

# Architected Microlattice Materials by Self-Propagating Waveguide Processing

A. L. Corrion, E. Clough, Z. Eckel, J. Hundley, C. Roper, T. Schaedler

HRL Laboratories, LLC  
Malibu, CA 90265, alcorrion@hrl.com

## ABSTRACT

HRL Laboratories has developed a platform technology to rapidly and scalably manufacture architected lattice materials based on polymers, metals, and ceramics suitable for a variety of applications. Architected materials with periodic cellular structure exhibit unprecedented properties that cannot be achieved with conventional materials. A self-propagating polymer waveguide process invented at HRL is used to additively manufacture architected polymer lattice structures 100-1000x faster than conventional 3D printing approaches such as stereolithography [1]. HRL's process is inherently scalable to large areas in addition to offering high throughput. Polymer formulations for high-strength, low-density sandwich panel cores have been developed as well as elastomeric formulations for padding and protective applications with improved impact protection. Polymer lattices formed using HRL's process can also be processed into hollow metallic structures such as ultralight metallic microlattices that are currently the world's lightest metal [2]. Such metallic structures can be used for a range of lightweighting applications in aerospace and automotive industries [3]. Finally, a recent breakthrough at HRL has enabled fabrication of ceramic lattices using the same platform technology with pre-ceramic polymers [4]. These ceramic structures can withstand temperatures up to 1700 °C, making them suitable for a variety of high-temperature and extreme environment applications including jet engine and rocket propulsion. HRL is currently pursuing commercialization of the platform technology used to produce these materials.

**Keywords:** microlattice, cellular materials, architected materials, additive manufacturing, breathable padding

## 1 INTRODUCTION

The emerging ability to add the element of architecture, or designed structure, to materials to enhance their performance is at the forefront of a new paradigm of materials science. Additive manufacturing is enabling the realization of architected structures beyond the constraints of traditional manufacturing techniques. However, inherent limitations on speed and throughput of these approaches can be cost-prohibitive for most applications. At HRL, we have developed a method of manufacturing three-dimensional lattice structures using self-propagation of photopolymers rather than layer based additive

manufacturing, making it both highly scalable to large dimensions and capable of supporting high throughput. Polymer lattice structures are fabricated and can be converted to a variety of other materials, including ceramics and metals, to achieve a wide range of properties. Depending on their architecture and composition, the lattice structures offer a unique combination of properties, including:

- Open-cellular geometry
- Relative density between < 1% to 30%
- Energy absorption / impact protection
- Low density (world's lightest metal [2])
- Tailorable in-plane architecture and density
- Fluid, air, and light penetration
- Biological compatibility
- Periodicity / diffractivity
- Meso-scale manufacturability (~10  $\mu\text{m}$  - >1 mm)
- High temperature stability (ceramics [4])
- Manufacturability/scalability/throughput (>1  $\text{m}^3/\text{min}$ )

Some of the applications of interest for leveraging these properties include:

- Lightweight breathable protective padding
- Lightweight high-stiffness sandwich panels
- High-temperature ceramic filters
- High-temperature extreme environment applications (rocket propulsion, jet engines, etc)
- Bio-scaffolds
- Blast protection
- Medical paddings
- Thermal management (heat exchangers [5,6])

among others. HRL is interested in collaboration or partnership opportunities aimed at commercialization of our microlattice technologies in these or other applications.

## 2 MANUFACTURING PROCESS

Figure 1 shows a schematic of the microlattice fabrication process. A two-dimensional mask with a pattern of apertures covering a photomonomer reservoir is exposed to collimated UV light. Within the photomonomer, self-propagating photopolymer waveguides originate at each aperture in the direction of the UV collimated beam and polymerize together at points of intersection. By

simultaneously forming an interconnected array of these fibers in three-dimensions and removing the uncured monomer, unique three-dimensional lattice-based open-cellular polymer materials can be rapidly fabricated.

