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Wire Arc Additive Manufacturing of Multi-material Parts Using H-13 Tool Steel[1]

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Abstract

H-13 tools steel's relative hardness, resistance to thermal fatigue, and high tolerance of thermal shock, make it very desirable for use in forging, pressing, casting, and extrusion processes[1]. H-13 is however typically quite expensive when compared to many other steel compositions. It is therefore desirable to encase a lower cost steel composition with H-13. This configuration allows for the benefits of H-13 tooling to be realized, at a considerably reduced cost. To demonstrate the viability of this concept, a casting tool was fabricated using a Wire Arc Additive Manufacturing (WAAM) process. Initial materials testing was conducted on a multi-material wall which consisted of one section of H-13 tool steel, and one section of 410NiNmo. These tests included scanning electron microscopy, energy dispersive X-ray spectroscopy, and hardness testing. This testing generated favorable results and subsequently a casting tool was fabricated for evaluation. Utilization of a Multi-Material WAAM process to fabricate large tooling in this manner could yield significant improvements in material cost, manufacturing agility, and supply chain complexity.

1 Introduction

For applications such as pressing, forging, or stamping, where metal forming is conducted at high temperature, it is often necessary to utilize a material which retains high relative hardness, demonstrates resistance to thermal fatigue, and exibits a high degree of toughness, even at elevated temperatures. One such material is H-13 tool steel. H-13 tool steel is prohibitively expensive compared with many other steels and subsequently manufacturing solutions which reduce the quantity of H-13 necessary to produce an item can dramatically reduce cost. One solution for minimizing this cost it to additively manufacture a multi-material tool which is comprised primarily of a lower cost steel, but has an exterior H-13 layer. This method of tool construction has the potential to reduce the costs associated with raw materials, power consumption, and production time. The use of additive manufacturing techniques also make the inclusion of features such as internal cooling channels and material reducing pockets, relatively straight forward. To demonstrate the viability of these strategies Wire Arc Additive Manufacturing (WAAM) was employed to create a multi-material casting tool.

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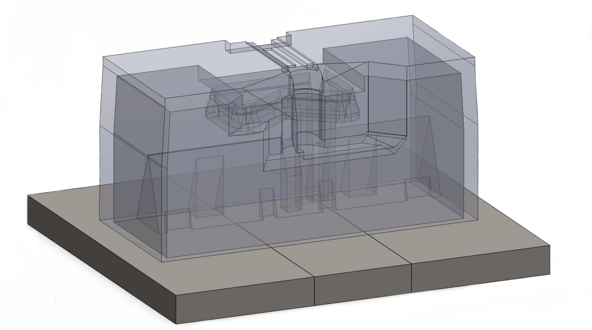

Figure 1: As Printed Casting Die

2 Manufacturing Configuration

Construction of the multi-material casting tool required the use of a WAAM printer which was capable of printing two different materials, while still maintaining a constant coordinate structure. In order to achieve this the ARC 1 system, located at the Oak Ridge National Laboratory, Manufacturing Demonstration Facility, was utilized. This system is configured with a single ABB IRB 2600 robotic arm, one Lincoln Electric Power Wave R540 welder, and two selectable welding torches with their own independent wire feeding systems. The first torch was configured to weld 410NiMo and the second torch was configured to weld H-13. Arc 1 has a pneumatically actuated mechanism which, when triggered by a command in the G-code, can switch between the two torches. The relatively large foot print of the part to be printed necessitated a large build plate and subsequently a multi-plate configuration was selected for both ease of handling as well as the potential benefit of breaking the load path in order to reduce stress in the base plate [2].

3 Novel Features

3.1 Multi Material

Modern automated casting systems utilize casting dies which are repeatedly subjected to high temperature molten metal being poured or injected into them. It is critical that the casting dies be manufactured from a material with the ability to withstand large and rapid temperature swings. It is also important that they are manufactured from materials which have both have a high relative hardness as well as the ability to maintain high relative hardness at elevated temperatures. When properly heat treated it is not uncommon for H-13 to reach values as high as 50 Rockwell C [3]. Historically, at roughly two to four times the cost of other common steel alloys, H13 has been prohibitively expensive to utilize. However, by using a WAAM multi-material process, that cost can be significantly decreased. The bulk of the multi-material WAAM casting die is comprised of 410NiMo with a thin outer layer of H13.

