THE STACK FORGING™ PROCESS

DIGITAL FABIRCATION FOR COMPLEX ALUMINUM AND COPPER COMPONENTS

An Advanced Manufacturing Technology

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THE COMPANY AND OUR PROCESS

Alloy Enterprises delivers high-performance thermal management components designed and manufactured in the U.S. Our patented Stack Forging™ process creates leak-tight, single-piece components with embedded microgeometries. These enable maximum heat transfer, reduced pressure drop by up to 4×, and improved thermal resistance by over 35%—dramatically lowering pumping power and energy use. Our solutions support a wide range of applications, including GPUs, CPUs, memory modules, NICs, power electronics, and semiconductor tools. Now shipping to leading data center, industrial, and military customers.

Alloy™ ENTERPRISES

Abstract

The data center, defense, and other high-power electronics industries seek cost-effective thermal management components with superior performance and flexible capacity that can scale into production. Finding a value-added supplier that can collaborate 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 computational geometry, laser cutting, printing, and diffusion bonding of a sheet-based feedstock to produce fully dense, complex components with superior material properties. Specifically, Alloy supplies finished end-use copper 110 and aluminum 6061 components to its customers. Alloy's components are single-piece, leak-tight construction with no additional assembly, eliminating the need to invest in additional tooling and reducing assembly costs. This helps customers accelerate time-to-market with the benefits of advanced manufacturing, but at the scale and cost 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 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, such as 50 μm microchannels. This technology enables the manufacturing of components with improved thermal performance and lower pressure drop, while remaining scalable and cost-effective.

How to Work With Us. Customers engage with Alloy to solve critical thermal management challenges. Alloy performs both value-added design and manufacturing of these components for customers. Design services include simulation, thermal performance testing, and CT scanning in addition to the design of the component itself. Alloy also offers customers a variety of post-processing options to streamline the delivery experience, including machining, disc finishing, tumbling, and plating.

Alloy's manufacturing facilities are located in Burlington, MA, and are ISO 9001 certified. Alloy also conducts certified inspections, thermal, and materials testing onsite.

Figure 1: Images from Alloy's Production facility.

Solutions

Alloy partners with customers seeking a supplier of end-use components. Customers choose Alloy for superior performance, scalability, 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 made from either aluminum 6061 or copper 110. Combining known 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, proprietary thermal geometries enables design engineers to tailor the thermal and flow performance of their components 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.

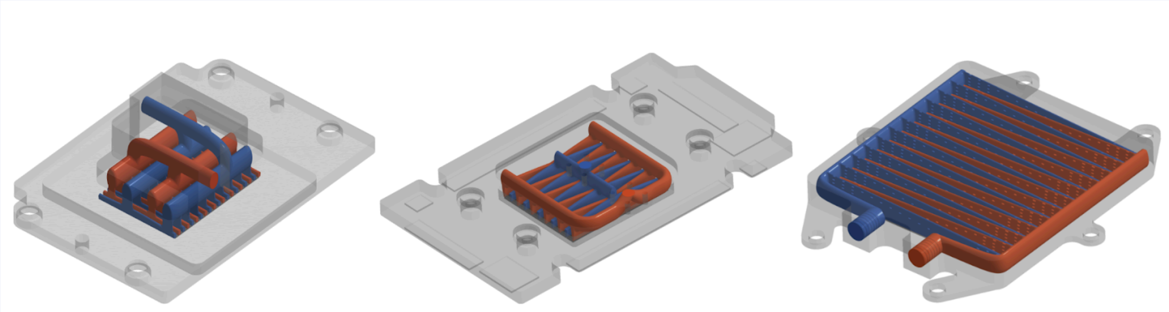


Figure 2: Renderings of high-performance microcapillary™ thermal management components fabricated with Stack Forging. Cold plates for GPU cooling (left, center), and CPU cooling (right). Inlet flow path highlighted in blue, outlet flow path in red.

