LOW COST PLATFORM FOR HYBRID MANUFACTURING OF LIGHT METALS

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ABSTRACT

Wire arc additive manufacturing (WAAM) uses an electric arc to locally melt and fuse wire to build parts layer by layer. The benefits are a high deposition rate, dense final structures, compatibility with light metals such as aluminum and magnesium, and low cost. In gas metal arc welding (GMAW), wire is fed continuously into the arc where it is melted to form a bead. WAAM parts typically need to be finish machined to achieve the desired final part geometry and surface finish on functional surfaces.

This creates a challenge when moving from an additive machine to a traditional machining center, as it is difficult to align machine axes without reference features. One potential solution is hybrid manufacturing, where the additive process and machining center are coupled. The work coordinate systems for the additive deposition and subtractive machining spindle are set from the same reference, enabling the part to be built and machined in the same setup. This reduces the required overbuild to ensure the part is encompassed by the printed structure and decreases setup time.

In this work, a commercial gas metal arc welder was mounted adjacent to a machine spindle and is triggered using the machine controller. A fixture plate was designed to isolate the machine from the thermal and current input. To develop an understanding of the process, a 5356 aluminum wire alloy was chosen as a less expensive and better understood alternative to more costly light metals, such as magnesium.

Keywords: Hybrid manufacturing, wire arc additive manufacturing, aluminum

INTRODUCTION

The additive manufacturing sector has grown from making small plastic parts to a technology promising flight-ready hardware built from expensive and difficult-to-machine materials, such as titanium and Inconel. Many processes have been developed in the metal additive space, with the main groups being powder bed, blown powder, and wire fed systems. Each of these systems uses an energy source to locally melt metal and build parts layer by layer starting from a build plate.

Additive manufacturing of metallic components dates to 1997, when AeroMet developed a Laser Additive Manufacturing (LAM) system to produce titanium components from powder [1]. Development of additive technology in the following years included the rise of a wide range of powder-based systems including powder fed, powder bed, and blown powder types. Melt energy sources for powder systems include fiber lasers, electron beams, and disk lasers [2]. Wire fed additive systems typically use electron beam, laser, and plasma arc heat sources which are used to locally melt wire into a bead.

Processes that use powder as the filler metal tend to produce parts with a higher resolution, down to a few micrometers, and better surface finish, but sacrifice build rate and part density. They are costly (the typical price for a powder based system in 2012 was $1M [3]) and handling of powders can pose environmental health and safety concerns. Wire fed systems can achieve the highest deposition rates and good final part density, but the resolution is limited by the size of the wire, deposition velocity, and material. In almost all cases, parts need some post processing, usually machining, to meet the required geometry or surface finish requirements.

While it seems more desirable to print parts as close to the final geometry as possible, this often results in a preform that does not contain the final part and is difficult or impossible to machine due to geometry or lack of stiffness. Given that post-machining is already a requirement, it is advantageous to choose an additive process that will give the highest build rates with less emphasis given to surface finish or resolution. For this reason, wire arc additive is the process often selected to produce large preforms in a minimum time frame. Wire is also more readily available, cheaper, and more stable than powdered metal.

For the majority of manufacturing job shops, a $1M investment, for example, in an emerging technology with significant challenges is difficult to justify, so a low cost, easy to implement solution is an essential first step to familiarize a large share of the workforce with the additive process. This paper outlines the development and use of a commercial gas metal arc welder and a three axis CNC milling machine (two units found in most machine shops) for use in WAAM of aluminum hybrid components.

While development of additive technology in metals has historically been driven by materials which are more cost prohibitive to machine, a 5356 aluminum wire alloy was chosen as a less expensive and better understood alternative to more costly light metals, such as magnesium, to develop an understanding of the process. Future work will be conducted in magnesium alloys due to its high strength to weight ratio.

DESIGN

Equipment selection

The general design goals for this platform were to keep cost, complexity, and machine modifications to a minimum to promote a cost effective and easy to implement system; see Fig. 1. The build materials of interest for this project are aluminum and magnesium alloys. Aluminum was selected as the initial build material as a cost-effective and better understood substitute for magnesium.

A pulse capable Miller 350P gas metal arc welder was chosen as the voltage and wire source. It has a 100% duty cycle at 225 A allowing for continuous operation and a maximum wire feed speed of 800 ipm. The welder has a push/pull style torch, where a small set of rollers feed the wire from the torch end and a slave motor rotates the wire spool. This configuration reduces the strain on the wire and prevents breakage and thinning.

