ORNL/TM-2023/3174

Local Modification of Cast Aluminum Alloys via the Cast-and-Print Process

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October 2023

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Lightweight Metals Core Program

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October 2023

Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, TN 37831
managed by
UT-BATTELLE LLC
for the
US DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

CONTENTS

ABSTRACT

Casting of aluminum alloys is a cost-effective way to mass manufacture bulk aluminum parts for automotive applications. However, the casting process requires filling of a mold, which imposes some limitations on the geometries that can be successfully cast and limits parts to be a uniform material. Therefore, we proposed that a hybrid casting plus additive manufacturing approach, Cast-and-Print, could be used to locally modify the properties and geometry of cast parts to create difficult-to-cast, functional features. Here, we report the results of the properties of deposited materials on cast substrate, the properties of the interface of the deposited and cast material, and the application of the Cast-and-Print method to deposit rivet tabs on high-pressure die cast plates. Ultimately, the approach appears viable, but there are engineering challenges to reliable additive processing of aluminum wires that need to be overcome for successful implementation of the technology.

1. INTRODUCTION

The use of hybrid manufacturing via combining additive material deposition processes with conventional manufacturing is a field of study that has been gaining recent interest as additive manufacturing technologies mature [1]. For example, cladding of aluminum alloy sheets with a directed energy deposition (DED) process was used to create a non-uniform thickness in the final formed part [2]. Directed energy deposition processing was also used for depositing a titanium alloy on a forged titanium part [3]. For rolled sheet products, the ability to change local thickness is a clear benefit, as sheet products should inherently be a uniform thickness. However, while the combined approach of conventional manufacturing and additive manufacturing has been demonstrated for rolled and forged products, there are fewer examples of such a technique being applied to castings.

High-pressure die casting (HPDC) parts designs are not inherently limited to uniform wall thicknesses, but thicker walls can have higher susceptibility to shrinkage porosity [4] and varying wall thicknesses can have different resulting microstructures [5]. However, the increased strength and decreased ductility of HPDC alloys leads to challenges in using mechanical joining via riveting to create assemblies from HPDC components [6]. Because of these challenges, local modification of geometry could enable creating localized properties for either improved performance or joinability.

The scale of the microstructure achieved through additive manufacturing processes is also much finer when compared to casting processes. Figure 1 shows a comparison between cast and laser-wire DED microstructures for hypoeutectic Al-Si alloys. The casting has secondary arm spacing of approximately 20-30 microns, whereas the DED secondary arm spacing is on the order of 5-10 microns. The finer microstructural features are desirable, because the primary and secondary arm spacings contribute to Hall-Petch strengthening mechanisms. Therefore, AM processes also offer material property benefits, which could allow for localized strengthening.

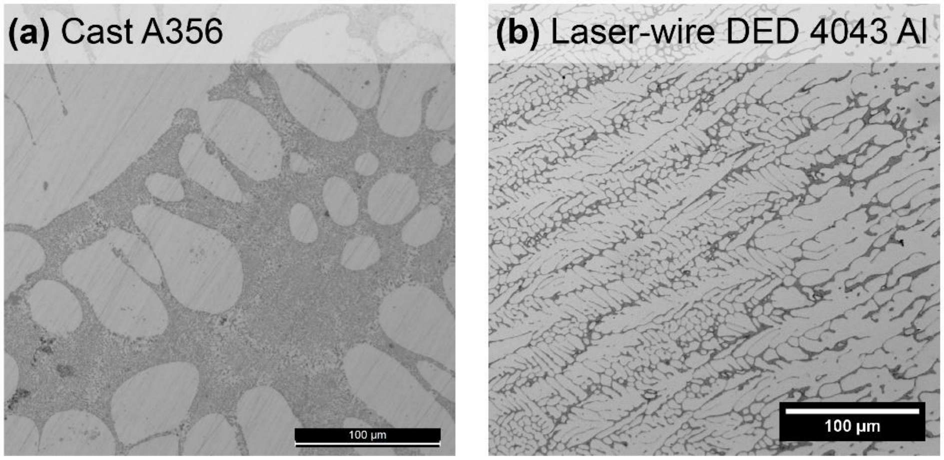

Figure 1. Difference in scale between (a) cast aluminum microstructure and (b) laser-wire directed energy deposition (DED) microstructure for hypoeutectic Al-Si alloys. The optical micrographs show large bright regions of primary dendritic aluminum and dark regions of interdendritic eutectic silicon.