Lead Time Reduction

Stack Forging enables the single-piece construction of components that would otherwise be made in multiple parts, reducing the number of assembly steps. Part consolidation reduces supply chain risk, lowers assembly and inventory holding costs, and supports higher-density products such as AI servers. By avoiding multiple process steps, manufacturers can launch replacement components or new products sooner while reducing overall risk in their systems. For example, cold plates are commonly CNC-machined from two plates and vacuum brazed. Customers have reported expected lead times for vacuum brazing of 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 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.

Cost-Effective

Stack Forging is a more cost-effective solution than other advanced manufacturing techniques, and has costs comparable with traditional manufacturing methods. Alloy's ability to offer competitive pricing is driven by low feedstock costs, process scalability, part consolidation, and improved performance. Many traditional manufacturing techniques for thermal management start with multiple parts that come together in separate steps, increasing the overall component cost. For example, Alloy can fabricate the cold plate shown in Figure 3 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.

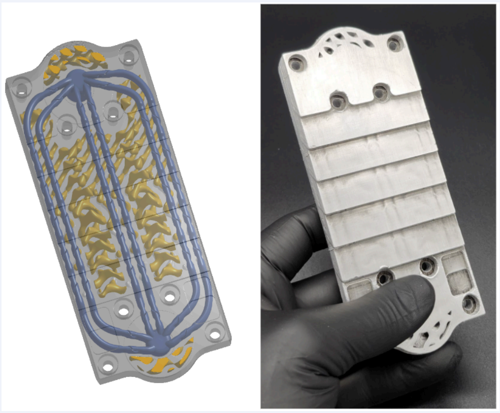


Figure 3: An example of a lightweight 6061-T6 cold plate component. CAD rendering with gyroid infill in yellow and spiral cooling channels in blue (left). Finished component (right).

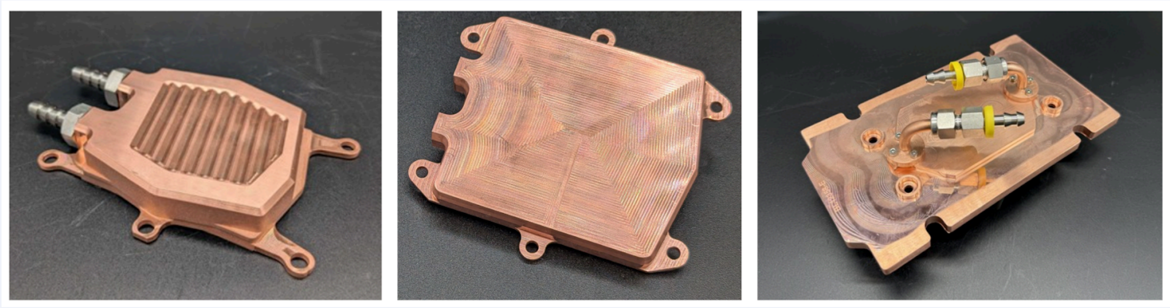


Figure 4: Examples of Stack Forged copper thermal management components

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 through single-piece construction, without tooling or additional assembly.

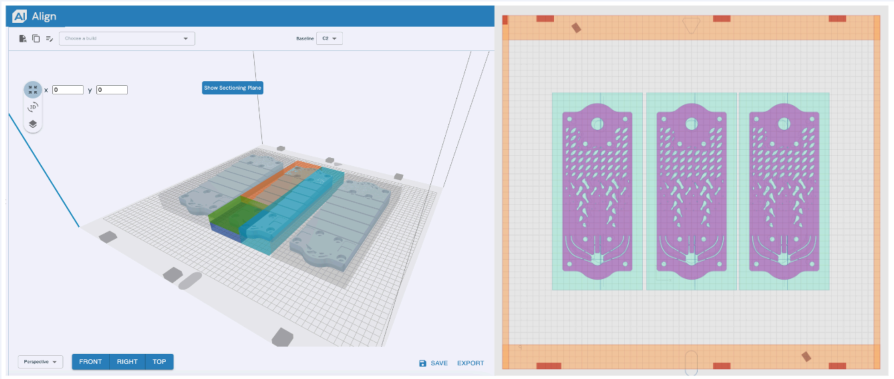


Figure 5: Alloy's 3D build configuration software Align (left) and 2D sliced output (right).

