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Letters

Limited-constraint WAAM fixture for hybrid manufacturing

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ABSTRACT

This paper describes a limited-constraint alternative to the traditional over-constrained build plate clamping in metal additive manufacturing. A fixture design is presented that enables build plate thermal growth within its plane while restricting deformation perpendicular to that plane. A prototype fixture is designed, fabricated, and tested for wire arc additive manufacturing (WAAM). Experimental results are presented for depositing 1.2 mm diameter 5356 aluminum wire on a 5052 aluminum build plate. The build plate deformation is measured for various clamping torques and a 77.3% reduction in distortion is achieved using the limited-constraint approach with identical WAAM parameters.

1. Introduction

Additive manufacturing (AM) is now a well-known and widely adopted technology for preform fabrication using layer-by-layer deposition. Application domains include aerospace, automotive, tools and molds, medical and dental, and others [1]. For metal AM, key processes include material extrusion, powder bed fusion, material jetting (i.e., photopolymers with metallic particles and UV light), binder jetting (i.e., liquid state binder and powder metals), and directed energy deposition (DED), which can be categorized as solid-state/kinetic and thermal depending on the energy input. Thermal energy-based DED processes selectively melt the metal powder or wire feedstock using a laser beam, electron beam, plasma, or arc. For example, wire arc additive manufacturing (WAAM) applies gas metal arc welding (GMAW), gas tungsten arc welding (GTAW), or plasma arc welding (PAW) to deposit material at higher rates and lower cost when compared to other metal AM processes.

Despite the rapid growth of the metal AM industry, challenges remain. These include production volume, standards compliance, post-processing requirements, available materials, training and workforce, maintenance, size restrictions, cost, and part quality [2]. A primary part quality challenge is residual stress that is produced by temperature gradients during thermal energy processes; this residual stress leads to part distortion and, potentially, delamination and build failure. Residual stress in WAAM, a fusion process, is a significant challenge due to shrinkage of large volume liquid metal pools during solidification and repeated heating and cooling cycles during layer-by-layer part fabrication. A recent study used machine learning to rank process variables that most strongly influence residual stress, including substrate preheat temperature, the gap between the solidus and preheat temperatures, the product of elastic modulus and the coefficient of thermal expansion, molten pool volume, substrate rigidity, and heat input [3].

While mitigation strategies, such as build plate preheating, double-sided deposition [4], active cooling for the build plate [5], and modeling the stress evolution during thermal cycling for clamped constraints [6] have been studied, residual stress remains a significant obstacle for metal AM preform production, including WAAM. A practical issue that must be addressed due to residual stress and part/build plate distortion is work holding during deposition. A common approach is massive over-constraint, where multiple toe clamps and stiff brackets are used to (ideally) hold the build plate flat as material is added. In this over-constrained condition, the number of restricted degrees of freedom is much higher than the minimum of six required to exactly constrain a rigid body. In the worst case, these clamps and brackets fail catastrophically due to the high stresses that are developed during material addition and pose a significant hazard to personnel and equipment at fracture. Even if the clamps do hold and can be safety removed, the plate and part deform when released based on the internal residual stress profile. As an alternative to the over-constrained strategy, this paper describes a limited-constraint alternative that enables build plate growth within its plane while restricting only

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deformation perpendicular to that plane. A prototype fixture is designed and tested. Experimental results are presented.

2. Fixture design

2.1. Mechanical

The fixture is composed of six parts: 1) aluminum jaws, 2) ceramic insulator, 3) titanium spacers, 4) steel base plate, 5) steel spacers, and 6) the grounding connection. The overall dimensions are 254 mm × 254 mm × 63.5 mm; see Fig. 1. The base plate is bolted to the machine table through two countersunk holes located on either side of a center locating bore. A steel spacer with clearance holes for the table bolts is positioned under the base plate. Steel was selected for its low cost, machinability, and higher electrical resistance than aluminum. The build plate is clamped between the aluminum jaws and titanium spacers. Titanium was chosen for its low thermal and electrical conductivity and corrosion resistance at elevated temperatures.

