TOWARDS POINT-OF-NEED MANUFACTURING TO REPLACE FAILED COMPONENTS ON THE BATTLEFIELD

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Abstract

The DoD is intrigued with "point of need" manufacturing as a means of being able to produce parts "on-demand" in extreme environments such as on a forward operating base, or on a ship, to increase our operational readiness, and reduce our huge military logistics tail. Additionally, research is being performed to determine whether recycled, reclaimed and/or indigenous materials can be utilized as feedstock for these components. However, there are technical challenges that need to be overcome to fully achieve this capability in the future. One such challenge is part quality, and whether such parts can provide a true replacement for military components.

Introduction

The vision for "point of need" manufacturing is to be able to replace or repair failed components at or near the theater of operations. The point of need could be the battlefield itself, a contingency base, or a reach-back CONUS facility. Readiness is a key concept for the military, and having this capability will not only improve operational readiness and materiel availability, it will provide critical repair parts with reduced resupply transportation, as well as responsiveness and flexibility, management of demand uncertainty and reduction in required inventory [1,2,3]. "Manufacturing" in the context of this paper is referring to additive manufacturing (AM) in most cases, although traditional manufacturing (i.e. metal casting, etc.) could be performed on the battlefield with enough resources. AM for the lay person is simply referring to a set of manufacturing processes that build a part "additively" in layers, versus the traditional means of manufacturing, which "subtractively" machines a part from bulk material.

Point-of-Need Manufacturing

The Army has been using 3D-printers in forward deployed areas in Afghanistan since 2012 [4]. These machines have made various plastic value-added components. In general, the US military is interested in the premise of AM for point-of-use manufacturing (the ability to produce spare parts, in the field, for immediate repair to support a mission) [5,6,7]. As

Dr. Thomas Russell, former Director of the US Army Research Laboratory, points out with respect to having the capability of having AM capabilities in-theater [8], "Logistically there are benefits. One of our biggest challenges in the Army is that there is a huge logistics burden. If we could forward-deploy manufacturing capabilities, we would have the opportunity to manufacture parts in-theater, or repair parts. This is not just about manufacturing a new part, it's often about how we can repair something that has been damaged. We have the opportunity to do that in-theater and use local materials. It's an exciting area. I don't think we've realized its full potential." Military officials see a lot of potential for on-demand 3D-printing on the battlefield. And while there's still a lot to be hashed out, commanders and decision-makers want to get it into the hands of troops sooner rather than later [9]. This new way of thinking will have ripple effects on the traditional military manufacturing supply chain and the resultant reduction in the logistics footprint.

Supply Chain

It is no secret that the time to resupply spare parts to the tip of the spear on the battlefield can be onerous. A 2008 GAO report indicates that managing spare parts for military weapon systems is a complicated, time-consuming and expensive task involving large inventories [10]. Spare parts are indeed important to keep weapon systems operational, but it can be difficult to assess which spare parts to bring to the battlefield. Which parts are likely to fail? How many should be carried in? One reference indicates that it can take weeks to get certain spare parts to the weapon system in-theater [11]. With the capability of making or repairing parts in-theater, this timeframe could be drastically reduced, perhaps to a day or two [4,12]. The making of spare parts through AM at the point-of-need is enticing, and these parts could be prime candidates for 3D-printing, especially if they have become obsolete or have long lead times, or are backordered due to diminishing sources and/or contractors not bidding on their production [13,14]. Whether it be the ability to additively manufacture on the battlefield, or on a ship, point-of-need manufacturing could provide the warfighter with parts that are good enough for the next mission, while the original part is ordered through the traditional channels. Or in other words, this technology, at first (until culture dictates acceptance, and safety critical parts are certified and qualified in-situ), may not replace existing supply chains, it may augment existing capabilities [13,15].

Logistics Footprint

It is often said that additive manufacturing is a "disruptive" technology, as it offers many advantages over traditional manufacturing. Although the technology for AM with metal powders is not mature enough for the battlefield as of yet, one can envision how it could dramatically reshape sustainment, improve system availability and affordability through reduced cost and logistics footprint associated with distribution, stowage and management of spare part inventories [16]. This streamlined process would go a long way in improving operational readiness, as weapons systems would not be idle for long, as a result of failed long-lead time or obsolete parts.

