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Investigation of Form-and-Print processing of wrought aluminum alloys for industrial applications

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INVESTIGATION OF FORM-AND-PRINT PROCESSING OF WROUGHT ALUMINUM ALLOYS FOR INDUSTRIAL APPLICATIONS

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ABSTRACT

Conventional manufacturing of wrought aluminum alloys generally involves rolling and forming of sheets of aluminum into the finished product. While these processes rapidly produce parts, produced parts are inherently limited to uniform thicknesses, specific geometries, and homogeneous material properties. Localized processing of formed parts could help overcome some of the geometric limitations imposed by forming, as well as allow for the possibility for localized property variation. Here, we present results from studies on the "Form-and-Print" process that uses additive manufacturing to locally deposit material where it is needed. In the context of these results, we discuss its viability for industrial applications and the key challenges facing the technology.

1. INTRODUCTION

Additive manufacturing (AM) is a manufacturing method that builds up material layer-by-layer to produce a near-net shape part. Aside from the AM machine, generally no additional tooling is needed to produce complex and varied geometries due to the layer-by-layer production. Therefore, AM is well suited to producing small runs of complex parts. However, there is a challenge in scaling AM to high-volume production, such as automotive manufacturing, due to the relatively low throughput rate of AM compared to conventional manufacturing processes such sheet forming operations. To alleviate the issue with low throughput for the creation of an entire part, in this report, we will discuss the targeted use of directed energy deposition (DED) AM to create functional, localized modifications to wrought aluminum products.

Creating features that enable different types of joining methods and features that improve the local properties of the sheet are two of the major applications for modifying aluminum sheet. In the first case, adding a dissimilar material at the area of a joint may ease the joining of the aluminum plate to a part made of a different material, such as a structural steel member [1]. In the second case, adding additional material or geometric features can increase the local stiffness of a sheet panel. Increased stiffness can be useful in a variety of circumstances, such as for increasing dent resistance of automotive body panels [2] [3] and improving the acoustic properties of panels to reduce road noise in vehicles [4, 5].

The use of additive manufacturing to create these features offers design flexibility, however, it also comes with a challenge of managing heat input during the process. Depositing metal in a fusion-based process requires high heat input, which can lead to heterogeneous microstructures in the fusion zone and heat affected zone [6-9], which can affect deformation behavior [6, 8, 10]. The size of such a heat affected zone is dependent on the heat put into the system and how fast it accumulates in the substrate. Heat accumulation is especially a concern if using high deposition rates to minimize manufacturing time, because high power is required to melt a higher volume of material. Therefore, the effect of any heat affected zone in the sheet needs to be assessed when using a fusion-based process to deposit material.

The remainder of this report will discuss the characterization of the material at the interface of the deposited material and the 6xxx series sheet substrates and several examples of modifications of sheet materials.

2. METHODS

The additive manufacturing system used for this work was the Mazak VTC-800G, a hybrid manufacturing system containing a laser hot-wire DED deposition head with an interchangeable multi-axis machine tool head. The laser hot-wire process uses Joule heating to heat a wire combined with a laser to create a melt pool on the surface of the material and to finish melting the wire. The heated wire can theoretically minimize the energy required by the laser to melt the material and reduce the size of the heat affected zone in the substrate. Additionally, the machine tool head enables surface finishing, which could be required for production parts.

The feedstock wire alloys used for deposition were chosen based on commercial availability and assessed compatibility with 6xxx series aluminum substrates. A thermodynamic assessment of the hot cracking criteria proposed by Kou et al. [11] was calculated for various combinations of commercial alloys and 6xxx series alloys using the model detailed in Kannan et al. [12]. As a result, three wire compositions were chosen for investigation—4043 (hypoeutectic Al-Si), 4047 (near-eutectic Al-Si), and 5356 (Al-Mg). The compositions of the alloys are provided in Table 1.

