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Additive Manufacturing and Testing of High Metal Content High Performance Ramjet Grains

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ADDITIVE MANUFACTURING OF HIGH-DENSITY SOLID FUELS FOR AIR-BREATHING COMBUSTION APPLICATIONS

EXECUTIVE SUMMARY

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Project Summary
Fuels with good combustion efficiency and high energy densities are needed to maximize the range and speed of future air-breathing systems. In order to achieve a higher energy density fuel, reactive metals are used as additives. In order to develop and maximize the energy density and performance, this work will leverage recent advancements in additive manufacturing (AM) to test low-density lattice structures using a new kind of 3D printing technology called liquid metal printing (LMP). LMP allows the rapid low-cost printing of aluminum alloys that can be used for producing parts for use in air-breathing systems.

This study investigated the 3D printing of aluminum lattices using LMP (Xerox ElemX) and successfully produced a number of parts with low-density infills with gradient patterns and dimensions. The study verified some of the dimensional constraints and capabilities of the commercial system, relevant in these applications such as the minimum feature size. Preliminary work with a modified nozzle system improved upon this limitation to print parts down to a feature size of 0.4 mm and produced some recommendations on further work with the system for air-breathing propulsion applications.

Keywords:
additive manufacturing, AM, 3D printing, liquid metal printing, LMP, aluminum alloy, propulsion, air-breathing

Background
Fuels with good combustion efficiency and high-energy densities are needed to maximize the range and speed of future air-breathing systems. In order to achieve a higher energy density fuel, metals are used in these applications. Fly out calculations performed by Naval Air Warfare Center Weapons Division (NAWCWD) show that these systems could increase range by up to four times as compared to regular munitions. However, achieving this is challenging, which also presents a great opportunity. Increased range and speed can have significant impact on system effectiveness at the battlefield. NAWCWD (as well as others) have a great interest in these systems.

This work will leverage recent advancements in additive manufacturing (AM). This study investigated the 3D printing of aluminum lattices using liquid metal printing (LMP). LMP is a new technology developed by Xerox and the Naval Postgraduate School was one of their first partners that had the opportunity to work with their unique high technological readiness level prototype system called ElemX. The system produces and deposits aluminum alloy droplets in a controlled way to 3D print parts rapidly. As with all new systems, the capabilities and their potential limit on part design were unknown and these were the major research questions in this study.

The study verified some of the dimensional constraints and capabilities of the commercial system, some of which can limit its use in these applications such as the minimum feature size. This work investigated the printability of a number of relevant low-density lattice structures with varying densities and feature sizes using LMP. The part dimensions were measured for comparison to the design values to assess print quality. The system resolution was also improved down to a feature size of 0.4 mm, providing new opportunities to use this system for air-breathing propulsion applications.

Findings and Conclusions

For this study, a number of lattice designs were investigated. Initial designs included regular lattices with uniform voids for simplicity. These forms had 50% void space with rhombic channels and minimum feature sizes of 0.8 mm, which is the droplet splat diameter, and it represents a single droplet. This geometry was not suitable for LMP, resulting in collapse of the channels at bottom layers.

The designs were further refined into different kinds of gyroid lattice structures with improved printability. Gyroid patterns have lower overhang angles compared to other lattices and are isotropic. Lattices with gyroid patterns could be successfully printed down to the feature size of 0.8 mm with ElemX. Lattices with gradient porosity from top to bottom could also be produced, where the void fraction was the highest at the top. Multiple identical parts (up to five) printed at the same time showed a significant deviation on part height and mass, which was discovered to be a bug in the software used. This allowed correction of this issue after an update.

A modification to the nozzle to reduce the opening size from 0.5 mm to 0.25 mm allowed a reduction in the droplet diameter, doubling of the system resolution. A new higher resolution gyroid lattice with a minimum feature size of 0.4 mm could be 3D printed using the finer nozzle.

Our results show that relevant aluminum lattice structures with low density and density gradients can be rapidly printed with no supports down to a feature size of 0.4 mm, which is a very high value reported for directed energy deposition AM approach. This length scale provides some new opportunities for using these parts in air-breathing systems and should be further investigated for direct applications in follow up studies for rapid transition. NAWCWD has great interest to test the performance of these parts and provide relevant designs for implementation.

Recommendations for Further Research

Our results showed great promise for the metal 3D printing approach proposed and implemented in this study for air-breathing propulsion applications. Lattice structures with application tailored geometries should be investigated in future studies. Further reductions in feature dimensions down to 0.1-0.2 mm can be implemented based on the nozzle modification approach employed in this study, making it comparable to powder bed fusion additive manufacturing approaches. Finally, other aluminum alloy types should be investigated that can provide optimal properties and performance for a number of components.

Acronyms

AM	additive manufacturing
LMP	liquid metal printing
NAWCWD	Naval Air Warfare Center Weapons Division