ARL-RP-0618 ● Oct 2017

US Army Research Laboratory

Towards Production of Additive Manufacturing Grade Metallic Powders on the Battlefield

by Marc Pepi

A reprint from the Proceedings of the International Conference Powder Metallurgy and Particulate Materials; 2017 June 13–16; Las Vegas, NV. Princeton (NJ): Metal Powder Industries Federation; 2017. p. 1016–1026.

NOTICES

Disclaimers

ARL-RP-0618 ● OCT 2017

US Army Research Laboratory

Towards Production of Additive Manufacturing Grade Metallic Powders on the Battlefield

by Marc Pepi
Weapons and Materials Research Directorate, ARL

A reprint from the Proceedings of the International Conference Powder Metallurgy and Particulate Materials; 2017 June 13–16; Las Vegas, NV. Princeton (NJ): Metal Powder Industries Federation; 2017. p. 1016–1026.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
October 2017

2. REPORT TYPE
Reprint

3. DATES COVERED (From - To)
June 2016–June 2017

4. TITLE AND SUBTITLE
Towards Production of Additive Manufacturing Grade Metallic Powders on the Battlefield

5a. CONTRACT NUMBER
SBIR-I A16-023

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Marc Pepi

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
US Army Research Laboratory
ATTN: RDRL-WMM-D
Aberdeen Proving Ground, MD 21005-5069

8. PERFORMING ORGANIZATION REPORT NUMBER
ARL-RP-0618

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
A reprint from the Proceedings of the International Conference Powder Metallurgy and Particulate Materials; 2017 June 13–16; Las Vegas, NV. Princeton (NJ): Metal Powder Industries Federation; 2017. p. 1016–1026.

14. ABSTRACT

The concept of manufacturing at the point of need in austere environments would provide many advantages to the military, including increased operational readiness, a reduction of the logistics tail, and a tactical advantage over our adversaries. Additional benefits of this technology include a reduction of energy and material costs related to less reliance on transportation. Research at the US Army Research Laboratory is showing that agile, expeditionary manufacturing could be accomplished through the use of materials indigenous to the location of our operating bases. Indigenous materials include not only the organic and inorganic materials naturally occurring in the area, but could also include recycled materials from the operating bases (metals, polymers, etc.) as well as battlefield scrap. This report highlights some of this research.

15. SUBJECT TERMS
additive manufacturing, indigenous manufacturing, cold spray technology, manufacturing at the point of need, battle damage repair

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					Marc Pepi
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER (Include area code)
Unclassified	Unclassified	Unclassified	UU	16	(410) 306-0848

Towards Production of Additive Manufacturing Grade Metallic Powders on the Battlefield

Marc Pepi

US Army Research Laboratory
Aberdeen Proving Ground, MD 21005

BACKGROUND

Many advantages can be gained by the military with the ability to manufacture at the point of need in austere environments, including a reduction of the logistics tail, and improved operational readiness. Additional benefits of this technology include: reduction of energy costs related to transportation, reduction of material costs due to reduced transportation costs, especially for well-established industries and, support of local businesses and resource bases [1]. Research at the US Army Research Laboratory is showing that agile, expeditionary manufacturing could be accomplished through the use of materials indigenous to the location of our operating bases. Indigenous materials include not only the organic and inorganic materials naturally occurring in the area, but could also include recycled materials from the operating bases (metals, polymers, etc.) as well as battlefield scrap.

CHALLENGES

There are many challenges associated with producing additive manufacturing (AM) grade metallic powder from indigenous materials in-theater. First, the materials must be readily available, and in relatively large amounts to be useful. Scalability of this process must also be taken into account. In addition, power and energy requirements will dictate whether these manufacturing processes will be possible on the operating base. A further concern is the effect of extreme environments (i.e., vibration and thermal and atmospheric conditions) has on the raw materials and the equipment needed for the subsequent processing steps.

IMPACT

The transportation of Army materiel to and from theatre is costly not only in terms of the logistic burden, but the time delays associated with replacing, repairing, and upgrading mission critical equipment, systems, and vehicle platforms. The average soldier alone generates up to 7-1/2 lbs of waste per day, and often has very limited means to remove the waste, so there is a need to address this from an environmental and health perspective. Multiple waste streams composed of organic and inorganic materials are produced (including meals-ready-to-eat [MRE] trash, cardboard boxes, cellophane and Styrofoam packing boxes, used oil and air filters, used motor oil, ammunition dunnage as well as empty brass cartridge casings, medical waste, used batteries, used steel belted off-road tires, etc. [2]). Such an effort should be focused to offer a safe and environmentally responsible way to reduce disposal requirements by turning specific waste-streams into value-added products.

