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Program Overview: Extra-Large, Metal Additive Manufacturing System, Targeted Towards Army Ground Vehicle Systems

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ABSTRACT

The Applied Science and Technology Research Organization of America (ASTRO America), Ingersoll Machine Tool (Ingersoll), MELD Manufacturing (MELD), Siemens Digital Industries (Siemens), The American Lightweight Materials Manufacturing Innovation Institute (ALMII), and the US Army CCDC-GVSC have partnered to show the feasibility of fabricating very large metal parts using a combination of additive and subtractive manufacturing technologies. The Army seeks new manufacturing technology to support supply chain strategy objectives to replace costly inventories and reduce lead times. While additive manufacturing (AM) has demonstrated production of metallic parts for military applications, the scale of these demonstrations is much smaller than required for large vehicle components and/or complete vehicle hull structures. Leveraging AM for large scale applications requires enhancements in the size, speed, and precision of the current commercially available state-of-the-art equipment. This program requires new AM system capabilities that can address large scale metallic components and performance requirements to create joint-free hulls for tanks and automotive requirements, such as the next generation combat vehicles (NGCV). Under the program, two machine tools will be discussed for their use in the development and fabrication of prototype components that will be comparatively tested against conventionally built subsystems. This program's success will be measured by the AM system's capabilities to enable and produce innovative *performance enhancing part designs, the resulting parts' performance, as well as the time and cost required for part production. When considering very large scale (i.e. > 1m*^{3}*) metallic components, the full production life cycle has to be accounted for; namely heat treatment and dimensional machining present two obstacles for producing desired parts rapidly. In anticipation of these challenges, the novel system is being built around MELD's patented solid-state processing technology, which processes material at lower thermal histories. This paper will provide a general overview of the large scale system being developed, as well as some preliminary material analysis of aluminum alloys deposited from the MELD system. Future, development directions are also discussed at the conclusion.*

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1. INTRODUCTION

Underbody threats are an age old problem for Army (and military) ground vehicles. During the Vietnam War it was estimated that 73% of all vehicle losses were suffered because of anti-personnel and anti-tank mines [1]. While improvements to maneuverability and protection systems have improved and aided the warfighter to avoid such threats, being able to rapidly replenish vehicle underbody inventory with constantly changing needs is critical.

Former Army ManTech programs for underbody hulls have focused on more mature manufacturing technologies such as forging and forming for consolidated hull structures, and high-energy buried arc weld to minimize weld porosity [2]. Figure 1 shows a forged underbody hull component from a previous US Army ManTech program. The goal of these programs was to look at different fabrication methods to design underbody hulls of vehicles that were thicker and with fewer joints (i.e. welds). These modifications would improve the effectivity of the hull against underbody blast attacks. While successful in demonstrating the fabrication of an aluminum hull that could withstand simulated blast conditions, the methods implemented in previous programs lacked geometrical freedom where either new design concepts could be explored or be rapidly implemented for other vehicle platforms. Furthermore, these methods were not cost effective or adaptable to full production rates when considering design and size requirements of various vehicle systems within a NGCV program.

Figure 1. Joint-less demonstrator component produced from forging process for US Army RDECOM (now DEVCOM) ManTech Program.

Additive manufacturing (AM) technologies present new paradigms in material processing and fabrication flexibility that make it a compelling avenue for rapid production of underbody, joint-less hulls, while expanding design spaces. An additive manufacturing method can be generally described as a freeform fabrication system that forms a component by digitally controlling a processing apparatus to combine feedstock material without the aid tooling such as molds, stamps, or dies. This opposed to subtractive manufacturing methods that starts with a bulk of material and removes it into a desired shape to form either the final component, tooling to form the desired shape (i.e. molding), or form various components to be joined into an assembly [3].