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
Al 6111	Remainder	0.7–1.1	0.5–1	0.4	-	0.1	0.15–0.45	0.15	0.1

In a recent investigation, the mechanical properties were characterized for substrate-deposit and interlayer interfaces in multi-pass, multi-layer deposits on bulk substrates [13]. It was found that the deposited material, having not undergone any cold work or aging, was expectedly weaker than the wrought 6061 bar used as a substrate. Additionally, the interlayer interfaces created during multilayer deposition of ally 4043 had localized deformation during tensile testing, which is generally undesirable for mechanical performance. To build on that previous work, the present investigation focused largely on single pass depositions, which are faster to deposit and add less weight and heat to the substrate. In all cases shown here, the samples were clamped to a flat steel fixture on the worktable within the system. Characterization of deposited material was done using optical microscopy of samples that were mounted, ground, and polished down to a final polish using 1 micron colloidal silica suspension. And Vickers microhardness indentation testing was used to assess spatial variability in material properties.

3. PROPERTIES AT THE LOCALLY MODIFIED INTERFACE

When depositing material on top of already processed wrought alloys via laser hot-wire AM, the added heat during deposition has the potential to create a heat-affected zone (HAZ) in the wrought substrate material. Additionally, when depositing dissimilar material on top of wrought material, the diluted region that is a mixture of the wrought and deposited material could have deleterious properties, despite efforts to avoid this possibility during wire material selection. To that end, this section discusses the process parameter development for single pass deposits on 2-mm thick 6111 aluminum alloy plates and the characterization of the locally modified interface using hardness testing.

To determine the appropriate processing parameters for deposition of wire on the 2-mm thick sheets, testing of single pass deposition quality was done for a wide range of processing parameters. Deposition was done on sheets that were sandblasted or roughened with a wire brush to improve laser absorption compared to the as-milled surface of the sheet. As shown in Figure 1, many defects were visually distinct, so visual inspection of the deposit served as a useful tool for making a pass/fail determination for a parameter set. After process parameter development, the best parameter set for all three feedstock alloys (4043, 4047, and 5356) was found to be 190 mm/min wire feed during burn-in, 1250 W laser power, 20 L/min for both nozzle and shielding gas, 130 mm/min wire feed speed during processing, and no power to the hot wire. Samples of each wire composition were made using that process parameter set for characterization.

Figure 1. Process parameter development of single passes on a 6" x 6" 6111 plate. Several different kinds of failed parameter tests are observed: #81 shows incomplete melting of the wire, #83 shows significant over-melting of the substrate, #88 shows partial melting of the wire, and #90 shows a relatively good deposit with only some over-melting at the beginning of the pass.

The manufactured samples were sectioned perpendicular to the deposition direction and imaged using optical microscopy. Vickers microhardness was measured using indentation with a 300g load. The resulting composite images of the optical microscopy with hardness data overlaid are shown Figure 2. The “tiles” observed in the composite micrographs are stitching artifacts, and the color of the diamonds corresponds to the hardness at that location. From the optical micrographs, it is clear that despite depositing the material with the same processing parameters, the degree at which the fusion zone penetrated into the 6111 plate varied significantly. For the 4043 alloy the fusion zone barely melted the plate, whereas the 5356 alloy fusion zone penetrated the entire thickness of the plate. Additionally, the variation in hardness of the deposited material was apparent, as expected, due to the different properties of the deposited material. However, despite the differences in the deposited material properties, there was no significant loss of hardness in the 6111 plate near the fusion zone. This supports that the heat affected zone was minimal for these processing conditions.

