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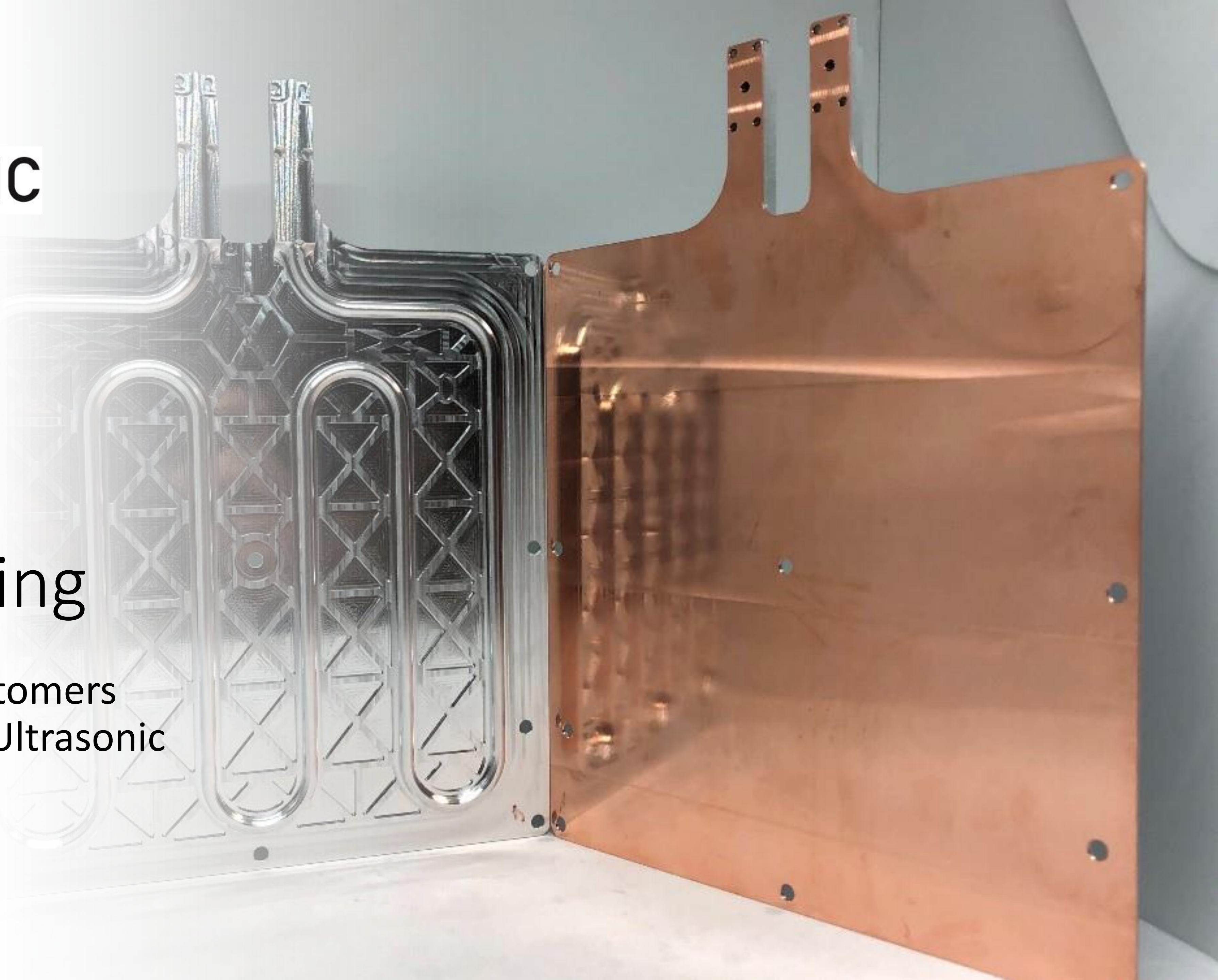
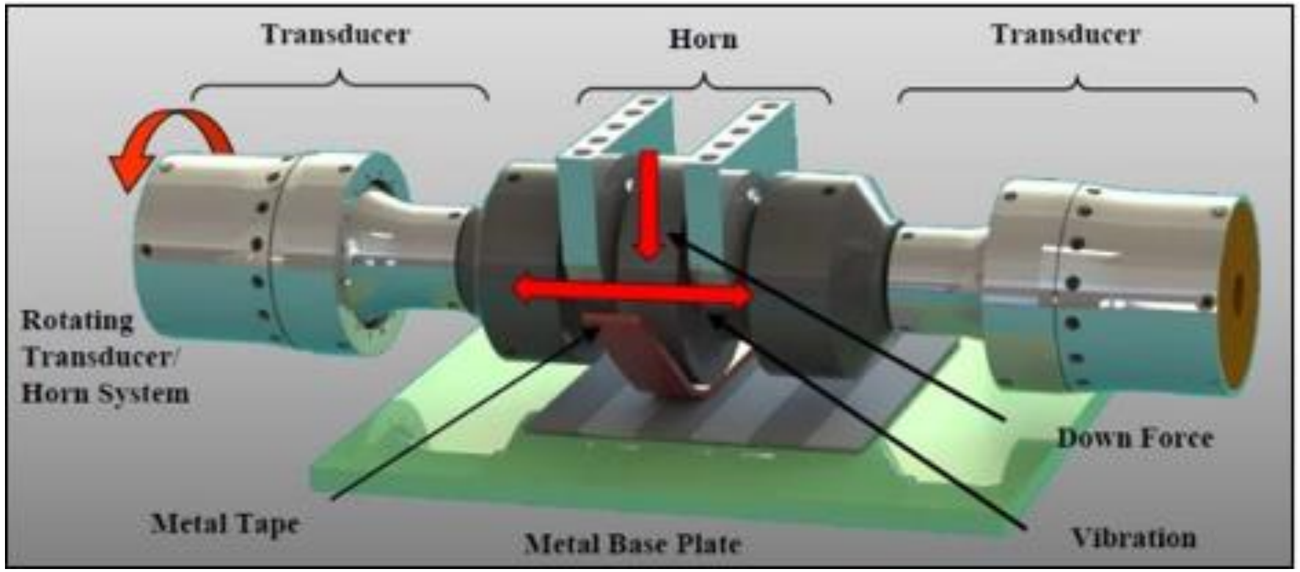
Ultrasonic Additive Manufacturing