The processing of large, metallic components (e.g. hull for armored vehicle) through an additive manufacturing process is still in its infancy. Large area additive manufacturing (AM) systems (>1m^3) have been demonstrated in recent years; most prominently for processing polymeric materials. While limited for Army vehicle applications, these systems have shown they can readily produce large scale tooling and even vehicle frames for prototyping applications.

Large scale metal AM systems have been demonstrated but to a lesser extent. Commercially available systems typically limit their processing volumes to around 1 x 1 x 1 meters; depending on the technology. While useful for many applications, the intent of the work laid out in this paper is to demonstrate a novel system and approach for expanding the print volume of a large scale metal AM system than what has been demonstrated.

2. PROGRAM OVERVIEW

In collaboration between ASTRO America, ALMII, and US Army CCDC-GVSC has formed a sponsored program to produce a large scale, metal AM system at the US Army's Rock Island Arsenal that is capable of realizing functional structures (i.e. underbody hulls) within the size range of common Army ground vehicles. The overall vision of the program is to combine large format fabrication machine tools and software, already implemented within industrial environments and combine that with a metal AM processing technology. Being that the system would be novel because of its size and performance requirements, a portion of the program is to study the fundamental material properties of the material processing to then inform and automate the digital process planning.

During the scope of the program, two systems will be constructed. The first, is a sub-scale system that is meant to process within an envelope of 1 x 1 x 1 meters. The intent of this system is to demonstrate the capability of the system and to act a test bed for materials development and process studies. The second system is intended to produce full scale parts, targeting a processing envelope of 10 x 6 x 3 meters (length x width x height). Figure 2 shows a three-dimensional rendering of the final, full scale system that will be produced at the end of this program. To date, the system would be the largest metal AM system that has been publicly released.

Within the scope of the program is to characterize and develop the process for producing targeted component (e.g. joint-less underbody hulls). This not only means characterizing the material specification and performance of the final part but also achieving geometric dimensions within a given tolerance. Therefore, it is intended for the system to also have subtractive manufacturing capabilities to that would assist in achieving the targeted geometrical tolerances.

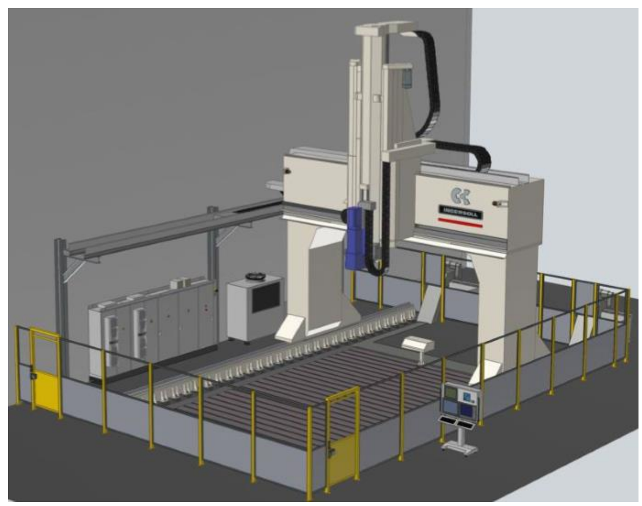

Figure 2. 3D rendering of the proposed large scale, metal additive manufacturing system.

2.1. Team Overview

The team selected to design, construct, and develop this is a three-part team consisting of a system integrator, industrial software developer, and metal AM process developer. Ultimately, to realize a large scale, metal AM system there will be multiple areas of expertise needed to bring a system like this together. Here are profiles of the vendors who are collaborating on the large scale, metal printer program:

Ingersoll (Rockford, IL)
Machine tool builder that has extensive experience in building robotics systems for the composites processing in the aerospace industry (i.e. "extra-large" components). They use off the shelf (namely Siemens), components and software but gantry systems and do system integration. The have recently adapted products for printing large scale (23' long) composites tooling [4].

