# STACK FORGING™

## DIGITAL FABRICATION FOR COMPLEX ALUMINUM COMPONENTS

An Advanced Manufacturing Technology

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September 2024

### THE COMPANY

Alloy Enterprises is a US-based company that designs and fabricates complex aluminum components, such as cold plates and fluid manifolds. Its applications span the semiconductor, electronics, heavy equipment, photonics, and defense industries.

### OUR PROCESS

Stack Forging™ is a novel manufacturing method that enables single-piece construction of components with complex internal geometries that cannot be manufactured through traditional methods. This technology allows for the design of cost-effective components with superior thermal and mechanical performance, reduced lead time, and no minimum order quantity.

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# Abstract

Manufacturers seek to source complex components with superior performance, cost-effectiveness, and a flexible capacity that can scale into production. Finding a value-added supplier that can collaborate with the manufacturer through design, qualification, and production to provide superior performance on a short timeline is challenging.

Alloy Enterprises has developed Stack Forging™, a novel fabrication process, to address this need. Stack Forging combines technological advancements in 3D geometry preparation software, laser cutting, printing, and diffusion bonding of a custom, sheet-based feedstock to produce fully dense complex components with superior material properties. Specifically, Alloy supplies finished end-use aluminum 6061-T6 components to its customers and has other metals in development. Alloy's components are single-piece construction with no additional assembly, eliminating the need to invest in additional tooling and reducing assembly costs. This helps manufacturers ramp up production and accelerate time to market with all the benefits of additive manufacturing but at the cost and scale of more traditional manufacturing methods. This paper outlines the process, material properties, and capabilities of Stack Forging. Examples of applications for which the process is well-suited are highlighted throughout.

# Introduction

*How Alloy is Different*. Alloy Enterprises provides customers with end-use components for thermal management, fluid handling, and structural applications. Alloy leverages the layer-by-layer cutting inherent to its Stack Forging process to create complex internal geometries and channels that cannot be manufactured through traditional methods. This technology enables manufacturing components with greater thermal performance, reduced lead time, and no minimum order quantity while providing cost-effective solutions for customers.

*How to Work With Us*. Customers can engage with Alloy to manufacture an existing component, work with Alloy through value-added engineering services to design a new component, or anything in between. Design services can be extended to include simulation, thermal performance testing, and CT scanning. Alloy also offers customers a variety of post-processing options to streamline the delivery experience, such as machining, disc finishing, tumbling, or plating.

Alloy's manufacturing facilities are located in Burlington, MA. They are on track to certify their Quality Management System to ISO 9001 by Q2 2025. Alloy also conducts certified inspections and materials testing onsite.

Figure 1:  Images from Alloy’s Production facility.

# Solutions

Alloy partners with customers who are looking for a supplier of end-use components. Customers choose Alloy for superior performance, reduced lead time, and cost-effectiveness.

## *Performance*

Alloy’s Stack Forging process enables the fabrication of application-specific components that can easily outperform industry-standard options. Alloy’s components are fully dense, vacuum-tight, and 6061. Combining 6061 material properties and complex geometry can improve thermal performance, increase strength-to-weight, reduce part count, and increase mixing efficiency.  Alloy’s broad library of unique patented infill and channel geometries allows design engineers to tailor their components' thermal and flow performance to meet demanding requirements. Finally, single-piece construction eliminates catastrophic failure points such as brittle brazing joints, leaky o-ring seals, and temperature-sensitive epoxy layers.

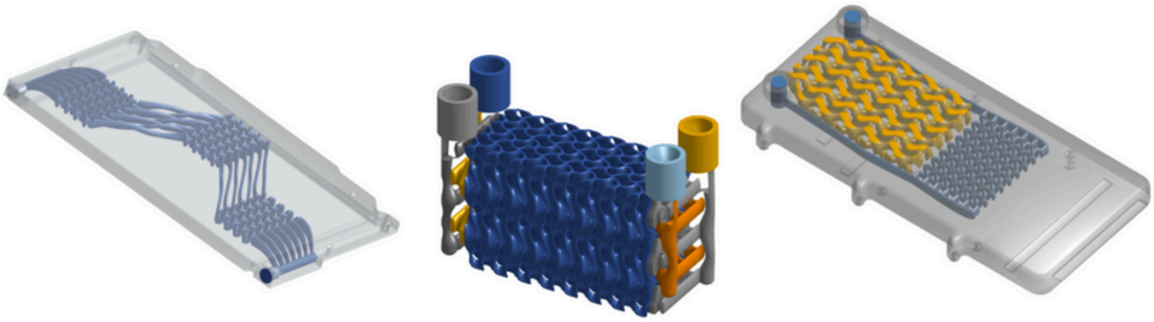

Figure 2:  Renderings of high-performance thermal management components fabricated with Stack Forging. Localized GPU cooling with oscillating micro-lattices (left). Liquid-liquid cross-flow heat exchanger using gyroid fins (centre). GPU PCIE card cooler with an oscillating micro-lattice cooling section in blue and gyroidal thermal isolation of inlet and outlet fluid in yellow (right).

## Lead Time Reduction

Stack Forging enables single-piece construction of components that otherwise would be made in multiple parts, requiring numerous assembly steps. Part consolidation reduces supply chain risk and lowers assembly and inventory holding costs. By avoiding multiple process steps, manufacturers can launch replacement components or new products in the market sooner while reducing the overall risk in their systems. For example, cold plates are commonly CNC machined as two plates and vacuum brazed. Customers have shared that expected lead times for vacuum brazing range from 18 to 50 weeks. Alloy's typical lead time for fabricating a similar cold plate is 6-8 weeks.