The Stack Forging process starts with a 3D CAD model. Typically, the customer provides CAD of the external shape, and Alloy's Solutions & Thermal Design Engineering teams design the internal thermal management geometries using Alloy's patented library. 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 similarly 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. Multiple parts can be nested or packed into the build volume to lower cost. There are no laminates or adhesives; the process bonds metal-to-metal and does not melt or sinter, thus preserving the grain structure. This creates components with material properties that match those of wrought metal, without concern for the complexity of print parameters that affect melt-pool dynamics. Therefore, the finished component inherently benefits from the base material, such as corrosion resistance, conductivity, and post-process compatibility. This makes new material development for this platform a lower risk than for other emerging manufacturing technologies. An additional benefit of the solid-state bonding process is the ability to have very small internal channels. In other processes, molten metal wicks into small channels due to capillary action. Since there is no melting in Stack Forging, it can theoretically create internal channels as small as 10 µm. After bonding, the support material is removed and recycled. Copper 110 parts end in an annealed state, while aluminum 6061 components are heat-treated for strength and hardness.

The current process utilizes a 400 µm sheet for copper feedstock and a 350 µm sheet for aluminum feedstock. Other thicknesses within the range of approximately 150-500 µm are also possible on the existing machines. For aluminum, 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 compositionally striated with the different alloys (Figure 7). A homogenizing heat treatment diffuses the alloying elements to achieve the desired alloy composition, 6061.

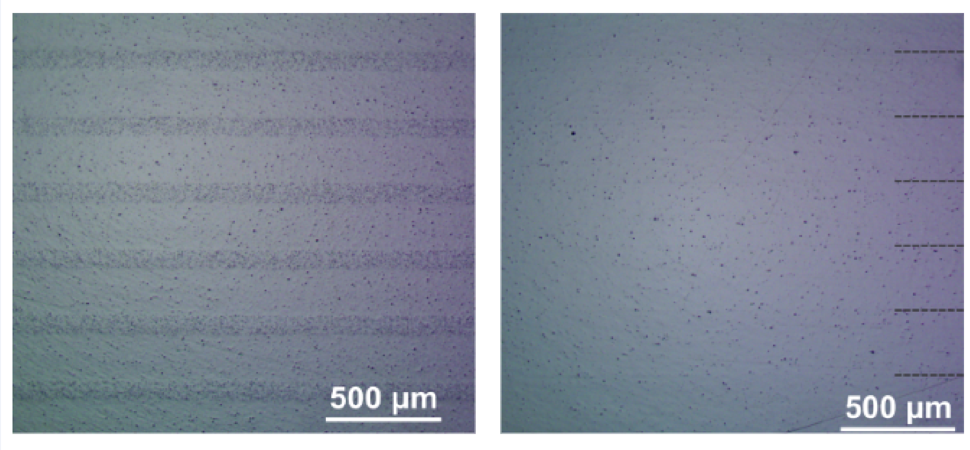


Figure 7: Micrograph of a bonded component's XZ[1] plane showing seven bonded feedstock sheets. The striations indicate the original multi-layer compositions (left), which are eliminated after the homogenization heat-treatment (right)

[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: Microstructure of a bonded copper component's XZ plane showing five bonded feedstock sheets. No bond lines are visible in the microstructure.

Layers are produced using perimeter laser cutting, enabling higher throughput than current melting- or fusion-based additive manufacturing methods. Alloy's aluminum feedstock supply chain currently produces material in 60-ton runs and has been fully qualified. For copper feedstock, Alloy has several qualified vendors. Alloy's current production machines have a build volume of 300 x 250 x 200 mm.

