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WIRE-ARC ADDITIVE MANUFACTURING: INVAR DEPOSITION CHARACTERIZATION

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Abstract

This paper explains and analyzes an investigation into the characteristics of Invar, a Nickel-Iron alloy, with regards to deposition through Wire-Arc Additive Manufacturing performed by the Metal Big Area Additive Manufacturing (MBAAM) team at Oak Ridge National Laboratory's Manufacturing Demonstration Facility (MDF). The Invar alloy is extremely valuable to multiple fields because of its thermal expansion properties. These fields will attain financial benefits when turning to additive manufacturing as the future production technique for their Invar parts. As such, it will be necessary for AM research to become accustomed with the characteristics of Invar deposition. One of the potential AM techniques that has the potential to carry out printing with this material is Wire-Arc AM. The goal of this paper is to narrow down and call out different welding parameters that optimize the characteristics of Invar deposition using the Wire-Arc AM technique.

Introduction

The Nickel-Iron Alloy Invar has an exceptionally low Coefficient of Thermal Expansion (CTE). For this reason, it has become a standard choice of material for composite layup molds in the aerospace industry. These molds are used to manufacture composites that require very tight tolerances. In the lay up molding process, it is necessary for the tool or "mold" to have similar CTE values to the part being produced by the mold. Invar's exceptionally low CTE easily meets this requirement better than any other metal and is much more durable than any other material commonly used for this application. [1]

The alloy is considerably expensive when compared to common metals, so production efficiency is a crucial aspect to Invar part manufacturing. A common metric used in evaluating production efficiency is the "buy to fly" ratio. This ratio compares the amount of stock material bought to the amount of material used in the field after production and processing. Naturally, the ratio's significance varies with the magnitude of production. With the relatively high cost of stock Invar (around five times the price of stainless steel), [2-3] the magnitude of production is even more significant for this material than common steels; as a result, the buy to fly ratio has even more significance.

Additive manufacturing has revolutionized production efficiency as it relates to the "buy to fly" ratio. For this reason, additive manufacturing should be considered as a potential means of production for Invar parts in the future. Wire Arc AM is a logical choice because this material is typically used to make parts that are too large for most powder bed systems. [4] In order to analyze the potential of the marriage of Wire Arc AM and Invar production, preliminary research must be done in order to legitimize the means of Wire Arc AM to successfully produce Invar parts. It will also be necessary to confirm that Wire-Arc AM production of Invar parts allows for the material to hold its CTE value.

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Application-Specific Process Description

These experiments were executed using a 6DOF robotic arm that was developed by Wolf Robotics for automated Metal Inert Gas (MIG) welding. The wire used was a Special Metals product - CF36. The robot was provided by Wolf Robotics to MDF as a part of a Cooperative Research and Development Agreement (CRADA) that revolves around the development of Direct Energy Deposition Metallic additive manufacturing. The robot's path movements are defined by ABB RobotStudio. A Wolf Robotics G-code add-in feature is used that takes G-code and translates it into robot path movements. The G-code used to feed into this G-code tool was developed by an ORNL-made slicer. [5]

The shielding gas used in these experiments is a "Tri-mix" consisting of 90% Helium, 7.5% Argon, and 2.5% CO2. It is known that this shielding gas is one of the best options available on the market for welding stainless steel. This Tri-mix was used for Invar under the assumption that it would also be the best option available for Invar. The welds performed in these experiments were controlled through a technology called Surface Tension Transfer (STT). STT was created by Lincoln Electric, the parent company of Wolf Robotics. Lincoln has been producing and selling welders and welding equipment since 1895, but only patented the STT technology in 1988. STT is a way to optimize the weld by controlling the current and voltage fed through the wire. The input is defined by a waveform that represents the change in input current over time. [6]