THE GOAL OF THIS PROGRAM

The goal of this study is technology development for the use of indigenous and recycling of captured/reclaimed resources for in-theatre AM-grade metallic powder production that can be potentially used to additively manufacture value-added products of use to the warfighter.

ADDITIVE MANUFACTURING ON THE BATTLEFIELD

The Army has been using 3D-printers in forward areas in Afghanistan since 2012 [3]. These machines come in handy in producing parts made of plastic, but to date, no metal additive manufacturing equipment has made it to the battlefield. As Dr. Thomas Russell, former Director of the Army Research Laboratory, points out with respect to having the capability of having metal additive manufacturing in-theater [4], "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." Further, General Dennis Via, former Commander of the Army materiel Command said that "printers could one day be embedded with squads, so that troops can manufacture weapons, tools or repair parts while they are in the field". [5]

PRODUCTION OF METAL POWDER ON THE BATTLEFIELD

Many challenges pervade in trying to produce AM-Grade metallic powder in an austere environment such as an operating base. These include the consumption of atomization gas usage (if gas atomization is chosen), or water (for water atomization). Hindrances also include the labor, time and infrastructure needed to assemble these potential systems once they are on the operating base, the amount of energy these systems require, the complexity of operation [6]. This reference suggested it would be more practical to just transport the metallic powders to the battlefield for AM. However, these metallic powders are flammable, which could pose a problem as well. Although these are legitimate concerns, it was decided to move forward with this research to determine whether the operations could be optimized to reduce the burden of these hindrances.

ARL submitted a Small Business Innovative Research (SBIR) entitled, "Production of AM-Grade Metallic Powder on the Battlefield", which was approved for Phase-I contracts. The goal of this program was to determine the feasibility of making metallic powder on the battlefield using recycled, reclaimed and battlefield scrap feedstock material.

Two companies were awarded a Phase-I contract, American Engineering and Manufacturing (AEM) teamed with the University of Ohio, and Molyworks Corporation. AEM proposed to use Lorenz force levitation and melting (see Figure 1) as a means of producing AM-grade metallic powder on the battlefield. The different technologies proposed by AEM included [7]:

- The use of an automated feed system to enable batch induction melting and Lorenz force levitation, in a controlled environment, to form a series of uncontaminated teardrops of molten material that will be allowed to fall from the melting/levitating coil into the next processing stage when the coil is de-energized.
- The use of Lorenz forces to reshape the teardrop, into a filament, before it passes into the next processing stage.
- The use of Lorenz forces in a low power form of "rail gun technology" or liquid metal pumping to accelerate the shaped molten stream to its burst point, i.e. the point at which the cohesive forces of the melt stream are overcome and fine spherical droplets are formed.

- The use of a cooling chamber in which the droplets will cool to powder. This chamber will be integrated with an ultrasonic sieving and packing system to place the powder in hermetically sealed containers.

According to Lawmon, the technology of induction melting, under Lorenz force levitation is well understood and has recently been adapted by The Ohio State University as a research tool to determine the relative crack sensitivity of different percentage combinations of weld filler metal and alloy plate. The first innovation that AEM proposed to add to this system is the ability to melt and hold the material while it degasses. It is expected that this degassing operation, that may be supplemented with melt agitation or spinning, will ultimately lead to powders that are essentially free of internal voids. The second innovation that AEM proposed was to add a feeder that will continuously replenish the melt chamber to increase the duty cycle to 50% and thus achieve a melt rate of 1 kg/hour with the current coil design. It is anticipated that this process could produce metallic powder of the following alloys: titanium, high strength steel, tungsten, nickel-base alloys, tool steels, stainless steels, cobalt alloys, tantalum and aluminum.

The other SBIR Phase-1 awardee, Molyworks, proposed to produce metallic powder in a mobile foundry. Although each of these companies were only expected to show a proof-of-concept in the Phase-I effort, Molyworks used their existing mobile foundry to actually produce metallic powder, including AISI 4130 steel, AA-6061, 316 stainless steel and Ti-6Al-4V (as of this writing). Molyworks also plans on producing copper at a later date. This mobile foundry is contained within an ISO container, and with further research and development, it is anticipated that the ancillary equipment (controller, gas supply, etc.) could also all be contained in an ISO container. The process is currently being optimized, and yields for metal additive manufacturing (approximately -325 mesh / 45-micron diameter) are nearing industry standards.