Tooling avoidance is another area where Alloy significantly reduces customer lead times. Alloy's customers have indicated that tooling lead times for cast parts can exceed 12 months. Stack Forging is entirely digital with no setup time. Complex components do not need to take longer due to the development of multiple tools.

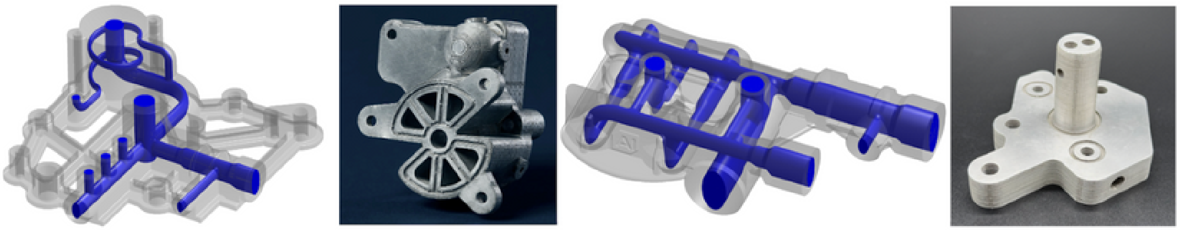

Figure 3: Examples of manifolds and pump housings developed and fabricated with Stack Forging to reduce lead time. Components of this complexity typically require multi-piece tooling, casting, impregnation, and machining.

## Cost-Effective

Stack Forging is a more cost-effective solution for manufacturers through tooling avoidance, part consolidation, or reducing inventory holding costs. Tooling can be expensive and may not be a reasonable option for low-volume components; permanent mold tooling costs typically range from $10-90k, and die-casting tooling costs usually range from $60-500k. Multiple parts that come together in separate steps also increase the overall component cost; for example, Alloy can fabricate the cold plate shown in Figure 4 below in a single piece, compared to the original method of machining and vacuum brazing two pieces together to achieve the internal channels. The two-piece assembly included costs for multiple vendors and additional shipment costs to transport the components to different facilities.

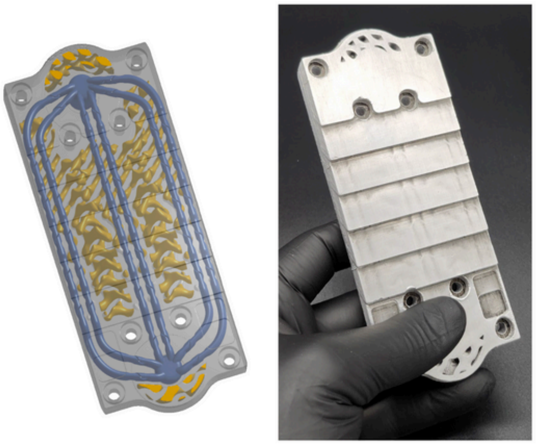

Figure 4:  An example of a lightweight 6061-T6 cold plate component. CAD rendering with gyroid infill in yellow and spiral cooling channels in blue (left). Finished component (right).

In addition, Alloy can support design changes or product families with different configurations without adding to lead time or cost. Furthermore, by fabricating on-demand and providing customers with the right components when needed, Alloy helps customers avoid inventory holding costs associated with larger batch production and shipping from overseas.

# Process Overview

Alloy has developed Stack Forging - a digital fabrication process that produces fully dense components with complex geometries, no porosity, and enclosed internal channels. Alloy's end-to-end process provides part consolidation with single-piece construction, no tooling, and no additional assembly.

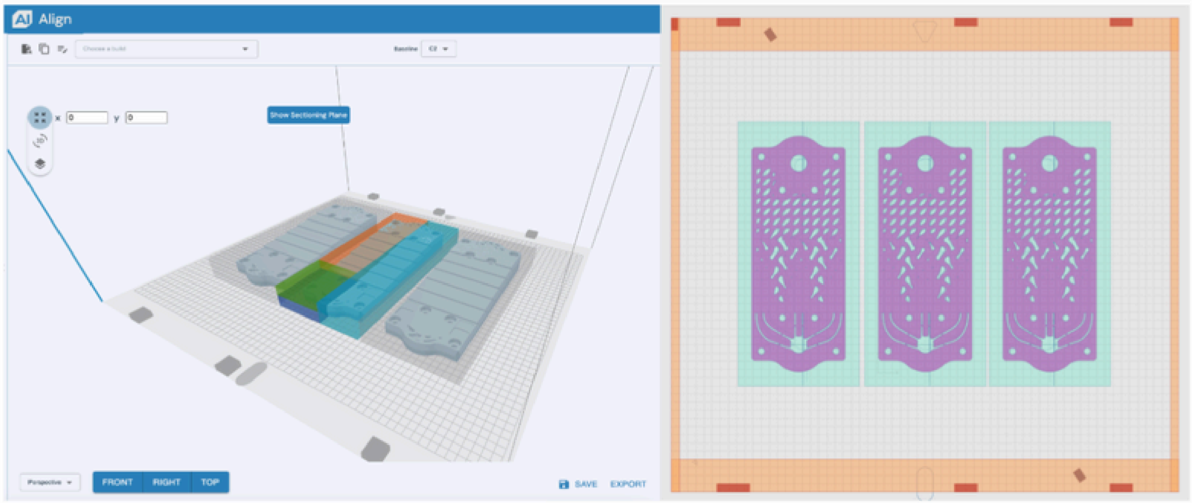

Figure 5: Alloy's 3D build configuration software Align (left) and 2D sliced output (right).