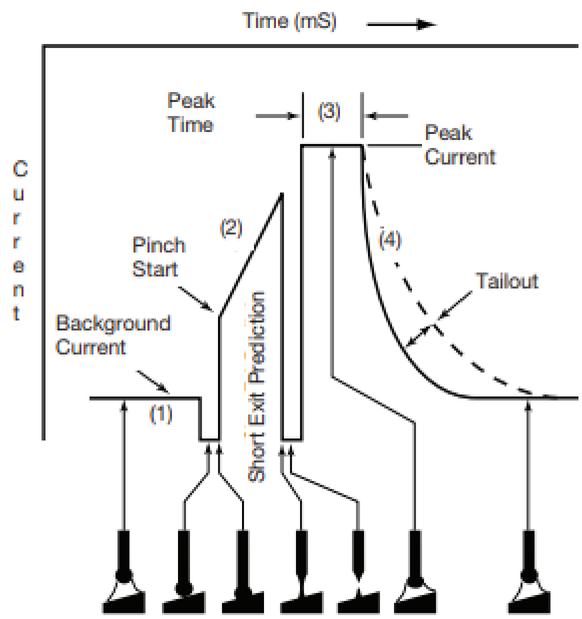

Figure 1. Visual Representation of the STT Waveform. [7]

Purpose

Weld quality can be extremely inconsistent when the weld is not performed in an appropriately controlled manner. Since this application uses welds as a method of deposition for additive manufacturing, it is crucial that the appropriate controls are known so that optimal build quality can be achieved. [8] In order to learn more about the appropriate controls, the purpose of these experiments was to acquire data that lays out different parameters and their appropriate settings. For decades, it has been known that Invar is weldable, [3] but this paper aims to prove that it is printable as well. This requires proving that the printed parts hold their thermal expansion properties after production.

Methods

In many cases, materials are only printable under specific parameters. Before being able to prove the material is printable, it is necessary to find parameters that might allow for the material to have desirable print characteristics. The primary characteristic of a desirable print is geometric accuracy of the final product as compared to the original design of the part. A secondary characteristic of a desirable print is high geometric complexity in the part, but only if the desired geometric accuracy is still present. The approach taken to demonstrate the printability of Invar is guided by these principles. Simple geometries were the first prints carried out. As the first few prints were enacted, process-relevant material properties were pointed out, and process parameters were tailored accordingly. Then, as the process parameters became more suitable, more complex geometries were printed.

Single Beads

Multiple single beads were printed as a starting point. Parameters were tuned for each bead in attempt to optimize the stability of the weld. In order to analyze stability, the welds were closely watched while in progress using a weld camera that was attached to the end effector of the robot, which sent a live signal to a desktop monitor. The controls that were tuned include peak current, background current, and travel speed. The amount of impact that these different controls have on the weld varies by material, so understanding these relationships for Invar was the goal of the first series of beads. The goal for the second series of welds was to apply these new understandings in a way that resulted in a stable weld process.

Table 1. Final Parameters Found From Single Bead Experiments

Parameters (LE Weld Mode 349)	
Gas flow rate	35 CFH
Wire feed speed	225 ipm
Travel Speed	20 ipm
Peak Current	260 A
Background Current	130 A
Tailout	0
HotStart	4 A

Walls

Walls were the next parts to be produced in the progression of geometric complexity. Different types of walls relevant to this task include walls with double, triple, and quadruple bead-thicknesses. Printing walls can demonstrate the simplest order of printability, but more importantly, these prints were done so that crucial print characteristics could be developed. After the production of the first few walls, the ideal bead spacing was identified; finding the ideal bead spacing is done by balancing the relationship between overlap and porosity between beads. After the identifying the ideal bead spacing, more walls were printed with that bead spacing value to expose what layer height and wall widths to expect.

