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Demonstration of a Desktop Liquid Direct Metal Write Additive Manufacturing System

Orlando Rios

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OAK RIDGE NATIONAL LABORATORY
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Advanced Manufacturing Office

Demonstration of a Desktop Liquid Direct Metal Write Additive Manufacturing System

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CONTENTS

LIST OF FIGURES

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This CRADA NFE-17-0653 was conducted as a Technical Collaboration project within the Oak Ridge National Laboratory (ORNL) Manufacturing Demonstration Facility (MDF) sponsored by the US Department of Energy Advanced Manufacturing Office (CPS Agreement Number 24761). Opportunities for MDF technical collaborations are listed in the announcement "Manufacturing Demonstration Facility Technology Collaborations for US Manufacturers in Advanced Manufacturing and Materials Technologies" posted at: http://web.ornl.gov/sci/manufacturing/docs/FBO-ORNL-MDF-2013-2.pdf.

The goal of technical collaborations is to engage industry partners to participate in short-term, collaborative projects within the Manufacturing Demonstration Facility (MDF) to assess applicability and of new energy efficient manufacturing technologies. Research sponsored by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Advanced Manufacturing Office, under contract DE-AC05-00OR22725 with UT-Battelle, LLC.

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We would like to acknowledge Eck Industries and David Weiss for developing the method of producing and providing the wire feedstock used in the development of the desktop DMW system.

We would like to acknowledge the support of Brigham Young University-Idaho's Mechanical Engineering Department for fabricating an optimized water-cooling assembly for the Altair 3D printer.

ABSTRACT

ORNL worked with PrintSpace 3D to demonstrate cost effective electromagnetic induction melting of aluminum alloys on their desktop Altair 3D printer. An electromagnetic coil design and susceptor have been optimized and paired with a high frequency power supply to melt Al-Ce alloys. The manufacturing feasibility of Al-Ce wire was also proven to be successful and precise process control of electro-magnetic heating was demonstrated. The system was found to have inherent safety benefits, requiring no powder handling and with very localized heating. Further research will demonstrate the ability to use DMW technology to print high temperature engine components for the transportation industry.

1. DEMONSTRATION OF A DESKTOP LIQUID DIRECT METAL WRITE ADDITIVE MANUFACTURING SYSTEM

This phase 1 technical collaboration project (CRADA No. NFE-17-06531) was begun on February 16, 2017 and was completed on August 21, 2019. The collaboration partner PrintSpace 3D is a small business. Through this project it has been determined that direct 3D printing of the high temperature (Al-Ce) aluminum alloy system is possible using electromagnetic induction.

1.1 BACKGROUND

PrintSpace 3D a small/medium enterprise has been working with the Manufacturing Demonstration Facility (MDF) at ORNL to further develop a new Advanced Manufacturing (AM) process that uses an electro-magnetically heated nozzle to directly extrude aluminum alloys with their Altair (3D) printer. This phase 1 CRADA agreement made possible through the AMO office of the DOE provided the collaboration necessary between ORNL and PrintSpace 3D to further prove the viability of DMW technology to further this new technology's acceptance into the additive manufacturing industry. PrintSpace 3D's goal is to become a leader in bringing robust, high speed, and energy efficient AM technologies to the market to increase US manufactures' ability to compete on a global scale.

Through pairing the DMW nozzle technology with the Altair 3D printer, PrintSpace 3D will be able to provide competitive metal print services and equipment allowing manufacturers to 3D print aluminum components giving them increased productivity over currently available 3D printers. PrintSpace 3D's goal is to give US manufacturers services and equipment capable of printing parts from high-strength aluminum alloys. This will allow for industry to economically create more complex technologies such as heat exchangers, smart structures, and organically optimized structures that will drive the creation of new industries. In addition to industrial advantages, the use of DMW system of structural alloys would be of great interest to space and microgravity environments. The production of metal parts with complex geometries on space missions is important to their future success, but the safety issues of current metal AM systems can be detrimental to mission safety. For example, safety concerns for powder feedstocks and high temperatures in wire and arc additive manufacturing are circumvented with the simplicity of an Al-Ce DMW system.