3.1.1 Material testing

Multi-material test walls were printed in order to conduct several material tests to better characterize the material properties of a part comprised of H-13 and 410NiMo. The test walls consisted of one bead of H-13 printed next to a wall of 410 NiMo. Once printed, these walls were then examined using Scanning Electron Microscopy (SEM), Energy Dispersive X-ray Sprectroscopy (EDS), and hardness testing.

3.1.1.1 SEM Imaging SEM imaging, shown in figure 2, reveals that there is a saw-tooth like interface between the two adjoining materials. The total width of this saw-tooth region is approximately 5mm. No cracking or defects are visible at the H-13/410NiMo interface.

3.1.1.2 EDS Mapping EDS mapping shows a rapid transition from H-13 to 410NiMo. Some variation was observed in the elemental composition of the first three layers. The elemental composition

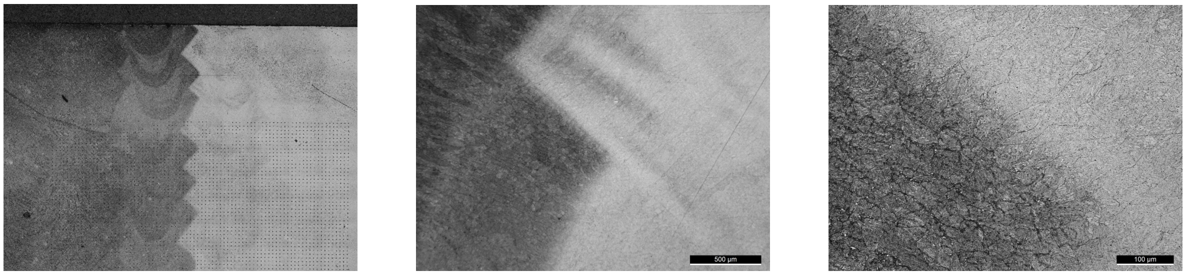

Figure 2: SEM Images of the H-13 to 410 NiMo Interface

from the fourth layer on showed minimal variation. Closer inspection of the element map, shown in figure 3, reveals that some Nickle and Chromium were transferred from the 410NiMo to the H-13.