The Stack Forging process starts with a 3D CAD model. This can be supplied by the customer or developed by Alloy's Applications Engineering team, which provides design and simulation services. The model is oriented and nested into a 3D build volume using Alloy's Align application (Figure 5). It is then optimized for support removal and discretized into layer-based machine instructions before being uploaded to the first of three machines. The Construct machine houses sheet-in-feed from a feedstock coil, laser cutting, inhibition printing, and stacking (Figure 6). The sheets are first cut with a laser that traverses the perimeter of the parts. The laser can also remove material to create internal channels and small voids. Next, an inhibition agent is selectively printed onto the surface to create an inhibition layer in designated areas of the design, which acts similar to a mold release. The cut and inhibited sheets are stacked and registered on a caddy to ensure tight tolerances.

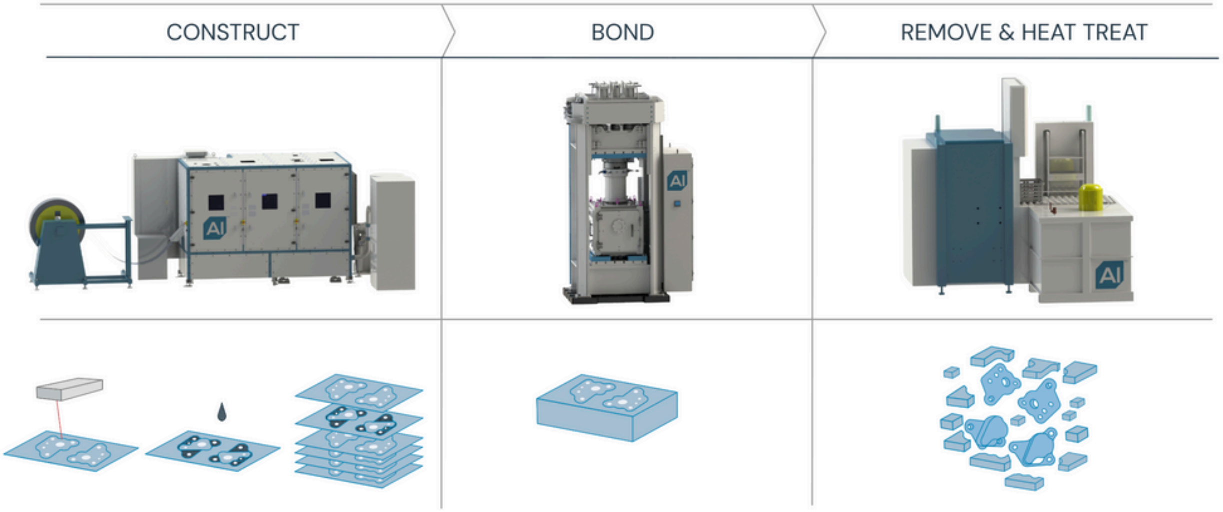

Figure 6: Alloy's Stack Forging Process Machines.

The caddy is then loaded into the Bond machine. The sheets are solid-state diffusion-bonded together using heat, pressure, and a controlled atmosphere to form a solid block, less any holes or internal channels. There are no laminates or adhesives; the process bonds metal-to-metal and does not melt or sinter, thus preserving the grain structure. Multiple parts can be nested or packed into the build volume to lower cost. After bonding, the support material is removed and recycled, and the fully dense 6061 components are heat-treated for strength and hardness.

The current process utilizes a 350 μm sheet feedstock. Other thicknesses within a range of approximately 150 - 500 μm are also possible on the existing machines. The feedstock comprises multi-layered or cladded aluminum alloys, similar in form factor to a brazing sheet. Full density is achieved during bonding, but the build volume remains striated with the different alloys (Figure 7).

A solutionizing heat treatment diffuses the alloying elements to achieve a global composition of the desired alloy, 6061. The bonds are produced by solid-state diffusion bonding, resulting in a metal-to-metal bond that preserves the grain structure. Because there is no melting, Alloy's process can create wrought alloys matching properties without concern for the complexity of print parameters affecting melt-pool dynamics. Therefore, the finished component inherently has the secondary and tertiary benefits of the established material, such as corrosion, conductivity, and post-process compatibility. This makes new material development for this platform lower risk than other emerging manufacturing technologies.

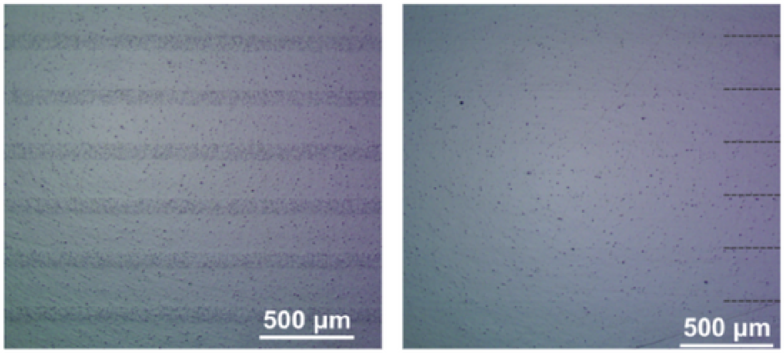

Figure 7: Micrograph of a bonded component's XZ[1] plane showing seven bonded feedstock sheets. The striations between the different alloys' precipitates indicate the original bond interfaces (left). A homogeneous micrograph of the XZ plane after homogenization of seven sheets with no bond lines evident (right).

Layers are produced using perimeter laser cutting, allowing for higher throughput than current melting or fusion-based additive manufacturing methods. Alloy's feedstock supply chain currently produces material in 60-ton runs and has been fully qualified. Alloy's current production machines have a build volume of 300 x 250 x 200 mm. Alloy has also worked with customers to manufacture end-use components larger than this build volume when pieces of that component can be produced modularly.