The conceptual benefits of using additive manufacturing technologies to locally modify cast parts are promising, but several aspects of the implementation of such as process had yet to be demonstrated. First, the interface between cast base part and the deposited material had to be assessed. Secondly, the properties of deposits made from commercial alloys needed to be assessed and compared to the properties of the base cast alloys. And lastly, the level of defects in produced parts needed to be characterized, as well as the effects of those defects on industrially relevant applications. Specifically, deposited walls were fabricated on HPDC aluminum plate to serve as joining surfaces for riveting. The remainder of this report will cover the research methodology used for the Cast-and-Print process, the results of process parameter development and rivet testing, and a discussion of the outlook and remaining challenges.

2. METHODOLOGY

To deposit the material on the cast substrates, a hybrid laser hot-wire and subtractive machining process was used, specifically the Mazak VTC-800G system. The laser hot-wire technology was chosen due to its relatively high mass deposition rate compared to powder bed fusion AM technologies, which would improve the potential throughput of the process in an industrial setting. The process, depicted schematically in Figure 2(a), uses a wire feedstock that is heated via Joule heating and then melted by a laser to deposit material on a cast substrate held via fixturing. The wire deposition head can be exchanged for a machine tool head that can remove material and create a smooth surface. Furthermore, the Mazak VTC-800G has a large build area, the area enclosed behind the orange front panels of the system Figure 2(b), which would potentially enable large cast parts to be modified.

The feedstock materials were chosen from commercially available aluminum alloy welding wire compositions, namely the 4xxx series (Al-Si) and 5xxx (Al-Mg) alloys. Specific alloys were chosen based on their estimated resistance to hot cracking in the dilution region that is formed when the deposited alloy is mixed with the representative cast substrate. The hot cracking estimation was done using an empirical hot cracking parameter [7] determined by our recently developed high-throughput CALPHAD approach to predict the solidification pathways, detailed in our published work [8].

To develop adequate processing conditions, single pass deposits were made with varying process parameters until deposits with good surface quality were obtained. When depositing on HPDC plates, melt through and visually observable deformation on the back of the plate were considered as indicators of poor process parameter selection.

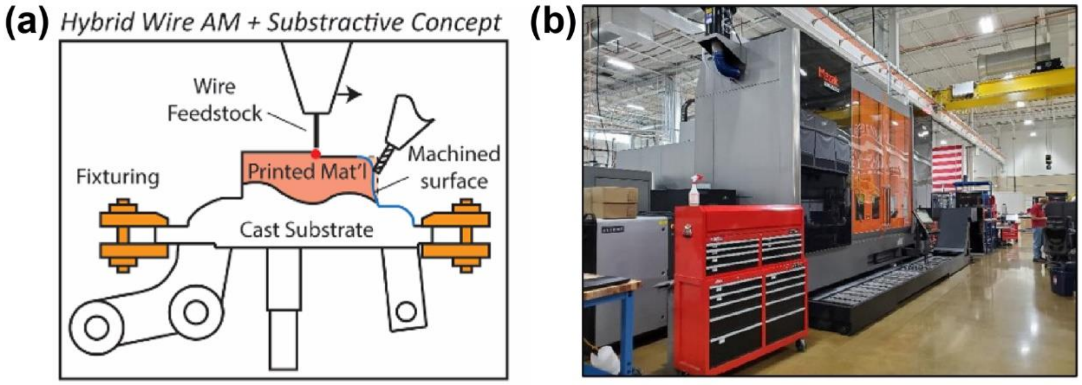

Figure 2. (a) Schematic of the hybrid cast and additive manufacturing (Cast-and-Print) process. (b) Photograph of the Mazak VTC-800G system at the ORNL MDF used for experiments.