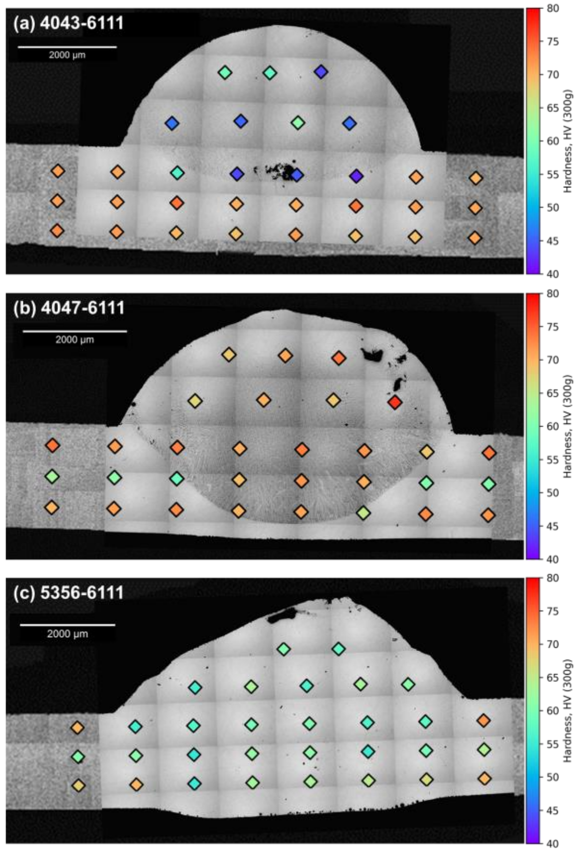

Figure 2. Hardness maps overlaid on optical micrographs of the transverse cross-section of single pass depositions of wire on 6111 sheets for various wire alloys: (a) 4043 wire, (b) 4047 wire, and (c) 5356 wire.

4. APPLICATION OF THE PROCESS TO INDUSTRIALLY RELEVANT PROBLEMS

With an understanding of the properties of single bead deposits, the deposition of single bead features was applied to problems related to increasing sheet bending stiffness and localized joining. The following subsections detail each application.

4.1 LOCAL MODIFICATION OF BENDING STIFFNESS

The local bending stiffness and bending toughness are determined both by the material properties and the bending moment of the geometry. Therefore, the local addition of a material with a similar or higher elastic modulus to the sheet material should increase the bending stiffness if there is a strong joint between the deposit material and the sheet.

From the single bead experiments, the 4047 aluminum wire had the highest hardness of the deposited materials, which generally corresponds to a higher elastic modulus. Therefore, samples were made with the 4047 wire on 6111 sheet, with each sample consisting of three parallel 50-mm long deposits. Samples were then subject to a three-point bending test with a load of 5 kN, a span of 35 mm, and a displacement rate of 1 mm/min. For comparison, the samples were compared with identically sized coupons of unmodified 6111 sheet. Three samples of each condition were tested.

The results of the bending tests are shown in Figure 3. Deformed specimens of the sheet with deposits and the unmodified sheet are shown side-by-side in Figure 3(a). Testing was ended after 8 mm of deformation, which is after plastic deformation began to occur, but before full fracture of the plate. While the 6111 plate did not have observable cracks, there was a visible crack in the 4047 deposits at the end of the test. Looking at the load-displacement curve from the tests shows that the added deposit provided additional stiffness. The load required for a 1 mm displacement being approximately 25% higher for the modified sheet compared to the unmodified sheet, and the load for a 2 mm displacement was approximately 50% higher in the modified sheet.