Challenges

Many challenges are currently restricting metal AM use in place of traditional manufacturing, never mind the challenges associated with battlefield manufacturing. These challenges include part certification and qualification (process control), legal concerns (intellectual property (IP) issues), security concerns (data storage and cyber threats), materials development, build volume limitations, lack of standards, AM workforce development [2,3,7,16]. When it comes to using this equipment on a battlefield, there are also issues of the surrounding environment (shock, vibration, sand, dust, temperature, and humidity, etc.), as well as the equipment footprint, power consumption, and part post-processing needs, etc. The two very important challenges of certification/qualification and intellectual property are discussed below.

AM Certification / Qualification

It is anticipated that AM on the battlefield will initially be used in a maintenance capacity for the repair of parts. As the technology matures, it is foreseen that spare parts may subsequently be produced. It is the author's belief that if and when this does occur, parts that are manufactured will only be required to be "good enough" to get the materiel back up and running and into the next battle, while simultaneously, the original equipment manufacturer (OEM) spare part would be ordered through the traditional supply chain. This "Band-Aid" approach would meet mission needs, and provide a strategic and tactical advantage on the battlefield. This may be the most logical route, since currently, no guidelines, neither documented procedures nor certification standards, exist on the approach for qualification of aeronautical parts manufactured through AM route [17]. It is anticipated that the inherent differences in AM compared to traditional manufacturing techniques will likely necessitate modifications to standard validation, verification and certification procedures [11], if safety critical parts were to be produced in-theater. This idea of temporary replacement could negate the need for qualification/certification [18], especially for non-critical parts.

Intellectual Property Concerns

Prior to the manufacturing of parts on the battlefield, decisions will need to be made regarding whether intellectual property rights (for example, patents, copyrights and perhaps trademarks) exist for those parts. Ignoring established protections could expose DoD organizations to the risk of litigation, and possibly jeopardize their relationships with defense industry partners [7]. According to [7], reverse engineering of a failed part in order to generate a CAD file would not be protected, but could be a patent infringement. However, it is imagined that in an emergency on a legacy systems, where the OEM is no longer in business, this may not be a problem (unless ownership of the part has transferred to another company) [3]. If the Government owns the technical data packages (TDPs) of these parts, it would not be an issue, but in most cases, these TDPs are cost prohibitive and ownership falls to the OEM. Liability of a failed AM part in service, that was fabricated on the battlefield, and nullified warranties of the weapon system it was emplaced, are also concerns, but beyond the scope of this paper.

Current Research

The goal of current research in this area by the US Army Research Laboratory (ARL) is technology development for point-of-need manufacturing, incorporating the use of indigenous, recycled, reclaimed and/or scrap resources for in-theatre additive or traditional manufacturing, to provide functional products of use to the warfighter. This paper will briefly describe research being performed by ARL in the following areas: the production of (AM) grade metal powder in a shipping container (intended to supply an operating base with feedstock for future metal AM operations at the point of need), and the utilization of indigenous desert sand for 3D-printed casting molds.

Use of Indigenous Materials on the Battlefield

Historically, the warfighter has used indigenous materials on the battlefield; from sticks and earth to form gabions and fascines, to sand and rock for sandbags, expeditionary earth-filled protective-barriers and Hesco-barriers. According to MIL-PRF-32277 [9], this latter family of earth-filled barriers is intended to provide protection from visual detection, small arms fire, indirect fire, and perimeter intrusion. It should be noted that all of these products are more utilitarian in nature, rather than technological innovations.

Metal Casting of Recycled Aluminum

Traditional casting has been in existence since at least 3,200 BC, and the earliest known sand casting dates back to 645 BC [19]. Research is being conducted to show a proof of concept of being able to cast parts on the battlefield with indigenous sand, and recycled and reclaimed scrap materials. This work focused on recycled soda cans, although there is not very much aluminum in them. It was found that salt fluxing was needed to help remove oxides and dross during the melting process. Sand found local to Montana Tech, Butte, Montana was screened to -50 mesh, and a non-dairy creamer was added as a binder, at approximately 2-3% by mass. The creamer used is the same as found in Meals-Ready-to-Eat (MRE) bags found on the battlefield. These dry components were mixed thoroughly. Subsequently, water was mixed a little at a time until the sand reached a relatively stable and compactable consistency. Since the amount of water needed seemed to vary, this is one area where further research and experimentation may be needed to provide the optimal mixture. Next, the part that will be cast is placed on a plastic plate within a mold frame (see Figure 1), and the casting sand is packed into the frame. For this experiment, a round section of tube approximately 2-inches in height was used. A mold release was used to keep sand from sticking to the part as it was packed into the ring firmly, and in multiple layers. Sand was leveled off at the top. The mold was then flipped, and the part removed carefully (see Figure 2), so as not to damage the imprint of the wrench. It was found that the non-dairy creamer mixture was much less stable as a binder than other mixtures, so this may also be an area for further exploration. Once this was completed, the recycled cans were melted in a Lindberg/Blue M Model 1100 box furnace (1.8kW) electric furnace at approximately 850°C. The furnace used was a traditional tabletop variety. A higher temperature was found to facilitate easier pouring and rapid melting. The melted aluminum was poured into the mold and allowed to cool (See Figure 3). Because oxide formation is so rapid, the aluminum flow was viscous and difficult to control in an open mold. Once cooled, the part was removed and allowed to finish cooling. It was found that the burned sand was non-reusable, but preliminary work with Bentonite clay showed this material could be reused. The cast wrench was subjected to milling and filing (tools available on the battlefield), with before and after photos shown in Figures 4 and 5. Although there were imperfections in the tool, and it most likely would not be strong enough to hold up to high stresses, it showed what could be accomplished towards casting of functional items on the battlefield.