Optimized process parameters from the single bead experiments were used to print pads. Additional difficulties associated with the process parameter development for the multi-layer deposits were found, so an interlayer machining approach was developed. That approach is described further in the results, Section 3.1. With the optimized process parameters and interlayer machining approach, aluminum alloy 5356 wire was deposited on HPDC Aural-5S (AlSi8MnMg) plates and then machined to make 20 mm long, 2 mm thick, and 10 mm tall "rivet tabs" that would be used for characterization and testing with a riveting system. A schematic of the rivet tab is shown in Figure 3, in which the rivet tab is used as a surface through which a rivet can join the thick Aural-5S substrate to another material.

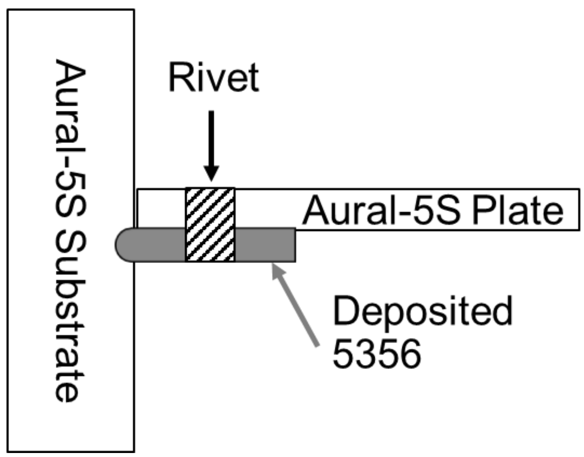

Figure 3. Geometry of the rivet tab and rivet experiment set up.

3. RESULTS

3.1 PROCESS PARAMETER DEVELOPMENT

Initial parameter development using single pass beads resulted in an optimized parameter set of 4200 W laser power, 1 W hot-wire power, and 200 in/min wire feed speed. While these parameters deposited single layers with little to no spatter, issues with balling of the melt pool were observed when transferring the parameters to multi-layer structures. This is shown for the deposition of a multi-layer wall in Figure 4(a-c) for Al 5356 wire deposited on an A356 ingot. The single layer deposit has a uniform surface, but there is significant balling of the deposited wire by the 3rd layer of the deposition resulting in an extremely rough surface. Enough material was able to be deposited to machine out a final part geometry, but significant porosity was visible.

Notably, the surface of the deposit after finishing a layer was covered in a visible oxide layer, which was a likely indicator of poor shielding gas coverage of the melt pool during processing. As aluminum alloys readily oxidize, a low oxygen environment is critical for successful processing. Due to constraints on modifying the shared laser hot-wire system, this inadequate shielding issue was not able to be resolved in the scope of this project. To proceed, it was found that surfacing the deposited material after each layer using the subtractive machining capabilities of the system significantly improved the quality of the deposited material. This process, shown in Figure 4(d-f), allowed for larger geometries to be built up with minimal lack of fusion defects for this small scale proof of concept research effort.