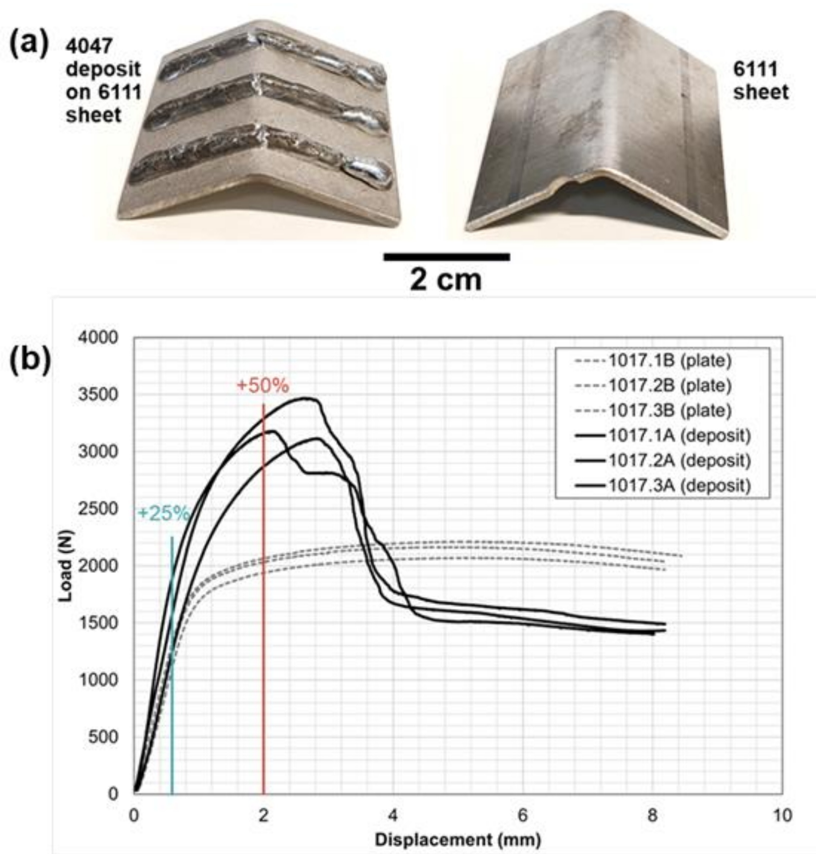

Figure 3. (a) Photographs of samples after bending test. (b) Load-displacement curve for locally-modified plate vs. the unmodified plate

4.2 HEM CLOSURE FOR INCREASED HEM STIFFNESS

In addition to locally modifying the stiffness of a metal sheet through the addition of geometric features, using a small amount of material to bond hemmed sheets could also reduce vibrations for external panels. In hemmed sheets, typically a polymer glue is used to close the gap to prevent corrosion and dampen vibrations, but a metallurgical bond between the two sheets could potentially reduce vibrations. However, as discussed in the previous section, using the laser hot-wire process to deposit material on 2-mm thick sheets required considerations for preventing melt through. Generally exterior automotive panels are even thinner, down to 1-mm thick, and have high requirements for surface finish on the exterior face. Therefore, the goal of this application was to demonstrate whether the Form-and-Print process can close hems without affecting the surface finish on the exterior face of a hem closure.

Like the process parameter development on the single pass deposits, poor process parameters were visually identifiable. Therefore, visual inspection was used to evaluate a series of process parameters to achieve reasonable deposit geometries of aluminum 4047 wire on the aluminum 6111 hem samples and avoid melt-throughs. Additionally, the machining capability of the hybrid manufacturing Mazak VTC-800G was used to provide a machine finish to the deposited material. Figure 4 shows pictures from several process parameter sets on different hems (also like the single passes, the surface condition significantly affected the laser-material coupling, e.g., an as-milled surface versus a pre-strained sheet surface). Notably, an inspection of the bottom surface of the hem showed that after deposition and machining of material there was no deformation of the outer surface.

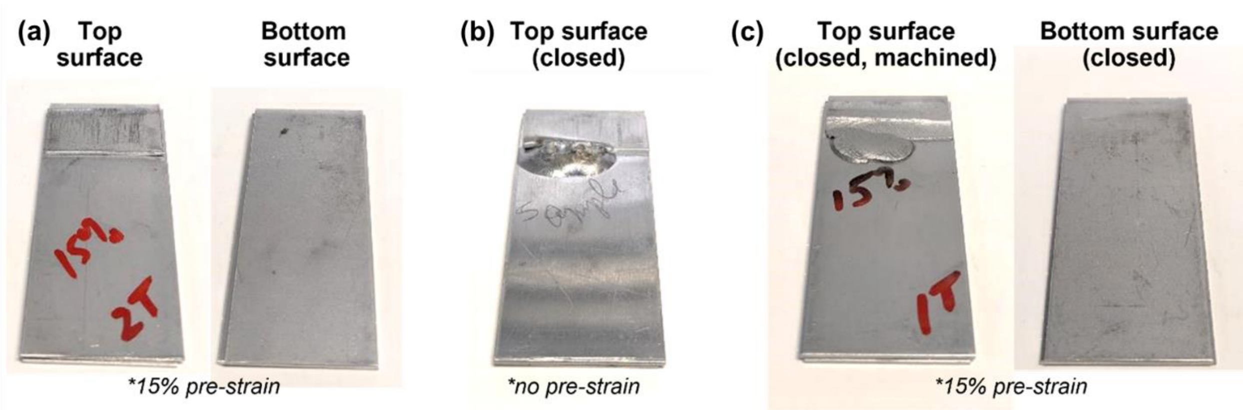

Figure 4. Photographs of hem closures showing (a) the as-received hem closures, (b) the as-deposited hem closure, (c) the top and bottom of the as-machined hem closure.

