DESIGN CONSIDERATIONS FOR ADDITIVE MANUFACTURING OF MACHINE TOOL STRUCTURAL COMPONENTS

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ABSTRACT

Historically, large machine tool structures have been manufactured as castings or weldments. Over the past several decades, the casting infrastructure within the United States has declined, leading to the international outsourcing of large structural components. Additive manufacturing (AM) may provide an alternative construction method that enables the reshoring production of these large machine tool structures. Additionally, the use of AM allows design features that are difficult or impossible to produce by traditional means. This paper outlines the design of the Y-axis structure for a gantry style, three-axis computer numerically controlled milling machine where the Y-axis structure will be produced using wire arc additive manufacturing.

INTRODUCTION

Additive manufacturing (AM) has changed the way parts are made by enabling complex shapes that were not feasible by traditional manufacturing processes, such as casting, forging, and machining. There are a wide variety of AM techniques, including wire arc AM, or WAAM. The WAAM process converts readily available metal wire into molten beads that link and form layers. The melting process heat is provided by an electrical arc. Once cooled, the molten metal solidifies to produce a final geometry that depends on the trajectory of the welding torch during material deposition.

Machine tools exist in a range of sizes and are built to suit a variety of applications. This paper investigates the design of one structural component for a computer numerically controlled (CNC) milling machine. Generally, CNC milling machines consist of stacked axes composed of multiple structural elements that position a rotating cutting tool relative to the stock to remove the desired material and reveal the design geometry. The stiffness and damping of the machine's frame and structure are critical to its performance. Various materials have been implemented in machine structures from steels to polymers to achieve the required performance. Typical performance factors include, but are not limited to, thermal stability, structural stiffness/damping, mass, and others [1]. Composites have been implemented due to their high stiffness-to-weight ratios [2].

The production of large machine tool production typically depends on the availability of large metal castings. Large castings are not as readily available in the US as prior decades because the number of US casting suppliers is decreasing. One opportunity to address this issue is the use of WAAM processes to print large metal structures. Because the WAAM process uses a readily available material form, metal wire, it can create large structures with the assistance of a computer-controlled robot [3]. However, some limitations are imposed by the WAAM process and guidelines should be followed to produce a

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usable part. These design rules dictate material choice, overhang limits, bead thickness, and others [4]. Based on experiences from previous WAAM fabrication of large parts, large structural machine tool components can be designed and manufactured with WAAM.

In [5], West et al. describe a three-axis CNC milling machine which was made with a concrete base that leveraged composite big area additive manufacturing to a polymer composite mold for the structure that was filled with low-cost concrete [5]. The structure that is described in this paper is a Y-axis that will be implemented on the next generation of the concrete base machine. The Y-axis is designed to be manufactured by the WAAM process. The design objective is to produce a structure with equivalent, if not better, dynamic stiffness than a similar component manufactured as a casting or a weldment. Other improvements that are possible through the WAAM process include light-weighting the internal structure to reduce mass and achieve higher accelerations [6].

DESIGN

Design processes are iterative, by nature. The design process followed, in this case, is based on the steps outlined by Slocum [7]. The tools and steps that guided the design are the error budget, overall machine dimensions, and design of mock structures. The outcome is the final Y-axis design.

Error Budget

The purpose of a machine tool is to position a cutting tool relative to the stock to remove material in a precise manner. Each component in the kinematic chain has an associated tolerance which directly correlates to the type of machine that is needed to meet the specified demands. The design process can be initiated using the error budget, or error apportionment. The total error of the machine tool is an accumulation of the errors from the geometric, thermal, load-induced, and process of each component [7].

In Slocum's method, values are estimated to assign starting error values attributed to each axis. With the input values shown in Table 1, the method calculates a linear sum of errors, a root square sum of errors, and an average of the two errors. The average was used in this design to assign allowable deflection errors for each axis: 7 μm per axis or 14 μm for the three axes. The average error was chosen because the linear sum of errors represents the worst case and the root square sum is the theoretical best case. It is worth noting that the error budget is a tool to assist with the design and that values were chosen to mimic the desired machine. This does not guarantee that the physical system performance will match the calculated values, but they can be expected to be reasonably close.