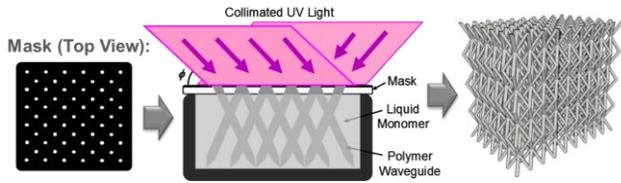


Figure 1: Schematic showing the polymer microlattice fabrication process. A patterned mask is placed over a bath of photopolymer, and collimated UV light penetrates the mask to cure the polymer. Due to a waveguide effect upon curing, the UV light propagates throughout the thickness of the bath along a straight line, creating a lattice member.

Figure 2 shows time-lapse Schlieren photography of a polymer microlattice during curing. Members begin to form within several seconds of exposure to UV light. This lattice structure was formed within 18 seconds and typical total exposure times are less than one minute. Following exposure, the solid lattice is removed from the liquid photopolymer bath. The remaining liquid photopolymer can be recycled for subsequent exposures.

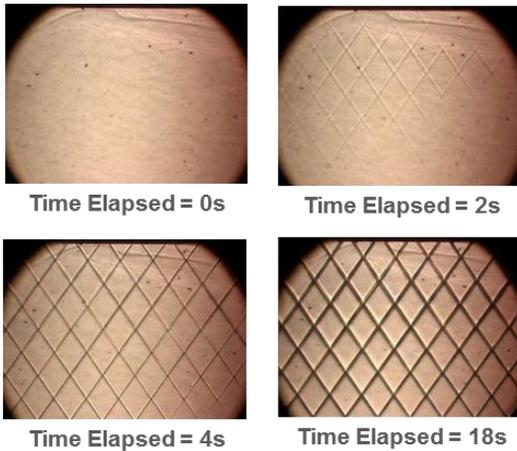


Figure 2: Time lapse photography showing formation of a polymer lattice upon exposure to UV light. Time to lattice formation is typically <1 minute.

We have investigated the limits of this process and with our current UV exposure capabilities, we can fabricate open-cellular materials with lattice member diameters ranging from ~10 μm to > 1 cm with a relative density (or solid volume fraction) between 2 % and 30%. The overall material thicknesses can range from 100 μm to over 25 mm

in a single exposure. Maximum achievable material thickness is dependent on the diameter of aperture, with smaller apertures propagating over shorter distances. Thicker structures can be built up through successive exposures. The lattice member angle with respect to the exposure plane can be controlled between 50° - 65° for directly intersecting waveguides as well as vertical, or near vertical members (90°).

### 3 POLYMER MICROLATTICE

Figures 3-5 show various forms of polymer microlattice produced using HRL’s proprietary process. The lattice member diameter, spacing, and angle can be tailored to achieve targeted properties. In addition, the in-plane architecture can be varied, with variable density and/or member diameter, and key features such as through-holes can be built-in to minimize post-processing requirements. Curvature can be added to the truss structures following formation by forming over a mandrel and post-processing thermal or UV curing.

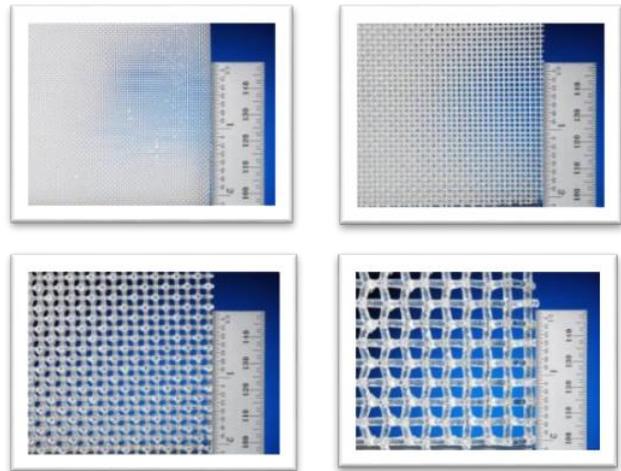


Figure 3: Photographs of polymer microlattice showing variable lattice member dimension and in-plane variation of density. All four lattices shown have the same porosity of 90%.

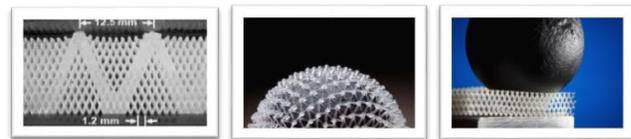


Figure 4: Polymer microlattices formed using HRL’s proprietary technique, showing hierarchical architecture (left), introduction of post-processing curvature (middle), and impact energy absorption (right).