To investigate the interior of the fused material, cross-sections of the samples were prepared perpendicular to the hem and imaged using optical microscopy. Figure 5 shows an annotated optical micrograph of a closed and machined hem sample. The top part of the hem was fused to the inner sheet with the fusion zone penetrating through the entire inner sheet. An air gap remained between the inner sheet and the bottom part of the hem. Based on the lack of penetration of the fusion zone to the outer sheet, the air gap likely served as an insulating boundary that limited heating of the outer sheet from the heat flux of the laser on the top-surface. This effect is beneficial for preventing distortion of the outer sheet and supports the use of a laser joining system compared to other methods, such as electrical resistance spot welding, that would require disruption of the opposing surface.

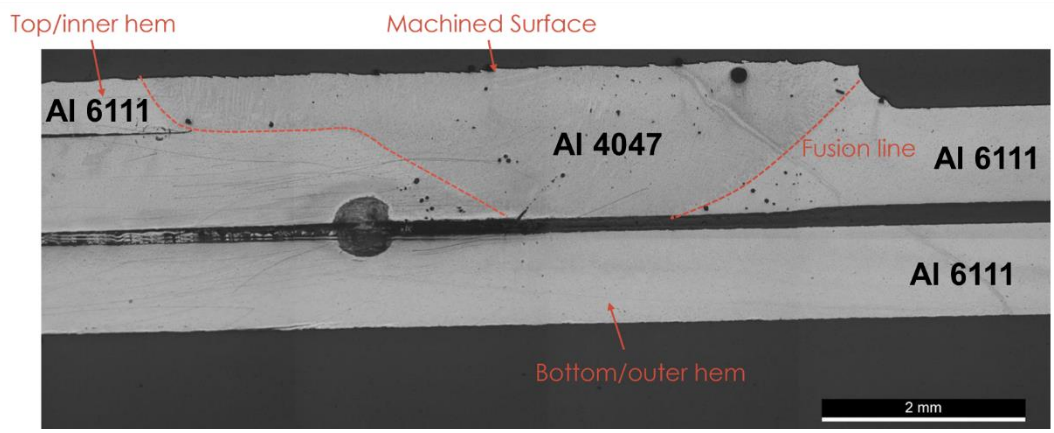

Figure 5. Optical micrograph of a machined hem closure with annotations.

4.3 LOCALIZED JOINING OF DISSIMILAR MATERIALS

While many joining processes exist, such as riveting, fusion welding and friction stir processing, the joining of dissimilar materials still has some challenges. Riveting is a common joining method for dissimilar materials, as it is a mechanically fastened joint and does not require metallurgical bonding between the two materials. However, riveting requires puncturing through the materials and can require post-processing to create a sealed surface. As demonstrated in the previous sections, optimized deposition via the laser hot-wire process can fuse material to 6xxx series aluminum sheet with small penetration depths and heat affected zones. Therefore, to investigate if the laser hot-wire process could be used to join dissimilar sheets, initial samples of similar 6111-to-6111 aluminum sheet joining were manufactured and characterized, followed by samples of 6111 aluminum joined to Stainless Steel 304 (SS304).

In both the similar and dissimilar joints, the deposition was done using a typical plug weld configuration. First, a countersunk through-hole was machined in the top-plate of the joint. Then the sheets were clamped in a fixture and 4047 aluminum wire was deposited into the hole to fuse to the bottom sheet and the walls of the hole. The surface of the plug was then machined near-flush to the surface of the sheet. Process parameter development was required to find parameters that created a bond to both the walls and the bottom sheet. The best parameters were found to be a laser power of 2500 W with the laser on for 5 seconds before the wire started depositing, so that the bonding surfaces were preheated enough to bond with the wire. Figure 6 shows a cross-section through the middle of one of the plug joints. The boundaries of the initial through-hole geometry are shown with red dotted lines. Notably, despite good filling of the countersunk region of the hole, the region near the bottom of the bore did not fill completely and crack initiated from the gaps. This type of defect could potentially be eliminated with additional investigation of process parameters and hole geometry. Additionally, gas porosity was seen within the deposited material (anecdotally, the gas porosity was noted in other experiments on the system at the time and it was determined that there were significant levels of oxygen at the weld surface despite the shielding gas).