Figure 1 Materials used to produce a casting of a wrench.



Figure 2 Wrench is removed from sand mold.



Figure 3 Melted soda cans being poured into a sand mold.



Figure 4 Crude "wrench" cast from melted soda cans.



Figure 5 Milled and filed end of wrench made from melted soda cans.

Metal Casting of Reclaimed Brass Cartridges

In similar research, attention was focused on melting and casting spent brass cartridges knowing there will probably be much of this material on the battlefield. The brass was also melted in a Lindberg/Blue M Model 1100 box furnace (1.8kW) at 1100°C, and poured with no fluxing agent produced poor quality plates (see Figure 6). Samples that were cast with 7.5% by weight professional grade flux produced a viscous liquid metal upon melting that failed to fill the mold completely. This problem was likely the result of quick cooling due to the water in the sand cast mold as part of the binder. In an attempt to counter this, pouring from both ends of the mold was performed, but this also failed to yield a complete plate. It was determined that this problem could possibly be alleviated by taking advantage of gravity. An open top casting mold (as that shown in Figure 7) was built to improve liquid metal flow, and allow the resulting gas to escape the pour. The results of using this mold yielded a better plate, although it did have some imperfections (see Figure 8). It is anticipated that these brass plates could be used on the battlefield to produce functional items through subtractive manufacturing, either with a traditional CNC mill, or by employing an "Othermill" or similar such equipment. This unit can subtractively produce items from plate material using a CAD drawing. Items such as washers, fittings and brackets, etc. could be machined for use on the battlefield.



Figure 6 Castings of melted cartridge brass with no fluxing (each casting was approximately 5-inches wide).



Figure 7 Open top mold used to improve metal flow and allow for the gas to escape.



Figure 8 Plate made with melted spent brass cartridges using an open top mold.

3D-Printing Casting Molds with Desert Sand

The ability exists to 3D-print with sand using commercial off-the-shelf printers. These printers require the use of OEM provided sand, as well as a binder to keep the build together. The benefits of using 3D-printed sand molds versus traditional sand molds include the following:

- Molds can be made in a shorter time, without complex and expensive tooling
- Molds are generated from CAD models
- Complex geometries can be accommodated, with faster design modifications

The benefit of being able to use indigenous sand means one less item that would need to be shipped to the battlefield. The concept is to 3D-print casting molds based on a CAD drawing of a part with desert sand in a shipping container at the point-of-need, and melt scrap, recycled and reclaimed materials for casting of metal spare or replacement parts. This process would yield a part that was not 3D-printed, so it may be more readily accepted by the end user.

ARL teamed with the University of Northern Iowa (UNI) on a Defense Logistics Agency (DLA) funded project, to determine whether indigenous sand (such as that found in a desert or beach) could be used with existing 3D-printers with an appropriate binder, for the purpose of manufacturing appropriate long lead time parts in-theater. As a proof-of-concept, sand from the Defense Training Center at Ft. Irwin, CA (Mojave Desert) was sent