Figure 5: Viscoelastic polymer microtruss suitable for lightweight breathable padding.

Polymer microlattice materials can be implemented as sandwich panel core material, as shown in Figure 6, with a wide range of skin options from metals to composites. In such applications, microlattice cores have been shown to meet or exceed the performance of competing honeycomb cores with the added benefits of open cellular architectures, tailored geometries for added functionality and mass savings and more cost efficient shaping.



Figure 6: Lightweight energy-absorbing sandwich panel formed using polymer microlattice.

#### 4 POST-PROCESSING APPROACHES

Polymer microlattices can be converted to a variety of other materials, including metals and ceramics. Figure 7 shows hollow metallic microlattices produced at HRL. The polymer lattice can be used as a template or scaffold for electro and electroless plating or thin-film deposition [7]. After deposition, the polymer is chemically removed or burned away leaving behind a hollow, thin walled lattice structure. Ultralight metallic microlattices have been created at HRL in this way, as shown in Figure 8. Alternatively, lost-wax casting of the polymer can be used to generate solid metallic lattice structures, as is demonstrated in aluminum in Figure 7.

In addition, HRL has demonstrated a novel method for creating fully dense ceramic cellular structures through the direct conversion of a pre-ceramic polymer microlattice. The polymer structure is pyrolyzed creating SiOC microlattices, as show in Figure 9. The resulting material is capable of withstanding temperatures of up to 1700 °C and demonstrated 10x compressive strength over conventionally manufactured ceramic cellular materials, These properties make it suitable for a variety of high-temperature and

extreme environment applications including jet engine and rocket propulsion.

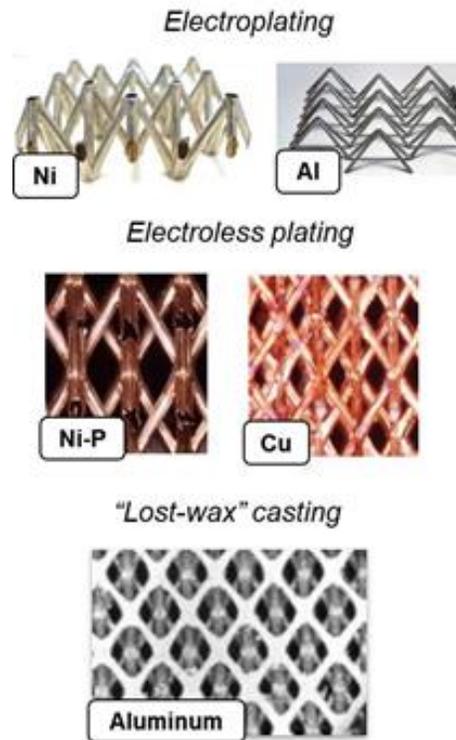


Figure 7: Hollow metallic microlattices created through plating of polymer structures and removal of the polymer core, as well as solid aluminum lattice created through lost wax casting.

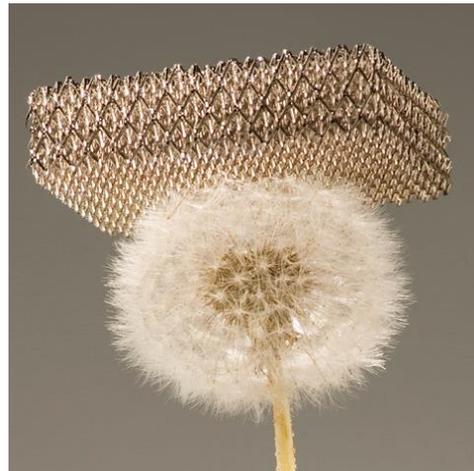


Figure 8: Ultra-light metallic microlattice.