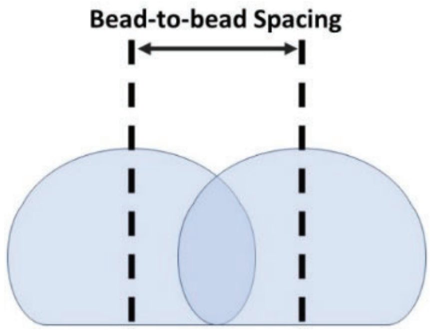

Figure 2. Overlap Involved with Proper Bead Spacing

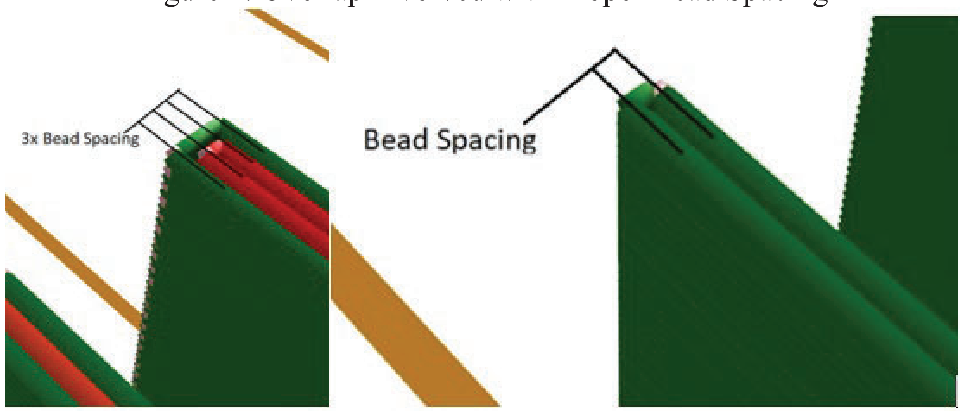

Figure 4. Visual Representation of Bead Spacing on Walls Inside Slicer

Table 2. Simple Geometric Data for 40 Layer Walls with 4.2 mm Bead Spacing

Wall Type	Avg. Width (mm)	Avg. Height (mm)	Layer Height (mm)
Double Bead	11.2	76.4	1.91
Triple Bead	14.3	90.6	2.27
Quadruple Bead	16.6	94.3	2.36

The parameters laid out in Table 1 allowed for our first attempt at printing a wall that satisfactorily met the design specifications. The first demonstration was a double bead wall designed to be 11.2 mm wide by 10" long by 12" tall. This wall was built in CAD, converted to an STL, then imported into the slicer. From there, the double bead layer height value was input into the settings on the slicer; the slicer used this value to determine how many layers would be necessary to achieve the desired height. The G-code from the slicer was then fed into the G-code tool in ABB RobotStudio, and then the robot code generated from that tool was uploaded to the robot and the program was run, building the designed wall.

Tubes

The next simple geometry that was approached was tubing. The relationship between bead spacing and common build characteristics (i.e. build height, layer height, and wall width) becomes more complex when curves are involved. In order to better understand this more complex relationship and confirm that suitable parameters can be achieved for predictable printing of features such as cooling channels, tubes of inner diameters from 8 mm to 30 mm (incrementing 2 mm each cylinder) were printed and analyzed. This experiment was done for single bead and double bead tubes, where the final bead spacing from the wall experiments was used for the double bead tubes – 4.2 mm.

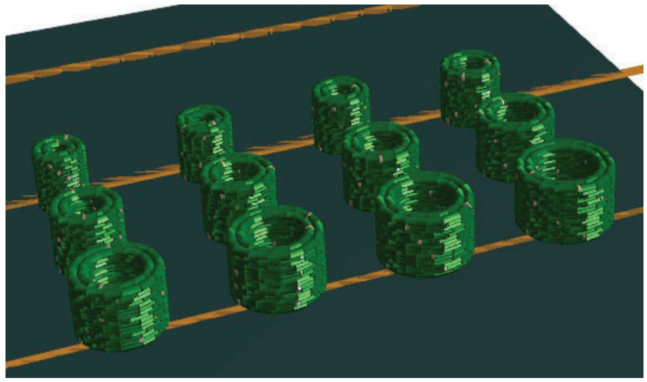

Figure 5. Full G Code Visualization for Tubes in Slicer

Heat is the primary contributor to the raised level of complexity. Different print geometries will result in different build characteristics; certain geometries, such as tubes, will hold more heat throughout the print than a simple wall. This is termed residual heat. Deposition consists of melting metal, then letting it cool off until it solidifies. More residual heat results in a longer period of molten material. When the material spends more time in a liquid state, the liquid gets more time to flow to the sides of the wall. In order to provide data that can be referenced when designing future parts, scans of the tubes were used to acquire the measured dimensions seen in the following diagram.

