Towards 3D Printing of Any Alloy

Zak C. Eckel*, John H. Martin*, William B. Carter*, Tobias A. Schaedler*, Brennan D. Yahata*, Justin A. Mayer*, Jacob M. Hundley*

*HRL Laboratories LLC, Sensors and Materials Laboratory,
Architected Materials Department, Malibu, California, USA., additive@hrl.com

ABSTRACT

Metal additive manufacturing (AM) has demonstrated significant potential to reduce mass, part count, lead times, and procurement costs across multiple high performance and high volume industries such as aerospace, automotive, consumer goods and medical devices. However, the potential of metal additive manufacturing has yet to be fully realized due to the limited number and the severely reduced performance of compatible AM metal alloys. Recently, HRL Laboratories demonstrated a scalable powder nanofunctionalization technique to manipulate solidification mechanisms in powder bed AM, leading to the world's first crack-free 3D printing of 6000 and 7000 series aluminum alloys [1]. This approach used an alloy-agnostic lattice-matching technique to assemble nanoparticle nucleants on the surface of commercially available high strength alloy powders, rendering these high performance qualified alloys amenable with the unique processing conditions in powder bed metal additive manufacturing [2,3]. The resulting crack-free, fine-grained microstructure, allows traditionally "unweldable" high performance alloys, such as Al7075 and Al6061, to be additively manufactured for the first time.

Keywords: additive manufacturing, 3D printing, aluminum, metallurgy, nanotechnology

1 INTRODUCTION

The ability to precisely control a material's microstructure during metal additive manufacturing adds an entirely new degree of freedom for the 3D printing community. In addition to the free-form geometry specification that 3D printing affords, designers and engineers now have the potential to spatially dictate the performance of the additively manufactured parts through the interplay of powder composition and nanoparticle nucleants. In this article, we will discuss the specific approach used to produce the first-ever 3D printed high strength wrought aluminum alloys and the impact that this new design freedom will have on the aerospace and automotive sectors. In addition, extension of these alloy-agnostic techniques to other high impact alloy systems, such as crack susceptible nickel and titanium alloys, will be discussed.

2 METAL ADDITIVE MANUFACTURING

Through additive manufacturing new architectures and geometries can be realized that were not previously, creating a new revolution for various industries such as aerospace and automotive allowing topologically optimized design for safety and efficiency and in medical device for patient customized medicine and new medical devices

However, these applications rely heavily on the high performance engineering alloys, which have been developed through decades of refinement. Due to the unique processing conditions in powder based metal additive manufacturing, only a handful of these alloys can currently be additively manufactured, limiting the impact of this technology. Therefore, a fresh look at metallurgy is required to address the dearth of material options. HRL has recently reported its newly developed nanofunctionalization process applied to conventional feedstock powders, which can render previously unprintable alloys compatible with commercially available printing hardware [1]. This is achieved by adeptly identifying lattice-matching nucleants to control the solidification of the feedstock powders during printing. The result is a metal 3D printed component with printed strength matching that of the parent's wrought specification. The approach is demonstrated with aluminum alloy Al7075 and Al6061 powders functionalized with zirconium hydride nanoparticles, resulting in crack-free, equiaxed, fine-grained microstructure. Figure 1a-g demonstrates the effect of the process developed and comparison to the conventional approach. This grain structure enables yield strengths in excess of 54 ksi as printed and with post treatment further increasing this to >60ksi and >15% elongation; a 15X improvement over unmodified powders. With these results, it is anticipated the nanofunctionalization process is effective across alloy and hardware families and thus will enable broader adoption and leverage of additive manufacturing.

3 MICROSTRUCTURE CONTROL

Conventional production routes for complex metal components rely on monolithic material sources machined or forged to a final geometry. These processes limit the final component to line site features. Whereas the common form of metal additive manufacturing utilizes pre-alloyed powder or wire and a directed energy source to locally, melt small volumes of material serially building a final part, thus enabling complex and non-line-of-site features. However, the compatible metals, to this unique processing route are severely limited, effectively excluding centuries of metallurgical progress in quality, performance and cost reduction. Alloy development has focused primarily on two