# Material Properties

## *Metallography & Density*

Density has been measured with a helium gas pycnometer at Covalent Metrology in Sunnyvale, CA. Specifically, an Anton Paar Ultrapyc 5000 was used with a microcell of 4.5 $cm^3$. The provided test accuracy was 0.1% and a repeatability of 0.05% using helium flow at 18 psi and 20 °C. The relative density was measured at 100.23%. Six samples from three build volumes were sent for pycnometer testing, all measuring over 100%.

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[1] The axis perpendicular or normal to a flat sheet is referred to as "Z", the "X" and "Y" axes are in-plane with a sheet. The "XZ" plane shows the cross-section of bonded layers.

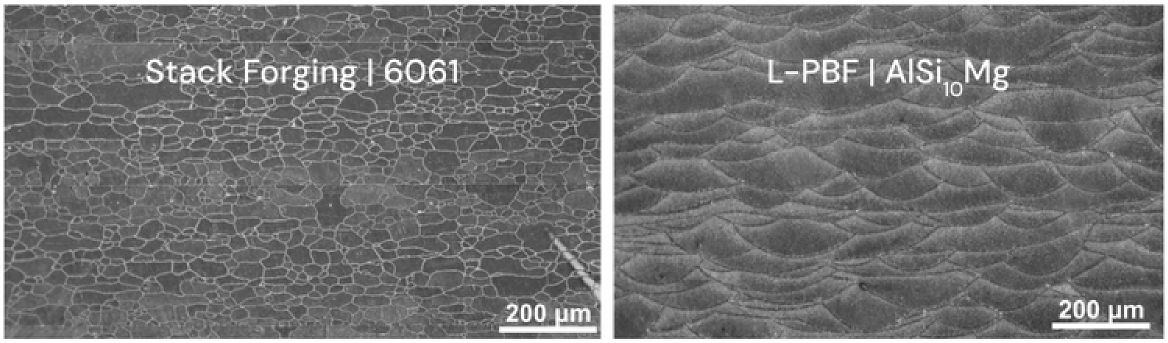


Figure 8: An etched cross-section along the XZ plane of an Alloy Stack Forged component (left). An etched cross-section of a component fabricated with laser powder bed fusion (right).

Metallography has been used extensively to verify density. A typical etched micrograph is shown in Figure 8 (left). The grain structure is preserved through the bonding and heat treatment steps. Bond lines can be observed with a similar thickness to grain boundaries. The bond lines also behave as grain boundaries when they fail during mechanical testing, failing ductility and necking across several layers. Measurement of pores per inch or percent porosity is impossible since pores are not observed. An example of laser powder bed fusion 3D printing with aluminum alloy AlSi$_{10}$Mg produced by Xometry is shown in Figure 8 (right). The grain structure in L-PBF is a direct result of the laser scan tracks from the printing process. Print process parameter variation across geometries and builds can change the grain structure and, thus, the material properties [1].

## *Composition*

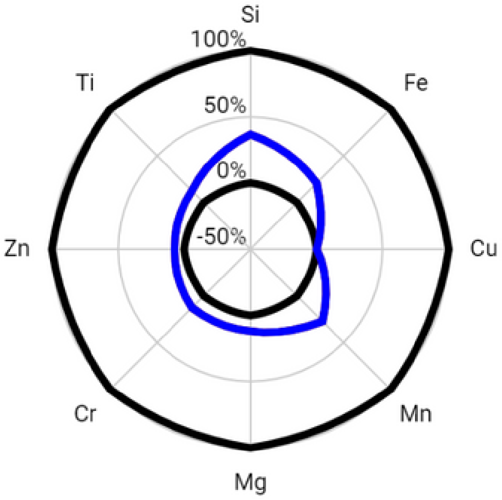


Figure 9: Radar chart of OES composition analysis of a finished part, Alloy Enterprises in blue, 6061 composition range in black.

Tensile Testing Metallurgical Laboratory in Cleveland, OH, measured global composition using optical emission spectroscopy (OES). A radar chart demonstrates how the composition lies within the minimum and maximum range of the common alloying elements for 6061 (Figure 9), indicating that the composition is within specification limits for 6061 [2]. The measurement was taken on the XZ plane across several layers, and the spot size was several millimeters in diameter.