A three axis Haas TM-1 VMC is used as the base for the hybrid platform. It has a maximum table feed rate of 200 ipm, maximum work volume of 30 in × 12 in × 16 in, and a maximum spindle speed of 4000 rpm.

CNC integration

Electrical

A wiring harness was built to divert the trigger circuit from weld torch to the Haas TM-1 controller. The harness connects to the existing machine and torch connectors and links the trigger circuit to a relay in the TM-1 electrical cabinet. The relay allows the gun to be turned on and off using an M code in the machine controller; see Fig. 2.

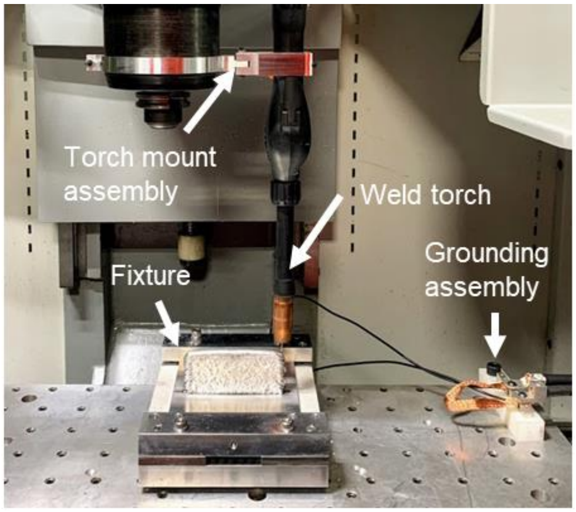

Figure 1: Front view of hybrid setup.

Figure 2: Welder trigger CNC integration cable.

Torch mount

Clamping the torch directly in the spindle would limit the hybrid work volume and require extensive modification to the machine and welder. The torch extension length was chosen to reduce the effects from the heat of the weld zone on the spindle. The clamp is comprised of a semi-permanent 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 compression from a fastened back plate. Two fasteners are used to connect the spindle ring and torch mount for easy installation and removal. The torch position is nominally perpendicular to the table; however, there is some deviation due to the lack of fine adjustment in the mount. An empty low projection length tool holder is loaded in the spindle to prevent any spatter or debris from collecting in the taper; see Fig. 3.

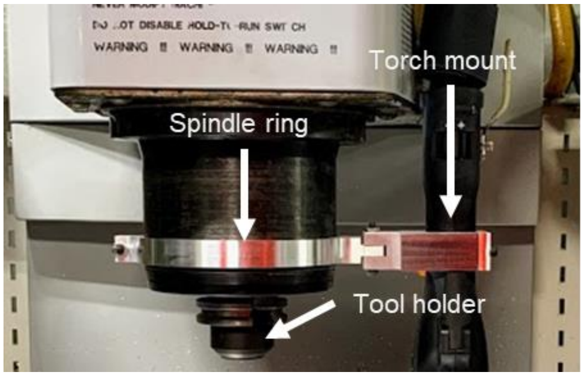

Figure 3: Assembled torch mount.

Fixture

Mechanical

The build fixture is composed of six parts: aluminum jaws, ceramic insulator, titanium spacer, steel base plate, steel spacer, and the grounding assembly. The overall dimensions are 10 in × 10 in × 2.5 in; see Fig. 4. The base plate is bolted directly 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 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 spacers do not run the length of the base plate to reduce contact with the build plate. The spacers, jaws, base plate, and spacer were machined to be flat and parallel to ±0.0015 in. The jaws are located with ground pins that are fixed in the steel base plate and have a RC1 close sliding fit with the jaws. Slots were machined into the jaws to reduce the moment on the locating pins while clamping and allow for plate growth in the Y direction. The clamping force is supplied by two stainless steel fasteners. While building the preform, the fasteners are tightened just enough to bring the jaw into contact with the build plate. This constrains the plate movement and thermal growth in the Z (vertical) direction, but allows it to grow freely in the XY plane. The intent was to limit the build plate distortion by avoiding over constraint of the plate during the build. For builds that require heavy material removal, 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 of both the machining spindle and weld torch. The bore is a 0.002 in clearance fit for the weld torch nozzle; see Fig. 4.