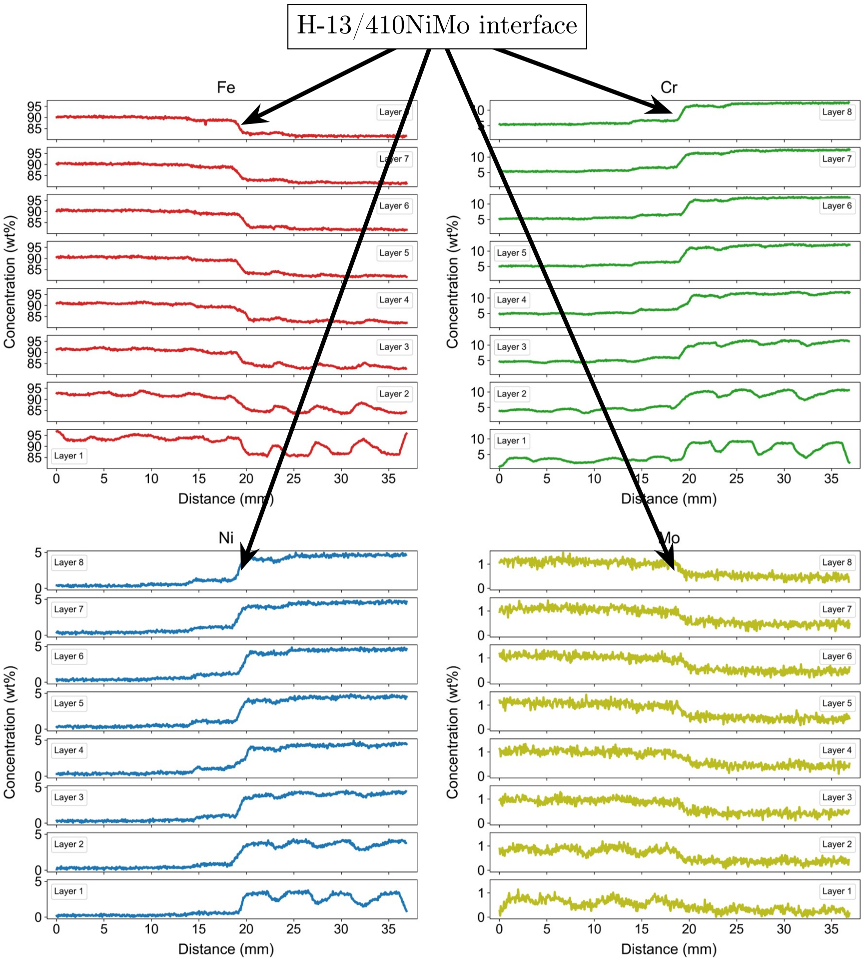

Figure 3: Elemental Composition at the 410NiMo/H-13 Interface

3.1.1.3 Hardness Testing Hardness testing of the test walls further demonstrates a rapid transition from H-13 to 410NiMo. The hardness of the first two test walls was quite consistent through out; however, there is a region of the H-13 component of the third test wall which exhibits a notable reduction in hardness. This reduction in hardness is believed to be the result of an interruption in the print, which allowed the part to cool. Inspection of the print under high magnification shows that the grain structure of the harder region of the wall has a high degree of directionality, whereas the area of reduced hardness does not.

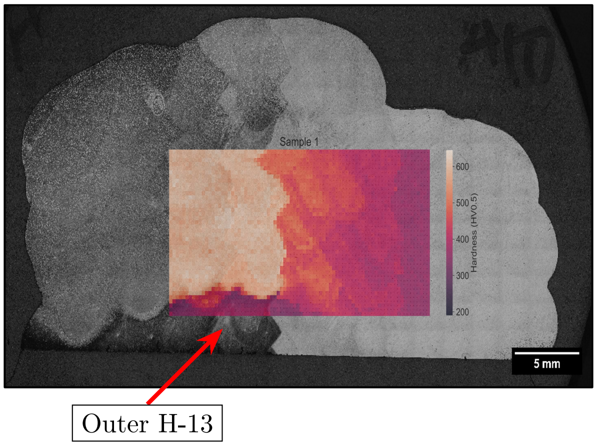

Figure 4: Hardness at the 410NiMo/H-13 Interface

3.1.2 Design Concept

For the purposes of designing a multi-material part that will be post machined, there are three important surfaces. The first is where the inner material meets with the external material. The second is the "designed surface" which is the target surface for the machining process. The third and last is the exterior printed surface. It is critical that the "designed surface" must fall in between the interface surface and the exterior printed surface at all points within the part.