Siemens
The Siemens team selected to participate in this program focuses on multi-axis, CNC based applications and process simulations, therein. The intent is for the large scale AM system to utilize commercially available software products and begin building process planning routines that are unique to the system.

MELD (Christiansburg, VA)
A developer of additive friction stir manufacturing cells. Their patented processing technology, processes feedstock material (i.e. rod or powder) in a solid state process that relies on interfacial heating and severe plastic deformation to deposit the material onto a build plate [5].

3. LARGE SCALE METAL AM

There are several AM technologies that can process metallic materials, but only a few of them can be reasonably scaled up to produce components within the scope of this program. In general, the configuration for a large scale AM system is one where a processing head is mounted on an agnostic, traversing gantry. This set up is most conducive to handling large, (heavy) metallic components, and also allows for flexible manipulation of manufacturing methods; in this case, the addition of a subtractive method.

Handling of the feedstock for the process is another major consideration. The ubiquitous metal AM methods employ metallic powders as their feedstock. While, directed (i.e. "blown") powder systems have been shown to scale up, powder bed systems have not. Though still in development, powder bed AM systems trade off speed and deposition rates for geometrical resolution. However, small particulates from the residual processing gases, as well as within the powder bed itself, are found to be hazardous and only get exaggerated at larger scales.

Ultimately, only a directly fed AM modality can fulfill the size requirements of this program's scope. Table 1 summarizes all the different AM modalities considered for this program.

Process		Description	Feedstock
	MIG/TIG Welding	Similar to conventional welding, wire fed process that melts wire via electric arc shielded by an inert gas	Wire
	Cold Spray	Solid state process that recombines material by accelerating metallic particles through high velocity gas flow.	Powder
	Laser Welding	Process that delivers metallic particulates through gas flow and recombines (i.e. melts) them with focused, radiated energy (i.e. laser)	Powder
	E-Beam Welding	Wire fed process that has to be processed in vacuum chamber because directed energy is provided by focused electron beam.	Wire
	Friction Stir Welding	Rotating head that uses mechanical energy through friction to recombine metal rod.	Metal Rod

Table 1. List of different metal AM processing modalities considered for this program.

3.1. Challenges at Large Scales

The recombination process is central to any AM process. Whether depositions or laser fused or photo-polymerized, the ability to recombine material with itself in a layered fashion is what distinguishes additive methods from subtractive. In the case of metal, it is usually required to heat the material beyond its melting temperature to recombine (or combine in the case of deposition). With careful control of the energy imparted onto the material during the process, it is possible to accurately (with lasers or electron beams) or quickly (with wire welded or directed energy) consolidate material.

The process of liquid to solid recombining, however, can be a problem on the large scale. When fabricating large parts, issues with thermal residuals stresses cause issues with maintaining geometrical tolerances during and after a build is completed. These distortions caused by the rapid melting and solidification of the material are typical of these processes. In large scale parts, this issue is exacerbated because of the processing envelope size and amount of energy input during fabrication. In addition, due to these internal stresses and porosity generation from trapped gasses there are expensive post processing needs. Hot isostatic pressing is often used to relieve stresses and close pores, but it is extremely costly and size limited.

In consideration of in-process stresses, lower temperature AM methods is the focus of this system's development. Namely, the unique solution offered by MELD Manufacturing was the most promising to fulfill the size and material performance requirements for this program. Nycz et. al. [6] summarizes other considerations for large scale, metal AM system, all valid within the scope of this program.

3.2. Additive Friction Stir Deposition

As previously stated, the additive friction stir deposition (AFSD) process is central to the development of this large-scale system. The technique consists of a hollow, rotating shoulder in which material is fed through and deposited onto a substrate. The rotation and pressure from the tool head onto the feedstock produces interfacial heating and plastically deforms the material onto a substrate or subsequent layer. Figure 3 depicts the additive friction stir deposition process [5].