Material Properties

Metallography & Density

The density of aluminum components 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 cm³. The provided test accuracy was 0.1% and repeatability was 0.05% using helium 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 of which measured over 100%.

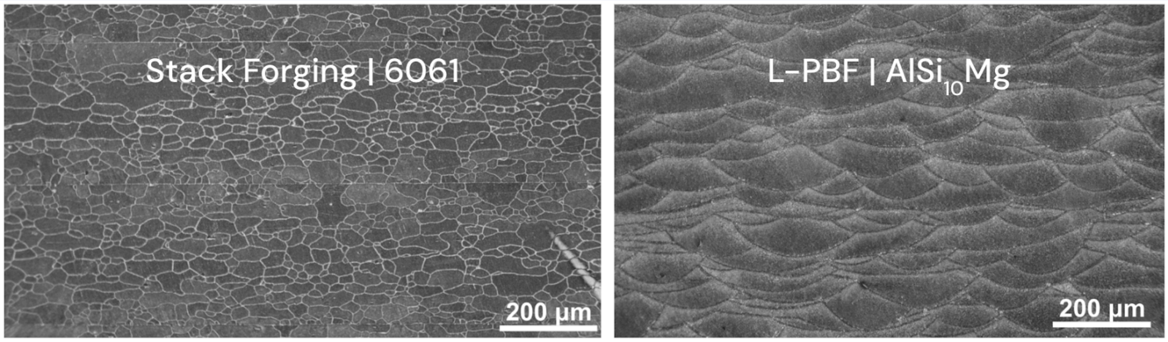


Figure 9: An etched cross-section along the XZ plane of an Alloy Stack Forged component (left). An etched cross-section of a component fabricated with laser powder bed fusion (right).

Metallography has been used extensively to verify density. A typical etched micrograph is shown in Figure 9 (left). The grain structure is preserved through the bonding and heat-treatment steps. Bond lines can be observed with a thickness similar to that of grain boundaries. The bond lines also behave as grain boundaries when they fail during mechanical testing, failing ductility and necking across several layers. Measuring pores per inch or percent porosity is impossible because 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 9 (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

Tensile Testing Metallurgical Laboratory in Cleveland, OH, measured global composition on an aluminum sample from Alloy using optical emission spectroscopy (OES). Their testing confirmed 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.