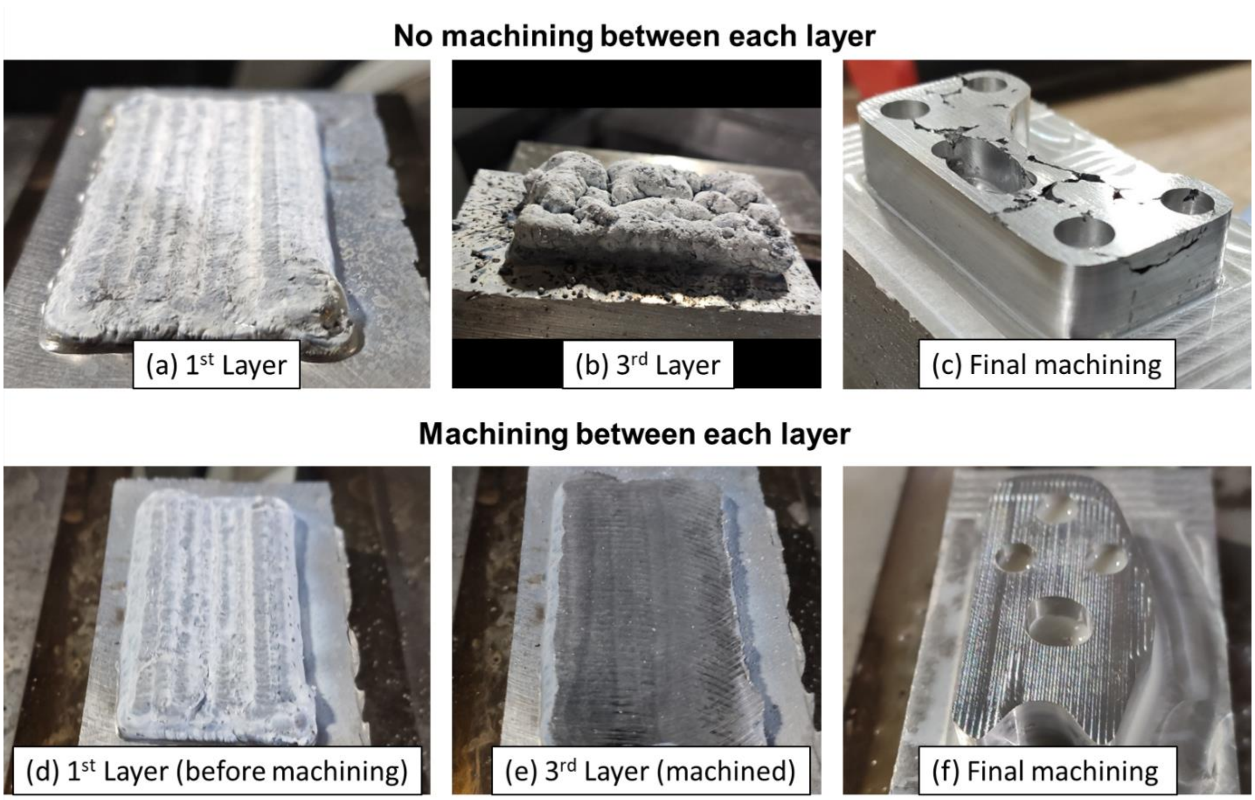

Figure 4. Demonstration of deposition of 5356 wire on A356 cast ingot with hybrid manufacturing. (a-c) Deposition of multiple layers with only final machining, (e-f) similar deposition of multiple layers with machining between each layer. Part height is 10 mm tall after final machining.

Blocks of material were deposited using the interlayer machine technique using three different aluminum alloy feedstocks: 4043 (hypoeutectic Al-Si), 4047 (near-eutectic Al-Si), and 5356 (Al-Mg). Compositions of these alloy feedstocks are provided in Table 1. Five SS-J3 subscale tensile specimens [9] were extracted from the as-built material in the horizontal direction of the deposits and loaded at a constant strain rate of 0.0016 s^{-1}. Figure 5 shows the results of the test, with the dark lines showing the average of the five tests and the grey regions showing one standard deviation. All materials showed relatively high engineering strain at failure, indicating that the effects of defects on the tensile strength were minimal. Using data for Aural-5S from the literature as a reference [10], all three materials had expectedly lower strength compared to high-pressure die cast Aural-5S material. That said, the Al 5356 alloy had nearly three times the ductility, indicating that it should be significantly more amenable to rivet-based joining techniques.

Table 1. Composition of the alloys used, as specified by the manufacturer. All compositions are in weight percent and single values indicate maximums.

