

CHALLENGES WITH METAL BIG AREA ADDITIVE MANUFACTURING FOR MACHINE TOOL CROSS BEAM MANUFACTURING

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ABSTRACT

Two main pillars of modern manufacturing consist of subtractive and additive manufacturing (AM). Many of the challenges with subtractive manufacturing have been understood due to its maturity. Relatively, the AM space has many new challenges that are being explored. New designs, geometries, and features are explored to see the limitations of AM and what can be done in both design and manufacturing to increase the reliability of the process.

This paper presents a case study of a machine tool cross beam that was designed for metal big area additive manufacturing (mBAAM) which was unable to be printed completely. The intent of the design was to additively manufacture a structure that could replace an existing crossbeam of a computer numerically controlled (CNC) machine from Oak Ridge National Laboratory (ORNL). The replacement mBAAM structure was designed to be printed with the MedUSA robotic cell of ORNL. The MedUSA cell consisted of three robotic arms that simultaneously deposit metal via gas metal arc welding (GMAW) onto a rotating table that served as the print bed. The mBAAM cross beam was approximately two meters by half a meter by half a meter with a mass of 673 kilograms consisting of mild steel. The failure of the print was due to significant distortion of the part which resulted in the termination of the print. Many factors contributed to the distortion of the part. Two main contributors to this part were residual

stresses and the fixturing method for the print. The print failure demonstrated flaws of metal AM for large scale parts and what challenges need to be overcome for future large scale metal AM parts.

MBAAM CROSS BEAM

Motivation

The United States (US) supply chain for castings and forgings have been subsidizing with a decrease in US foundries and a heavily reliance on imported metals [1, 2]. Castings and forgings are critical to machine tool structures. Machine tools are the foundation for US manufacturing and the demand for more machine tools can be met through new methods of constructing machine tools applying new materials and technologies.

West et. al. from Oak Ridge National Laboratory (ORNL) designed and manufactured a machine tool with a base that consisted of an additively manufactured mold that was filled with concrete [3]. The new machine tool base demonstrated the viability of redesigning a machine tool's structural component with advanced technology and materials. This case study builds upon West's et. al. concrete base machine tool with the intention of replacing the machine's cross beam, a structural member of the machine tool shown in Fig. 1 and 2, with a similar structure that leverages new manufacturing methods.

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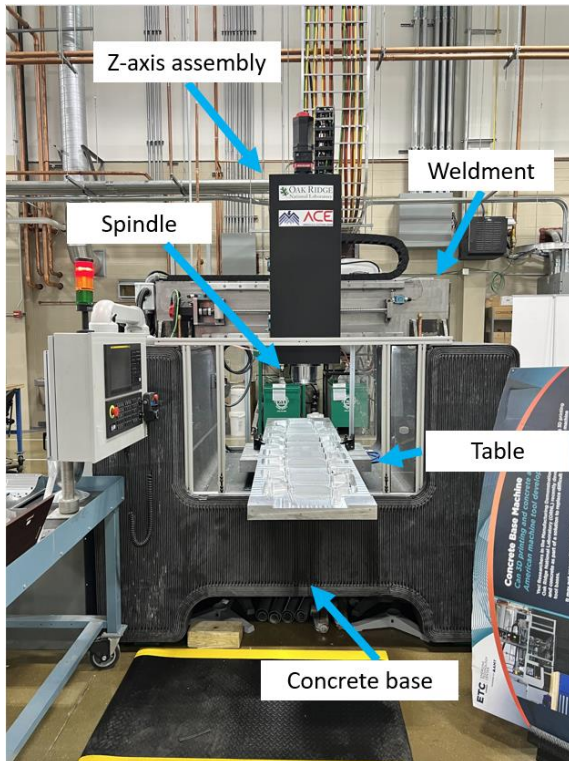


FIGURE 1. Concrete base machine tool with the cross beam weldment supporting the Z-axis and spindle assembly.



FIGURE 2. Identical cross beam weldment that is from the concrete base machine tool.

The design of the machine tool cross beam used metal big area additive manufacturing (mBAAM). mBAAM which is a form of big area additive manufacturing (BAAM) that is characterized by high deposition rates and larger print volumes. The goal was to leverage mBAAM technology to reduce the mass of the cross beam while maintaining dynamic stiffness. The ORNL MedUSA system was used for wire arc additive manufacturing (WAAM) deposition, offering higher metal deposition rates than traditional methods.

To inform the new design, finite element analysis (FEA) was employed to model the static and dynamic deflection of the original weldment cross beam. Modal analysis through impact testing validated the FEA predictions, ensuring the design inputs for the WAAM cross beam were accurate. The design also had to account for various constraints, including compatibility with the existing machine tool and the workspace limitations of the MedUSA system, which used three robotic arms for simultaneous material deposition.