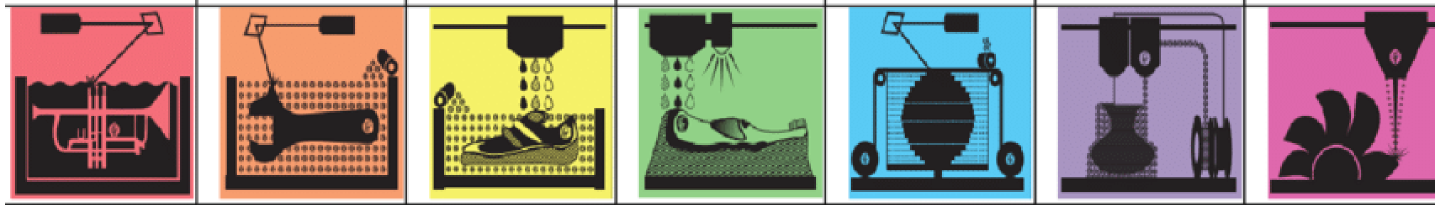
Design Guide for Customers and Engineers using Ultrasonic Additive Technology



Ultrasonic Additive Manufacturing is a subset of Sheet Lamination

- Rather than vats of polymers, or metal powders, or even wires, in Ultrasonic Additive Manufacturing (UAM) sheets or tapes of metal foil are bonded to substrates using an ultrasonically activated tool called a sonotrode (or horn).