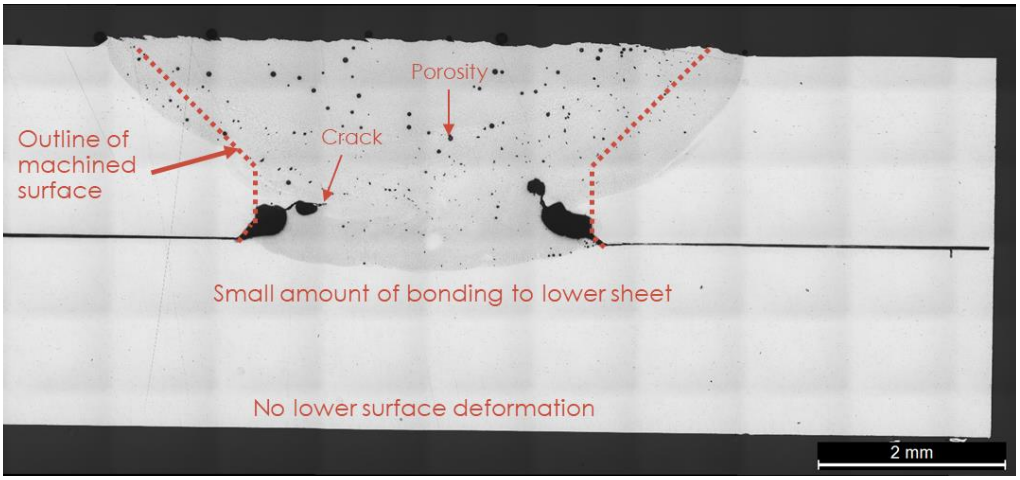

Figure 6. Al 4047 plug fill through hole in a 6111 aluminum plate to bond to a similar 6111 plate. Features are annotated in red text.

Process parameter development for joining of the dissimilar 6111 and SS304 plates using the process parameters for the similar material plug joint as a starting point. The joint geometry was similar to the 6111-to-6111 plate case, except the top plate was exchanged for a SS304 plate. Ultimately, the best found parameters had a reduction in the laser power and laser on-time before deposition to 2000 W and 4 seconds, respectively. Due to the relatively high melting point of the SS304 top-plate, higher laser powers ended up over-melting the aluminum wire and caused wire feeding issues. A photograph of the joints is shown in Figure 7(a) and an optical micrograph of the indicated section is shown in Figure 7(b). While the deposited 4047 aluminum bonded with the 6111 aluminum plate, the joint with the SS304 sheet was mechanical in nature. No melting of the SS304 alloy was observed and there was a clear gap between the deposited aluminum and SS304 plate.

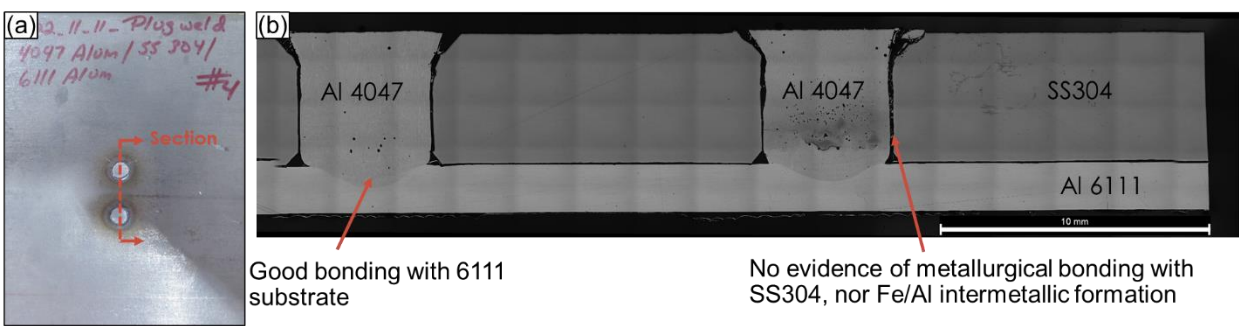

Figure 7. Al 4047 plug fill through stainless steel 304 plate to join to an Al 6111 plate. (a) Top-down view of sample. (b) Cross-section of plug fill showing only mechanical joining with no metallurgical bonding.