Within the mobile foundry, a certified alloy and/or battlefield scrap is placed into the crucible (in the future, it is hoped that metallic powder could be made solely from battlefield scrap), melted, and atomized by inert gas. The metal powder is formed and collected in the cyclones at the end of the equipment. Figure 2 shows optical microscopy of the AISI 4340 steel powder, while Figure 3 shows the 316 stainless steel powder that was produced within the mobile foundry. In each instance, it is clear that the particles are, for the most part, spherical, and contain some satellites.

To determine the feasibility of using scrap in this process, ARL furnished Molyworks with a piece of scrap metal and scrap aluminum, to be added to certified steel and aluminum, respectively. The AISI 4130 steel plus scrap heat powder looked similar to that shown in Figure 2, and the aluminum powder plus scrap powder is shown in Figure 4.

Figure 1 Lorenz force projection and melting technique proposed by AEM for production of AM-grade metallic powder on the battlefield.

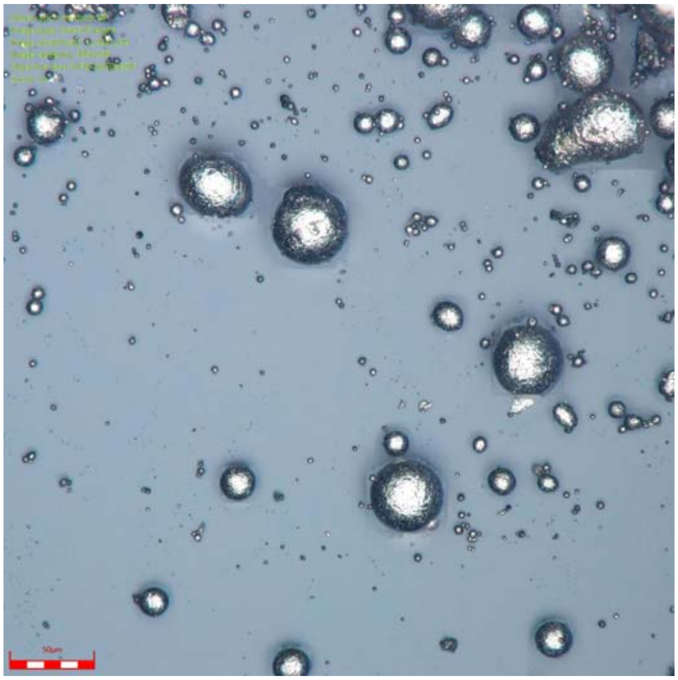

Figure 2 AISI 4130 steel powder (-325 mesh) made in the Molyworks mobile foundry using certified alloy starter material.

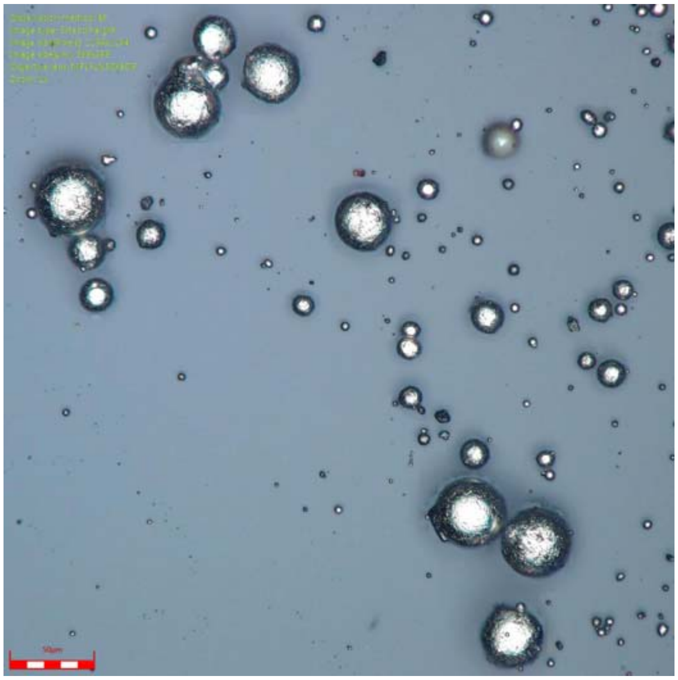

Figure 3 316 stainless steel powder (-325 mesh) made in the Molyworks mobile foundry using certified alloy starter material.