Alloy	Al	Si	Mg	Fe	Cu	Cr	Mn	Zn	Ti
Al 4043	Remainder	4.5–6.0	0.05	0.8	0.3	-	0.05	0.1	0.2
Al 4047	Remainder	11–13	0.1	0.8	0.3	-	0.15	0.2	-
Al 5356	Remainder	0.25	4.5–5.5	0.4	0.1	0.05–0.2	0.05–0.2	0.1	0.06–0.2
Aural-5S									

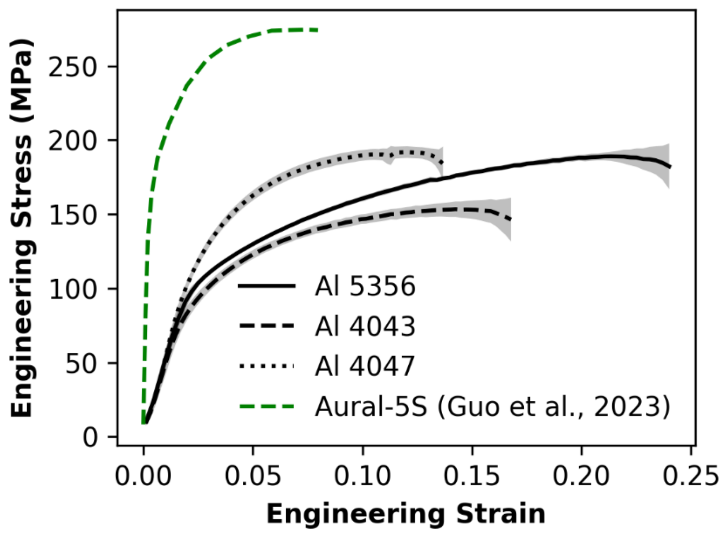

Figure 5. Engineering stress-strain curves measured from as-built SS-J3 format tensile specimens from the blocks of material deposited using the interlayer machining technique. Lines show the properties of aluminum alloys 4043 (dashed), 4047 (dotted), and 5356 (solid) with shaded regions showing the standard deviation for five measurements. The green dashed line shows data for Aural-5S adapted from the literature [10].

3.2 RIVET TABS DEPOSITION, CHARACTERIZATION, AND TESTING

To deposit material on the HPDC Aural-5S plates, additional process parameter optimization had to be done due to the relatively thin plate (4.4 mm) compared to the previously used A356 ingots. The reduced thickness of the plate meant that the substrate was less effective as a heat sink and over-melting and balling were observed in the previously developed process parameters. After deposition of a combination of single pass and multi-layer test wall, the resulting process parameters used to deposit the rivet tabs were 2250 W laser power, 0 W hot-wire power, and 123 in/min wire feed speed. The interlayer machining was used to ensure that each layer was 1 mm tall after deposition, meaning that 10 layers in total were deposited. Six walls were manufactured for characterization and testing with the riveting system. As shown in Figure 6, wall #2 had significant visible surface porosity, so it was not used for characterization or testing. One wall was sectioned immediately after machining to check for interior porosity, seen in the back-right of the image.

Rivet tabs were sectioned, mounted, and polished in resin mounts, and then imaged using optical microscopy. Hardness measurements were also taken along the height of the walls to see if there were any variations in the properties as a function of height. Figure 7 shows the optical microscopy and Vickers microhardness measurements for two of the walls. The Vickers microhardness of the aluminum 5356 walls ranged between 64-72 HV, whereas the hardness of the Aural-5S substrates ranged between 68-74 HV (substrate indents are outside the field of view of the micrographs). Figure 7(a) shows a wall that is largely free of porosity, however a horizontal crack can be seen in the wall approximately 1 mm above the substrate—corresponding to one of the interlayer machining planes. An exaggerated version of that defect is also seen in Figure 7(b), where an internal lack of fusion defect is seen in addition to the horizontal crack. The values for hardness in the sample were consistent as a function of height. Though the interlayer machining did help to mitigate the effects of oxide formation and uneven surfaces causing lack of fusion porosity, it is apparent that there was still process instability that led to lack of fusion defects. This is almost certainly due to the same factors that led to the balling and lack of fusion shown in Figure 4(a-c), mainly the presence of oxygen in the melt-driven DED build environment.