The titanium spacers do not extend across the full base plate width to reduce contact with the build plate and, therefore, conductive heat transfer. The spacers, jaws, and base plate were machined to be flat and parallel to within ± 38 µm. The jaws are located with ground pins that are fixed in the steel base plate and have a RC1 close sliding fit with the pins. Slots were machined into the jaws to reduce the moment on the locating pins while clamping and enable plate growth in the Y direction. The clamping force is supplied by two stainless steel fasteners. During preform deposition, the fasteners are tightened just enough to bring the jaw into contact with the build plate. This constrains the build plate movement and thermal growth in the Z (vertical) direction, but allows it to expand in the XY plane; note that there is lateral space beneath the jaws to enable this thermal growth of the plate. The intent is to limit the build plate distortion by avoiding overconstraint during deposition.

For preforms that require significant material removal by machining after deposition, additional fasteners can be added to directly clamp the build plate to the base plate. A precision bore in the center of the fixture base plate is used to set the work coordinate system for the welding torch (and milling spindle for hybrid manufacturing). The bore was sized to provide a 51 µm clearance fit for the weld torch nozzle in the setup implemented for this study.

2.2. Thermal

For hybrid manufacturing, deposition and machining can occur using the same machine axes. In this work, a low-cost solution was realized by clamping the welding torch to the milling spindle in a three-axis CNC milling machine [7]; see Fig. 2. The clamp is comprised of a fixed spindle ring and torch holder. The spindle ring is installed over the spindle and indicated so that the front of the mounting tab is parallel to the Y (horizontal) axis. The torch is mounted in the torch holder with a slight interference fit and compressed using a back plate. Two fasteners are used to connect the spindle ring and torch mount for convenient installation and removal. The torch orientation is nominally perpendicular to the table. An empty, low projection length tool holder is loaded into the spindle to prevent any spatter or debris from entering the tool holder taper during deposition.

One challenge associated with combining a fusion-based additive process and milling machine is the heat generation during the AM process. When the build plate is directly mounted to the machine table, the deposition heat transfers from the build area to the table, guide ways, spindle, and base. As these components heat and thermally distort, positioning errors are induced in the machine and degrade its geometric accuracy. Since a machine tool takes many hours to reach thermal equilibrium, it is advantageous to isolate the build area from the machine tool.

The fixture designed for this platform uses a high-strength calcium silicate ceramic sheet as a thermal insulator under the build plate to limit the heat transfer to the machine; see Fig. 1. The remaining conduction pathway is through the contact between the aluminum jaws and the build plate. The jaws dissipate most of the remaining heat, with little energy transferring to the steel base plate through the titanium spacers. The steel base plate rests on a spacer, increasing the surface area for convection and minimizing the area contacting the machine tool table.

2.3. Electrical

The welding process requires a path from the arc back to the welding unit to complete the electrical circuit. The main copper