to UNI to research its potential use with a 3D-printer. The original equipment manufacturer (OEM) sand that is typically used with these printers is silicon dioxide, shown in Figure 9. For comparison, Mojave Desert sand is shown in Figure 10 at the same magnification. Noticeable differences exist, including size distribution (which can be countered through sieving), composition, and the fact that the OEM sand is washed (no dust). The OEM sand actually looks closer to beach sand than desert sand based on the lack of dust (see Figure 11 for comparison). A CAD drawing of a mock component (Figure 12) was utilized to determine if it could be cast in A356 aluminum using Mojave Desert sand. A mold was made using the OEM powder for comparison. UNI screened the material to eliminate oversize and undersize particles and bond strength tested the sand using conventional foundry resins. Because desert sands may contain materials that effect the curing of conventional resins, various chemical hardeners were investigated. Once the molds were 3D-printed with desert sand, the aluminum was poured, and the parts allowed to cool. Figures 13 and 14 show the parts made with OEM, and desert sand, respectively. The part made with desert sand appeared to have a rougher surface finish, and would most likely need more post-processing than the part made with the OEM sand.



Figure 9 Typical OEM sand used with 3D sand printers. Micron marker = $500 \mu m$.



Figure 10 Sand from the Defense Training Center, Ft. Irwin, CA (Mojave Desert). Micron marker = 500µm.



Figure 11 Sand from Clam Pass, Naples, FL. Aside from the bits of shells, etc., the beach sand compares favorably to the OEM sand used with 3D sand printers. Micron marker = $500\mu m$.

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Figure 12 CAD drawing of a mock component to be aluminum cast using 3D-printed sand molds.



Figure 13 Cast aluminum A356 part using a 3D-printed mold with OEM sand.



Figure 14 Cast aluminum A356 part using a 3D-printed mold with Mojave Desert sand. Note what appears to be a rougher surface as compared to the part made with the OEM sand (Figure 13).

Towards Production of Metal Powder on the Battlefield

One of the challenges associated with future metal AM on a forward operating base is the transport of flammable metal powders for use with these processes. To counter this, ARL has teamed with MolyWorks Corp in an effort to produce AM-grade metal powder in a shipping container. The problem with traditional metal powder production in-theater (such as gas or water atomization), is that too much infrastructure would be needed, including the equipment, utilities (electric power, water, and inert gas), post-processing of the powder, need for cleanliness, etc. [20]. This report concluded that it would be more practical to stock an inventory of alloy powder for anticipated battlefield needs. Although these are legitimate concerns, the goal of this research was to determine whether the operations could be optimized to reduce the burden caused by these hindrances.

MolyWorks used their existing mobile foundry, contained within a shipping container to produce metallic powder from certified alloy bar stock, including AISI 4130 steel, titanium 6Al-4V, copper (Cu-101), 316 stainless steel (Figure 15) and 6061 aluminum alloy (Figure 16). With further research and development, it is anticipated that the ancillary equipment (controller, power supply, gas supply, etc.) as well as the mobile foundry could also all be contained in a shipping container. Within the mobile foundry, the metal is placed into the crucible, melted, and poured over flowing argon gas. The metal powder is formed and collected in the cyclones at the far end of the equipment.

To determine the feasibility of using scrap in this process, ARL furnished MolyWorks with a piece of actual battlefield scrap steel and battlefield scrap aluminum, to be added to certified steel and aluminum alloys, respectively. MolyWorks was also able to produce aluminum powder made solely from aluminum battlefield scrap (Figure 17). It is clear that the particles are, for the most part, spherical, and contain some satellites.



Figure 15 316 stainless steel powder (-325 mesh) made in the MolyWorks mobile foundry using certified alloy starter material. Micron marker = 50μ m.



Figure 166061 aluminum alloy powder (-325 mesh) made in the MolyWorks mobile
foundry using certified alloy starter material. Micron marker = 50μm.



Figure 17 Aluminum powder (-325 mesh) made entirely from aluminum battlefield scrap within the MolyWorks mobile foundry. Micron marker = 50μ m.

ARL also wanted to determine whether the powder produced in the mobile foundry could be used with the cold gas dynamic spray (cold spray) process. This is important, in that it would show that AM-grade metallic powder produced on the battlefield could potentially be used with a portable cold spray machine for the repair of parts in-situ, extending the life cycle of these components, and reducing the logistics needed to get a spare part back to the theater of operations. Both the 316 stainless steel powder and aluminum powder made entirely from battlefield scrap was placed within the powder feeder of the VRC Gen II portable cold spray system, and sprayed onto 316L stainless steel substrate panels, and AA 6061 panels, respectively. For comparison to the 316 stainless steel powder made by MolyWorks, a sample of Praxair FE-101 316 stainless steel powder was also cold sprayed onto the 316 stainless steel substrate. It took 35 passes to build up 0.10-inch of MolyWorks powder, as opposed to only 25 passes for the Praxair powder. In addition, the surface finish of the cold spray build using the MolyWorks powder was rougher than that of the Praxair powder (see Figure 18). To determine the reason for this difference, the panel was sectioned and metallographically prepared. Figure 19 shows a comparison of the cross sections of the two cold sprayed powders. The MolyWorks powder appeared to have less porosity, but more microcracks, indicative of higher residual forces within the build. This process would need to be optimized, but it did show that the powder could be cold sprayed with a portable unit. The Praxair powder was analyzed to determine how it compared to the MolyWorks powder. Figure 20 shows that the Praxair powder was water atomized, making "splat" shaped particles, versus the spherical particles produced from gas atomization.