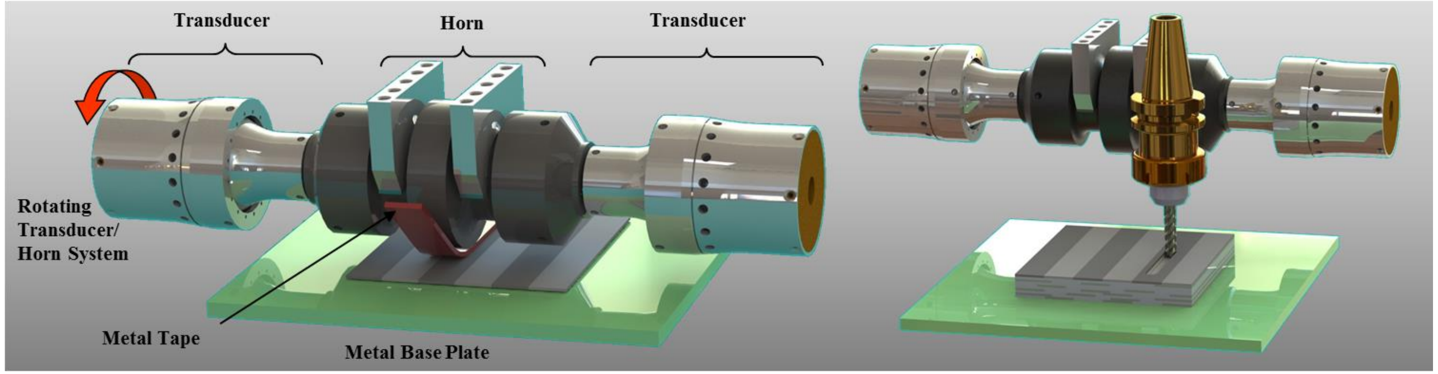


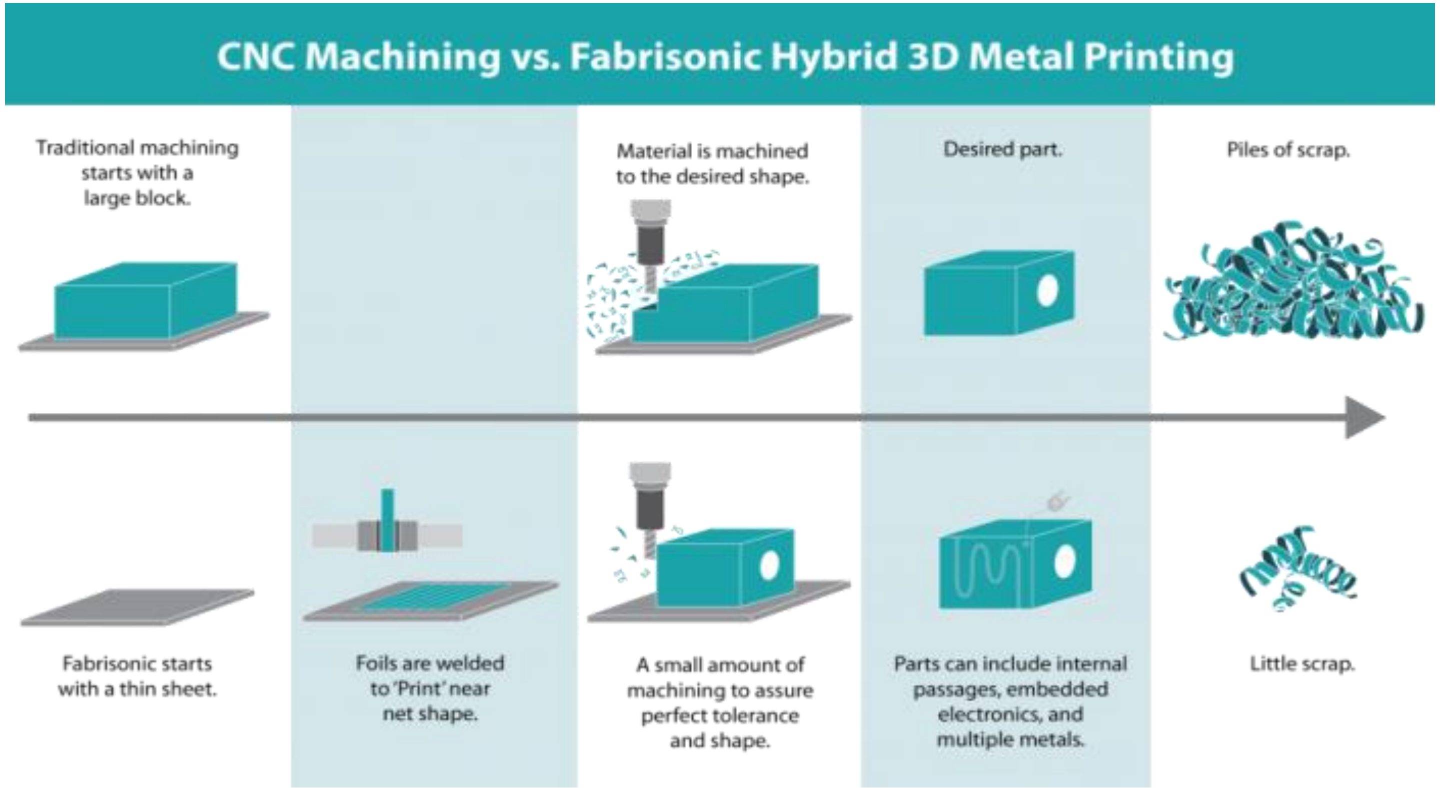


Vat photo polymerization	Powder bed fusion (PBF)	Binder jetting	Material jetting	Sheet lamination	Material extrusion	Directed energy deposition (DED)
A vat of liquid photopolymer is cured through selective exposure to light and converts exposed areas to solid part.	Powdered material is selectively consolidated and/or melted using a heat source such as laser or electron beam.	Liquid bonding agents are selectively applied onto thin layers of powder material to build up parts.	Droplets of material are deposited layer by layer to build up the parts.	Sheets of material are stacked and laminated to form an object using adhesive, chemicals, ultrasound, etc.	Material is extruded through a nozzle or orifice in tracks or beads, and combined into a model.	Powder or wire is fed into a melt pool on the part build which is generated using and energy source such as laser.

Ultrasonic Additive Manufacturing is a *Hybrid* Manufacturing Process

UAM machines comprise an ultrasonic welding system integrated into a CNC platform, providing users with the ability to add and subtract material throughout the build process. The CNC capabilities of UAM machines allow engineers to design 3D parts, with both complex internal and external features