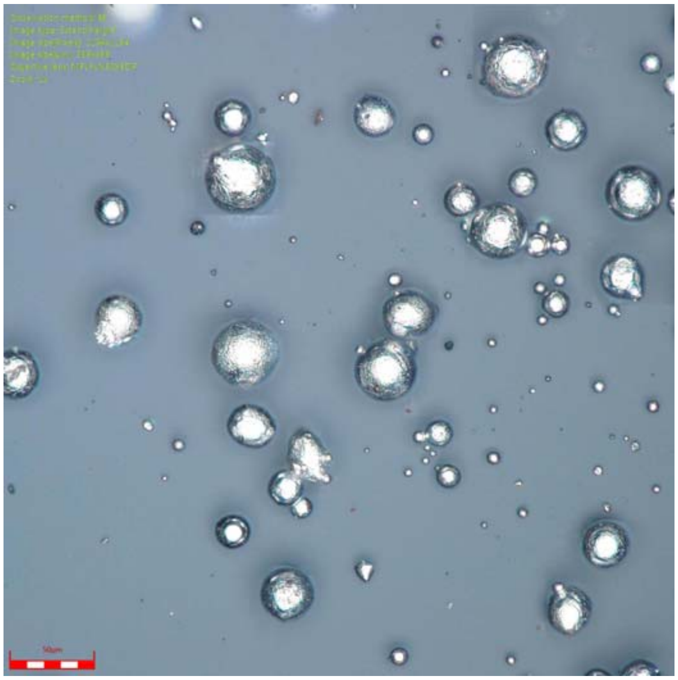

Figure 4 AA6061 (-325 mesh) made in the Molyworks mobile foundry using certified alloy starter material plus a piece of battlefield scrap.

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. Portable cold spray is the additive technology that will most likely make it to an operating base because of its current maturity level. Other AM techniques such as friction stir processing with powders, and laser bed methods are likely further away from in-theater operation. The 316 stainless steel powder was placed within the powder feeder of the VRC Gen II portable cold spray system, and sprayed onto 316L stainless steel substrate panels. For comparison, a sample of Praxair FE-101 316 stainless steel powder was also cold sprayed onto a substrate. It was determined that 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 cold spray build using the Molyworks powder was much rougher than that of the Praxair powder (see Figure 5). To determine the reason for this difference, the panel was sectioned and metallographically prepared. Figure 6 shows a comparison 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. Figures 7 and 8 show a magnified view of each of these deposits. This process would need to be optimized for the Molyworks powder, 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 9 shows that the Praxair powder was water atomized, making “splat” shaped particles, versus the spherical particles produced from gas atomization. It appears this geometry of metal powder led to a better cold spray deposit than the spherical geometry.

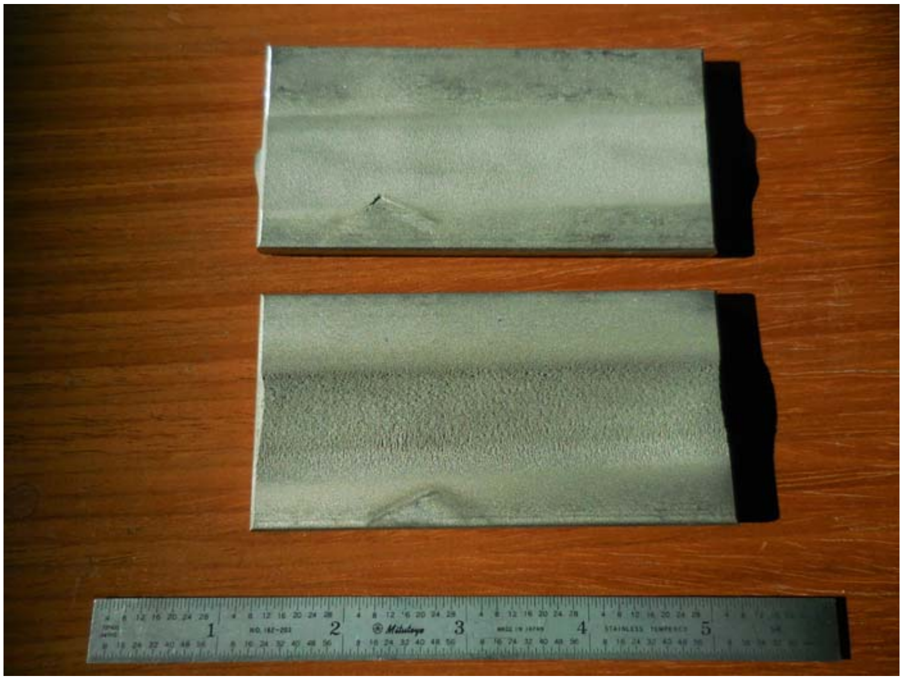

Figure 5 Oblique lighting photograph of cold sprayed 316 stainless steel powder (-325 mesh) made by Praxair (top) and the Molyworks mobile foundry (bottom). Note the rougher surface finish of the cold spray build using the Molyworks powder.