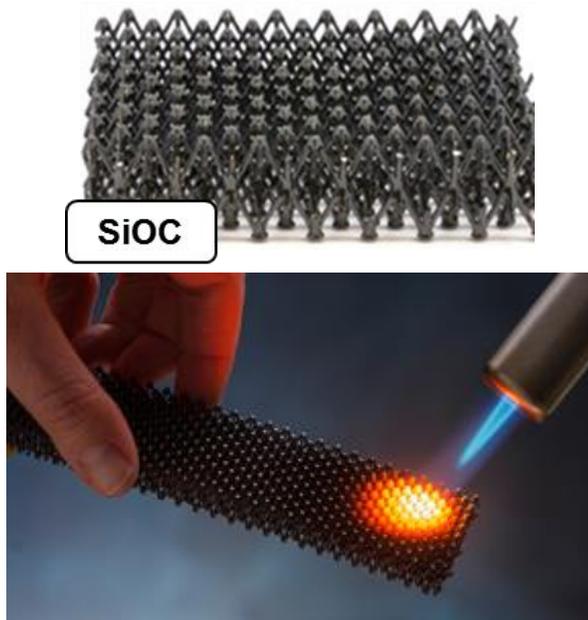


Figure 9: High-temperature-stable SiOC lattice generated through direct conversion from a pre-ceramic polymer lattice.

## 5 SUMMARY/CONCLUSIONS

HRL has developed a platform manufacturing technology for open-cellular lattice structures. HRL's microlattice fabrication technology occupies an ideal space in the landscape of available methods for making ordered open-cell structures. This technology has the potential to form a wide range of free-standing three-dimensional polymer structures based on linear rod-type elements. The fabrication process is directly analogous to stereolithography in that a bath of liquid resin is exposed to UV light followed by removal and recycling of the remaining uncured resin. The major differences are the speed of polymerization to create the three-dimensional structure and the types of structures that can be generated. For stereolithography, the three-dimensional structure is sliced into two-dimensional sections that are written layer-by-layer in a serial fashion. This process is time consuming (typically 4-12 hours) but allows for near complete freedom of form. HRL's optical waveguide process generates all elements of the structure in parallel with a single exposure step (typically lasting < 1 minute), but architectures are constrained to the linear extension of the mask used to pattern the elements. The optical waveguide method combines aspects of solid free-form manufacturing methods, such as stereolithography, with the scalability of mechanical methods, such as deformed perforated sheet manufacturing, to form lattice-type cellular materials. The manufacturing method is therefore both inherently scalable and high-throughput, with a manufacturing speed 100-1000x faster than conventional 3D printing approaches.

Base polymer lattice structures created using HRL's technology can be converted to metallic and ceramic structures through a number of post-processing approaches. The resulting polymer, metallic, and ceramic materials are appropriate for a variety of applications, including lightweight breathable protective padding, sandwich panel cores, high-temperature extreme environment applications, and bio-scaffolds, among others.

HRL is currently seeking commercialization opportunities for the microlattice technology. Inquiries should be directed to [innovation@hrl.com](mailto:innovation@hrl.com).

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

## REFERENCES

- [1] A.J. Jacobsen, W.B. Carter and S. Nutt, *Adv. Materials* 19, 3892 (2007)
- [2] T.A. Schaedler, A.J. Jacobsen, A. Torrents, A.E. Sorensen, J. Lian, J.R. Greer, L. Valdevit and W.B. Carter, *Science* 334, 961 (2011).
- [3] E.C. Clough, J. Ensberg, Z.C. Eckel, C.J. Ro and T.A. Schaedler, *Int. J. of Solids and Structures* 91, 115 (2016).
- [4] Z.C. Eckel, C. Zhou, J.H. Martin, A.J. Jacobsen, W.B. Carter, T.A. Schaedler, *Science* 351, 58 (2016).
- [5] C.S. Roper, R.C. Schubert, K.J. Maloney, D. Page, C.J. Ro, S.S. Yang, A.J. Jacobsen, *Adv. Materials* 27, 2479 (2015)
- [6] K. J. Maloney, K. D. Fink, T. A. Schaedler, J. A. Kolodziejska, A. J. Jacobsen, C. S. Roper, *Int. J. Heat Mass Transfer*, 55, 2486 (2012).
- [7] K. J. Maloney, C. S. Roper, A. J. Jacobsen, W. B. Carter, L. Valdevit, T. A. Schaedler, *APL Mater.* 2013, 1, 022106.