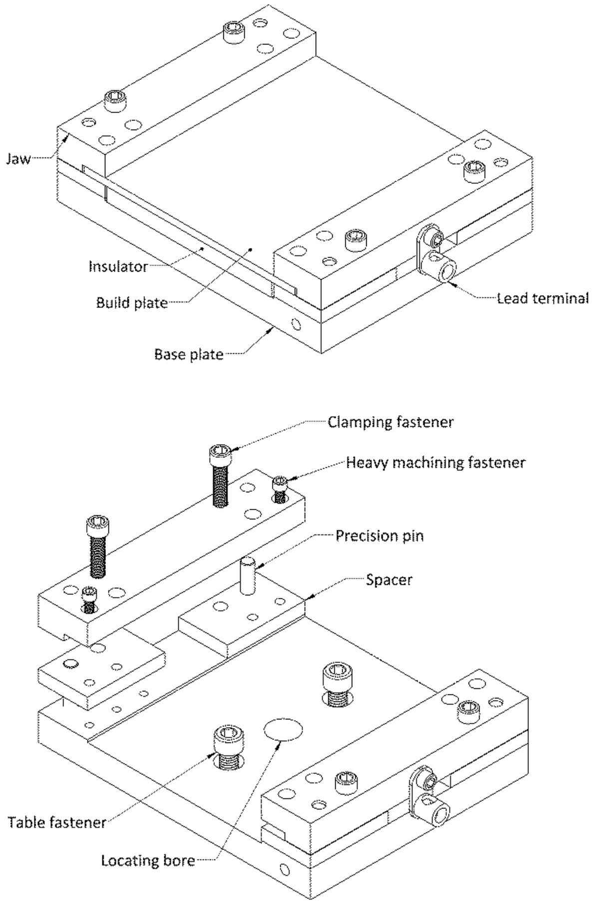

Figure 4: Assembled and exploded view. Build plate and insulator hidden on the exploded view.

Thermal

One of the challenges of coupling an additive process and a machine tool is the heat generation. When the build plate is directly mounted to the machine table, the heat from the build moves from the build area to the table, guide ways, spindle, and base casting. As these components heat up, errors are induced in the machine. Without any isolation from the build process, the machine should be allowed to reach a steady state temperature before finish machining or be compensated for the thermal growth. Since a machine tool takes many hours to return to 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. The 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.

Electrical

The welding process requires a path back to the welding unit to complete the circuit. The main copper 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 for 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.

SETUP

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 weld gun is secured in the torch 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 test dial indicator. A probe is loaded into the machine spindle and is used to find the center of the bore. The weld torch is carefully lowered into the center bore to find the center. The tight clearance fit between the bore and weld gun nozzle allows for a repeatable zero (±0.001 in). The machining Z zero is set at the top of the build plate using the machine probe. The additive Z zero is set on the top of the build plate using the end of the contact tube.

Process parameters

The current procedure for determining additive parameters is trial and error with geometries of increasing complexity until a viable final part is produced. This platform does not allow for in process changes to the wire feed speed, so an initial wire feed speed was selected based on the manufacturer recommendation and the table feed rate was varied to establish a relationship with single beads. Using the table feed rate that produced a desirable bead geometry, a wall was printed and the parameters were adjusted to reduce the start and stop defects. The same process was repeated using a fixed table feed and varying the wire feed rate.

Build strategy

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

RESULTS

A low-cost hybrid system was successfully implemented with no modification required to the off-the-shelf components; see Fig. 5. The benefit of this approach is that it can be applied to most existing machine tools and gas metal arc welders, enabling broader adoption of hybrid techniques without the need for a large capital investment.

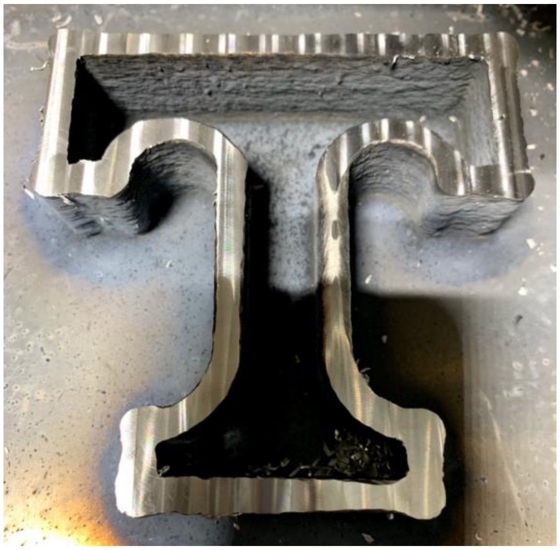

Figure 5: First successful complex shape part and final machining operation on the hybrid platform.

The fixture proved to be a repeatable way to set the work coordinate system (WCS) of the spindle and torch. While the WCS was defined from the same feature, an error in the torch mount design caused some part misalignment that defeated the purpose of the shared coordinate system. The torch was not able to be aligned perpendicular to the table and would shift if bumped during setup. This resulted in the final parts being shifted by approximately 0.050 in from the machine spindle center. Depending on the final part geometry and overbuild, this level of accuracy may be sufficient.