TABLE 1. Inputs for error apportionment calculator.

Number of axes:	3
Total allowable error [μm]:	50
Source of error factor:	
Geometric [-]:	0.50
Thermal [-]:	1.00
Load-induced [-]:	0.00
Process [-]:	0.80

Machine Specifications

The overall machine as shown in Figure 1 was designed with an intended final work volume of 1 m x 0.5 m x 0.5 m. The open gantry design enables the machine to produce parts with high length-to-width (and height) aspect ratios. Another key aspect of the machine tool requirement was the spindle and its performance. For this design, desired metal cutting parameters and a respective endmill size were chosen to calculate target spindle speed and torque values. A Setco 223A spindle was selected to meet the machining requirements [8].

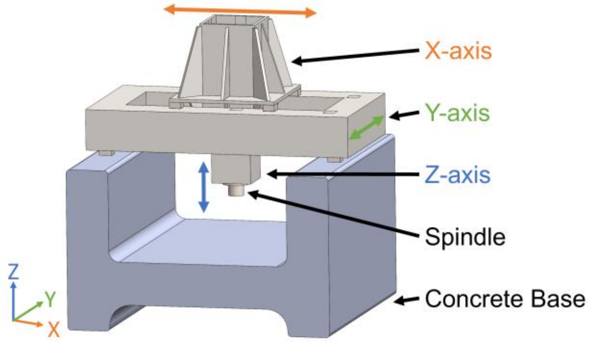

FIGURE 1. Isometric view of concrete base machine.

Mock Z-axis and X-axis Design

Due to the nature of a gantry-style, fixed table machine, the Y-axis is an intermittent component between the workpiece and the cutter. The Y-axis for this design is responsible for transporting the X-axis, which carries the Z-axis, which supports the spindle. To understand the deflections of the Y-axis, theoretical Z-axis and X-axis designs were needed. From the inputs of the error budget, spindle mass, and dimensional requirements, a Z-axis was designed to support the spindle as well as choosing appropriate off-the-shelf linear rails and bearing pads to support the structure. The X-axis was then designed to accommodate the mass of the Z-axis and spindle. The mock designs of the Z-axis and X-axis are shown in Figures 2-4.

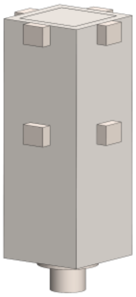

FIGURE 2. Isometric view of mock Z-axis. The spindle is inserted in the frame and extends from the lower end.

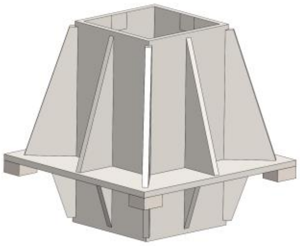

FIGURE 3. Isometric view of mock X-axis.

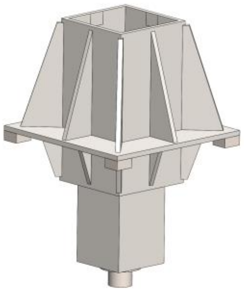

FIGURE 4. Isometric view of mock X-axis and Z-axis assembly.

Y-axis Design

The initial Y-axis design accommodated both the mock X- and Z-axis. The total mass of the spindle, Z-axis, X-axis, and associated components was used to inform the initial box shape design. The box shape design's purpose is to model a Y-axis geometry produced by a casting or a weldment. To replace the Y-axis with an additive manufactured part, the theoretical box shape structure shown in Figures 5 and 6 was developed to meet the deflection and geometric requirements of the Y-axis. The boxed-shaped Y-axis serves as a design profile to enclose the additively manufactured part and gives insight into the deflection of the Y-axis. The theoretical overall design meets the deflection requirements of the intended design. The deflections were simulated using Solidworks Finite Element Analysis (FEA).