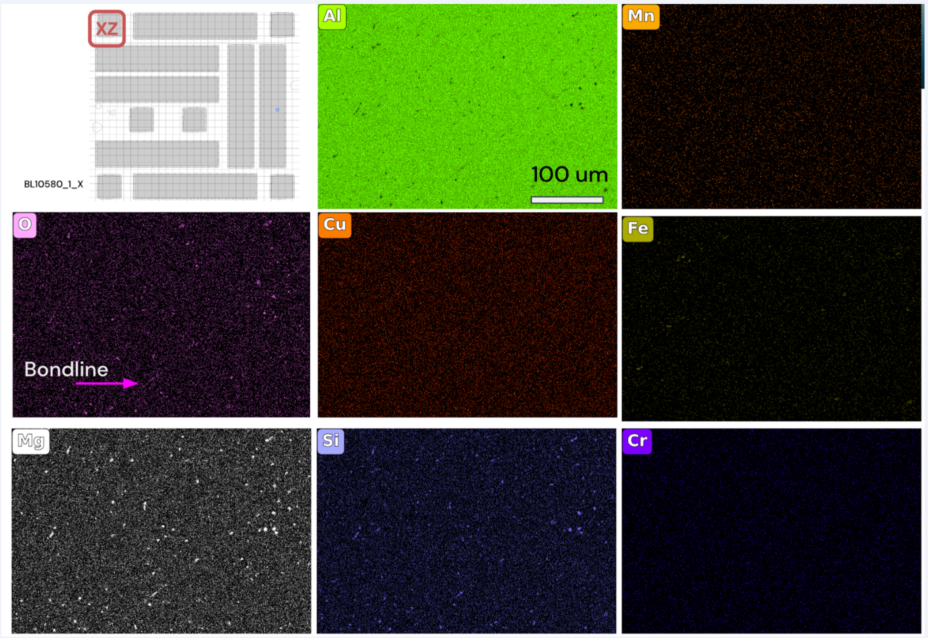


Figure 10 - EDS maps of the XZ plane taken from the top left corner of a build.

Composition maps were collected on an aluminum sample from Alloy using a scanning electron microscope (SEM) with an energy-dispersive spectroscopy (EDS) detector 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 in the matrix was uniform across all samples, with the typical intermetallic precipitates expected in 6061-T6, such as Mg_2Si and iron/manganese phases (Figure 10). This was further confirmed with local SEM images and EDS analysis.

Mechanical Testing

Alloy performs tensile testing in accordance with ASTM E8. The tensile properties for aluminum tensile bars manufactured by Alloy 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. In Z, the ultimate tensile strength (UTS) averaged 343 MPa, the yield stress averaged 264 MPa, and the elongation at break averaged 16%. In X/Y the results showed an average UTS of 345 MPa, yield stress of 267 MPa, and elongation at break of 20%. The data represents 396 samples from nine build volumes and includes multiple machines and material lots.

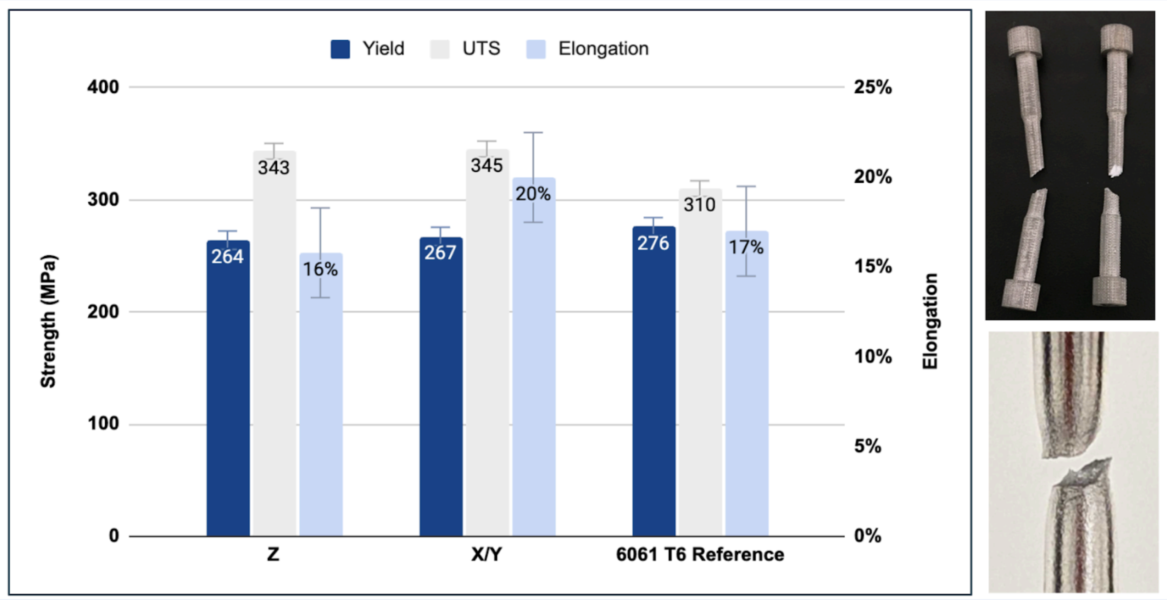
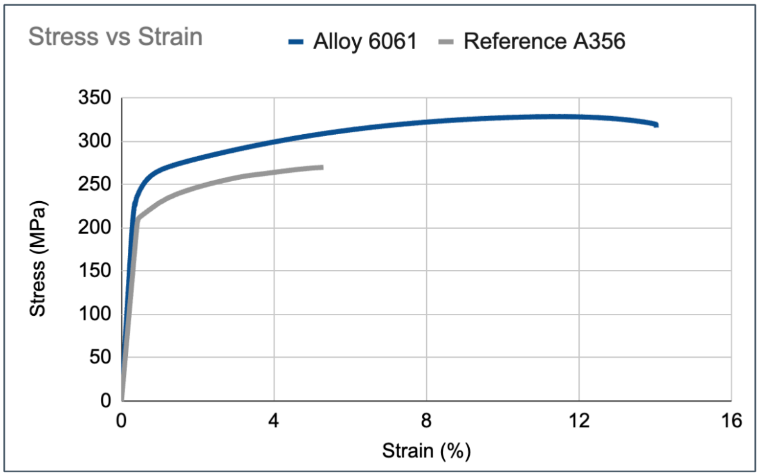