This Phase I CRADA research allowed PrintSpace 3D to find the technical barriers in pairing the two technologies and to determine a plan for subsequent work.

PrintSpace 3D has expertise in developing new AM technologies as well as experience in bringing products such as the advanced Altair 3D Printer to market. Through manufacturing high-performance 3D printers and developing custom 3D printing applications utilizing advanced materials. Known for sleek design, large print volume, and 20+ materials selection, PrintSpace 3D's printers are especially geared towards engineers and are used by national laboratories and universities across the country.

Al-Ce is a new engineering-grade aluminum alloy intended to be used in demanding automotive and aerospace industrial applications. To date, there is no commercially available printer capable of printing with this new alloy, yet it is becoming of significant interest to engineers for the design of high-strength components in operation under extreme temperatures. Liquid Al-Ce has a shear-thinning rheology ideal for extrusion through a nozzle. Its surface energy was found to be improved for printing by the formation of a high-enthalpy intermetallic. This promotes bead shape retention after the liquid metal has left the nozzle. After solidification, many of the casted parts using Al-Ce alloys have shown to have improve high temperature resistance. These qualities make it a great solution for high-performance combustion engine applications and lite-weighting aerospace applications produced using a DMW system.

In Phase I a power supply was integrated with the Altair to enable precise melting of Al-Ce on the Altair platform. The selected power supply had sufficient power to melt aluminum wire which will be further developed in Phase II along with process control for full scale printing.

1.2 TECHNICAL RESULTS

An integrated electromagnetic hot-end has been developed for the Altair 3D printer platform through which Al-Ce wire was fed and melted within a steel susceptor. Both low frequency and high frequency EMF power supplies have been tested with variations of coil types. The high frequency power supply was found to be more efficient and less energy was lost within the power leads connecting the power supply to the coils. In parallel ORNL has co-developed a larger scale system focusing on materials properties and selection. This allows for the project to fill multiple developmental spaces while improving process development for both small and large-scale printers. Powders are inherent to powder bed technologies but also a consideration for DED, where welding dust and redeposited metal vapors are a concern. In fact, current laser and electron beam metallic AM systems require frequent enclosure cleaning to deal with redeposition of particles. Conversely, the DMW system feeds and extrudes material with a mechanical actuator, while the extruded filaments maintain shape via a reactive skin before and during solidification. While the powder bed process requires an enclosure and atmospheric pressure control, in DMW filaments are directly printed and bonded to underlying layers, while the reactive surface holds the surface together. The increased safety affects by reducing material vapors makes DMW a viable technology for safely and cost effectively printing Al-Ce structures. Additionally, in microgravity the powder bed process is completely disrupted by particle drift, DMW filaments are directly printed and bonded to underlying layers, while the reactive surface holds the surface together. There could, however, be differences in layer flattening due to gravitational changes but can be avoided using parameterization of the print. Powder bed and DED systems can cause significant safety risks, as floating powders could be inhaled by personnel or infiltrate electronics or seals, causing subsystem failures. These differences in safety under microgravity can be seen in Fig. 1 below.

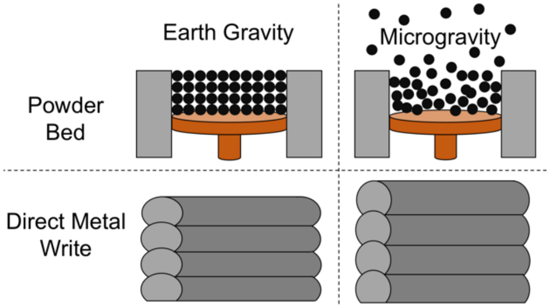

Fig. 1. Comparison of powder bed and direct metal write technologies in earth and microgravity. Note that in microgravity, powder is not constrained while filaments immediately bonds to underlying layers of DMW.