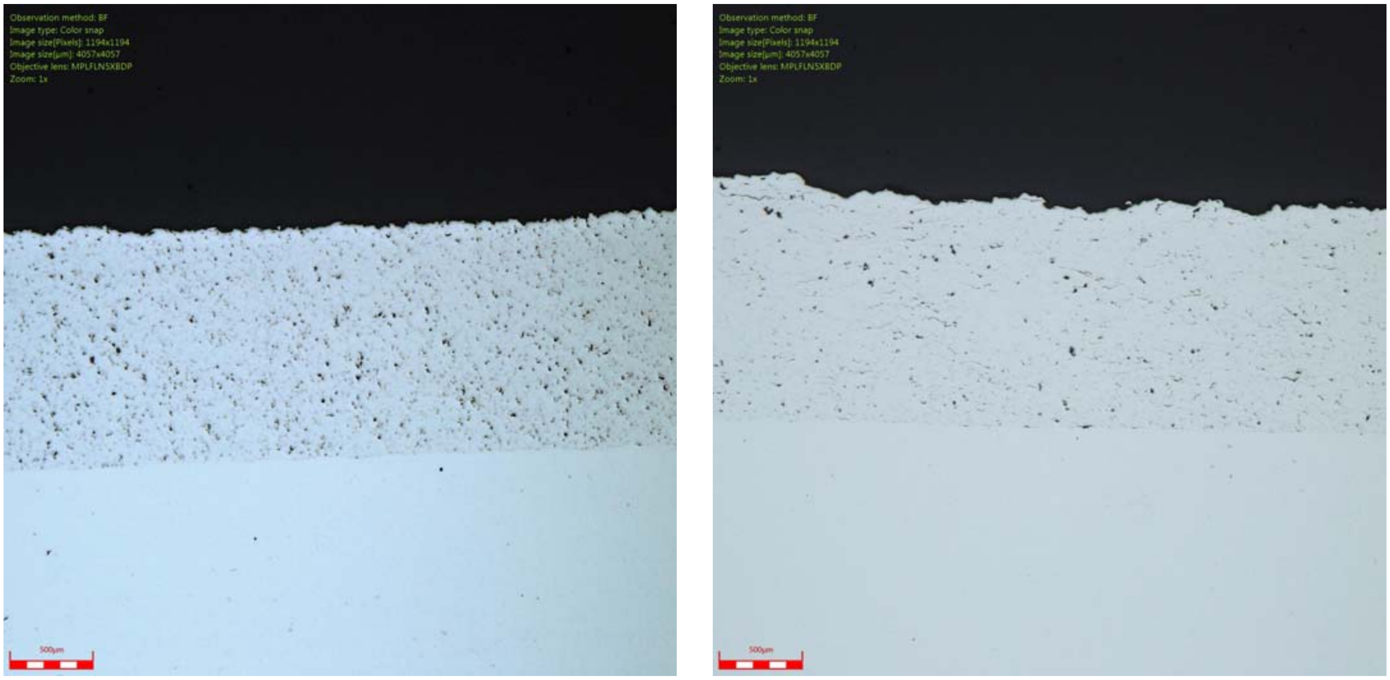

Figure 6 Micrographs of cold sprayed 316 stainless steel powder (-325 mesh) made by Praxair (left) and the Molyworks mobile foundry (right). Although the Molyworks deposit appeared to have less porosity, it contained microcracking.