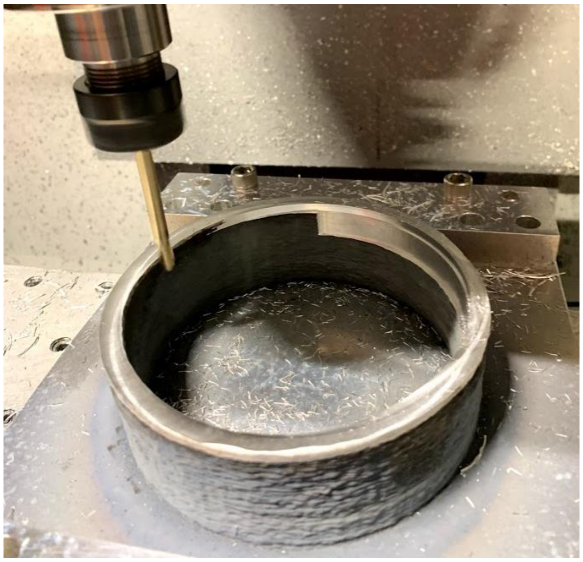

Figure 6: Printing and machining from the same locating feature. Note the part shift and uneven machined surface.

The effect of the build plate clamping condition on final part distortion was tested using identical build geometries, paths, build plate material, and build plate geometry. There was some variation in the wire feed rate for the first five beads between builds. Cylinders were built as a continuous spiral on a room temperature build plate fixture; see Fig. 6. The first build plate had clearance holes (0.266 in) drilled in the corners for the heavy machining fasteners (¼-28). 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. The plates were flat to within 0.005 in before the build. The most part distortion was observed in the first build, with the highest clamping torque and fasteners in place. The lowest distortion was observed in the builds with just enough torque to bring the jaw into contact with the plate and no fasteners in place. The plate distortion was measured by placing the plates on a flat surface and measuring the height of the warped section and subtracting the plate thickness measured at that point. No distortion was noted at the clamped ends. These are preliminary results and more work is needed to test the effect on a larger sample size and on other non-symmetric build geometries; see Fig. 7.

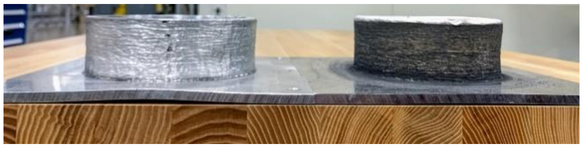

Figure 7: Comparison of two builds with identical build parameters and different clamping conditions.

Table 1: Clamping torque and distortion.

Clamping torque (ft-lb)	Maximum distortion (in)
40	0.106
20	0.086
5	0.024

(Bolt torque ±5%, distortion ±0.005)

FUTURE WORK

A new fixture and torch mounting assembly will be designed to address some of the process issues, including torch perpendicularity, better thermal isolation, and a reduction in the XY plane constraints. The effects of clamping conditions on final part distortion and residual stress is of great interest. It is possible that constraining additive parts purely in the build direction would significantly reduce the residual stresses. A model of the process will be developed to predict bead behavior at varying wire and table feed rates with the goal of controlling bead and part geometry effect in an open loop system. Minimizing the number of sensors and control systems keeps the barrier to entry low and allows for better final part geometry predictions. Magnesium alloys will be tested for their compatibility with the WAAM process.

CONCLUSIONS

The bulk of manufacturing occurs in small job shops that do not have the resources to make large capital investments in an emerging technology. With the approach described here, it is possible to build a hybrid system with a small investment. An easy-to-implement and inexpensive solution allows the technology to spread from machine tool manufacturers and research labs to every corner of the manufacturing sector. Through the implementation of this platform, it was observed that over constraining build plates in additive processes contributes significantly to the final part residual stresses and warping. Implementing a fixturing system that constrains the build plate in the part direction while allowing it to grow in the planar directions may significantly reduce these residual stresses.

REFERENCES

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APPENDIX A: SETUP DETAILS

A summary of the platform specifications is provided in Table A1.

Table A1: Platform specifications.

Wire alloy	5356 aluminum
Wire diameter	0.047 in
Build plate alloy	5052 aluminum
Build plate thickness	0.25 in
Shielding gas	99.995% argon
Gas flow rate	45 cfh
Wire feed range	200 ipm to 450 ipm
Table feed range	35 ipm to 100 ipm