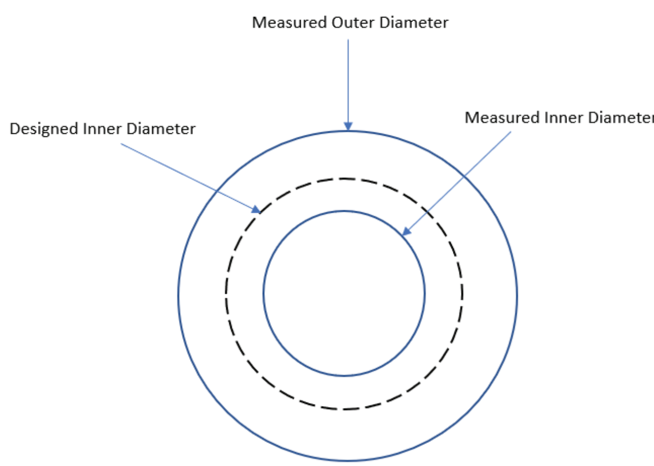

Figure 6. Geometric Tube Characteristics

Table 3. Dimensions of Tubes

DESIGNED ID (mm)	Single Bead Tubes		Double Bead Tubes	
	ID	OD	ID	OD
8	null	17	null	24.4
10	5.5	19.3	6.9	25.4
12	6.9	20.5	9.4	27.1
14	10.3	22.6	10.9	30.7

16	11.5	23.8	14.7	32.5
18	13.5	25.2	16.3	33.1
20	15.9	27.9	18.9	34.5
22	17.1	29.8	20.1	38.3
24	19.6	31.9	21.7	40.5
26	21.3	34.5	24.8	40.9
28	23.5	36.1	26.1	42.3
30	26.5	38.3	28.3	46.2

Infill

Another milestone that was achieved was printing a part that needs the use of infill. The part was intended to implement infill into a part that utilizes the information learned from the previously performed prints (walls and tubes).

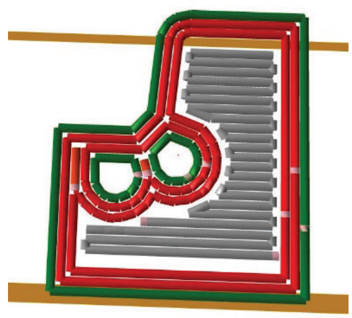

Figure 7. Visual representation of the GCode for infill part

One of the most common setbacks confronted in this process was overbuilding of infill as compared to the other features of the part, such as the perimeters. The cause for this phenomenon boils down to the nature of this method of printing. In relying on tight bead spacing to prevent pores, a new problem is encountered when you must fill the space encompassed by perimeters, assuming you use the same bead spacing. That tight bead spacing ends up causing a taller layer height in the infill region when compared to layer height of the perimeter section. The characteristics of this phenomenon as it is relevant to Invar have been acknowledged so that, in the future, designing larger parts can be done more efficiently.

Overhang

The final aspect of printability that was tested was overhang. A model was developed through CAD that included simple parts of two bead thickness that involved overhang angles varying from 20 to 25 degrees. These parts were printed with no dwell time between layers. The result of no dwell time is inferior build quality; this simulates the most natural characteristics of Invar under the overhang conditions. The results of these prints are used to validate the possibility of printing parts that require overhang features in perimeters.

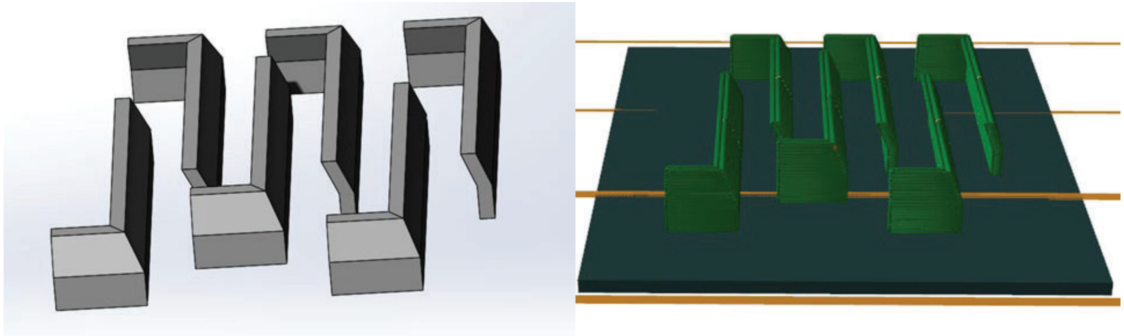

Figure 8. CAD and Gcode of the Overhang Test Parts

Results

In order to analyze the resulting geometries of these prints, the parts were scanned using a Faro arm scanner in congregation with 3D Systems software called Geomagic Control X that allows the generation of a “cloud point file” containing spatial information for each detection point picked up by the Faro arm. This software has the capability of importing CAD files so that they can be compared to the final part. This process involves aligning the reference geometry to the measured geometry through various methods, then generating spatial comparisons between every point in the cloud and the closest spot on the reference geometry. The output of this process is visualized on a color map pasted on to the reference geometry, the different colors correspond to average errors or deviations in that area.