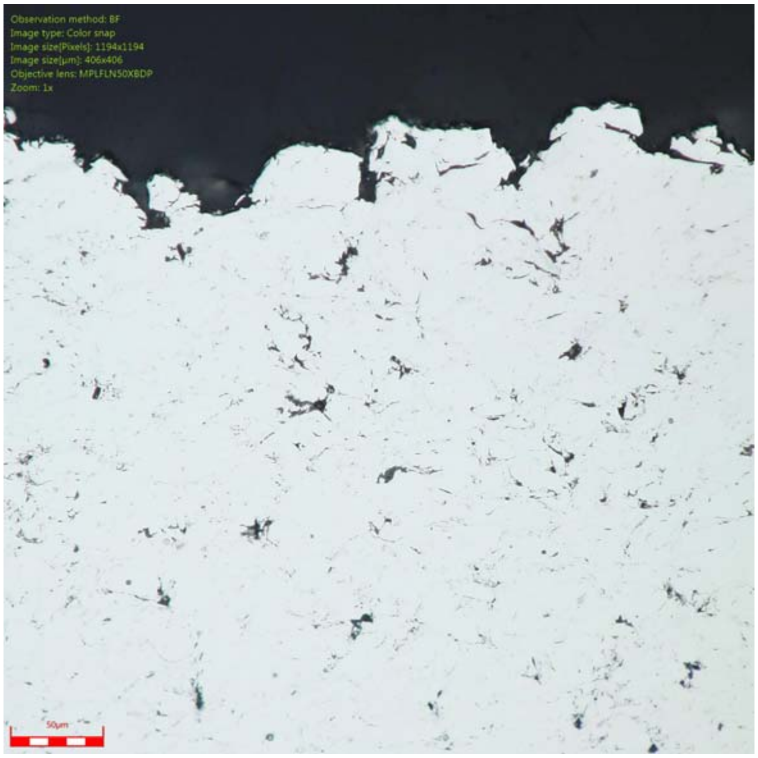

Figure 7 Higher magnification micrograph of cold sprayed 316 stainless steel powder (-325 mesh) made by Praxair.

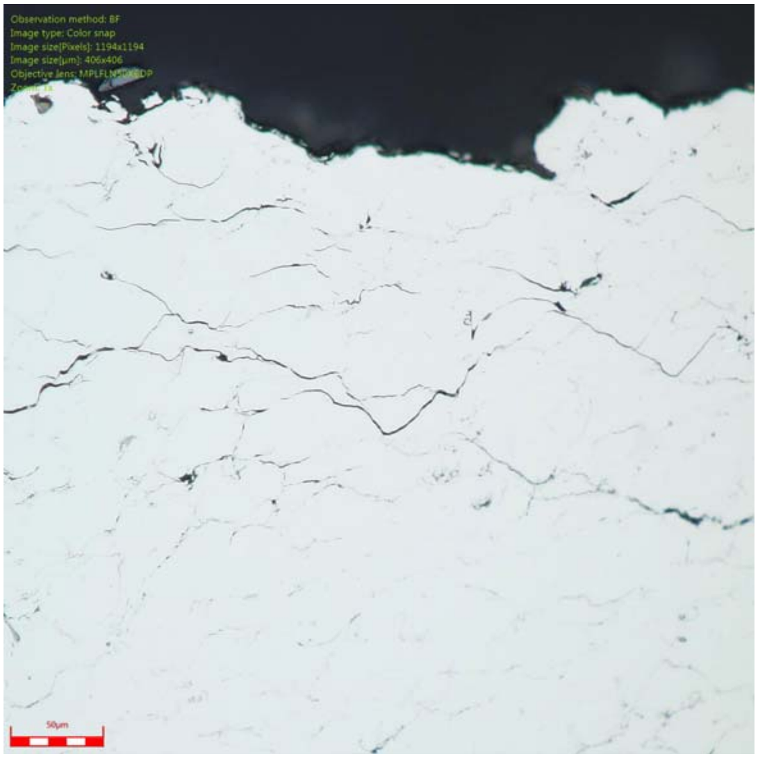

Figure 8 Higher magnification micrograph of cold sprayed 316 stainless steel powder (-325 mesh) made by Molyworks. Prevalent microcracking can be seen.