Figure 11: Tensile test properties in Z and X/Y (left). As-built tensile bars with ductile failures (top right). A machined tensile bar failed by necking, with a characteristic cup-and-cone failure (bottom right).

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, which is attributable to the specifics of Alloy's heat-treatment process. Z elongation matches the 6061 reference properties within the experimental uncertainty. However, both the as-built (printed) tensile bars and the machined tensile bars fail after necking and fracturing across several bond lines (Figure 11).

Stack Forged copper samples were also tested to determine their UTS. Ram tensile specimens were created per the MIL-J-24445 specification and resulted in a UTS measurement of 223 MPa, compared to the reference UTS of 220 MPa for fully annealed copper 110.



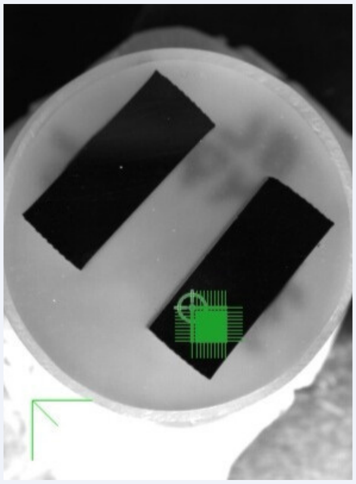


Figure 12: An example stress-strain curve for Alloy's 6061 and an investment casting alloy, A356 [4], demonstrating superior elongation at break (left). Image of XZ plane specimens prepared in a puck and polished for microhardness testing (right).

Microhardness testing via indentation with a Struers DuraScan model indenter was used to measure the Vickers hardness across the bond lines on aluminum samples. 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 aluminum 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.

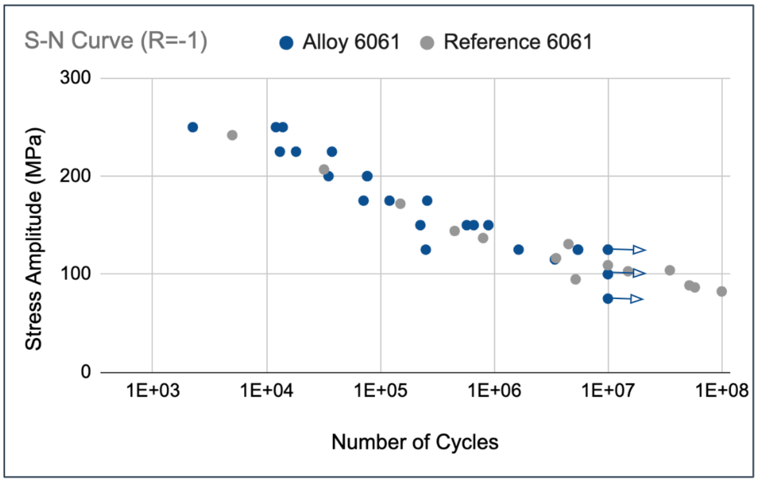


Figure 13: S-N curve with a fatigue ratio of -1 for 16 samples with results for Alloy's 6061 material and a Mil-spec reference for comparison. Arrows indicate tests that were allowed to "run out."

