

Thermal Process Monitoring for Wire-Arc Additive Manufacturing using IR Cameras

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Abstract

Wire-arc additive manufacturing systems use robotic MIG welders to build parts using welding wire. As a part is built the temperature rises as energy is input and the thermal mass increases. While some pre-heat is ideal for welding, improper thermal management can lead to defects and negatively affect material properties. Thermal imaging allows for non-contact thermal monitoring and can be used to track thermal gradients as well as layer temperatures before and after deposition providing a method to ensure proper thermal management. A typical IR camera setup on an mBAAM system is discussed along with methods to use thermal monitoring to improve material properties and reduce defects in the final part.

Introduction

Wire arc additive manufacturing is an additive manufacturing process that uses a metal inert gas (MIG) welder to deposit beads of metal to build parts layer by layer. [1] It is typically a near-net-shape process where a part is overbuilt then machined down to the final shape. [2] This allows for a final surface finish that's better than what can be achieved using wire-arc deposition alone. Wire-arc additive manufacturing systems consist of a MIG welder on some sort of positioning system, usually a robotic arm. The Metal Big Area Additive Manufacturing system (mBAAM) used at Oak Ridge National Laboratory (ORNL) and made by Wolf Robotics consists of a Lincoln Electric MIG welder and a six-axis robotic arm with a two-axis positioner made by ABB Robotics (Figure 1). The system has two torches for depositing using multiple materials and/or weld modes and can deposit material at rates up to 15lbs/hr. Typical materials for wire-arc additive manufacturing include mild and stainless steels. [3] Typical applications include tooling, such as hot stamping dies, aerospace components that typically involve long machining times and large amounts of wasted stock material, and complex shapes such as excavator arms and marine propellers (Figure 2). [4]



Figure 1 – mBAAM wire-arc additive manufacturing cell at ORNL

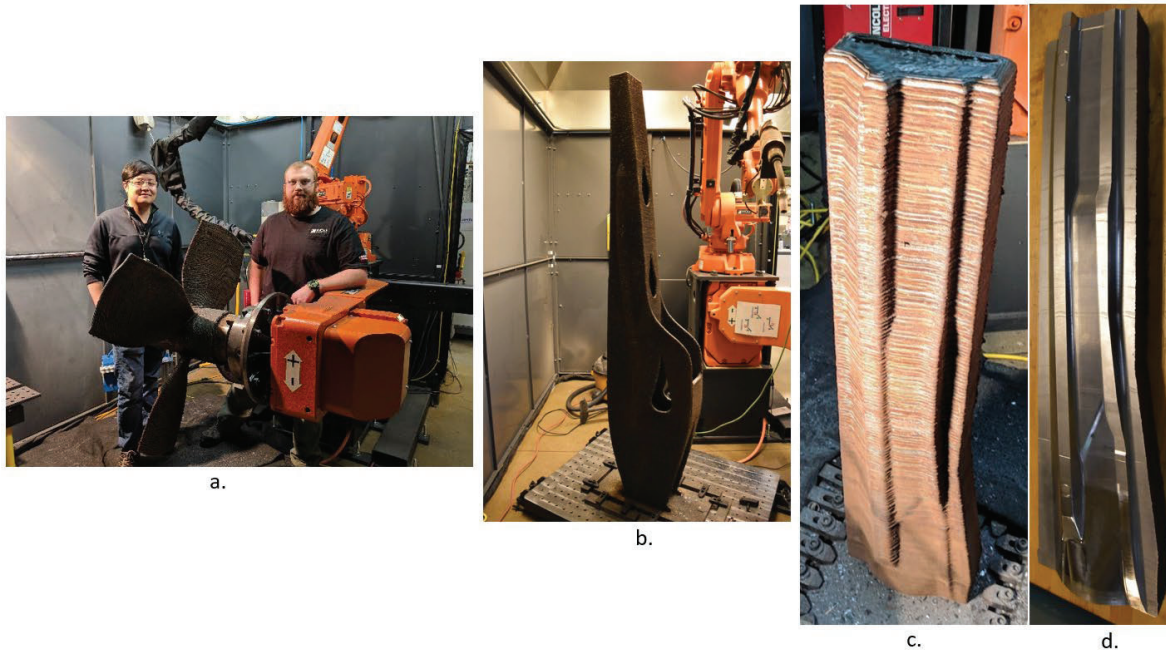


Figure 2 - Parts created using wire-arc additive manufacturing. a.) Marine propeller b.) Excavator arm c.) Multi-material hot stamping die before machining d.) Multi-material hot stamping die after machining

Since wire-arc additive manufacturing involves significant amounts of heat input into the part thermal management is key to improving part quality. [5] As a part is built the temperature rises and the thermal mass increases. Some preheating is ideal for the welding process but too much can lead to defects in the finished part (Figure 3) and poor material properties. Infrared (IR) cameras can be used to monitor the part during the build in order to ensure proper thermal management. Additionally, IR imaging can be used to track the temperature profile and cooling of the part in order to identify problem areas and potentially predict microstructure.