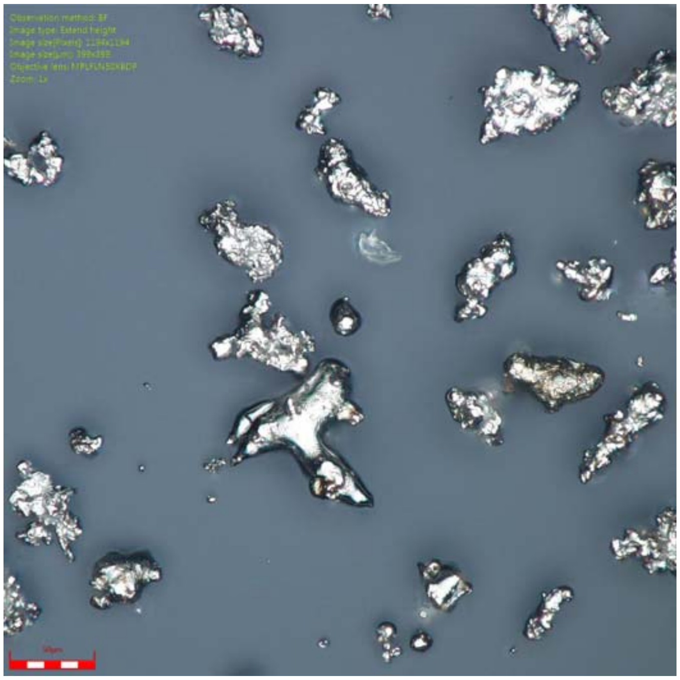

Figure 9 Praxair FE-101 -325 mesh 316 stainless steel powder Praxair that has been water atomized. Contrast to 316 stainless steel powder made by Molyworks that was gas atomized (Figure 3).

Particles of 316 stainless steel were mounted and polished, and subjected to scanning electron microscopy. Figure 10 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. This may also have an effect on the cold spray ability of the powder.

Molyworks also had Optomec, Inc. (New Mexico) perform AM builds with their 316 stainless steel and Ti-6Al-4V powders made in the mobile foundry. Cubes and tensile bars were printed with an Optomec laser engineered net shaping (LENS) system (see Figure 11). The cubes will be tested for density and the bars will be tested for tensile properties.

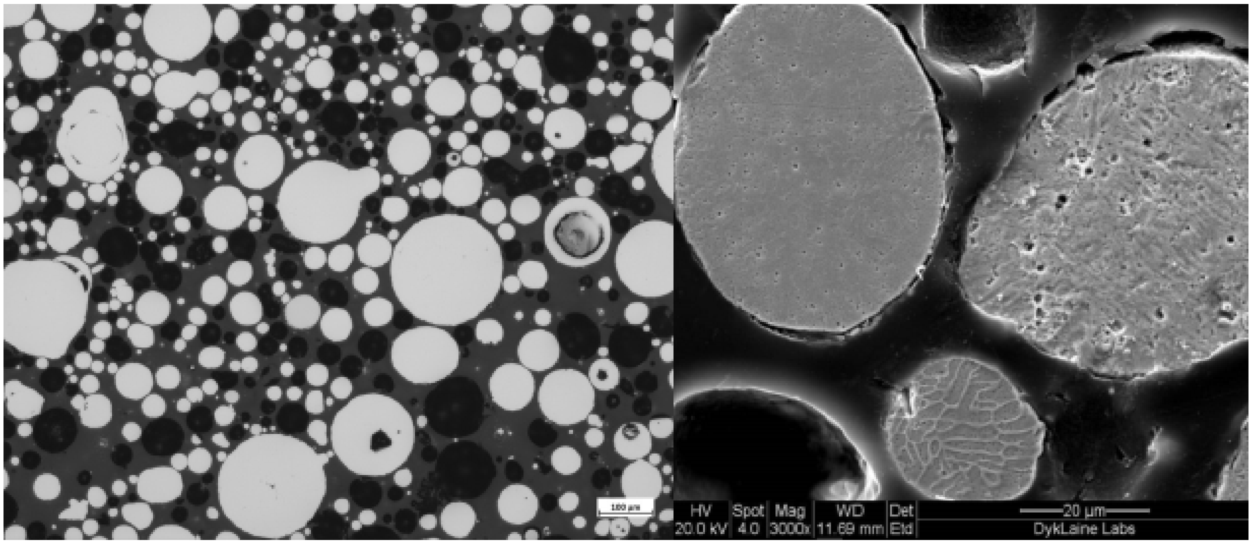

Figure 10 SEM images of the 316 stainless steel powder produced by Molyworks in the mobile foundry (100x left, 3000x, right).