Figure 18 Oblique lighting photograph of cold sprayed 316 stainless steel powder (-325 mesh) made by Praxair (top) and the MolyWorks mobile foundry (bottom). Note the rougher surface finish of the cold spray build using the MolyWorks powder.



Figure 19 Micrographs of cold sprayed 316 stainless steel powder (-325 mesh) made by Praxair (left) and the MolyWorks mobile foundry (right). Although the MolyWorks deposit appeared to have less porosity, it contained microcracking. Micron marker = 500µm.



Figure 20 Praxair FE-101 -325 mesh 316 stainless steel powder Praxair that has been water atomized. Contrast to 316 stainless steel powder made by MolyWorks that was gas atomized (Figure 15).

Particles of 316 stainless steel were mounted and polished, and subjected to scanning electron microscopy. Figure 21 confirms that the powder produced by the mobile foundry is mostly spherical, with a smaller amount of spheroidal shapes, and very few angular shapes. Some porosity is seen in the cross sections, which is likely a result of atomization gas becoming trapped in the molten particles during solidification. The microstructure appears to vary from particle to particle for the 316 stainless steel, perhaps due to variability in the manufacturing process.



Figure 21 SEM images of the 316 stainless steel powder produced by MolyWorks in the mobile foundry (100x left, 3000x right).

The aluminum powder made entirely from aluminum battlefield scrap was also subjected to the cold gas dynamic spray (cold spray) process, and was deposited successfully as shown in Figure 22. Three grooves were machined onto the test panels. Two grooves were filled with the portable cold spray system, and one was machined back to the level of the substrate. The cold spray deposition machined nicely, and no defects were visually noted. Figure 23 shows the mechanical mixing that was noted at the interface, which is indicative of a strong adhesive bond.



Figure 22 Cold spray deposition of aluminum powder (-325 mesh) made entirely from battlefield scrap within the MolyWorks mobile foundry onto three panels.



Figure 23 Section through one of the small samples shown in Figure 22 showing mechanical mixing at the interface of deposition and substrate. Micron marker = $20\mu m$.

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Conclusions

Reducing the dependence on the logistical supply chain at the point of need will not only increase operational readiness and the self-sustainability of warfighters in-theater, but also improve the safety of the warfighter by reducing threat vulnerabilities associated with our military logistics tail. The ability to fabricate or repair needed parts on demand, in-theatre in austere environments with available resources would be game-changing for the military.

Although further research is needed to optimize the process, we have shown a proof-ofconcept of melting and casting recycled and reclaimed scrap metals using simple tools and equipment that can be subtractively manufactured into functional items.

We have also shown that desert sand can be 3D-printed into casting molds to produce parts via traditional foundry casting. This proof-of-concept showed that locally available sands, with little processing could be effectively utilized to produce metal casting molds of sufficient strength to cast light metal alloys. This capability may someday allow for manufacturing of parts in-theater using indigenous sand, and recycled/reclaimed battlefield scrap.

With respect to the production of AM-grade metallic powder in-theater, we have made great strides in producing powder in a mobile foundry contained within a shipping container. The batches can be made with either certified alloy or scrap metal, and the subsequent powder can be cold sprayed. The vision is to have the future capability to produce this powder in-theater for real-time repair of components (for example, with cold spray technology), or the building of spare parts (for example, combined cold spray and subtractive manufacturing).

This initial research has shown the realm of the possible with respect to the use of indigenous, recycled, and reclaimed materials at the point of need for the repair or manufacturing of parts.

Future Work

ARL is interested in any and all manufacturing processes that can be utilized in-theater with indigenous, recycled and reclaimed materials, and will pursue paths leading to the ultimate use of traditional or AM on the battlefield using these materials as feedstocks.

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