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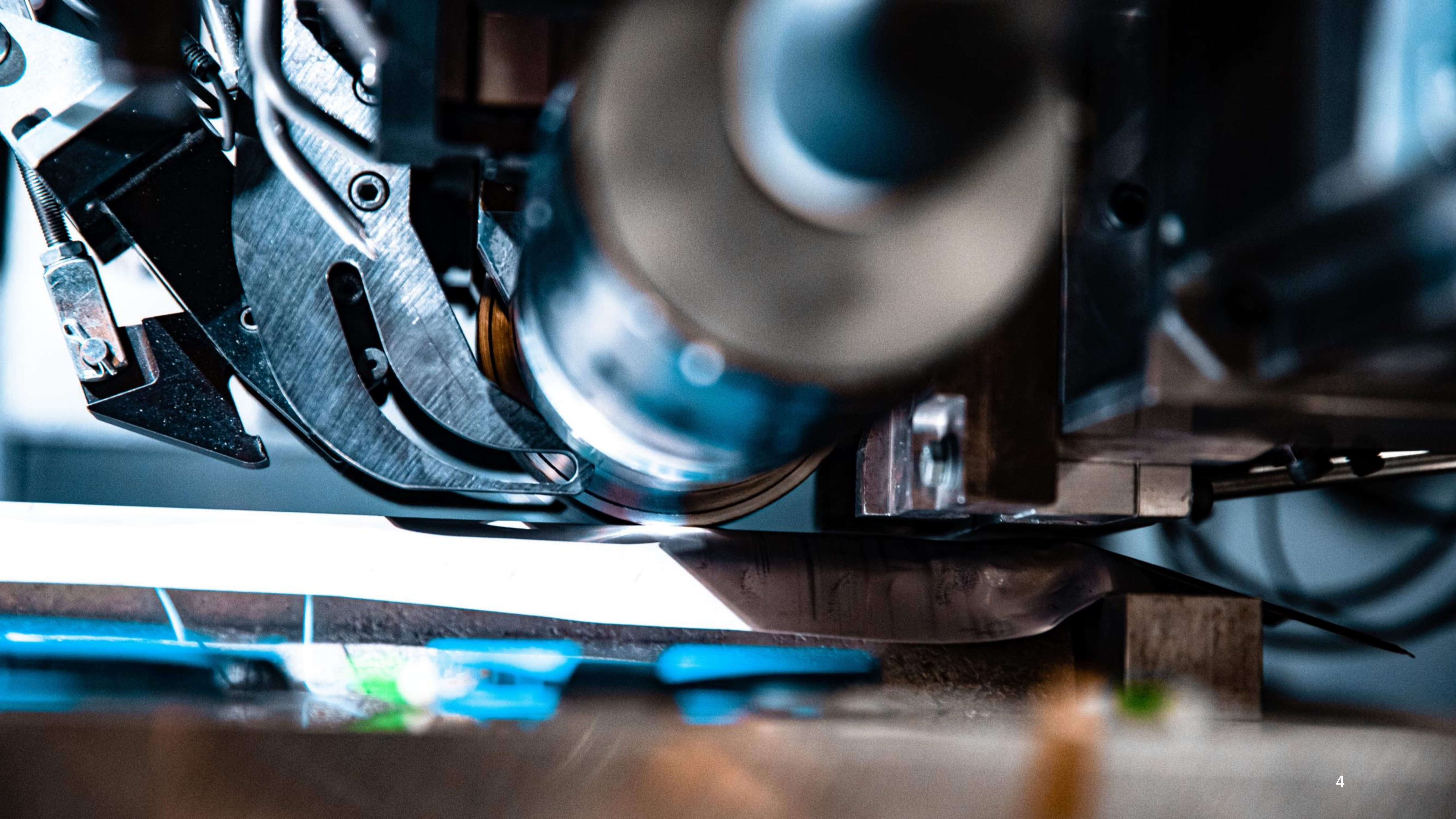