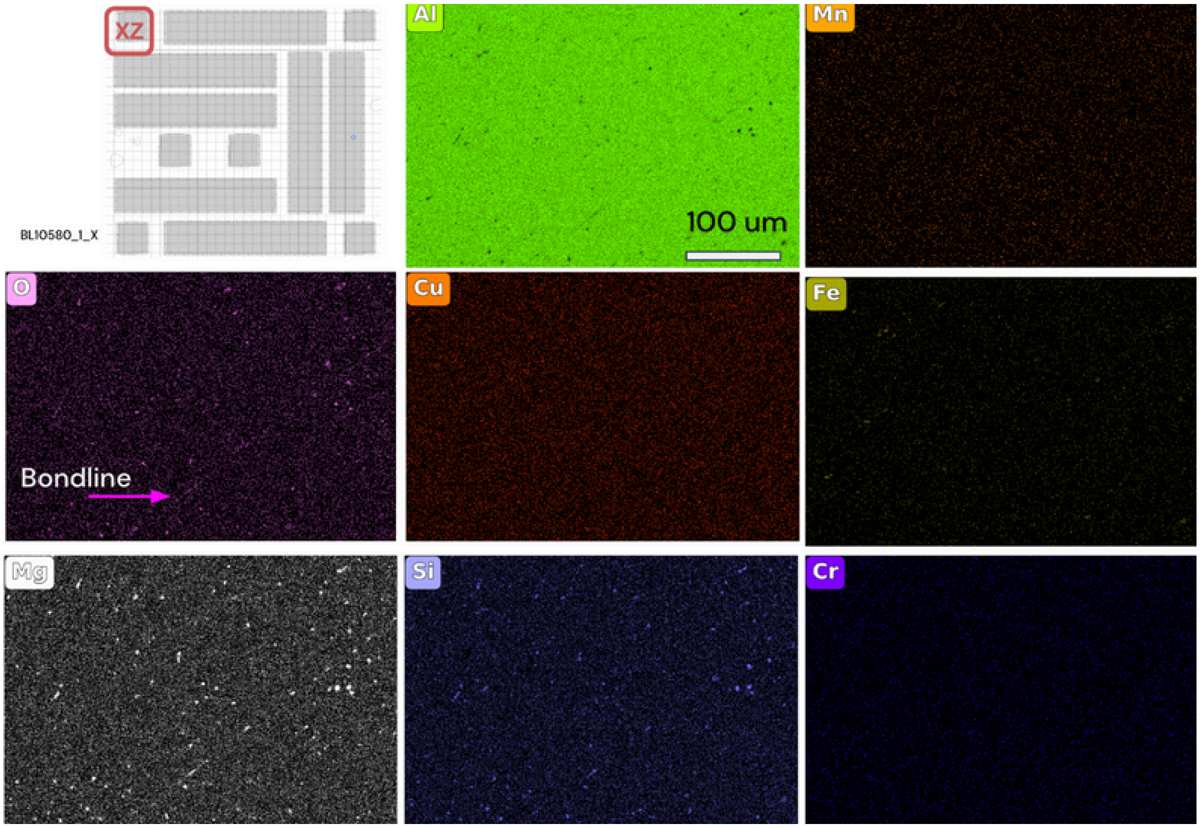


Figure 10: EDS maps of the XZ plane taken from the top left corner of a build.

Composition maps were collected with a scanning electron microscope (SEM) with an energy dispersive spectroscopy detector (EDS) at 15 kV accelerating voltage. Specimens were prepared at Alloy, and Covalent Metrology performed the measurements in Sunnyvale, CA. Maps were collected from three separate builds and three different areas within those builds. A faint bond line can be seen in the XZ and YZ planes as a minor concentration of oxygen and magnesium. The remaining chemical distribution of the matrix was uniform across all samples, with the typical intermetallic precipitates expected to be found in 6061-T6 (Figure 10), such as $Mg_2Si$ and iron/manganese phases. This was further confirmed with local SEM images and EDS analysis.

## *Mechanical Testing*

Alloy performs tensile testing following ASTM E8. The tensile properties are presented in Figure 11 using the mean of all samples and +/- one standard deviation. Specimens were machined to size at Alloy, and final mechanical testing was performed on an Instron dual-column testing system, Model 34TM-50, with a 50 kN load cell. A model 2630 extensometer was used to measure elongation. Yield stress is calculated using the 0.2% offset method. The tensile bar diameter was 4 mm, and the gauge length was 20 mm - incorporating 56 sheets within the gauge length. The Z tensile properties represent 115 samples from four build volumes. The ultimate tensile strength (UTS) was 319.7 +/- 8.5 MPa, the yield stress was 245.9 +/- 6.5 MPa, and the elongation at break was 13.1 +/- 2.7%. The X/Y data represents 13 samples from six build volumes fabricated in either the X or Y direction. The results showed a UTS of 320.1 +/- 9.7 MPa, yield stress of 248.8 +/- 11.3 MPa, and an elongation at break of 18.9 +/- 2.8%.

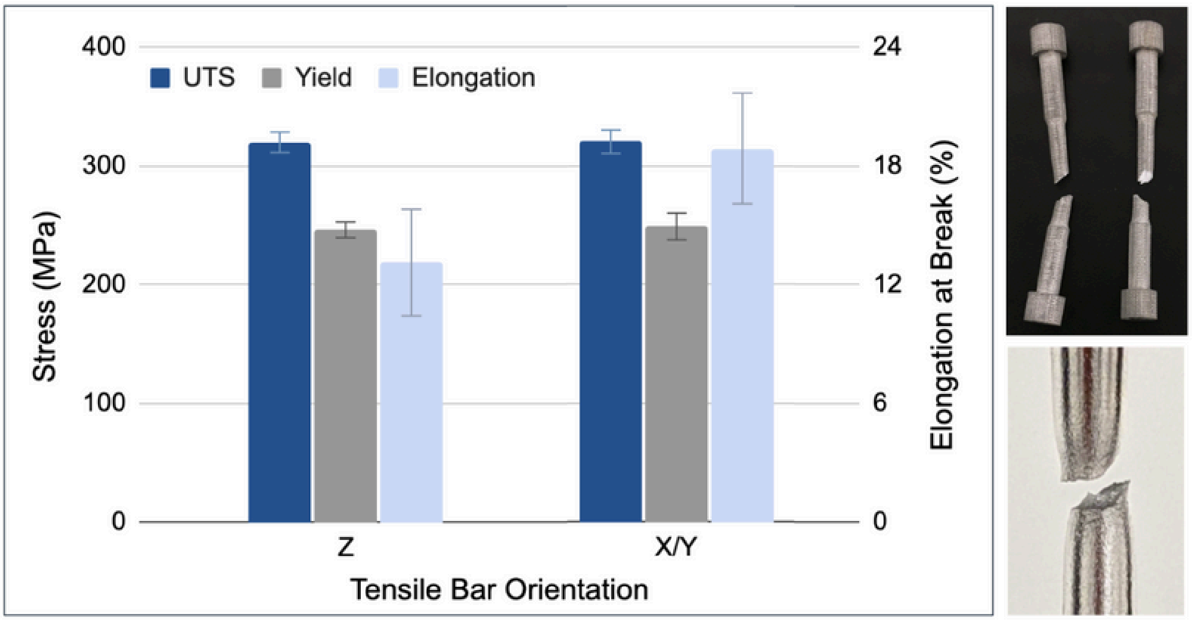


Figure 11: Tensile test properties in Z and X/Y (left). As-built tensile bars with ductile failures (top right). A machined tensile bar failed after necking with a characteristic cup/cone failure (bottom right).

