chamber can affect its microstructure, safety, and performance. Additional testing is required for high process variability to ensure part quality, which adds additional costs to the production process, such as a large amount of testing, which can add substantial expense.

It can be broadly classified into three sources of uncertainty: material, part fabrication process, and post-processing. The material is used in three different forms: wire-fed, powder-fed, and powder bed, which require different sets of parameters to be monitored. For a given process, the features of the material can differ broadly from the material supplier. The dimensions of the powder particles for powder-fed and wire dimensions for wire-feed systems and the composition of the base material vary with supplier capabilities and affect the quality of the final part.

GAPS AND OPPORTUNITIES

Based on the review of the literature presented in the previous sections, some gaps have been identified. These gaps offer opportunities for research on high-deposition WAAM processes using twin-wire GMAW.

Problem Formulation

The problem statement for the present work is as follows:

"An examination of twin-wire GMAW as a candidate for high-deposition rate in additive manufacturing processes by assessing the stability of the welding arc, bead profile, and overlapping bead model to improve the acceptability of the process."

The fabrication of bulk components by additive manufacturing requires a high-deposition rate welding process to produce a perfect weld bead with increased productivity. At the start of this work, inadequate data is available on twin-wire GMAW for high deposition in additive manufacturing. This research aims to better understand process characteristics through a systematic approach of studying the effect of the welding parameters on weld bead profile. Again, no previous investigation on the effect of the welding parameters on weld bead profile in the transverse orientation of the torch has been reported in the literature. This examination is expected to offer the essential information to develop welding conditions and establish mathematical expressions for easier interpretation of the relationship between torch orientation, welding parameters, and weld bead profile.

The objectives of this study, which aims to develop a general twin-wire weld deposition-based additive manufacturing, can be summarized as follows:

- To investigate the GMAW twin-wire welding technique for assessing arc stability in tandem and transverse torch orientations using welding signatures of current and voltage.
- The effect of welding parameters and the effect of the torch inclination angle in the transverse direction on the control of the weld bead geometry were studied.
- To develop a weld bead profile model and overlapping model for twin-wire GMAW in transverse orientation deposition.
- A mathematical model was developed to predict the weld bead characteristics and overlapping steps over distance.
- The stability of the chosen weld parameters and deposition strategy in a multi-layer scenario was validated.
- Determining the suitability of twin-wire GMAW processes for a large component WAAM.

CONCLUSIONS

The driving force of the present research is to design twin-wire GMAW-based additive manufacturing processes for bulk deposition in the fabrication of large components. Accordingly, the principal objective of this study is to assess transverse twin GMAW as a candidate for bulk deposition by assessing arc stability, weld bead characteristics, bead model, bead overlapping model, and bead overlapping model optimization of the WAAM process. These investigations provide the designer with the ability to specify the range of parameters for depositing defect-free, sound WAAM parts, resulting in some conclusions, which are listed below:

- The wire orientation influences the shape of the weld bead. The reinforcement profile of the weld bead had a single height in both the tandem and transverse twin-wire GMAW processes. In contrast to tandem, the transverse twin-wire GMAW has two penetration depths that tend to merge with an increase in the welding current. The tandem orientation had deep penetration, whereas the transverse orientation attained a wider bead with almost the same penetration.

- The stability of the arc welding process was quantitatively evaluated using wavelet-energy-entropy (WEE). The WEE of the signal shows the amount of disorder in the signal. Bior 5.5 wavelet was a suitable candidate for analyzing the welding signals. The stability of the process is inversely proportional to WEE. The complex interaction between arcs in twin-wire robotic GMAW under different process conditions was explained by WEE analysis of current signals that showed relatively stable transverse orientation.
- In twin-wire welding, the arcs attain extra stability when the currents at the primary and secondary electrodes are unequal. Arc interactions considerably influence the heat input of the primary and secondary electrodes.
- Arc instability can be quantified and predicted using a regression model of WEE as a function of welding current, wire position, and wire orientation in twin-wire GMAW. Although arc interactions cannot be eliminated, they can be reduced. The process variables (i.e., the wire orientation should be transverse at a given welding speed) should be maintained to maintain a stable arc with improved quality and properties.

Scope of Future Work

This study focuses on the structural steel substrate and ER70S6 wire combinations as part of the investigations for bulk WAAM deposition using the twin-wire GMAW process. The thesis provides a sequential series of experiments addressing arc stability analysis and its impact on weld characteristics, bead model, asymmetric bead overlapping model, weld bead predictive model, and optimization of twin-wire WAAM. Consequently, the scope of future work is multidirectional. Future work will be related to bulk depositions for WAAM using twin-wire welding. The tested procedures can be applied and further verified using various wire diameters, different welding wires, and other welding processes. The transverse twin-wire GMAW can be further explored for its commercial viability as a candidate for bulk deposition in WAAM fabrication. It is proposed that mechanical strength (tensile, fatigue, and toughness strength), the effect of substrate heating, cooling strategies during deposition, and heat treatments could be investigated based on the potential benefits shown thus far. The present thesis deliberates only the fabrication of elementary geometries and can be extended to geometrical features such as overhangs and sharp corners.

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