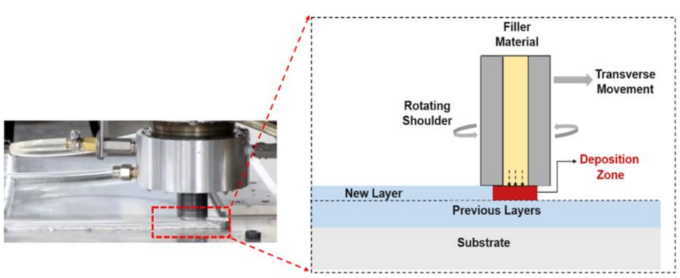

Figure 3. Depiction of an Add. Friction Stir Deposition head **[5]**.

Similar to other deposition based AM techniques, the deposition head is traversed throughout the processing envelope, laying down a single track of material on the order of ~0.5 mm thick. Throughout the process, the material is maintained below its melting temperature, this minimizes the thermal gradients and residual stresses. Specifically, these temperatures can range from 60 % - 90% of the material melt temperature [5]. This not only makes it amenable to processing without cracking from residual stress, but can reduce (or prevent) the formation of voids (i.e. porosity) which is common in most liquid to solid AM processes.

Furthermore, it has been reported that AFSD produces a fine equiaxed grain structure, as opposed to wrought or cast components which exhibit larger directionally solidified grains. In summary, the processing mechanism has been shown to produce a refined grain structure as reported by Perry et. al. [7].

3.3. Scaling with Add. Friction Stir

The lower operating temperature of the AFSD process has highlighted some advantages over more traditional manufacturing methods and other large scale AM systems. First, because the system can process material at temperatures below the material's melting temperature, the system itself does not require a specialized chamber (i.e. vacuum chamber, advanced air handling). Parts can therefore be manfacturered in open, warehouse type environments; reconfigured as needed for given application. This reconfigurability is what makes AFSD particularly attractive for large scale vehicle components because less time for production preparation is needed for a given component.

The second important advantage, is that the lower processing temperatures allow for there to be less residual stresses due to temeprature gradient present during the fabrication process. Other large scale AM process require material to melt then solidify with subsequent layers to form components. Handling these stresses usually slows an AM process because the temperature gradient across the component has to be managed such that the stress do not form and begin to distort or even fracture a component during building.

MELD manufacturing (Christiansburg, VA) has already demonstrated several uses of AFSD at large scales in open air evironments. Figure 4 shows a large, metallic component already produced by MELD manufacturing in an open evirionment.

Figure 4. Example of large scale component printing (top) and end result (bottom) **[8]**.

4. INITIAL PRINT RESULTS

Current development of production level systems for the AFSD program will begin in June of 2021. In the meantime, characterization of the deposited material has already begun. This section will present some initial results from early production trials of a comparable AFSD processing head using Al-6061-T6 as the feedstock material.

4.1. Sample Preparation

A 5cm tall test wall was built using the continuous feed process at the MELD manufacturing facility. The temperature of the tool head was maintained at 420 ºC during the build process. Once deposited a sample from the wall was sectioned off for imaging analysis. The samples were mounted and polished to 0.05 µm and imaged in the unetched and etched condition.

The sample was cross sectioned transverse to the print direction, as depicted in Figure 5. From this samples, a section at the center of the print was removed, then mounted, polished, and etched as outlined in section 4.2.

4.2. Sample characterization

The unetched samples were imaged on an SEM FEI Quantra 600 FEG in the Nanoscale Characterization and Fabrication Laboratory (NCFL) at Virginia Tech. The same sample was then etched with Keller's reagent and then imaged on a Keyence VHX-7000 digital microscope. Figure 5, shows a macro image of the etched sample of the deposited material. Both images were taken from the center of the build and are meant to be representative of the whole. Figure 6 shows the deposited material in the unetched condition and its corresponding elemental map of the deposited material from BSE imaging. These images were taken from an area at the center of the polished SEM image.