Alloy's 6061 material properties are isotropic in strength and yield. The material properties exceed the 6061 standard [3] of 310 MPa in UTS but have a yield stress slightly lower than 276 MPa. If customers need these properties further refined, the T6 heat treatment can be tuned. The yield stress drastically outperforms die-casting alloy A380, which has a 160 MPa yield stress standard and 3.5% elongation. Alloy continues to work toward isotropic properties for elongation at break. However, both the as-built (printed) tensile bars and machined tensile bars fail after necking and fracturing across several bond lines (Figure 11).

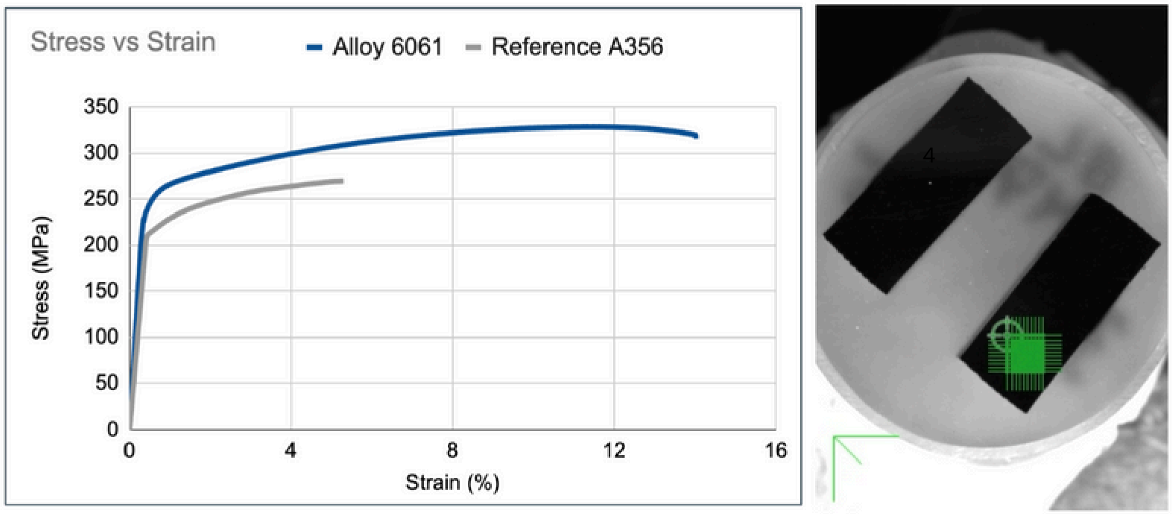


Figure 12: An example stress-strain curve for Alloy's 6061 and an investment casting alloy, A356 [4] demonstrating superior elongation at break (left). Image of XZ plane specimens prepared in a puck and polished for microhardness testing (right).

Microhardness testing via indentation with a Struers DuraScan model indenter was used to measure the Vickers hardness across the bond lines. In one experiment, the stylus measured hardness at a 45° angle to the bond line in a 10 x 10 grid for a total of 100 measurements. No variation in hardness was detected along the bond lines, and the mean hardness was 118.5 +/- 2.4 HV standard deviation.

Fatigue testing was performed at Element Materials Testing Laboratory in Wixom, MI. A total of 16 specimens were tested across three build volumes. Z-axis cylindrical specimens with a 6 mm diameter were machined and tested at room temperature at a fatigue ratio of -1. Reference data from MIL-HDBK-5J January 2003 [4] for 6061-T6 are also plotted for comparison (Figure 13). Stress amplitude was varied from 75 - 250 MPa for specimens from each of the three build volumes. Samples were allowed to "run out" at 1E+07. The results indicate that Alloy's Stack Forged 6061 behaves as wrought 6061 would in fatigue.