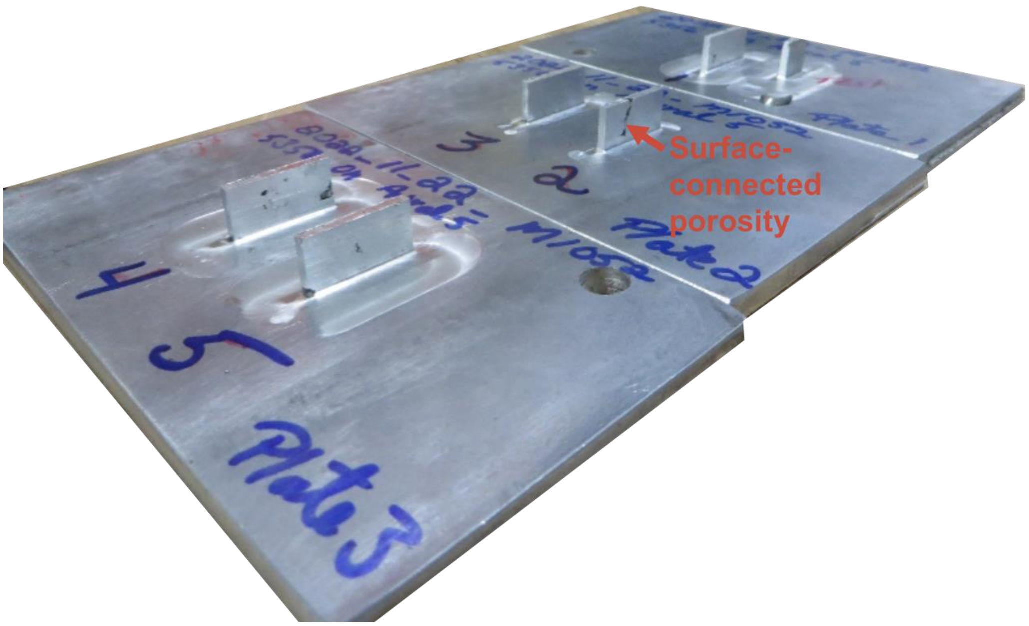

Figure 6. Deposited rivet tabs for characterization and testing. Deposited material is 5356 aluminum alloy.

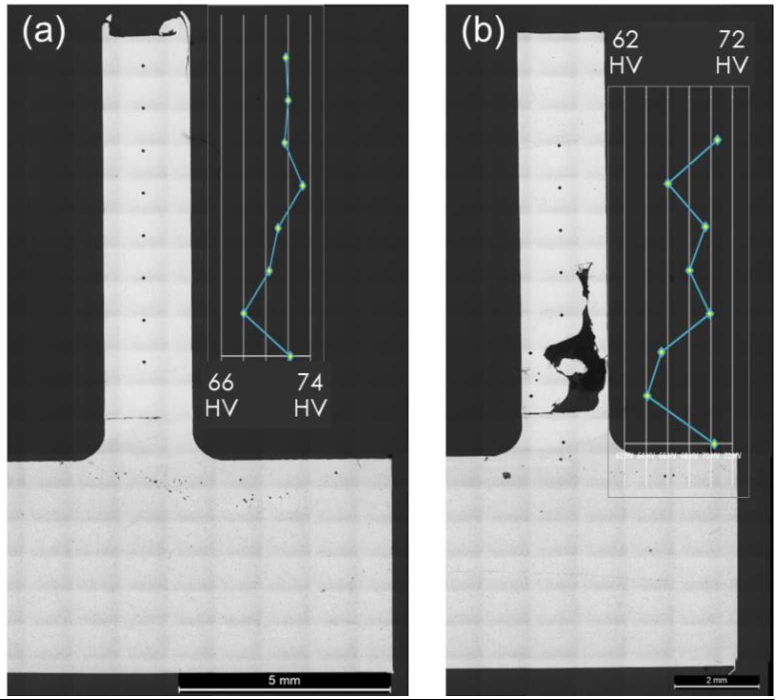

Figure 7. Hardness measurements overlaid on optical micrographs of the rivet tab cross-sections. Hardness measurements correspond to the indent at the same height in the image.