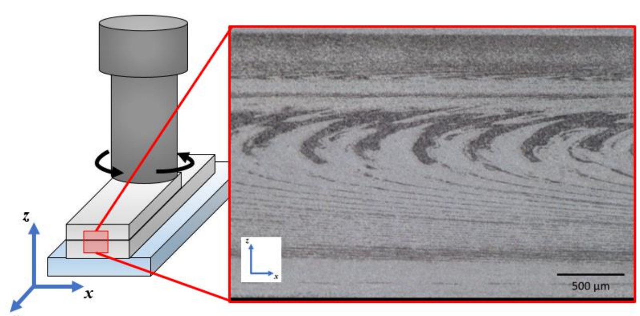

Figure 5. The flow lines of the deposited material after a Keller's etch at 50x, as well as the print orientation of the sample

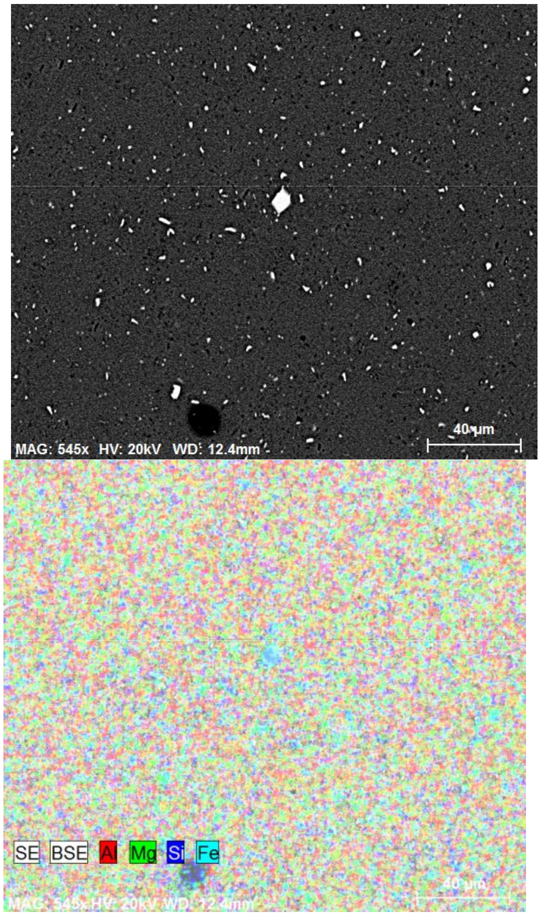

Figure 6. The MELD material in the unetched condition (top) and the elemental map (bottom).

4.3. Results

From the SEM images and elemental map, we can see that the iron particles in the microstructure are rounded off and evenly dispersed. The predominate elements in the deposited material are Mg, Si, and Fe which is expected for an Al-6061 alloy. In addition, in the microscopy image the flow lines are similar to those from friction stir welding processes. Due to the inherent stirring nature of the MELD process the material deposited is very homogenous and dense [9].

Future work will be on the characterization of the material deposited by the MELD process. Focus will be given to the performance of the interfaces in of a MELD build in quasi-static and high strain rate mechanical testing. The purpose of this testing is to create a baseline understanding of the MELD materials performance with large scale applications in mind.

5. CONCLUSION

The program outlined in this paper describes the motivation and approach to produce an AM system that can produce metallic components for large scale vehicle components. The emphasis is to realize a system that can rapidly fabricate large metallic structures with a tool-less process. After considering drawbacks and limitations of other large scale metal AM processes, it was determined that non-melt processes were best to extend to the intended program scales because it would minimize the amount of residual stresses that would arise in the component during production. Within the scope of the program, as the full scale system is being produced, materials sample will be tested and analyzed to optimize the system’s processing conditions and characterize end use properties. Ultimately the focus will be on producing a flexible manufacturing cell that extends the design capability for light-weighting Army ground vehicles, while maintaining performance requirements.

6. REFERENCES

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