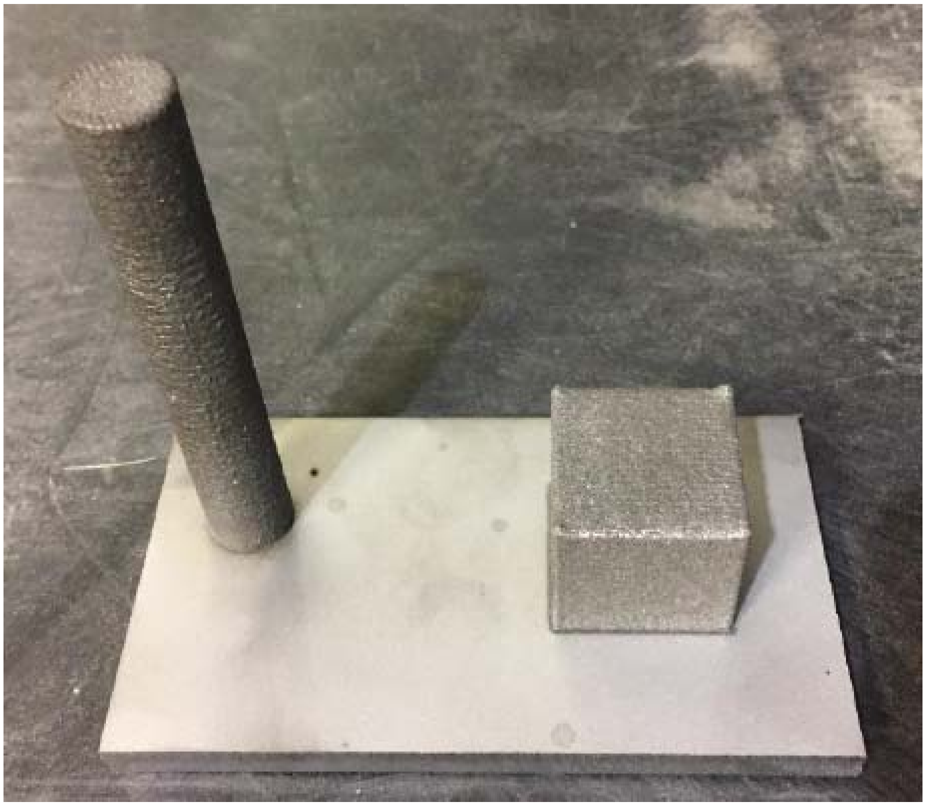

Figure 11 Tensile rod and cube built from 316 SS powder made in the mobile foundry using LENS technology.

CONCLUSION

Reducing the dependence on the logistical supply chain on forward operating bases 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. The ability to fabricate needed parts on demand, in-theatre in austere environments with available resources would be game-changing for the military.

With respect to the production of AM-grade metallic powder in-theater, AEM is researching a novel means of producing AM-grade metallic powder, and Molyworks has made great strides in producing powder in a mobile foundry contained within an ISO container. The Molyworks batches can be made with scrap metal, and the subsequent powder can be cold sprayed and additively manufactured using the LENS process. 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.

If metal printers that make use of these solidified droplets can be made rugged enough to withstand the battlefield, then broken parts will become recyclable, supply chains may no longer need to deliver even raw materials and, the logistics taken care of, more thought can be given to the little matter of strategy [8].

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 AM on the battlefield using these materials as feedstocks.

ACKNOWLEDGEMENTS

The authors wish to thank the following individuals for their contributions to this work: Andrew LaTour and team from Molyworks Corp. and John Lawmon and team from AEM, Inc.

REFERENCES

[1] “http://earth.sustainablesources.com, referenced 12/8/11.
[2] Personal conversation with CPT Terry Wilkin, USA, 12 August 2014.
[3] Cox, M., “Army Sees Rapid Prototyping as Key to Rapid Innovation”, 4/1/15.
[4] “Dr. Thomas Russell: Research Vision for 3-D Printing”, Army Technology Magazine, RDECOM Public affairs, 7/5/14.
[5] Insinna, V., “Military Scientists Developing New 3-D Printing Applications”, National Defense Industrial Association (NDIA) Technology Bulletin, June 2014, http://www.nationaldefensemagazine.org/archive/2014/June/Pages/MilitaryScientistsDevelopingNew3-DPrintingApplications.aspx.
[6] Strauss, J., “Feasibility Study on the Deployment of an Atomization System Contained Within Conex Shipping Containers to Operate at a Forward Operating Base”, 11/25/15, special report for ARL.
[7] Personal conversation with John Lawmon, AEM, 16 August 2016.
[8] Sutherland, B., “Military Supply Lines – Having no Truck with it”, The Economist, Science and Technology, 11/5/16, The Economist Group Limited, London 2016.

1 (PDF)	DEFENSE TECHNICAL INFORMATION CTR DTIC OCA
2 (PDF)	DIR ARL RDRL DCM IMAL HRA RECORDS MGMT RDRL IRB TECH LIB
1 (PDF)	GOVT PRINTG OFC A MALHOTRA
1 (PDF)	DIR ARL RDRL WMM D M PEPI