1.2.1 ORNL Large Scale System

A large-scale system developed in parallel to PrintSpace 3D determined the printability and material characteristics of the Al-Ce alloy in a DMW print system. The larger scale system uses a similar induction heating system, but directly couples to the feedstock instead of heating a nozzle susceptor. The print system termed Direct Reactive Interface Printing (DRIP) can be seen in Fig. 2.

The heating inductor is a helical wound round solenoid type inductor with an even pitch of 4 turns in 2.5 cm length. The conductor is oxygen free copper tubing that is actively cooled by either water/industrial coolant but can also be cooled using compressed gasses such as ambient air, argon, nitrogen, etc. The print head is induction heated to ~650 C to melt the cylindrical ingot while under closed-loop force control. Once extrusion begins, the process is then driven by a closed-loop constant-displacement controller, common to extrusion-based AM platforms. The feedstock consists of 125 mm long cylindrical ingots (dia. = 12.5 mm) of Al–Ce (6–10 wt%-Ce, 0.1–10 wt%-Mg). A fully liquid melt zone forms at the base of the extrusion nozzle, and the push rod advances. Fully molten material flows through the nozzle, and the extruded filament behaves as a viscoelastic solid exhibiting a yield point that enables net-shape production. The nozzle design (Fig 2.) itself can be further improved with a detachable tip that can be replaced. Additionally, build volumes are limited to the size of one cylindrical ingot, but a multi ingot feed system has been designed to increase print volumes. This systems design is preliminary to implementation on larger manufacturing AM systems and to determine design focus for PrintSpace 3D's small-scale system.

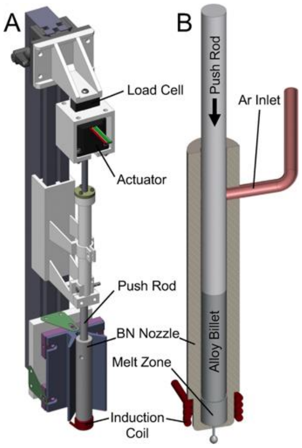

Fig. 2. Schematic of the (A) printing head and feed mechanism and (B) the printing nozzle, where the alloy is inductively heated. [Kesler et al.]

Fully liquid metal was 3D printed in a square multitiered part of Al–6Ce (wt%) in air at 8.5 mm/s^{-1} onto a heated (400°C) aluminum build plate. Fig. 3A-D shows photographs taken during the DMW process. In Fig. 3C, the part is competed the nozzle tip rises ∼4 cm above the build plate. Extruded material retains its shape until it loses contact with the extrusion nozzle and collapses. The Al-Ce alloy remained in the molten state during the entire rise. Likewise, Ce-containing Al alloys demonstrate exceptional lateral spanning capability, bridging about 6 cm in the lateral dimension and 12 cm at an angle of ∼45° (Fig. 3E-F). This bridging ability shows high dimensional stability at large scales that is advantageous for AM processes.

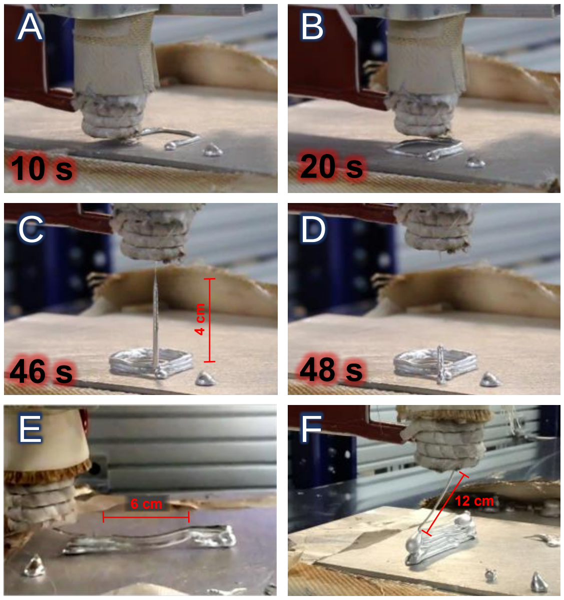

Fig. 3. DMW of an Al–Ce alloy at (A–D) successive images exhibit a multi-layer 35 mm × 35 mm build, with 3 mm thick layers. Surface stabilization of a filament extends several cm vertically, and is captured at 46s, after which the filament collapses, confirming it is still molten. Al–Ce exhibits (E, F) excellent lateral spanning capability, as shown in these bridging experiments. [Kesler et al.]