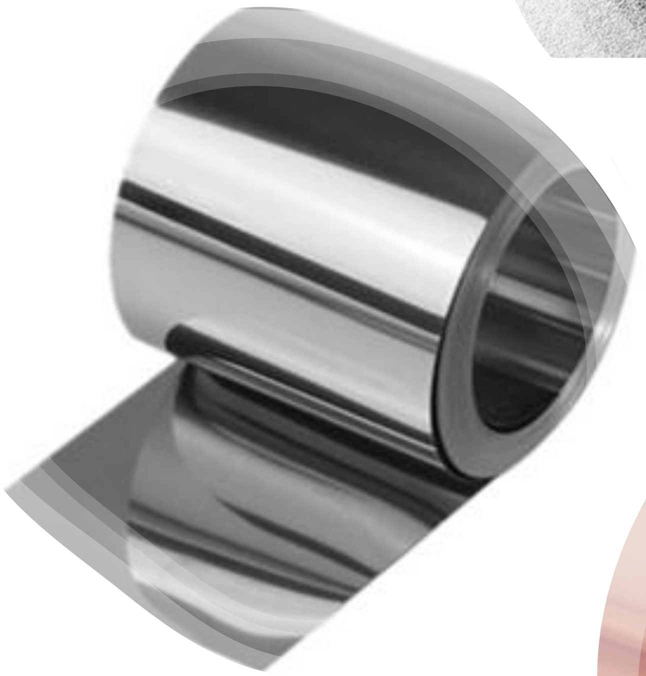
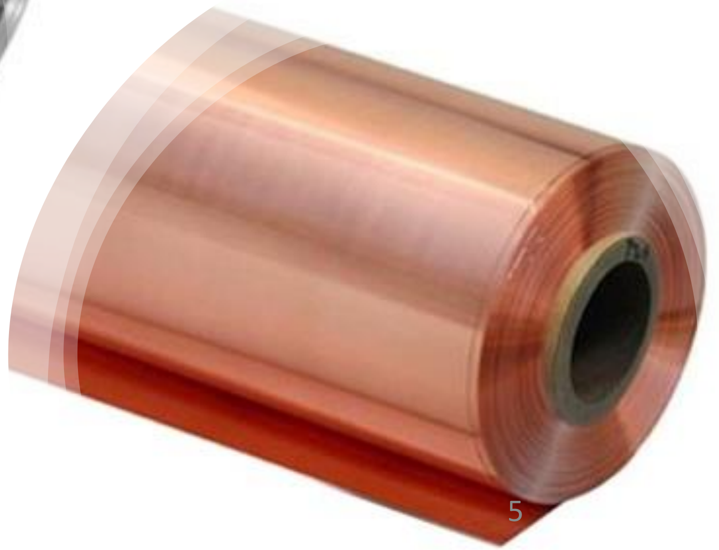