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 that of standard 6061 (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.

Thermal conductivity testing was also performed on a Stack Forged copper component. The test was performed using the same flash method and at the same lab as was used for the aluminum test. The test showed that Alloy's Stack Forged copper maintains wrought material thermal conductivity (within the experimental uncertainty of the measurement technique). Additionally, the test results shown in Figure 14 demonstrated that thermal conductivity in X, Y, and Z was generally isotropic, another indicator of the quality of Alloy's bonding process.

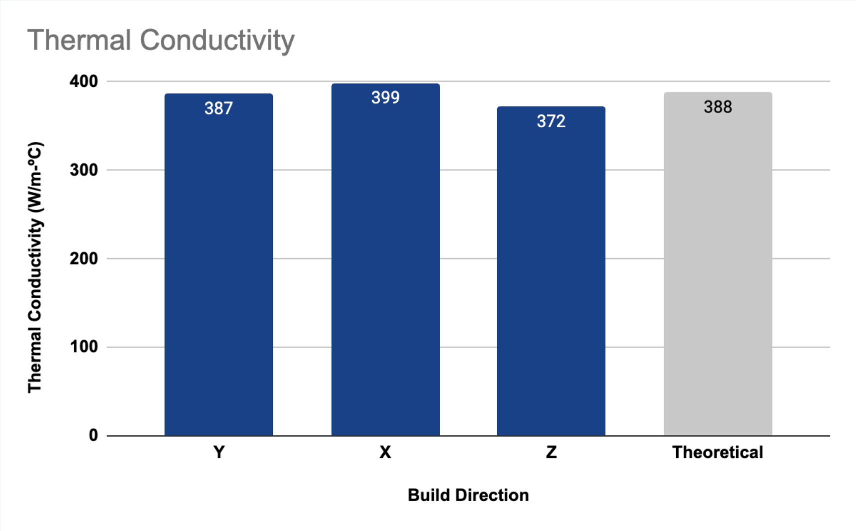


Figure 14: Thermal conductivity of Stack Forged copper 110 compared against reference data.

Leak Testing

Four aluminum single-phase liquid cooling plates were designed and fabricated using Stack Forging for a semiconductor processing application (Figure 15). 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.

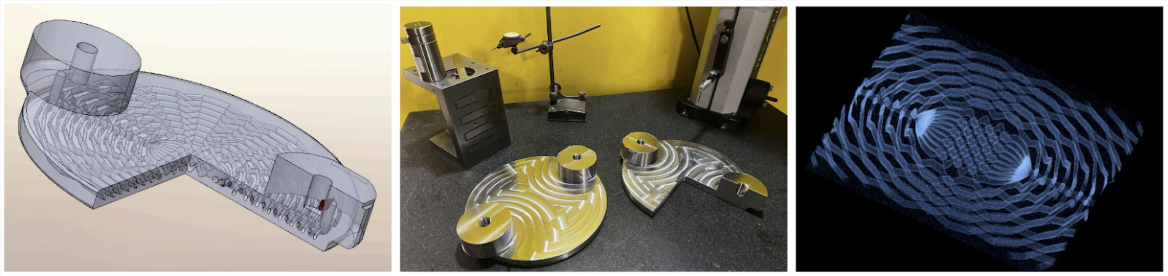


Figure 15: Single-phase liquid cooling plate for a semiconductor process application. Transparent CAD rendering (left). Fabricated, post-process machined, and sectioned (center). CT scan of the internal cooling channels in a Stack Forge component (right).