The large-scale system was successful in showing that the material is printable using a standard AM control scheme. Further optimization of nozzle design and material feeding would make the technology successful. This work on the large-scale system was used as a basis for PrintSpace 3D to develop their own desktop system.

1.2.2 PrintSpace 3D Small Scale System

PrintSpace 3D has used its developmental expertise in AM to design and integrate a small scale DMW system for Al-Ce alloys on their Altair printers seen in Fig. 4. PrintSpace 3D has developed the Altair printers with a high resolution and precise repeatability. An 8.5 in diameter by 10 in tall print volume, optional enclosure, 32-bit controller, and the Simplify3D slicing software make the printer versatile and easy to use for the end user. When printing traditional polymers, the system can print layer heights of 0.01 mm which are almost imperceptible to the human eye. The maximum positioning speed is 300 mm/s but can be reduced in real-time if finer control is desired. The fine control that can be achieved using the Altair system can be transferred to achieving better DMW prints on the Altair platform. Finer control makes the parameterization of the DMW process more easily achieved.

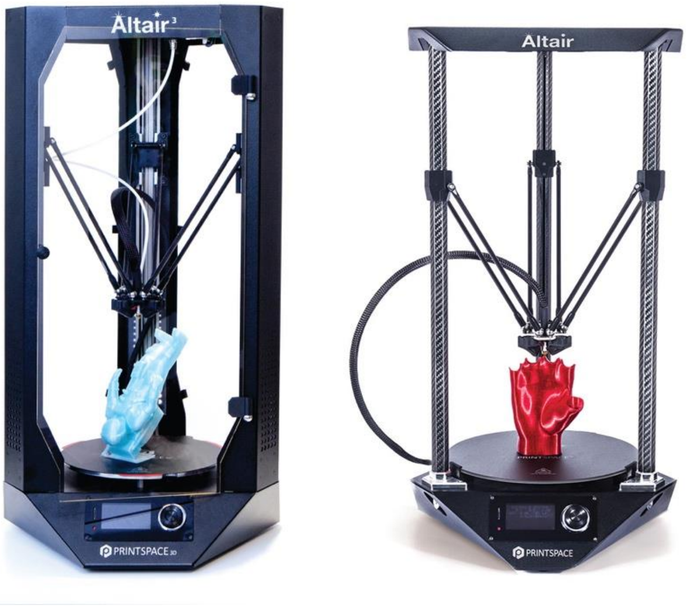

Fig. 4. PrintSpace 3D's Altair product line provides additive manufacturing solutions by merging engineering grade materials with reliable, innovative technology allowing customers to print with over 20 thermoplastics and composite materials. PrintSpace 3D plans to bring affordable DMW printing to the desktop.

The Altair printer in Fig. 5A was modified with an induction heated nozzle used to print Al-Ce alloys. The modified nozzle design for a wire fed system uses a specialized coating inside a susceptor heated by an induction system. In this case, the susceptor is designed to couple effectively with the induction system and provide localized heating to melt the Al input. Susceptor materials were selected and determined to be adequate at protecting against molten aluminum interactions at elevated temperatures while also protecting the susceptor from oxidation. Fig.5 B-C shows the original system designs for a polymer-based system that helped to determine the optimal susceptor materials. Continual testing will need to be done to know if this will be adequate for extruding Al-Ce for long periods of time (100+ hours) between susceptor changes. On the small-scale printer the susceptor and nozzle are combined into a single component. One of the benefits of the induction system is rapid response and correspondingly low latency. The system is capable of changing from 10 W to 1 kW heat input in less than one second. When coupled with the high latent heat of Al (10.8 kJ/mol), the rate of Al melting can be carefully controlled by the heat input and matched to the tool path and speed. This would not be possible in a system based on resistive heating.