UAM Material Form Factors

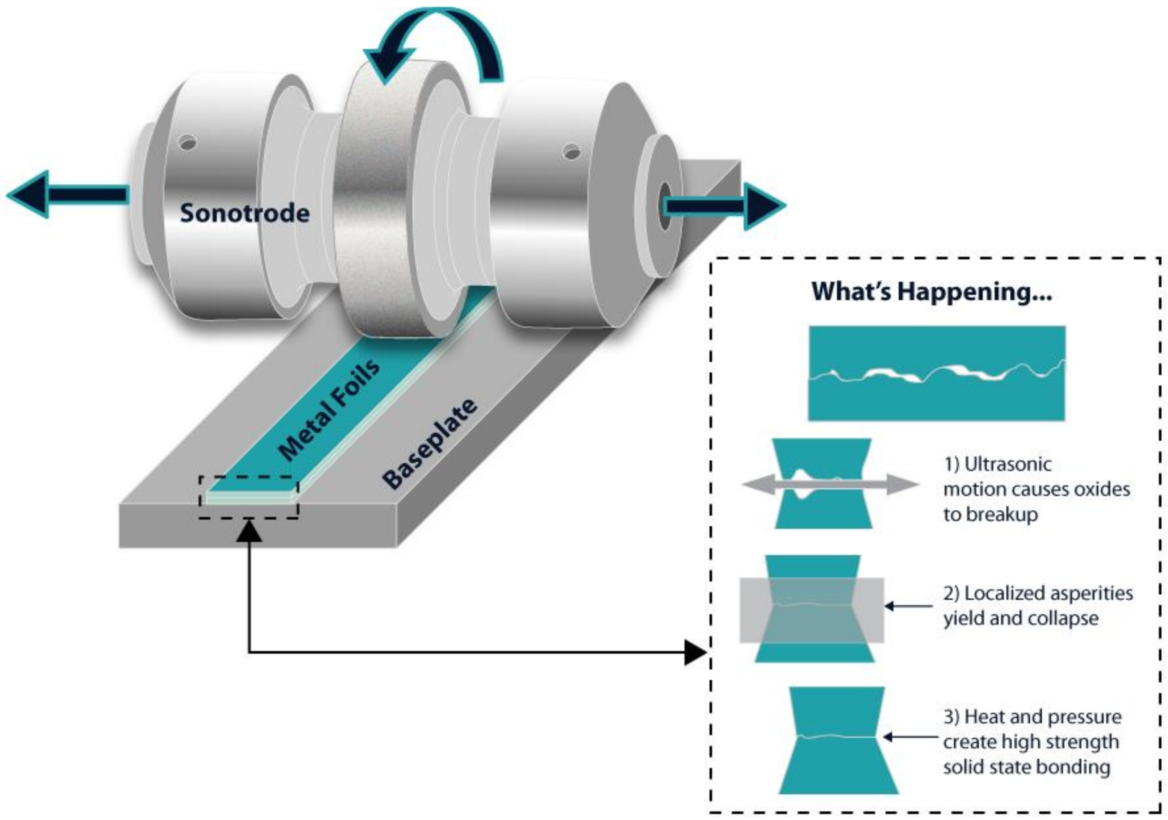
- The UAM process uses metal foils in sheets or continuous ‘tapes’. These are generally commercial off-the-shelf (COTS) commodities readily available via numerous metal foil producers.
  - No expensive (and highly explosive) powders
  - No inert gasses are consumed
  - No special environment required
  - Foils bought to existing AMS specifications
- These foils are usually between 0.001” to 0.010” thick, with the most common foils used in UAM in the range of .005”-0.006” thick.