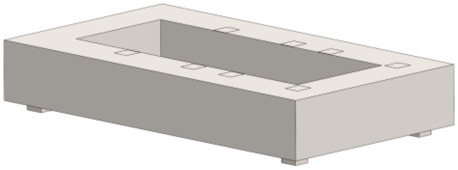

FIGURE 5. Isometric view of box-shaped Y-axis.

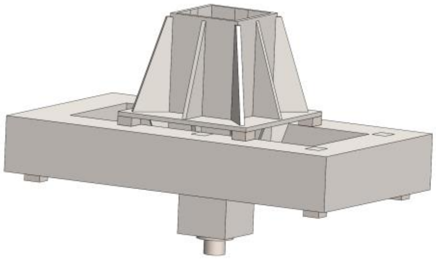

FIGURE 6. Isometric view of mock X-axis and Z-axis with box-shaped Y-axis assembly.

WAAM DESIGN AND SIMULATION RESULTS

The WAAM process has one of the highest AM deposition rates. Because the Y-axis of this machine is large, the only viable way option is the WAAM process. To make this structure, a partnership with Oak Ridge National Laboratory's Manufacturing Demonstration Facility (MDF) was established. The structure will be printed with the MedUSA robotic cell. The MedUSA robotic cell is comprised of three six-degree-of-freedom robotic arms that are capable of manipulating gas metal arc welding torches.

With every additive manufacturing process, there are design constraints that must be implemented to achieve a successful print. Early in the design process, the MDF WAAM team was consulted to understand the MedUSA capabilities along with features to avoid for large-scale WAAM. As with most designs, numerous issues must be simultaneously considered to prepare a successful design. A few of the important design factors are provided:

- There is a list of materials that are compatible with the MedUSA cell; LA100 from Lincoln Electric was selected
- Material properties can differ from the wire properties and can be position dependent due to the WAAM process heating and cooling profiles
- 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) which must be later removed
- The WAAM process has shown better results for continuous bead prints than short, segmented print paths
- Overlapping joints should be avoided and, if necessary, there should be only one overlap
- The design must be able to be sliced using the in-house slicing software, which generates the robot 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 cost
- Overhangs should generally be avoided, but 20°-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 bead overlap
- Three models need to be constructed
    - A model that has the desired geometry and specifications for post machining
    - A model for slicing that has the wall thicknesses which account for the bead overlap
    - A model that has an added 1.5 mm of material to all surfaces to account for the waviness of the walls to get a closer approximation of the true mass of the system
- Making the design with the least amount of printed material will reduce the print time and cost dramatically

A separate study for the Y-axis design was to analyze various patterns that meet the continuous printing preference and provide high strength-to-weight ratios. Some initial patterns that were investigated were the honeycomb and isogrid. However, these patterns are difficult to print due to the large amounts of overlaps and the need to stop and start the print beads. As an alternative, sinusoidal geometries are preferred because they encourage long print paths with similar "pocket" connectivity as the honeycomb and isogrid options.

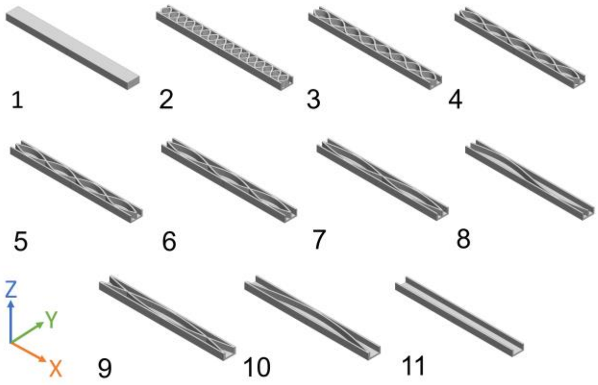

FIGURE 7. Cross-sections of 11 iterations of sinusoidal waves for simulation.