The number of coil sizes and various diameters and shape configurations have also been tested to optimize the efficiency of the system. It was found that a single walled eight coil system was optimal for bringing the susceptor to the desired temperature range of 650˚C to 750˚C. The optimized coil design was used in unison with an EMF noise mitigation PID controller. This heating system is sufficiently able to hold the temperature within +/- 5˚C of the setpoint. The nozzle design uses a thermal isolation approach for the hot end. Water cooling for excess heat rejection was determined to be necessary which can be achieved using a small chiller running water through the induction coil.

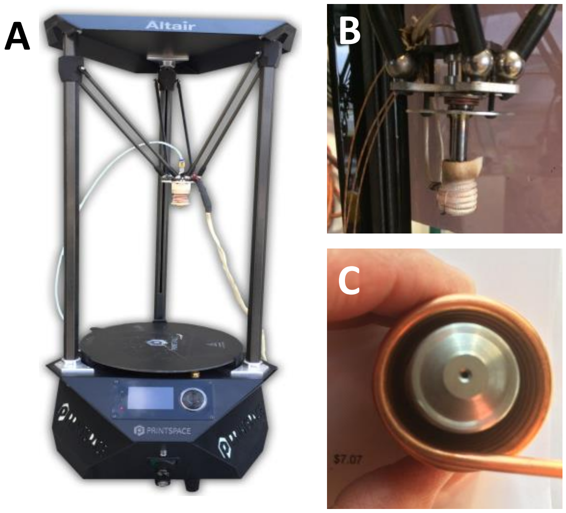

Fig. 5. A) PrintSpace 3D Altair printer with a modified B) induction heated nozzle for Al-Ce-X metal wire. These modifications were made from the original C) polymer fed induction heated nozzle.

The use of a low-cost feedstock in DMW is key to making a small-scale metal printer successful. Fig. 6A shows extruded wire using traditional aluminum manufacturing techniques. The low cost of feedstock production that could fit into current manufacturing streams would reduce the cost of any feedstock material choice. Fig. 6B-C show Al-Ce wire being successfully extruded through the modified Altair printer's induction heated nozzle. The shape of the bead is similar to that found in the large-scale system during initial testing. Further parameterization of the system needs to be done to achieve continuous printing. The nozzle design itself is cost effective and allows for quick changeout of degraded nozzles with a new one with no need to replace the induction coils.

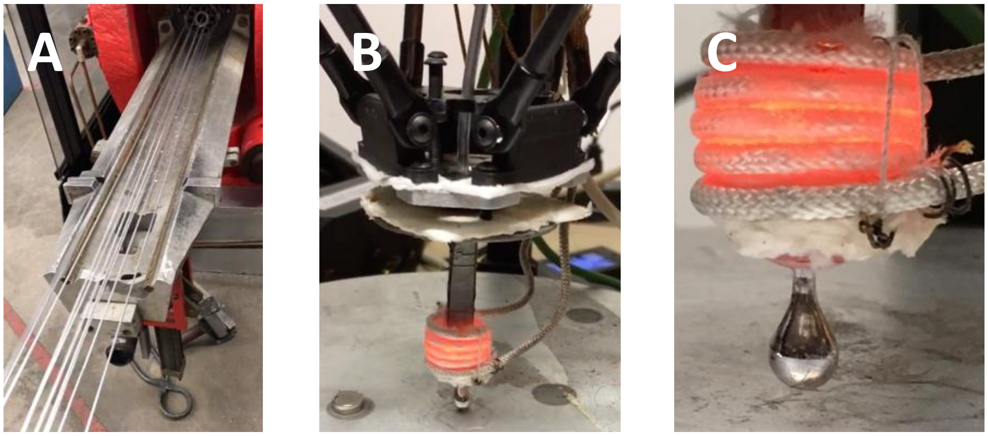

Fig. 6. A) Extruded Al-Ce wire used produces through extrusion in large quantities. B) The induction heated nozzle using Al-Ce metal wire mounted on the PrintSpace 3D Altair printer and C) the heated nozzle extruding a metal bead similar to the large-scale system. Note that this is an ambient air-cooled system before using the current water-cooled system.