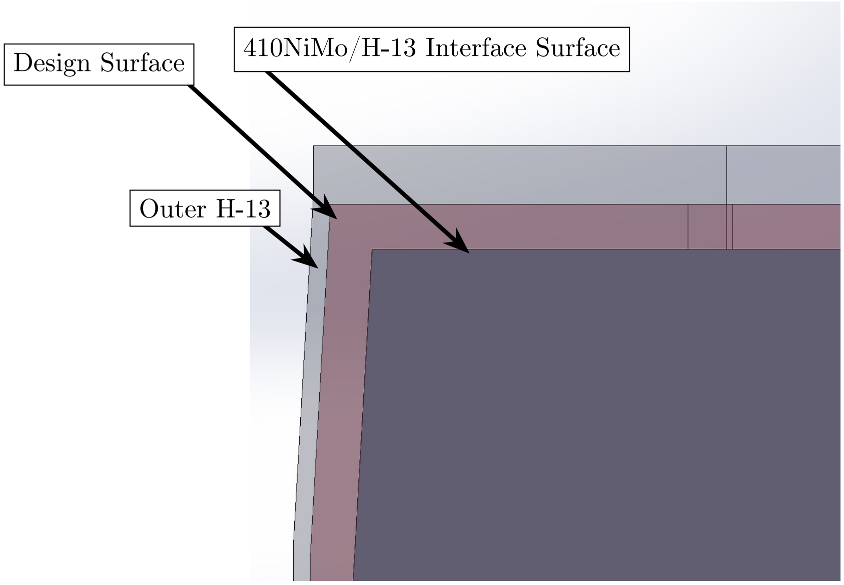

Figure 5: Important Surfaces for Design

When the WAAM portion of the manufacturing process is complete the die must be machined to it's final geometry. With this in mind it is necessary to ensure that there is enough separation between the outer H-13 and design surfaces to allow all of the surface irregularities resulting from the WAAM process can be milled off before the design surface is reached. To be certain that this was the case, the design surface was placed one full beads-width (or 4.5mm) inside of the outer H-13 surface.

Another important consideration when designing the print geometry is the required transition distance between the two materials. To characterize this distance, multi-material samples were generated and then examined using scanning electron microscopy, energy dispersive X-ray microscopy, and hardness testing. The results of the material testing showed a rapid transition between the materials. In order to minimize the presence of 410NiMo at the machined surface, a minimum of three beadwidths of H-13 seperates the designed surface and the 410NiMo/H-13 interface surface.

3.2 Integrated Cooling Channels

The traditionally manufactured casting die utilizes machined cooling channels in order to keep the casting surfaces from overheating, and to decrease the time required for the molten metal to cool to a solid state. The machining process required to create these cooling channels can be eliminated by simply incorporating the cooling channel geometry into the WAAM process, which in turn reduces cost and complexity. The location of the inlet and outlet for the WAAM cooling channels is the same as the traditionally manufactured cooling channels in order to ensure no modifications are necessary for the remainder of the final casting assembly. The WAAM cooling channels were designed with a flat bottom and sides in order to simplify the tool path as well as to maximize part density. There is currently not a viable mechanism for creating support structures in the WAAM process, the top portion of the cooling channel could not be designed as a flat section, and instead a 20° overhang geometry was incorporated. The ability of WAAM to produce near net shape geometries has the potential to significantly reduce overall cost [4].

3.2.1 Drip Reduction Techniques

In order for the cooling channel to work effectively, it is important that there are as few obstructions as possible. One such obstruction which is commonly seen with WAAM overhangs is the presence of drips. Drips are thought to occur when the gravitational force acting on the deposited material is able to overcome the force of surface tension, causing the molten material to drip before it is able to solidify[5]. Two strategies were employed in order to reduce this possibility. First the energy levels for the weld were minimized to reduce the time required for the material to solidify. Second, an algorithm was developed which identifies overhanging beads and reduces the spacing between them and their nearest neighboring bead. This is thought to allow the overhanging bead to roll down the face of the adjoining bead. When properly optimized the bead will solidify once it reaches the desired location. In order to determine the optimal reduction in bead width, a matrix of walls with 20° overhangs were printed. The bead spacing for each successive wall was reduced in increments of 0.5mm. The results of this test showed a bead spacing reduction of between 1.1mm and 1.5mm produced the least drips. For this die, a bead spacing reduction of 1.5mm was selected. While this strategy does reduce the probability of drips, the resulting shift in the bead geometry does not allow the overhanging beads to converge normaly. To correct this issue a reduced overhang angle was introduced at the top of the enclosure which did not require shifted bead spacing to prevent drips. Bead space shifting is not utilized on lower overhang angle portion of the geometry, and as a result it was necessary to compensate for this shift in the CAD geometry, as shown in figure 6.