A wall sample was prepared for testing with a newly integrated friction-self piercing rivet (F-SPR) system at the Materials Joining Group at ORNL following the layout shown in Figure 3. The experimental set up corresponding to the schematic is shown in Figure 8(a). To obtain a sample geometry compatible with the rivet system, a slice of the substrate containing the wall had to be cut out from the larger substrate. The rivet was then spun and pierced from the rivet tool through the Aural-5S plate and the deposited material with a backing anvil. A visual inspection of the rivet showed it was able to form a bond with the material, the interaction of the shear and axial plunge forces from the rivet with the defects inside the wall were sources of failures. The horizontal cracks observed in Figure 7 can also be seen in Figure 8(b), labeled as the “interface crack.” The straightness of the fracture in that region is telling of the crack being due to the interlayer machining. Additionally, cracks were observed near the edge of the rivet where lack of fusion can be seen as glob-like morphology crack surfaces. In general, torsional/stir riveting can reduce the sensitivity of rivets to porosity in the substrates; however, it is apparently that there was an unacceptable level of defects in the manufactured walls.

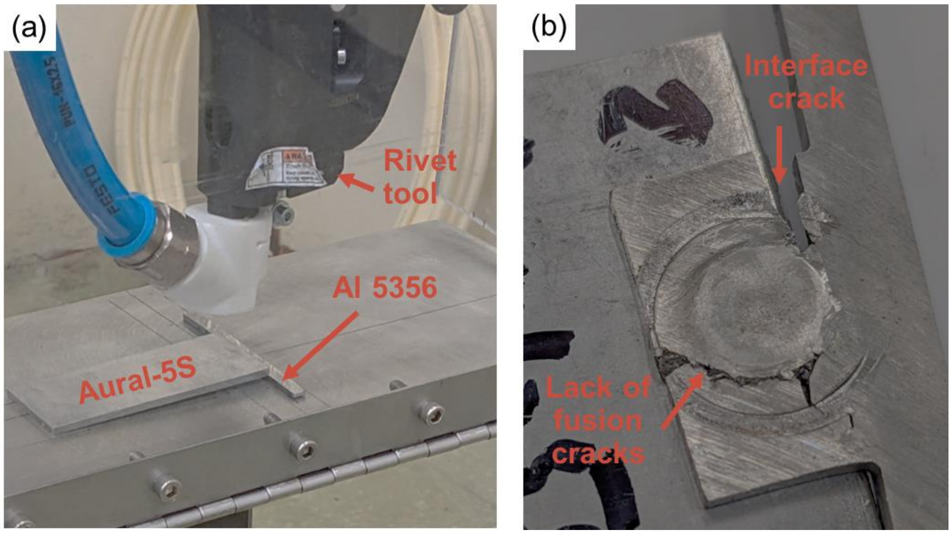

Figure 8. (a) Experimental setup showing 5356 rivet tab on the anvil with the high-pressure die cast Aural-5 alloy above it. (b) Photograph of the bottom of the rivet through the rivet tab with several cracks annotated.

4. DISCUSSION

During processing of the additively manufactured features on the cast substrates, the largest barrier to implementation in an industrial setting is the ability to obtain defect free parts due to oxygen contamination during DED wire processing of aluminum. This was somewhat surprising due to previous work that had deposited aluminum alloy 4043, an Al-Si alloy, using the laser hot-wire process on a different system that had resulted in a well-bonded part with low porosity [11]. This was mostly likely related to differences in the deposition head configuration for the system used during the initial tests and the system used for the bulk of this project. While the oxygen content in the melt pool is an issue for process repeatability, future work focused on improving the shielding gas flow would allow for the noted defects to be removed.