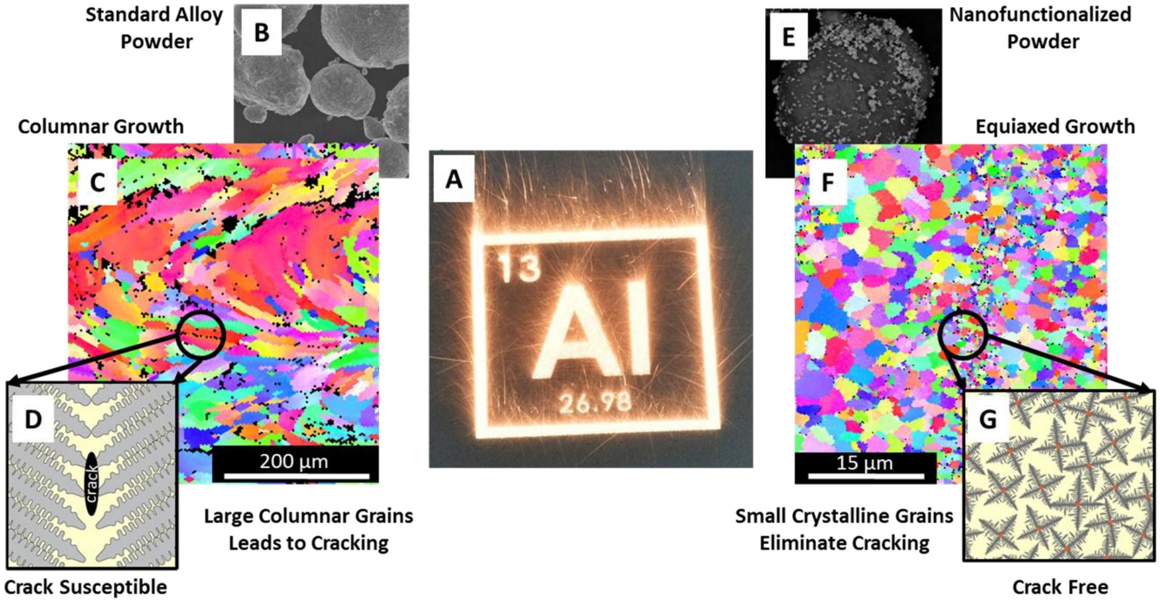

Figure 1: Nanofunctionalization of high strength alloy powders enables additive manufacturing of engineering-relevant alloys. A)SLM of 7000 Series aluminum, B) Standard 7075 Aluminum powder, C) Cracked microstructure in Standard 7075 Aluminum powder from SLM printing, D) Schematic representation of crack formation in standard aluminum E)HRL's nanofunctionalized high strength 7000 series aluminum powders, F)Microstructure in HRL's nanofunctionalized high strength aluminum powder G)Schematic of the crack resistant semi-solid microstructure

main categories, cast or wrought with significant understanding generated between the process-structure relationships. Microstructure in the alloy is set by the processing conditions applied and are well controlled and understood. In additive manufacturing repeated and sequential melting and solidification steps are imposed adding serious complexity to controlling and understanding the process conditions. Metal additive manufacturing more closely resembles a welding process performed at the microscale, repeated millions of times and as such, the alloys typically used for additive are easily welded. Choosing only weldable alloys severely limits the alloys available further which limits the applications in which additive manufacturing can be used. Only about 10 of more than 5000 alloys can be 3D printed. These include Inconel 718, Ti6Al4V, CoCr, and AlSi10Mg [4, 5], which are either poorer performing or expensive. Excluded are alloys of great interest, the high performance aluminum alloys such as the 6000 and 7000 series, which are commonly used in aerospace, military, commercial and increasingly automotive applications.

Mimicking the process of welding, additive manufacturing produces a columnar grain structure. In welding, the grains grow parallel to the relatively high thermal gradient. Thus in an additive process the accumulation of welds is additive through the build direction and can lead to preferential grain selection. The produced component has a highly textured microstructure and can be seen in a common additive alloy, such as AlSi10Mg, (Figure 1c). This preferential columnar grain selection can lead to accumulation of thermal stresses and anisotropic material properties [6].

If alloys which are unweldable are processed via additive manufacturing the resulting part, if any, is full of hot tearing and cracking defects offering little in the way of retained strength or engineering relevance, also visible in Figure 1c. Alloys such as Al7075 or Al6061, are complex alloys in which the transition through solidification solute rejection occurs leading to an unbalance of composition and the dendritic crystals and columnar grains form entrapping a eutectic liquid. This eutectic solidifies at temperatures greater than 100ºC below the initial solidification temperatures of the preferred alloy phases. Many high strength wrought aluminum alloys have a high volumetric shrinkage (>6%) during solidification and high coefficient of thermal expansion which leads to strain and deformation of the semisolid structure. The large columnar grain structure becomes locked due dendritic coherency and the result is cavitation, tearing and cracking in the final component, demonstrated in Figure 1d. To prevent these deleterious effects from forming the grain size should be decreased at the onset of crystallization and by creating fine equiaxed growth during solidification; one can prevent preferential columnar growth. In this case, coherency is delayed through the deformation of the new semi solid skeleton, behaving as a granular solid as opposed to a rigid structure as demonstrated in Figure 1f and g. Alternative approaches to controlling additive manufacturing microstructure have been demonstrated with mixed levels of success and narrow applicability to single alloys systems. Additive manufacturing hardware offer various levels of process control via manipulation of the laser parameters or the scanning methods thus allowing the use to control the thermal gradients and solidification velocities. Thus transitioning from a columnar to equiaxed grain [7,8]. This approach is time intensive, requires significant thermal modelling and diagnostic as well as experimental verification. It also may not be applicable beyond one printing geometry or alloy. A further complexity, which must be considered, is the inconsistencies in microstructure that can occurring across the machine bed. Cumulative effects may be present due to the layered based building approach. Chamber size and part geometry effect the residual heat accumulation and transfer causing unique thermal gradients and solidification velocities. These affects are highly build to build specific and would require adaptation to every new desired geometry, increasing cost and manufacturing times for the AM components.