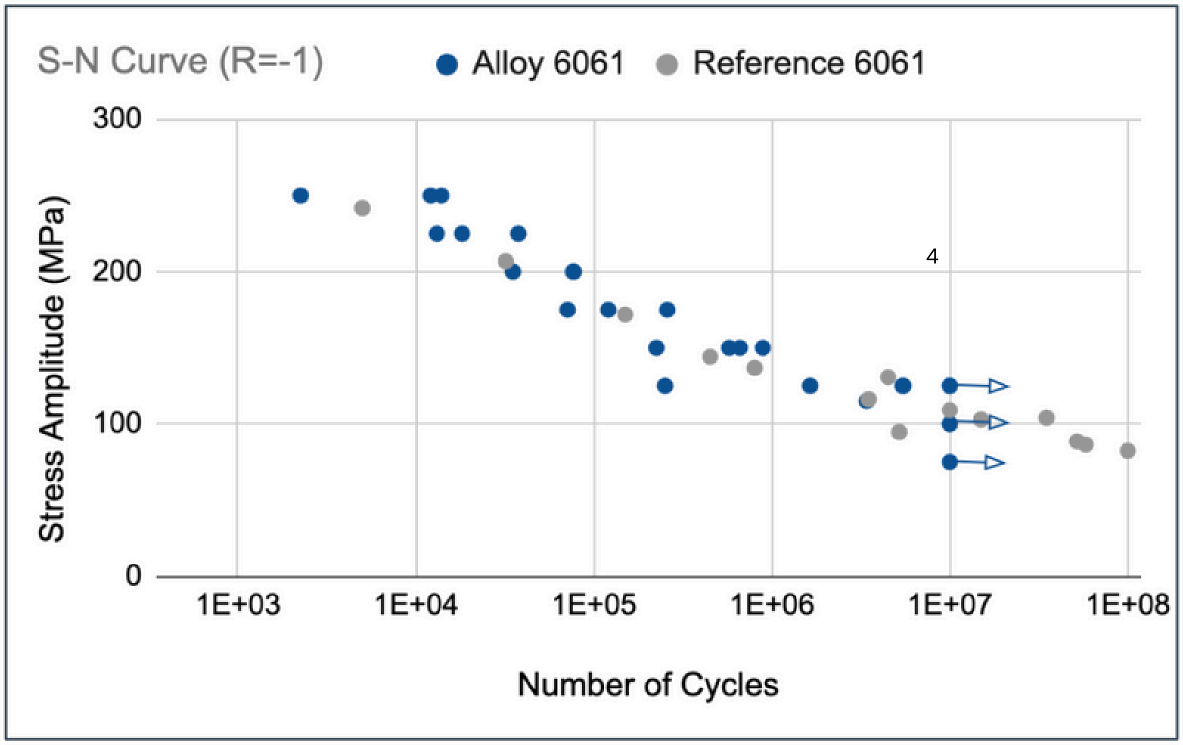


Figure 13: S-N curve with a fatigue ratio of -1 for 16 samples with results for Alloy's 6061 material and a Mil-spec reference for comparison. Arrows indicate tests that were allowed to "run out."

## *Thermal Conductivity*

Thermal conductivity was determined by the flash method according to ASTM E1461 [5] by Edward Orton Jr. Ceramic Foundation in Westerville, OH. Two specimens in each X, Y, and Z were tested. The average value for these tests was 187 +/- 4.7 W/mK. The Alloy specimens' thermal conductivity was higher than standard 6061's of 167 W/mK. This is likely because the composition of a finished part is on the lower end of the alloying element content for 6061.

Most casting aluminum alloys have a tradeoff between thermal conductivity and mechanical strength. For example, A380 has a yield stress of 159 MPa, which is high for common cast alloys, but a thermal conductivity of only 109 W/mK. Whereas DX17, a die-cast alloy with similar thermal conductivity to 6061, has a yield strength of less than 117 MPa. $AlSi_{10}Mg$, a common Powder Bed Fusion aluminum alloy, has a thermal conductivity of just 105 W/mK in the as-manufactured state. Alloy's results in this area eliminate the need for these compromises with a yield strength of 246 MPa and a thermal conductivity of 187 W/mK.

## *Leak Testing*

Four single-phase liquid cooling plates were designed and fabricated using Stack Forging for a semiconductor processing application (Figure 14). These plates were leak tested by Advanced Leak Detection, Inc. in Milford, NH, with an Adixen by Pfeiffer Mass Spectrometer calibrated to 6.2x10-8 STD. cc/sec. of helium and processed in conformance with the requirements, specifications, and drawings. The leak rate at the time of testing was <1x10-9 STD. cc/sec. of helium.

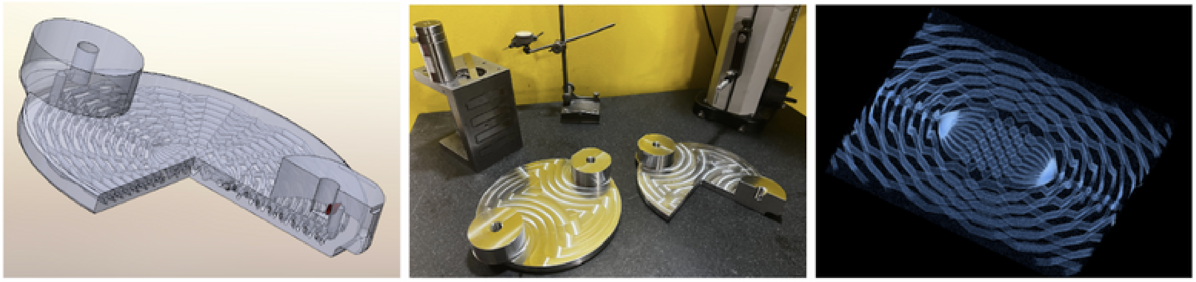


Figure 14: Single-phase liquid cooling plate for a semiconductor process application. Transparent CAD rendering (left). Fabricated, post-process machined, and sectioned (center). CT scan of the internal cooling channels in a Stack Forge component (right).

## *Length-scales*

Stack Forging is categorized as an advanced manufacturing process because it combines additive and subtractive manufacturing. As a result, the process spans many length scales. Intricate channels and features down to 200 μm are possible. At the same time, large features up to 300 mm are fabricated very quickly. As a result, Stack Forging can be leveraged to localize small features among large components. An example component is shown in Figure 15. With additional development, the Stack Forging process can span from 10 μm to 1 m.