Despite the defects in the rivet tabs resulting from the inadequate shielding gas, the tensile properties of the deposited materials, especially the aluminum alloy 5356, are promising for localized property modification for joining. The ductility of the 5356 alloy was approximately three times higher than values for ductility of Aural-5S in the literature, meaning that the deposited material would be more receptive to self-piercing rivets or stir rivets.

While there are still some engineering challenges to overcome, we also consider if there would be any impact to the recyclability of parts due to the addition of material through the Cast-and-Print process. To analyze how deposition of material may affect the recyclability of a car body, we must assume a composition of aluminum alloys in a generic modern car body. Using standard alloy compositions [12], the generic car was assumed to contain 80 kg of 6111, 160 kg of 6061, and 30 kg of A356. A target usage of the recycling stream must also be assumed, so in this case it was assumed that the recycled scrap would be feedstock for A356 aluminum alloy manufacturing. Figure 9 shows that a mixed aluminum scrap recycling stream is already out of specification for direct processing into A356 due to an increased Mg content from 6xxx series alloys. In the case where the Cast-and-Print process is used extensively and 1-10 kg of Al 5356 is added onto existing cast parts, the effect on recyclability of the mixed scrap stream is minimal.

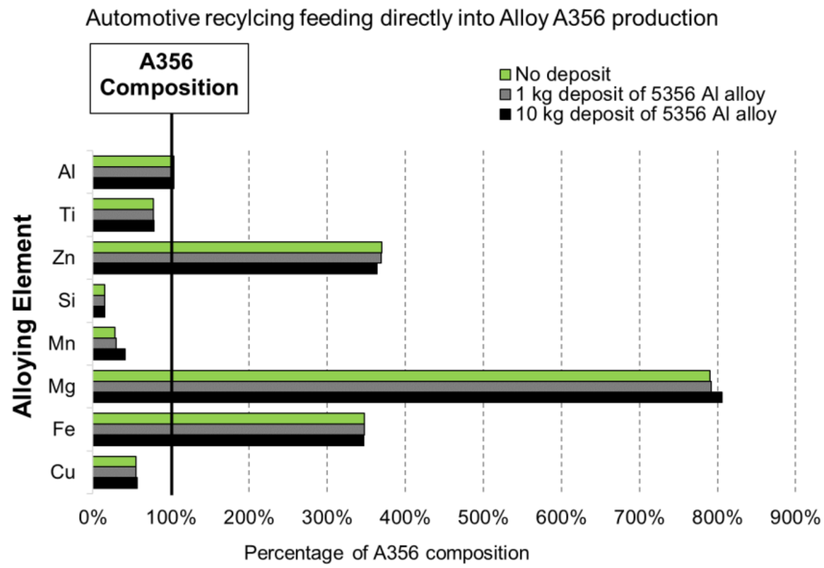

Figure 9. Recycling stream impact analysis of added aluminum alloy 5356 to an alloy A356 recycling stream.

Overall, the Cast-and-Print process still requires process development to demonstrate the repeatability of the process when processing aluminum alloy before it can be adapted to a commercial environment. The observed defects were associated with oxygen contamination of the melt pool during processing, but in cases with minimal contamination the tensile properties of commercially available wire feedstock demonstrated a good combination of tensile strength and good ductility. The availability of feedstock and ability to finish part features with the hybrid manufacturing aspect of the demonstrated laser hot-wire system support that such as process could have a low energy barrier for implementation.

5. ACKNOWLEDGMENTS

This manuscript has been authored by UT-Battelle, LLC under Contract No. DE-AC05-00OR22725 with the U.S. Department of Energy. The Lightweight Metals Core Program was supported by the DOE Vehicle Technologies Office and performed work at the ORNL Manufacturing Demonstration Facility supported by the DOE Office of Energy Efficiency and Renewable Energy Advanced Manufacturing Offices. Yong Chae Lim assisted with the friction-self piercing rivet experiment. The authors also acknowledge the cooperation and support of the Mazak Corporation and Lincoln Electric, as well as Ford Motors for supplying high pressure die cast plates.

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