Though metallurgical bonding of the dissimilar materials was not achieved, the mechanical bond formed by essentially pinning the SS304 material to the 6111 aluminum plate has potential as a fastener. Notably, the outward face of the 6111 plate was not deformed by the deposition of the material, so this approach could potentially be used to join dissimilar materials to an outward facing aluminum sheet. Compared to riveting, the outward facing sheet would not have any deformation, though there would still be a disruption in the surface finish on the opposite side of the sheet. Analysis of the strength of such a joint would have to be assessed for application-dependent loading, because the diameter, depth, and countersink geometry of the plug hole would determine the performance under different loading conditions.

5. DISCUSSION

In the three demonstrations shown in Section 4, the deposition of material to provide local modification of properties or geometry was demonstrated. Sound metallurgical bonding between 6111 aluminum plate was shown to occur for multiple materials (aluminum wires 4043, 4047, and 5356) and process parameter development was able to avoid excessive melting in the substrate even for thin substrates.

Some challenges remain as barriers to implementing this process beyond a research setting. While the additive manufacturing process is inherently flexible, significant process parameter development had to occur for different combinations of material and geometries of the deposit and the substrate. A model-based or empirical database would be required for reducing the process parameter development time to fully take advantage of the flexibility of the process. Additionally, aluminum alloys are specifically challenging to manufacture via fusion-based processes due to the outcomes being sensitive to oxygen in the environment. Highly consistent control of oxygen content in the processing environment through the design of the shielding gas flow is necessary to achieve consistent results with minimal gas porosity.

A tangential, but relevant concern to the potential implementation of such as technique in a mass manufacturing setting, such as the automotive industry, is a change to the composition of the recycling stream. 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 [14], the generic car was assumed to contain 80 kg of 6111, 160 kg of 6061, and 30 kg of A356. Assuming that a mixed recycling stream (no separation of wrought and cast alloy components) was feeding into 6111 sheet production, the impact of adding the various wire alloys was assessed. Figure 8 shows the result of this analysis and it indicates that the impact of up to 10 kg of material is minimal compared to the effect of a mixed recycling stream. Of course, this analysis would change depending on the degree of sorting of autobody parts before recycling, but in most scenarios any added Si or Mg from small quantities of deposited alloys should be negligible compared to contributions from cast alloy components.

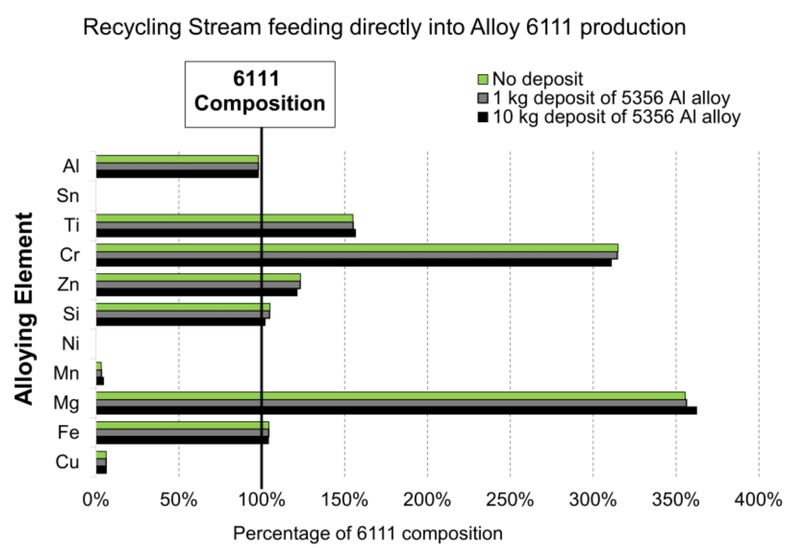

Figure 8. Recyclability analysis for 5356 aluminum wire deposits with the recycling stream feeding into 6111 aluminum sheet production.

Overall, this work demonstrated that the Form-and-Print process could be used to create features on millimeter-thick aluminum sheets with a minimal heat affected zone and little-to-no deformation on the opposite side of the sheet from the deposited feature. While further process development would be needed for application in a production environment, the presented results show that a hybrid system capable of both additive manufacturing and machining can be applied to a wide variety of applications.

6. ACKNOWLEDGEMETNS

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