How UAM Works

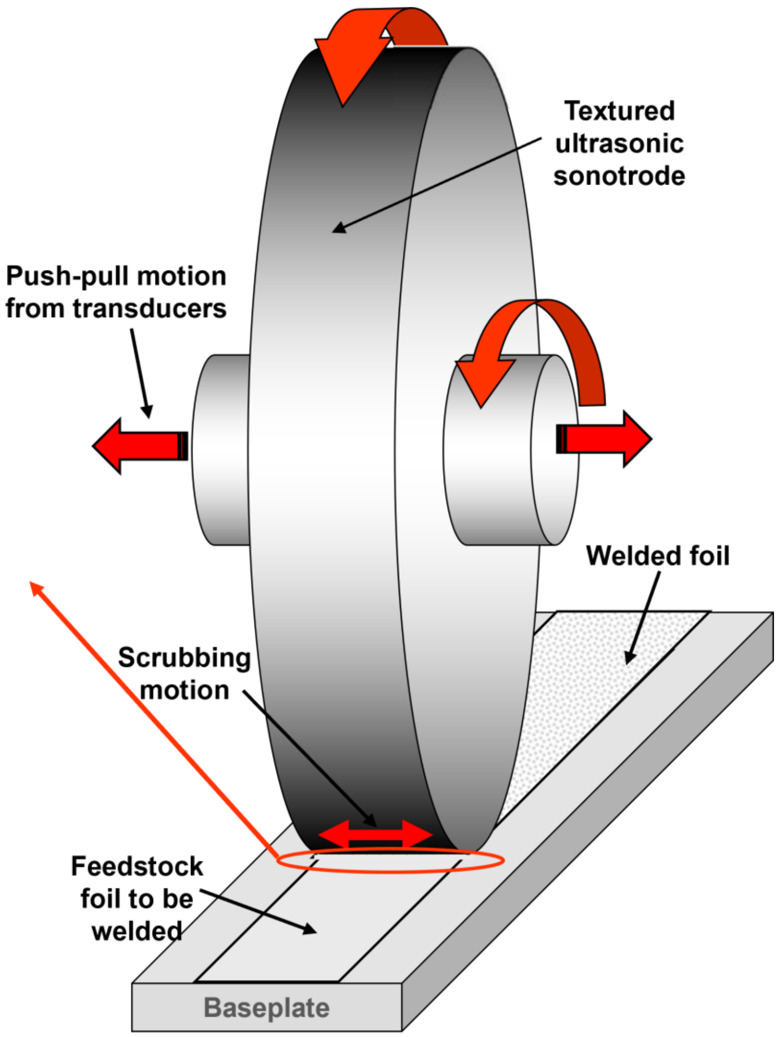
Metals like to stick to other metals, but on earth, this is inhibited by oxides that cover the surface of every metal. The UAM process scrubs metal foils at 20k times per second—a process that disrupts and breaks apart the oxide layers of metals. By combining the oxide breaking process of the ultrasonic vibration of the sonotrode with the downforce applied by the UAM system, local asperities are collapsed, material plastically deforms, and virgin metal is pressed against virgin metal, thus the two metals bond.