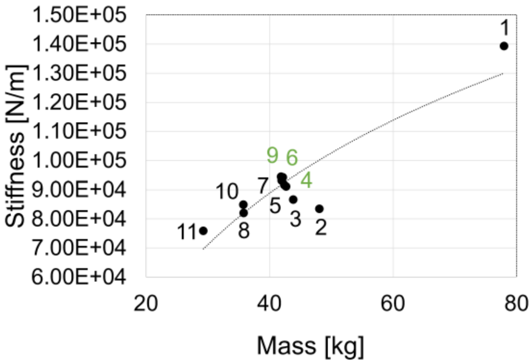

FIGURE 8. Mass versus stiffness with a Z direction force with designs 4,6, and 9 with the highest stiffness/mass ratios.

To compare sinusoidal geometries, simulations were completed using FEA to calculate the deflection as a function of the material volume. Eleven 0.1 m x 0.1 m x 1 m beams were designed, and their internal structures are shown in Figure 7. These designs were then simulated as pinned-pinned beams and a 1 N static force was applied in the center of the beam in the X and Z directions separately. The deflections of each structure were then used to calculate the stiffnesses and were plotted with their respective masses shown in Figures 8 and 9. The outcome was that three designs had the best mass versus stiffness ratios and those designs would be implemented in the Y-axis design.

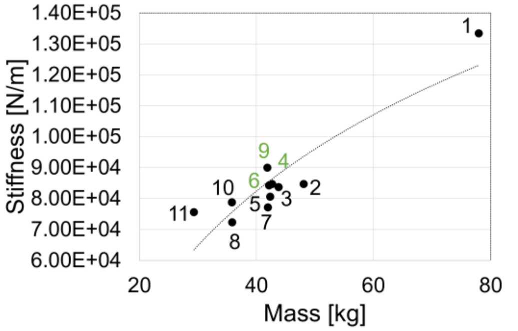

FIGURE 9. Mass versus stiffness with a Y direction force with designs 4,6, and 9 with the highest stiffness/mass ratios.

Several designs of the Y-axis were then made and analyzed. Each structure was modeled in Solidworks and statically simulated to understand if the design met the deflection criteria prescribed by the error budget. It was decided that the design would leverage large metal plates that would assist with the stiffness of the structure while also eliminating the need to print the tall flat structures that are not suitable for WAAM. The final print geometry is shown in Figures 10 and 11 along with the Y-axis with its additional metal plates shown in Figures 12 and 13. The resulting static deflection of the entire system is shown in Figures 14-16 for each axis with a 1 N static force; the deflection value is then inverted to find the stiffness in each axis direction (see Table 2).

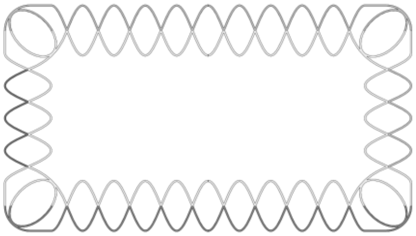

FIGURE 10. Top view of final WAAM print geometry.

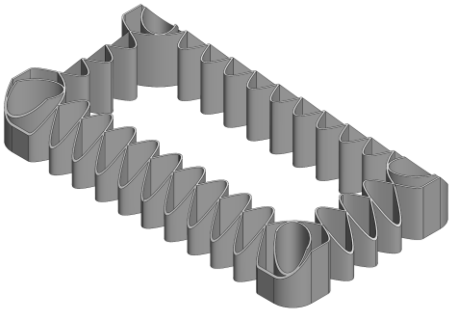

FIGURE 11. Isometric view of final WAAM print geometry.

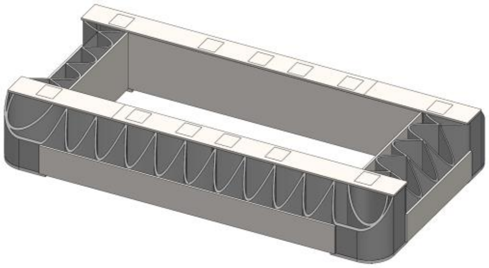

FIGURE 12. Isometric view of final WAAM print geometry with steel plates.