4 NANOFUNCTIONALIZATION

As such it was determined, the most prudent method**s** for controlling solidification were not in build parameters but control at the materials level. A method was developed for promoting the desired equiaxed grain growth during the solidification of the melt pool. We leverage the effect of heterogeneous nucleation by introducing highly active nucleation sites into the melt pool requiring only minimal amounts of undercooling; this in essence seeds the crystal microstructure throughout the melt pool as opposed to seeding from the previous layers grain eliminating the columnar structures. The seeding of the nucleants was achieved through nanofunctionalization**.** In the case of aluminum, it was determined that the FCC-alpha aluminum structure would be the target phase for nucleation and a nucleant should be chosen to promote the formation of this phase. Further analysis determined that the ideal crystallographic pairs would be the Al3Zr phase and would most effectively promote heterogeneous nucleation. An ideal target composition was chosen for the nanoparticle nucleant and then assembled onto the surface of the 7075 target aluminum alloy powder, Figure 1e shows a decorated microparticle. Surface assembly ensures homogenous distribution of the nucleant within the build bed and eliminates the potential gradient microstructures. The functionalized alloy powders were then printed in a Concept Laser M2 system, a commercial additive manufacturing printer.

5 PRINTING RESULTS

The results of additively manufactured nanofunctionalized Al7075 and Al6061 can be seen in Nature, Martin et. al. (2017), however the main results are described in Figure 1 and Figure 2 [1]. Through nanofunctionalization, the microstructure is shifted from columnar to equiaxed in both an AL 7075 and 6061 alloy system. Hot cracking is completely eliminated and the resulting strength falls within the bounds of conventional wrought Al7075-T6 plate as well as substantial higher in both strength and ductility over the commonly printed additive aluminum alloy, AlSi10Mg. The stress strain curves for the tensile testing are compared in Figure 2a and in Figure 2b a strain map produced with digital image correlation (DIC) demonstrates local plasticity >30%. For consistency and to eliminate effects of processing, equivalent laser parameters were used for the alloys in this initial study. Due to the non-optimized laser parameters significant vaporization of high vapor pressure elements in