Weldment Cross Beam

The cross beam weldment was designed for a three-axis, vertical spindle concrete base machine tool. The weldment, mounted above the concrete base's vertical columns, supports the spindle and Z-axis assembly. It was constructed from welded A36 steel plates, forming a rectangular box section with an internal rib for added stiffness and two footpads for mounting. The front face served as the primary mounting surface for the Y-axis guide rails and motor assembly, while the steel feet connected it to the concrete base.

Measuring 2029 mm by 610 mm by 432 mm, the weldment's design ensured structural stability as seen in Figure 2. Without impacting the operation of the concrete machine tool, a duplicate of the weldment was outsourced for manufacturing. The weldment utilized in free-free boundary condition impact testing to validate the finite element analysis (FEA) predictions. This testing facilitated direct comparison with the mBAAM cross beam for evaluating performance under similar conditions.

Design

Many design constraints for AM are established due to the manufacturing method, machine, and materials. ORNL's MedUSA cell was used to print the mBAAM cross beam because of its high deposition rate with three-robots as seen in Figure. 3. The MedUSA cell used WAAM as its deposition method which was compatible with Lincoln's LA100 wire. LA100 was chosen for it mimicked the material properties of A36 steel which was the material of weldment cross beam.

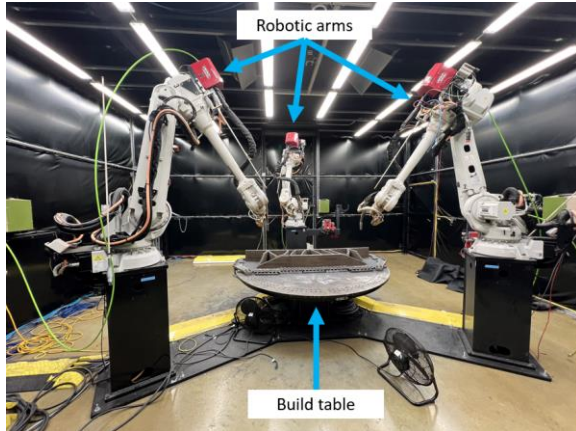


FIGURE 3. The MedUSA cell at ORNL.

Summary of Design Constraints

- There is a list of materials that are compatible with the MedUSA cell; LA100 from Lincoln Electric was selected for its weldability and strength.
- Material properties can differ from the wire properties and can be position-dependent due to the WAAM process heating and cooling profiles and temperature gradients.
- The print bead width can vary from 6 mm to 8 mm.
- The print must be made on a build plate (or several build plates).
- The WAAM process has shown better results for continuous bead prints than short, segmented print paths due to reduction in traveling moves caused by maintenance routines (i.e., trimming the welding wire) after the end of a toolpath.
- Weld beads that cross one another should be minimized to avoid overgrowth that can cause torch-to-part collision and, if necessary, there should be only one bead intersection.
- The design must be able to be sliced using the ORNL slicing software, which generates the robots' tool paths.
- The printed surface will be wavy (up to 1.5 mm surface height variation) and the cross-sectional area that is used for calculating mechanical properties must account for the surface variations.
- The WAAM process is not suitable for printing large flat surfaces or walls due to thermal deformations and print time and cost.
- Overhangs should generally be avoided, but 20° to 25° angles from vertical are possible.

- If there is a surface that needs to be finished (by machining, for example), there should be at least 3 mm of additional material.
- Features should be at least two beads thick and there should be adjacent bead overlap (slicer limitation).

Design Process

The design process for the WAAM cross beam was iterative, with numerous concepts analyzed and refined to achieve the project's objectives. The primary goal was to reduce the structure's mass while maintaining the weldment's stiffness. Critical surfaces and clearance profiles between the weldment and the WAAM cross beam, such as mounting feet and rail locations, were preserved to ensure compatibility with the concrete base and column assembly. By maintaining these profiles, the new designs could be directly compared to the weldment's deflection under load.

Throughout the iterations, various cross-sections and mass-reduction patterns were implemented, with restrictions against overhangs and external stiffening plates. Any design exceeding the weldment's mass of 702 kg was excluded. FEA was used to assess each design's deflections against the original weldment, with both mass and stiffness serving as key selection criteria. The ORNL WAAM team also provided feedback, suggesting design adjustments to improve print feasibility and streamline the manufacturing process. This collaboration minimized the need for significant design changes later in the project.

Final Design

After analyzing the FEA simulation results, a final WAAM design, shown in Figure 4, was selected with overall dimensions of 2028.8 mm by 609.6 mm by 601.4 mm. A notable feature of the design is the use of catenary arches on the front and back faces, a geometry commonly used in buildings and bridges to enhance stiffness. These arches, described by the hyperbolic cosine function, were chosen for their ability to improve stiffness in the X-Z plane without significantly increasing mass.