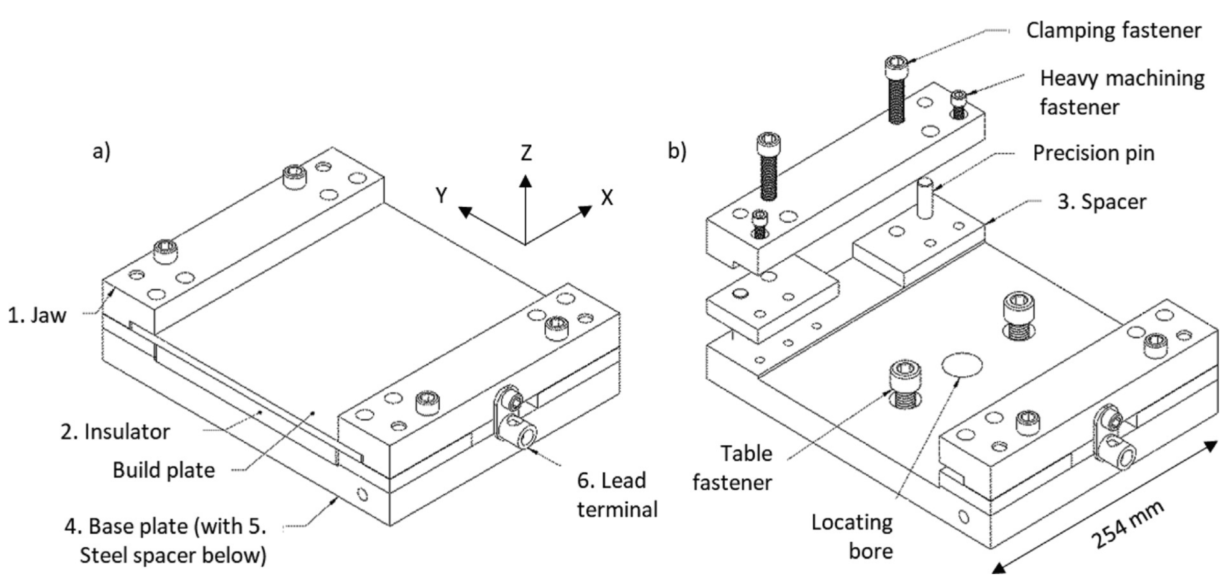

Fig. 1. A) Limited-constraint fixture; b) exploded view (insulator and build plate are not shown).

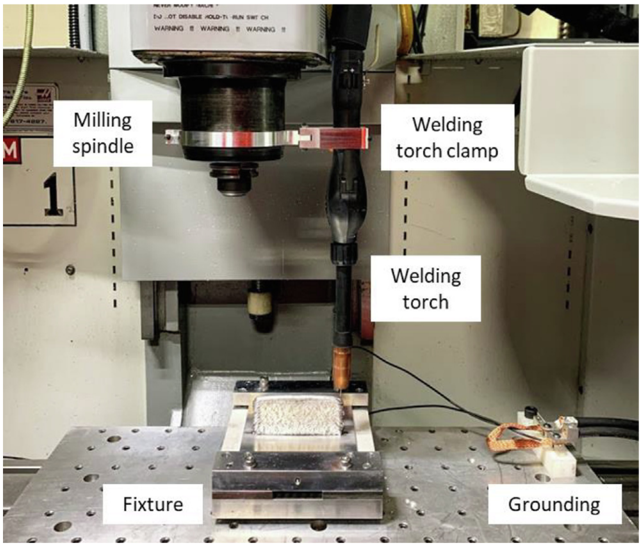

Fig. 2. Low-cost WAAM setup with a Miller 350P GMAW torch clamped to the Haas TM-1 CNC milling machine spindle and limited-constraint fixture attached to the machine table.

work lead (sized from the manufacturer recommendation) is bolted directly to the aluminum jaw, creating the lowest impedance path back to the welder. Titanium and steel were used for the spacers and base plate, respectively, in part due to their higher electrical resistance. Secondary smaller leads are connected to both ends of the machine table and the steel base plate. The main and secondary leads are connected to a common ground bar, which is connected back to the welder. The secondary leads help prevent erosion of the linear bearings from possible stray eddy currents and provide some protection to the controller in the case of a poorly grounded build plate.

A wiring harness was prepared to move the trigger circuit from the welding torch to the Haas TM-1 controller. The harness connects to the existing machine and torch leads and links the trigger circuit to a relay in the TM-1 electrical cabinet. The relay enables the gun to be turned on and off using an M−code in the machine controller.

3. Experimental setup

3.1. Coordinate systems

The torch mounting fixture is installed by aligning the mounting flange of the spindle ring to the Y axis of the machine. The welding torch is secured in the mount and the assembly is bolted to the spindle ring with two fasteners. The fixture is bolted to the machine table and aligned to the X axis using a dial indicator. A touch trigger probe is loaded into the machine spindle and is used to find the center of the bore. The welding torch is lowered into the center bore to find the center. The tight clearance fit between the bore and torch contact tube provides a repeatable zero (±25 μm). The additive Z zero is set on the top of the build plate using the end of the welding torch contact tube. The machining Z zero is set at the top of the build plate using the machine probe.