This method was used to determine the accuracy of our prints. Although a lot of these tests were done in order to attain information that allows for more accurate part production, a general idea of printability can be attained from these preliminary prints as well. Apart from the infill overbuilding problem, we found that the maximum deviations for all parts remained within 10 percent of the dimension of the bounding box of the designed STL that most closely lined up with the direction of deviation. This quality was used to decide that the material is printable.

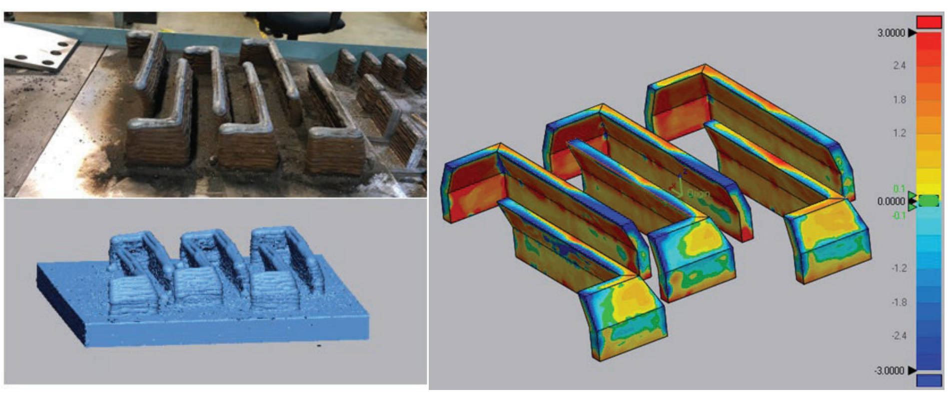

Figure 9. Demonstration of Overhang Results

For this material, being printable is not enough in determining whether Wire Arc AM is suitable as a standard means of production. Since Invar is usually used when the very low CTE of the material is necessary or desirable for the specific application, Wire Arc AM production must not increase its CTE beyond an acceptable amount. An acceptable amount was determined based on the most common application of this material – composite mold tooling for the aerospace industry. For this application, the primary goal is that the tool CTE matches the CTE of the material that is being created with the tool. The most common part produced with this technology has a CTE of 3.5 x 10^{-6} /°C [1]. If the post deposition CTE is lower than this standard, Wire Arc AM is a feasible means of Invar part production. We found that the post deposition CTE is comfortably below this standard.

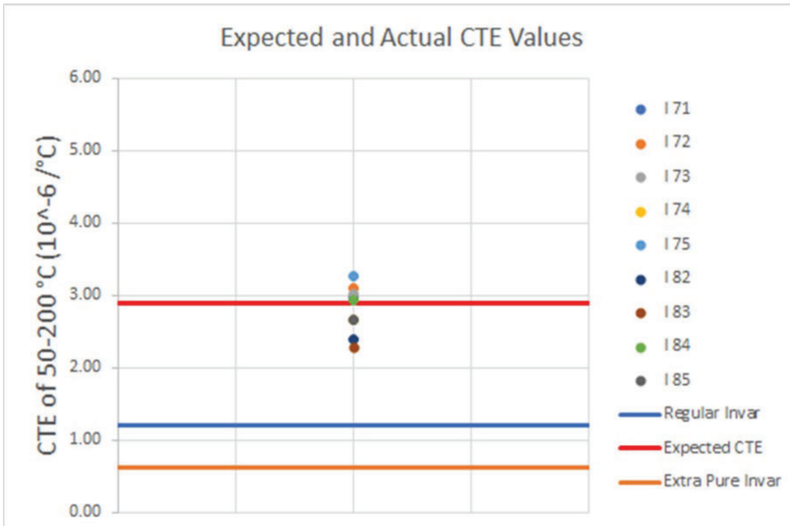

Figure 10. Chart Showing CTE Results at Different Heights of A Printed Wall

Conclusion

The feasibility of using Wire Arc Additive Manufacturing to produce Invar parts was investigated. In learning that it is feasible, the parameters used and the associated geometric characteristics were identified and recorded. If in the future it is decided to attempt to print a prototype for an industrial application, the information obtained from this investigation can be used to allow for a more streamlined approach to developing the G-code that would allow for a successful print.

Acknowledgements

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