Similar leak tests were performed on a Stack Forged copper GPU cold plate using Alloy's in-house Helium leak tester (Leybold Phoenix Quadro Dry). The leak rate was tested to be <1x10-9 STD. cc/sec. of helium.

Capabilities

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 50 µm are produced. 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 within large components. An example component is shown in Figure 16. With additional development, the Stack Forging process can span from 10 µm to 1 m.

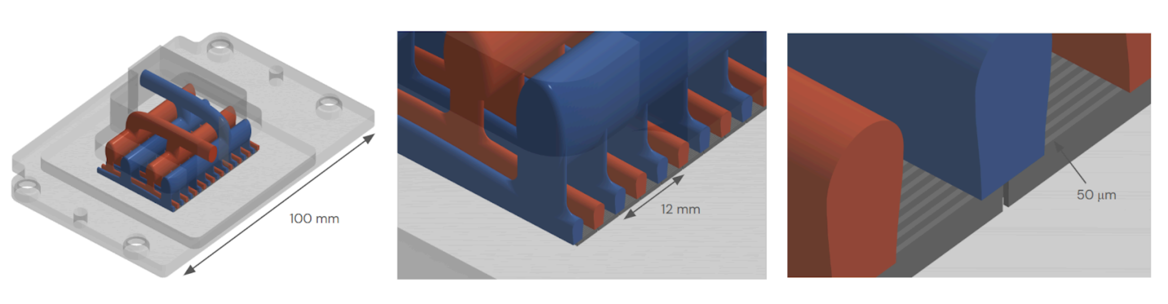


Figure 16: An electronics cooling component with microcapillary channels across length scales.

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; +/- 500 µm at 250 mm
Layer Thickness	350 µm (aluminum) 400 µm (copper)	**Z linear dimension & position tolerance**	+20 / -350 µm
Min vertical wall thickness*	1 mm (external); 100 µm (internal);	**X/Y hole cylindricity**	+/- 0.05 mm for a 1 mm diameter hole
Min hole size	70 µm	**X/Y pin cylindricity**	+/- 0.1 mm for a 10 mm diameter cylinder
Min channel width	50 µm	**Surface roughness on XZ plane*****	10 µm
Thin angled walls*	2-3 mm thick at 30-60°	**Surface roughness on XY plane**	1 µm

*Numbers are the subject of current process development efforts. Lower values are possible with part-specific development efforts.
**Tighter tolerances are available on components with additional development builds
***Surface roughness is as-built 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. Compared with traditional metal additive manufacturing technologies, Alloy offers clear improvements in cost, material properties, component performance, and scalability. Stack Forging has been designed from the ground up to solve the most challenging thermal management. Alloy has demonstrated the ability to deliver true copper 110 and aluminum 6061-T6 components at scale. Key features of our process include:

- Material composition with material properties comparable to wrought for both copper 110 and aluminum 6061
- The ability to create advanced internal features to drive industry-leading thermal performance
- On-demand, reduced lead-time from prototype to production
- True scalability to meet the needs of customers in the data center, defense, and high-power electronics industries

Alloy continues to innovate, with a robust technical roadmap that includes high-performance geometries, new materials, and larger build volumes. Alloy is a key partner who can help your organization unlock the promise of advanced manufacturing without the compromises of the past.

References

1. Hyer, Holden, et al. "Understanding the laser powder bed fusion of AlSi10Mg alloy." Metallography, Microstructure, and Analysis 9 (2020): 484-502.
2. International Alloy Designations and Chemical Composition Limits for Wrought Aluminum and Wrought Aluminum Alloys, The Aluminum Association, 2018.
3. ASM Handbook, Volume 2: Properties and Selection: Nonferrous Alloys and Special-Purpose Materials, 1990.
4. Metallic materials and elements for aerospace vehicle structures, MIL-HDBK-5J January 2003.
5. ASTM International E1461 Standard Test Method for Thermal Diffusivity by the Flash Method. https://www.astm.org/e1461-13r22.html

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