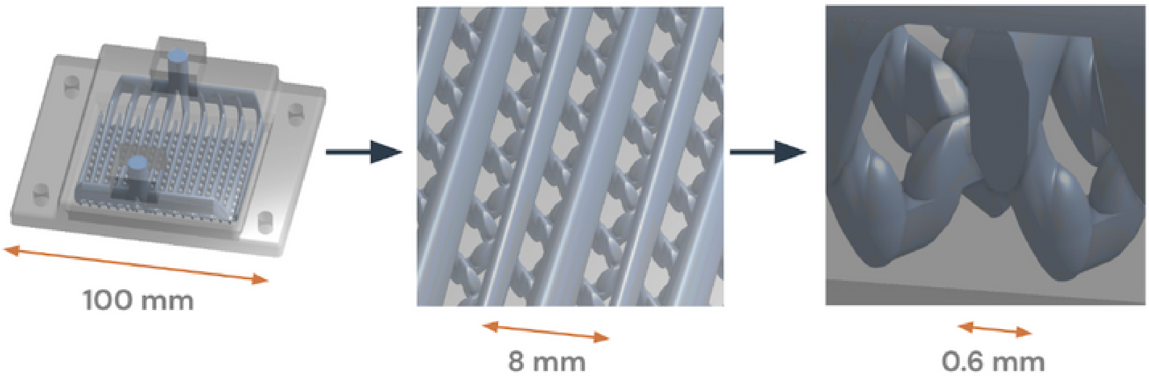
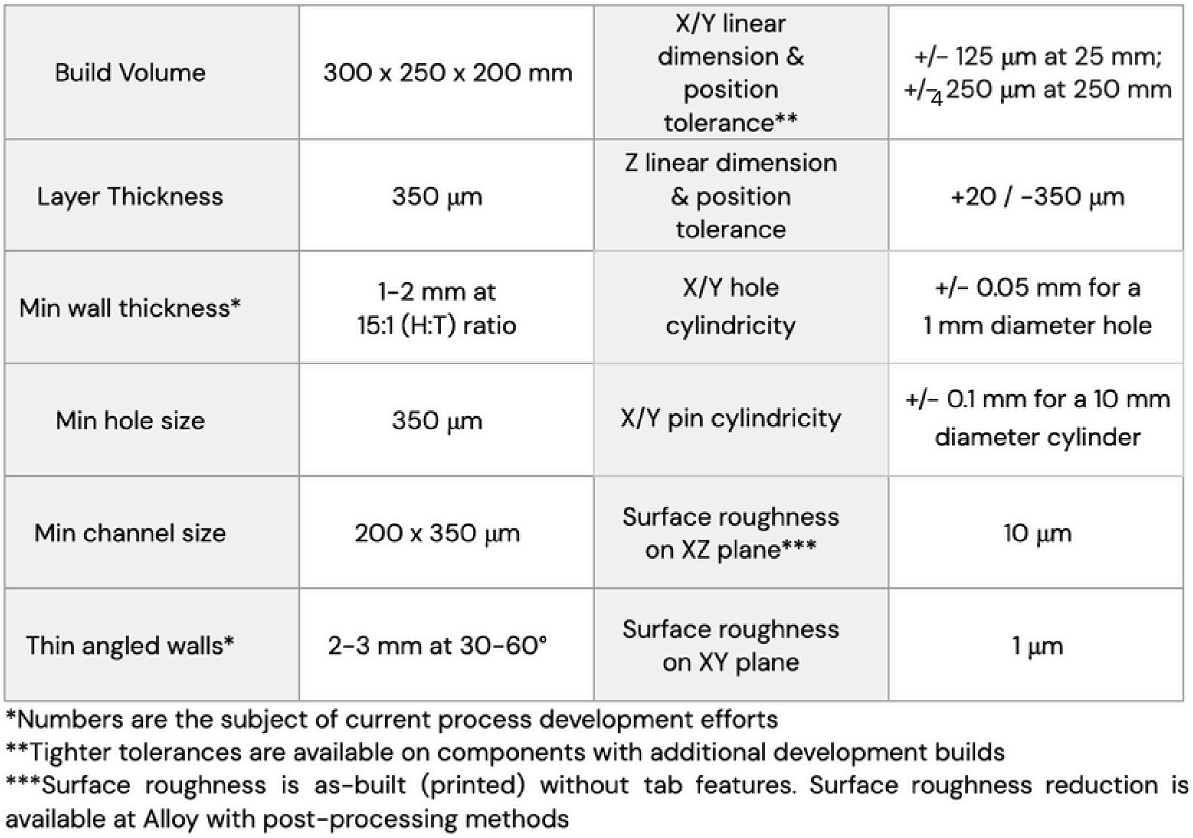


Figure 15: An electronics cooling component with oscillating micro-lattices across length scales.

## *Design Guidelines*

Table 1: Design guidelines for Stack Forging.



| | | | |
|---|---|---|---|
| Build Volume | 300 x 250 x 200 mm | X/Y linear dimension & position tolerance** | +/- 125 µm at 25 mm;<br>+/-250 µm at 250 mm |
| Layer Thickness | 350 µm | Z linear dimension & position tolerance | +20 / -350 µm |
| Min wall thickness* | 1-2 mm at 15:1 (H:T) ratio | X/Y hole cylindricity | +/- 0.05 mm for a 1 mm diameter hole |
| Min hole size | 350 µm | X/Y pin cylindricity | +/- 0.1 mm for a 10 mm diameter cylinder |
| Min channel size | 200 x 350 µm | Surface roughness on XZ plane*** | 10 µm |
| Thin angled walls* | 2-3 mm at 30-60° | Surface roughness on XY plane | 1 µm |

*Numbers are the subject of current process development efforts

**Tighter tolerances are available on components with additional development builds

***Surface roughness is as-built (printed) without tab features. Surface roughness reduction is available at Alloy with post-processing methods

# Conclusions

This paper has summarized the capabilities and use cases of Alloy's novel Stack Forging process. As opposed to traditional metal additive manufacturing technologies, Alloy provides clear improvements in cost, material properties, component performance, and scalability. Stack Forging has been designed from the ground up to meet the needs of the modern industrial base. Alloy has demonstrated the ability to deliver true aluminum 6061-T6 components at scale. Key features of our process include:

- 6061-T6 material composition with material properties comparable to wrought
- The ability to access advanced internal features to drive thermal-fluid performance
- On-demand, reduced lead-time from prototype to production
- True scalability from 1s to 10,000s of components

Alloy continues to innovate, with a robust technical roadmap that includes continued advancement of material properties and tolerances, creating more complex high-performance geometries, new materials, and larger build volumes. Alloy is a key partner who can help your organization unlock the promise of additive manufacturing without the compromises of the past.

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TM

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