Table 1
Clamping torque and distortion.

Clamping torque (N-m)	Maximum distortion (mm)	Percent distortion reduction (%)
54.2	2.692	–
27.1	2.184	18.9
6.8	0.610	77.3
(Bolt torque ± 5%, distortion ± 0.127 mm)		

3.2. Process parameters

The WAAM parameters were selected based on welding best practices for the 1.2 mm diameter 5356 aluminum wire used for this study. An initial wire feed was selected based on the manufacturer recommendation and the table feed rate was varied to establish the relationship between feeds and bead width and quality for a single bead geometry. The same process was repeated using a fixed table feed and varying the wire feed rate. The wire feed range was 5.080 m/min to 11.430 m/min and the table feed range was 0.889 m/min to 2.540 m/min for the selected wire-build plate combination. The shielding gas for all trials was 99.995% argon with a gas flow rate of 45 cfh. A 5052 aluminum build plate with a 6.35 mm thickness was selected as the deposition surface.

3.3. Build strategy

A continuous spiral build path was chosen to eliminate start and stop defects and maximize the deposition rate. As the build increased in Z height, the table feed was increased to maintain a constant bead geometry by compensating for the additional heat in the part.

4. Results

The effect of the build plate clamping condition on final part distortion was tested using identical build geometries, paths, wire, and build plate. Cylinders were deposited as a continuous spiral on a room temperature build plate to test the plate/preform distor-

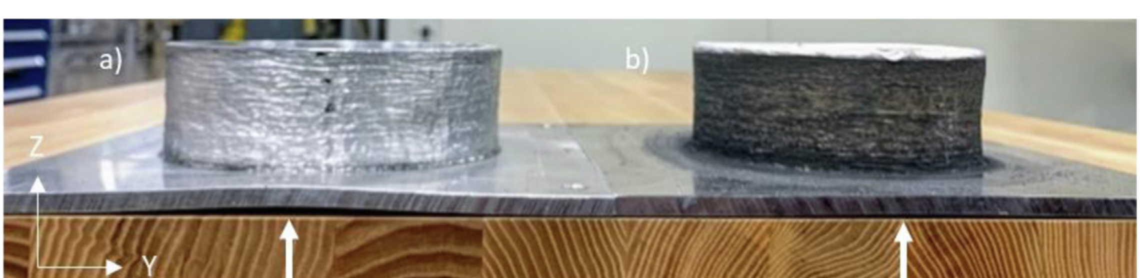

Fig. 3. A) Part distortion for higher clamping force; b) part distortion for lower clamping force. The arrows indicate the maximum distortion at the plate center in the y direction.

tion. The first build plate had clearance holes (6.8 mm diameter) drilled in the corners for the heavy machining fasteners (¼-28 socket head cap screws). The fasteners were placed in the holes, but not tightened. When the plate had cooled, imprints of the threads could be seen in the clearance holes, suggesting the plate grew sufficiently to press into the fasteners and cause plastic deformation. The plates were flat to within 127 μm before deposition.

As shown in Fig. 3, the largest part distortion was observed for the highest clamping torque with the heavy machining fasteners in place. The lowest distortion was observed when just enough torque was applied to bring the jaw into contact with the plate and no heavy machining fasteners in place. The plate distortion was measured by placing the plates on a flat surface, measuring the height of the warped section, and subtracting the plate thickness measured at that point. No distortion was noted at the clamped ends. Results are summarized in Table 1.

5. Conclusions

A new fixture design for WAAM was evaluated where the lateral constraint for a horizontal (XY plane) build plate could be modified by change the torque for bolts used to clamp vertical jaws against the build plate. The intent was to allow lateral build plate thermal expansion in the XY plane at low clamping torques, while providing Z direction constraint at the plate ends only. It was observed that limiting the torque and, therefore, enabling lateral thermal growth, reduced the Z direction plate distortion significantly. While these results are preliminary, they suggest that the limited-constraint fixture presented in this study provides a viable alternative to the traditional massive over-constraint clamping techniques for WAAM and other metal AM processes.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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