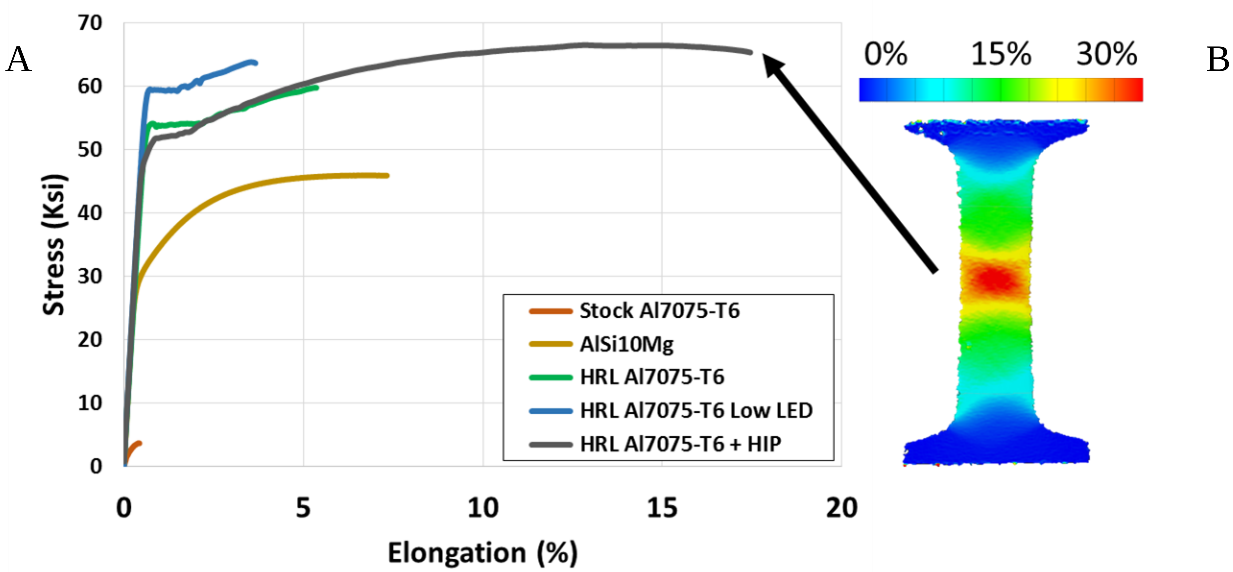

Figure 2: Nanofunctionalization of high strength alloy powders enables additive manufacturing of engineering-relevant alloys. A)Stress strain curves highlighting the mechanical properties of AlSi10Mg, Al7075 and nanofunctionalized Al7075 under different processing and post processing conditions, B)Principle strain map produced using digital image correlation indicating >30% local plasticity before fracture.

TechConnect Briefs 2018, TechConnect.org, ISBN 978-0-9988782-5-6

Al7075 (Zn and Mg) was observed and left residual porosity in the part. From this porosity, a decrease in strength from the wrought baseline was observed. Therefore, additional gains could be made in both strength and ductility to reach the upper bounds of wrought Al 7075-T6 properties. By decreasing the laser energy density and performing a hot isostatic press (HIP) treatment after the build the vaporization of the precipitation strengthening components zinc and magnesium, can be prevented and porosity can be reduced.

A decreased laser energy density resulted in a >75% retention of the strengthening elements and a 10% increase in yield and ultimate tensile strength over the nanofunctionalized Al7075 with the ALSi10Mg parameters. It was also shown in the first case, nanofunctionalized Al7075 processed with AlSi10Mg parameters, that an industry standard HIP treatment increased the elongation by 3X and the elastic modulus by 5%. Both indicating an elimination of residual porosity, which promotes early fracture and decreases the effective cross-section area during tensile testing. Through this work we have shown the a resilient pathway to equiaxed grains in crack free additively manufacture high strength aluminum with potential optimization of the scan strategies and laser parameters bring final strength closer to the wrought strength of the parent material.

6 SUMMARY/CONCLUSIONS

HRL has demonstrated a world first in in its ability to additively manufacture crack free 7075 and 6061 aluminum alloys by leveraging its unique nanofunctionalization method. Ongoing efforts will use this approach to modify non-weldable and crack susceptible alloy systems rendering them printable in additive manufacturing hardware and expand the available alloy portfolio. In addition, it has been shown while the material is robust and microstructure control and heterogeneous nucleation is accomplished primarily through the material design, processing conditions and parameter optimization will be important to achieve the highest performance. This new approach to microstructure control addresses an important requirement consistent across additive processes. It is anticipated this HRL technology will be applicable to other additive manufacturing processes such as LENS, EBM, and wire fed approaches. By expanding the available alloy portfolio for additive manufacturing HRL has made a significant contribution in enabling the adoption of metal additive manufacturing for important industries such as aerospace, automotive, consumer goods and medical devices. By being able to 3D print any metal alloy, the revolutionary benefits of additive manufacturing can be realized.

HRL is currently seeking commercialization opportunities for the metal alloy technology. Inquiries should be directed to additive@hrl.com.

Acknowledgements: We would like to acknowledge Alan J. Jacobsen, who contributed to the development of the nanofunctionalization technology, invented the self-propagating polymer waveguide technology at HRL and is the Founder and former CEO of Light Orthotics.

REFERENCES

1. Martin, J. H. et al. 3D printing of high-strength aluminium alloys. Nature 549, (2017).
2. Martin, J. H., 2015. Nanoparticle-coated multilayer shell microstructures. United States of America, Patent No. US9738788B
3. Martin, J. H. et al. , 2015. Semi-passive control of solidification in powdered materials. United States of America, Patent No. US20170021417A1.
4. Lewandowski, J. J. & Seifi, M. Metal Additive Manufacturing: A Review of Mechanical Properties. Annu. Rev. Mater. Res. 46, 151–186 (2016).
5. Frazier, W. E. Metal additive manufacturing: A review. Journal of Materials Engineering and Performance 23, (2014).
6. Basak, A. & Das, S. Epitaxy and Microstructure Evolution in Metal Additive Manufacturing. Annu. Rev. Mater. Res. 46, annurev-matsci-070115-031728 (2015).
7. Dehoff, R. R. et al. Site specific control of crystallographic grain orientation through electron beam additive manufacturing. Mater. Sci. Technol. 31, 931–938 (2015).
8. Raghavan, N. et al. Numerical modeling of heat-transfer and the influence of process parameters on tailoring the grain morphology of IN718 in electron beam additive manufacturing. Acta Mater. 112, 303–314 (2016).