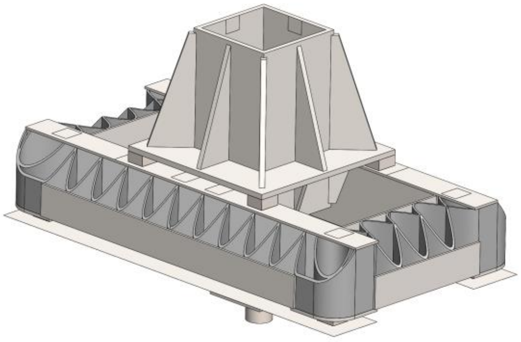

FIGURE 13. Isometric view of final WAAM print geometry with steel plates and mock Z- and X-axis assembly.

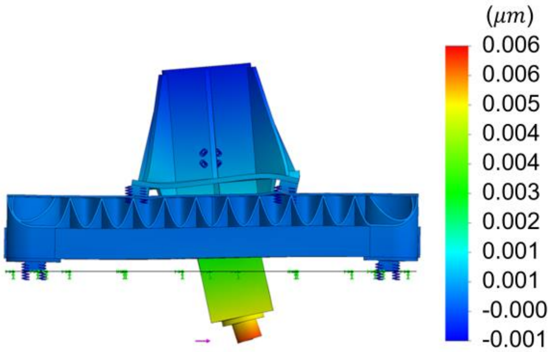

FIGURE 14. Static analysis of the full assembly with a 1 N force in the X-direction.

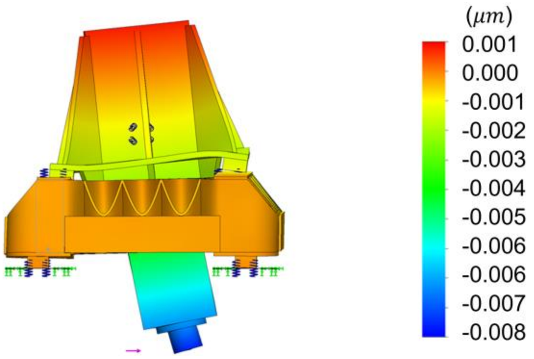

FIGURE 15. Static analysis of the full assembly with a 1 N force in the Y-direction.

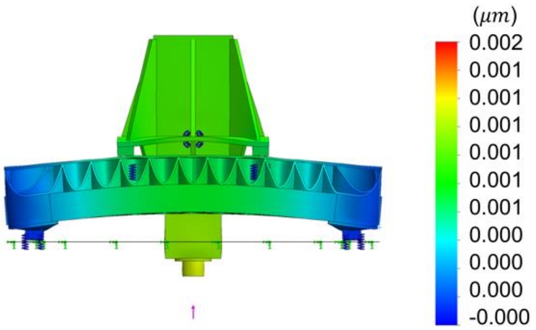

FIGURE 16. Static analysis of the full assembly with a 1 N force in the Z-direction.

TABLE 2. Stiffness values of the final design.

Axis	Stiffness [N/m]
X	1.67×10^8
Y	1.25×10^8
Z	1.00×10^9

CONCLUSIONS

The next steps for the machine tool Y-axis are to print and machine the structure. Potentially challenges after printing are:

- Removing the build plate
- Warping due to the thermal residual stresses
- Welding of the additional structural plates to the WAAM geometry
- Locating a large oven to heat treat and relieve the residual stresses
- Machining the large structure to the required tolerances for final assembly

The outcomes of manufacturing the structure will be documented and compared to the simulated design. Because this is a case of a unique structure for a specific machine tool, not all the design inputs will apply to other structures. However, the overall process of the design for a large-scale WAAM print will have the same procedure as detailed in this paper.

As additive manufacturing is becoming a more viable method for producing large-scale functional components, a new design environment can be explored. The need for augmenting the large castings and forgings supply chain is growing and WAAM can be a method of fulfilling that demand. The capability of manufacturing a large-scale machine tool structural component by WAAM provides new design opportunities that can be implemented across various industries.

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