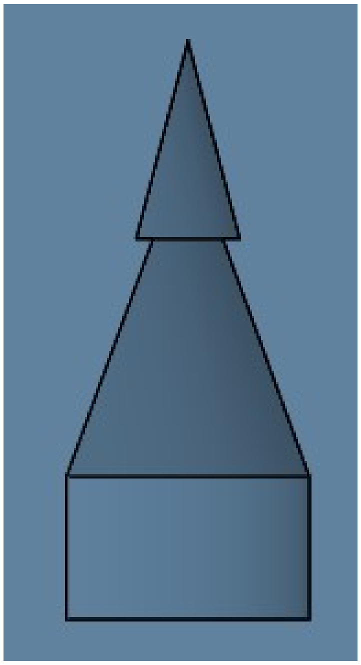

Figure 6: Cooling Channel Cross Section

3.3 Weight and Material Reduction Cavity

The use of WAAM to manufacture this stamping die, allowed for the creation of internal features that would not otherwise be possible using traditional manufacturing methods. One such example in this die, is the inclusion of a material reduction cavity, which can be seen in Figure 7. This cavity takes the form of a 20° overhang feature in the base of the part. The volume of the cavity is approximately 92 in^3 and subsequently reduces the overall weight of the part by 25 lb and reduces the material cost by approximately $250.

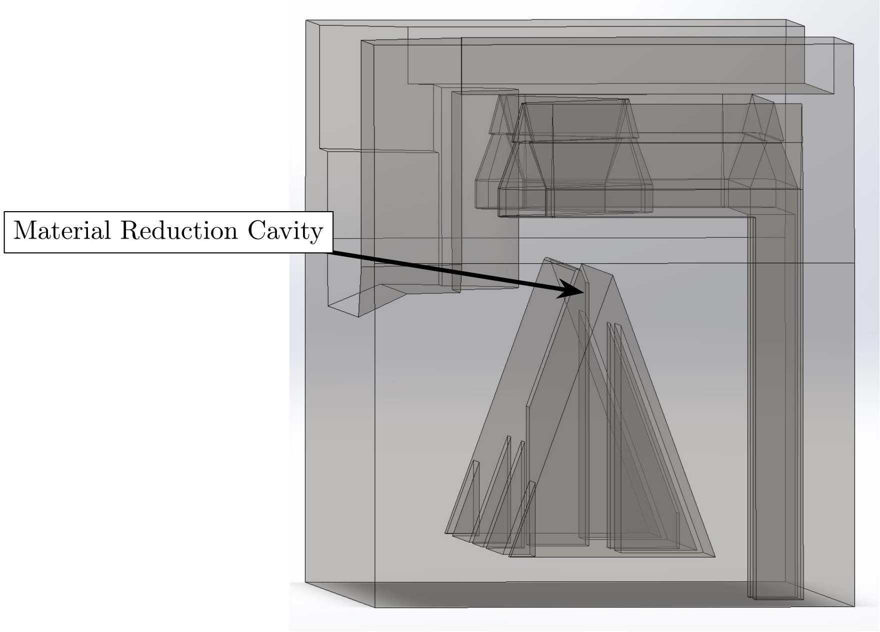

Figure 7: Important Surfaces for Design

4 Results

As compared to a Traditionally manufactured H-13 part, 65 percent of the volume H-13 was replaced with 410NiMo, resulting in a material cost reduction of approximately $10,000.

H13	Multi-Material
$28,556	$18,404

The final printed part was Scanned using a Faro Quantum Max articulating arm coordinate measuring machine and compared to the design geometry. the largest observed deviations between the design geometry and the scanned geometry was 2mm.

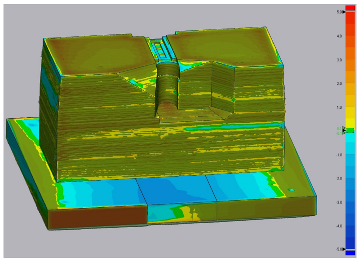

Figure 8: Scan Data

5 Conclusion

This initial research demonstrates that H-13 and 410NiMo show adequate compatibility and that multi-material WAAM printing of a H-13 and 410NiMo part does appear to be a viable strategy for producing hot work dies for casting and forging. Further development and use of this process show the potential to significantly reduce the logistical complexity as well as cost associated with producing casting and forging components in the future. Additional research must be conducted to verify that the resulting part is capable of withstanding the post processing operations required to render a usable die.

6 Acknowledgments

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