The design also incorporated curved vertical supports that connect the front and back walls, mimicking a sinusoidal pattern. This geometry not only provides continuous print paths but also increased stiffness while reducing mass. The supports were slanted to reduce weight while maintaining structural integrity, and the front wall

is thicker in the middle where the largest deflections occur. The build plate for the WAAM deposition was divided into five sections of 25.4 mm thick A36 steel plates, making it more cost-effective and easier to procure. After deposition, the sections were planned to be welded together, completing the base structure for the cross beam.

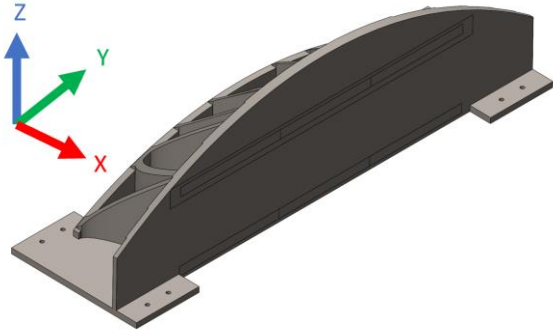


FIGURE 4. Front isometric view of the computer aided design final model.

FABRICATION

The printing of the WAAM cross beam began on April 4th, 2023, at the MDF. Given the size of the part, the print required multiple days to complete, with the team opting for two print shifts per day, from 6:00 AM to 1:00 PM and from 1:00 PM to 8:00 PM. Before starting, the final model was provided to the WAAM team, who sliced the design and generated tool paths for each layer. Once the model and paths were finalized, the print commenced, with the machined build plates which were clamped onto the build table shown in Figure 5.



FIGURE 5. MedUSA build table with five separate build plates before implementing steel clamps.

The WAAM team secured the build plate using steel strap clamps around the perimeter of the

part, as well as custom-designed end clamps made from 25.40 mm thick A36 steel to reinforce the four corners of the print as seen in Figure 6. This print was, at the time, the largest attempted on the MedUSA system, requiring robust clamping strategies. The three robotic arms began printing the initial layers slowly to ensure proper heat and material bonding to the build plate, after which the print speed increased as the beam's tapered design allowed for faster progress.

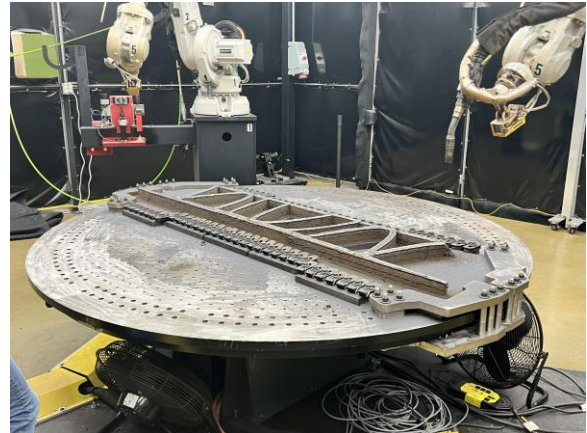


FIGURE 6. MedUSA build table initial printed layers and steel clamps.

After six days, the print was halted due to significant deformation. While the end clamps held up, the step clamps failed, leading to part distortion that impacted the steel build table. The part began to bow upwards at the edges, with a distortion exceeding 25 mm as demonstrated in Figure 7. These deformations raised safety concerns, prompting the team to stop the project at this stage.



FIGURE 7. Deformed mBAAM cross beam and build table.

At the time the print was stopped, 245 layers had been completed, reaching a height of 330 mm, with approximately 406 kg of metal deposited. This left the part 271 mm short of the intended height, and it was estimated that 77% of the part had been completed by mass as seen on figures 8 and 9. The remainder of the print would have required an additional 122 kg of material to finish.



FIGURE 8. Front face of the mBAAM cross beam at the end of the print.

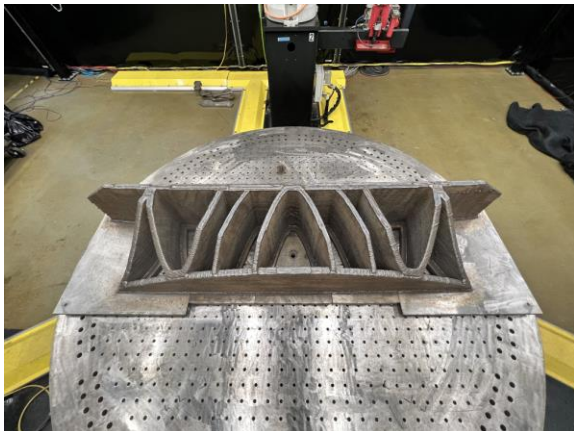


FIGURE 9. Back top view of the mBAAM cross beam at the end of the print.