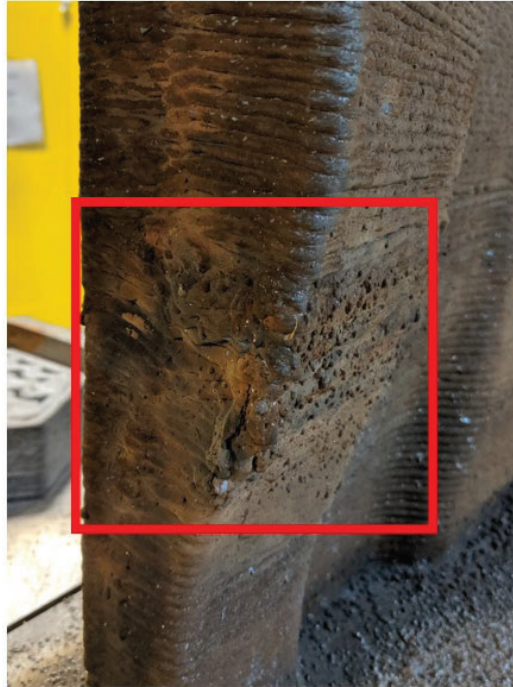


Figure 3 - Melting caused by improper thermal management

Thermal Monitoring Method

Traditionally thermal monitoring for wire-arc additive manufacturing at ORNL has been done by observing the color of the glowing part. Because the color of the glow of hot steel is consistent at certain temperature ranges this can give a rough estimate of the part temperature and whether or not it's safe to continue a build. Since 400°C is typically used as the threshold temperature the system operator can roughly estimate that the part is cool enough to continue once it stops glowing which typically corresponds to a temperature between 400°C and 500°C . Some automation can be added to this process by setting a minimum required layer time causing the robot to automatically wait until a timer expires until continuing to the next layer. However, due to variations in the layers, the required time changes throughout the build requiring the operator to constantly adjust the wait time or accept an inconsistent part temperature. Additionally, using this method relies on the operator to consistently interpret the color of the part, something that can be subjective and can change based on lighting conditions. Using thermal imaging allows for direct temperature measurements during the build taking the system operator and subjectivity out of the equation. The software collecting images from the IR camera can be used to find the maximum temperature on each layer and communicate with the robot to let it know when the part is cool enough to continue. This automation allows for less operator interaction increasing the number of systems a single operator can monitor at one time.

These experiments used a Wolf Robotics wire-arc additive manufacturing system consisting of an ABB Robotics six-axis robot arm with a two-axis positioner and a Lincoln Electric MIG welder. A Flir A35 IR camera was used to collect thermal images. This camera was used due to its low cost, compact design, acceptable temperature range, power-over-ethernet (PoE) capability allowing for a single cable to be used for both power and data, and GigE interface allowing for easy integration with the LabVIEW based data acquisition system. The

camera was mounted directly above the part being built allowing it to see the entire layer. Additional cameras can be mounted to give a side view of the part allowing for the temperature profile during cooling to be observed. The part built consisted of short layer times and a 25° overhang which, when combined, create a part that effectively demonstrates the effect proper thermal management can have on a build (Figure 4). The part was built twice, once without any thermal management or operator intervention, and once with the robot pausing after each layer until the operator saw a maximum temperature measured by the IR camera to be less than the threshold temperature of 400°C.

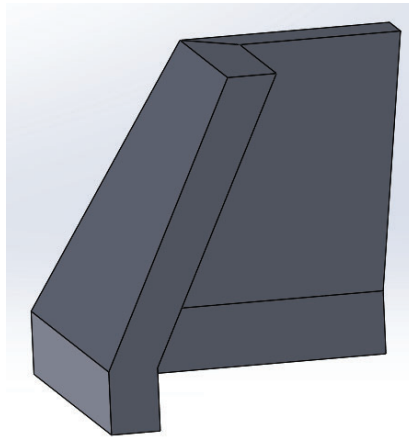


Figure 4 - CAD model of thermal management demonstration part

Results

When the part was allowed to print without interruption the final result was covered in drips on the overhang and was almost two centimeters short in height due to sagging. While the system was able to finish the build due to automatic adjustments made by the robot, the defects and dimensions that fall outside of the acceptable range cause it to be considered a failed build (Figure 5).



Figure 5 - Thermal management demonstration part without the use of thermal management

When an IR camera was used to monitor the temperature of the part and the operator paused the system until the maximum temperature on the most recent layer was below 400°C, the final result had no drips, excellent surface quality, and was almost the full design height, short by just a third of a centimeter (Figure 6). Although it ended up slightly shorter than

designed, repeating layers is common in builds with overhangs due to current slicers not being able to account for the slight sagging that occurs when wire-arc system attempt overhangs and this build is considered successful. Research is currently being done on ways to automatically compensate for and even prevent the sagging that's common in overhangs on wire-arc builds.



Figure 6 - Thermal management demonstration part when thermal management was used to ensure the layer temperature is below the threshold temperature before continuing to the next layer

Conclusions and Future Work

The use of thermal monitoring for wire-arc additive manufacturing produced a significant increase in part quality. It reduced the number of surface defects and drips as well as reduced part sagging. Additionally, it enables overhangs that would be otherwise impossible. It can ensure that the part is cool enough to print without leaving it open to interpretation by the operator and worrying about the effects of uneven lighting. The direct measurement of the layer temperature makes it possible to automate the process reducing the amount of required operator intervention and allowing a single operator to monitor several systems at the same time. Additionally, it allows for in-situ process monitoring and the collection of large amounts of data on the thermal history of the part. This data could be analyzed to identify potential problem areas due to high residual stresses or defects as well as predict microstructure.

Future work will involve implementing a closed-loop control system in the wire-arc systems at ORNL that will use feedback from IR cameras to ensure that layer temperatures are below the desired threshold before the next layer is deposited. Additionally, multiple cameras will be added in order to collect data from multiple angles allowing for the temperature profile of the part during cooling to be monitored and a complete thermal history to be captured for later analysis. This data will be combined with the rest of the data from an instrumentation package that is currently in development in order to further investigate the wire-arc process and allow for a greater degree of closed-loop control and improve the build quality of future parts.

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