1.3 IMPACTS

Traditionally the difficulty with additively manufacturing aluminum components is that they available process are not only expensive but are highly reactive requiring a fully inert environment to overcome the material's propensity to oxidize. Machining or casting processes are the common methods of manufacture with aluminum alloys. Machining requires expensive equipment and leaves a lot of wasted product. Compared to powder AM, the feedstock cost and safety required for handling can exceed throughput requirements for production at scale. The initial machine and on-site equipment costs for powder systems can far exceed initial investment interests for production of metal parts. DMW will allow substantial savings and waste reduction with additive manufacturing. By decreasing upfront costs for tooling, this will reduce a manufacturer's minimum order quantity in-turn speeding up the design cycle for new products and allowing them to get to market more quickly. DMW may reach cost targets for metal manufacturing due to high throughput, low machine costs, and more affordable feedstocks; penetrating markets were powder based metal AM is cost prohibited.

With Altair, and the FDM printing process, there is a lower initial machine purchase costs compared to selective laser sintering (SLS) PEEK machines. FDM also allows for ease-of-use in printing with spooled high-performance polymer filament as opposed to powder.

We see a future where manufacturers print their own metal high-strength, end-use parts in-house. A paradigm shift in manufacturing will occur with the introduction of DMW technology as it is combined with complimentary proprietary technologies. Manufacturers and engineers will be able to more effectively design and create end-use components or assemblies.

Increasing the scope of this research and expanding this combined effort across industries and professions will only echo those savings in energy and emissions. For example, work can be done to make the small-scale DMW system available to microgravity environments, making the shipping of parts cheaper where only raw material needs to be sent into orbit. A desktop DMW system is a platform technology that takes advantage of its robust manufacturing tolerances to produce complex metal parts.

1.3.1 Subject Inventions

There are no subject inventions associated with this CRADA.

1.3.2 Publications

Kesler, Michael S., Max L. Neveau, William G. Carter, Hunter B. Henderson, Zachary C. Sims, David Weiss, Tian T. Li, Scott K. McCall, Martin E. Glicksman, and Orlando Rios. "Liquid direct reactive interface printing of structural aluminum alloys." *Applied Materials Today* 13 (2018): 339-343.

1.4 CONCLUSIONS

This CRADA was successful in that we have determined that Al-Ce wire can be cost effectively manufactured and extruded on a desktop printer platform. It has also been concluded that the Al-Ce volatiles resulting from printing with this process are not a cause of concern for safety of the operator. The next step for the desktop DMW system would be to further parameterize the system and improve print times. Following the success of the large-scale system similar steps taken to improve printing can be done for the PrintSpace 3D system and integrate it into a commercially viable printer for manufacturing and metal part production.

2. PRINTSPACE 3D BACKGROUND

PrintSpace 3D is an advanced manufacturing company that creates and advances new 3D printing technologies. Participant is a trusted, go-to company, known for excellence that professionals and technical educators come to for 3D printers, materials expertise, print services and products. PrintSpace 3D provides productive solutions to customers by merging engineering grade materials with reliable, innovative technology and superior customer service. PrintSpace 3D understands the impact that DMW printing in aluminum alloys can have on US industry and manufacturing.

A portfolio of technologies from PrintSpace 3D focus on high performance high resolution additive manufacturing in a desktop profile. PrintSpace 3D offers a verity of desktop 3D printers that can achieve high tolerance prints repeatably with a varying material set. The current print materials offered by include PLA, ABS, Nylon, Polycarbonate, PVA, HIPS, PETT, TPU, Metallic fill, “Tough” PLA, Flexible PLA, Carbon Fiber PLA, and more. PrintSpace 3D has a vested interest in the use of AM technologies in space applications wherein the desktop DMW print system can be a direct competitor to current metal AM technologies.

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