There are no current plans to resume or restart the WAAM cross beam print. The project concluded with valuable lessons learned about the challenges of printing large-scale WAAM parts, including the need for more robust clamping strategies and solutions for managing part distortion during extended print times.

DISCUSSION

The print of the WAAM cross beam was stopped due to significant deformation, which also permanently deformed the build table. Upon review, various factors were identified as

contributors to the distortion, including design aspect ratios, the build plates, fixturing, print strategy, and thermal behavior.

The design of the cross beam played a role in the deformation, primarily due to the structure's aspect ratio and material choice. The long, narrow shape of the beam (1:3 length-to-width ratio) likely amplified bowing distortion. Additionally, the use of LA 100, a strong tensile steel, increased the likelihood of distortion compared to weaker steels. A raft was added to the print base, which was implemented to prevent the part from detaching from the build plate. Previous use of LA100 exhibited significant build plate separation without a raft which is extra print material around the initial layers of the print.

The build plates were segmented, seen in Figure 10, to allow room for expansion and reduce distortion. However, this was the first time a segmented build plate had been used for an mBAAM print at ORNL, and the impact of this approach on the final distortion remains uncertain. Customized steel clamps were also employed to hold down the part, but the large clamps, along with the deformed build table, were major reasons for halting the print.



FIGURE 10. Bottom of the print once removed from the build plate revealing the segmented build plate.

The deformation of the build table highlighted the issue of over-constraining the part may have caused internal stresses to build up excessively. A dynamic clamping system, which adjusts force based on part geometry, might have helped the part deform without damaging the table. In addition, a more robust build table could have reduced the impact of distortion, but it wouldn't fully eliminate the internal stresses caused by the WAAM process.

The print path strategy could have also contributed to the distortion. The use of three robotic welders enabled faster material deposition, but the long-axis print beads, seen in Figure 11, may have induced additional stress

along the beam's length. While this approach sped up the printing process, it likely increased the thermal gradient, resulting in uneven heat distribution and greater distortion.



FIGURE 11. Print beads on the mBAAM part along the long axis could have contributed to the uneven thermal gradient of the print.

Thermal behavior played a critical role in the print's failure. The size and geometry of the cross beam, combined with a relatively low overall temperature during printing, led to significant internal stresses. Maintaining a higher temperature, possibly through a heated base plate or environment, might have minimized the distortion by relieving internal stress during the print.

An additional complication arose when the print was paused overnight, allowing the part to cool and undergo multiple thermal cycles throughout the duration of the print, which exacerbated the distortion. Continuous printing at an elevated temperature would have been ideal for preventing these thermal effects. For future large WAAM prints, maintaining consistent temperature and avoiding pauses in printing could be essential to reduce distortion.

CONCLUSION

The WAAM cross beam project, though incomplete due to significant deformation, offered valuable insights into the challenges of using mBAAM technology for large-scale machine tool cross beam manufacturing. One of the major hurdles encountered was the thermal distortion that led to the print being stopped. This issue highlighted the need for better thermal management and improved print strategies to minimize deformation and ensure the integrity of future large metal prints.

The project pointed out several contributing factors to the distortion, such as the method of securing the build plate and the clamping strategies employed. As one of the largest parts ever attempted by the ORNL WAAM team, the print revealed the limitations of the current mBAAM setup for handling large-scale parts. Further experimentation, including dynamic clamping techniques and alternative print paths, is essential to refine the process and address these issues before mBAAM can reliably produce successful, distortion-free components.

Despite the challenges, the WAAM cross beam print, which was 77% complete, demonstrated that large-scale mBAAM prints are feasible. The partially printed structure showed promising results, indicating that with improvements in handling internal stresses and thermal behavior, the technology is close to achieving the final design. Continued research and smaller-scale experiments are critical to understanding and mitigating the factors that lead to deformation in future projects.

REFERENCES

- [1] U.S. Census Bureau "All Sectors: County Business Patterns by Legal Form of Organization and Employment Size Class for U.S States, and Selected Geographies 2018", 2018.
- [2] U.S. Census Bureau 1992 Census of Manufacturers 1996 Washington, D.C.
- [3] West, J.L., Betters, E.D., Schmitz, T.L., Smith, S., Roschli, A., Nuttall, D., Lindahl, J. and Love, L., 2022. Rethinking production of machine tool bases: Polymer additive manufacturing and concrete. *Manufacturing Letters*, 31, pp.33-35.