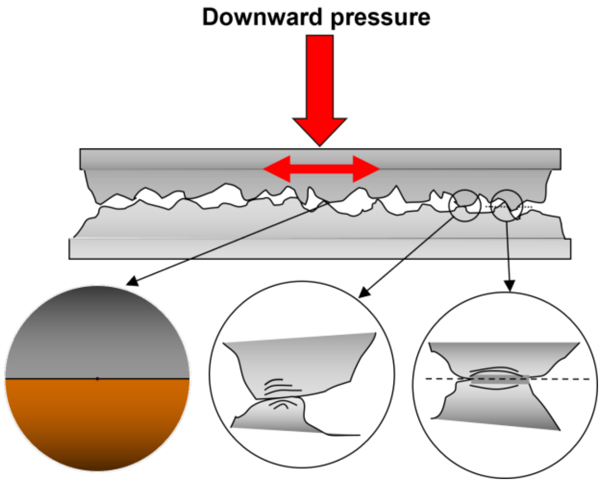


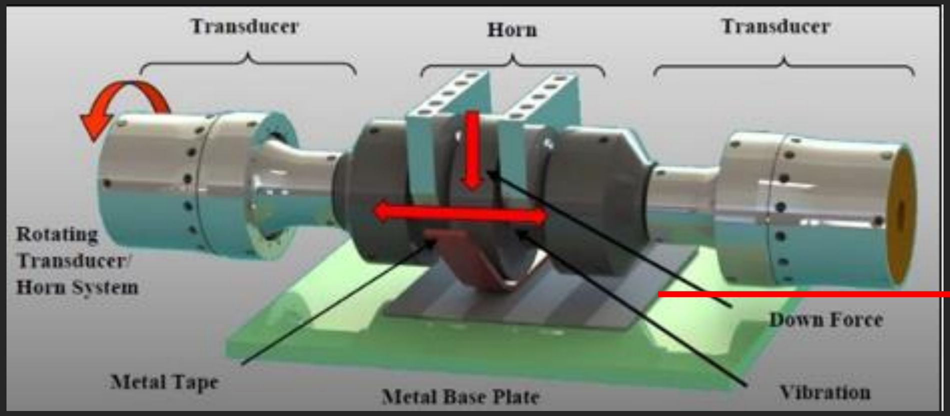
UAM Parameters

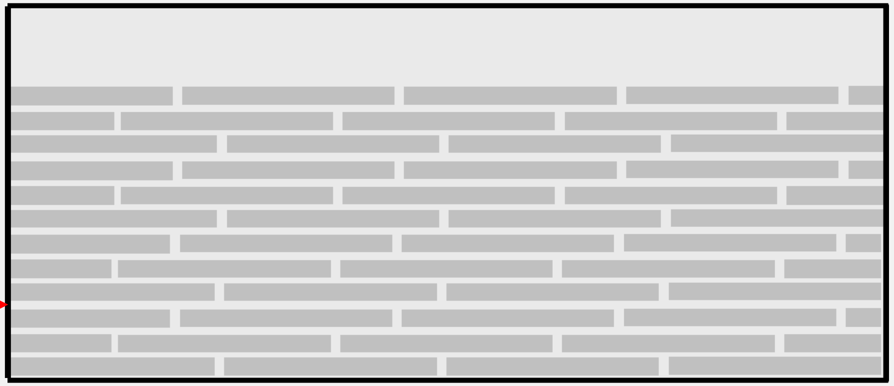
There are three main parameters for UAM

1) Amplitude: the side-to-side scrubbing displacement of the sonotrode
2) Downforce: how much force the sonotrode applies to the material being welded
3) Weld speed: the rate at which the sonotrode rolls across the material









Each tape layer staggered from one below so seams do not line up. In practice, there are no gaps between adjacent tapes.

UAM with Foil Sheet and Tape

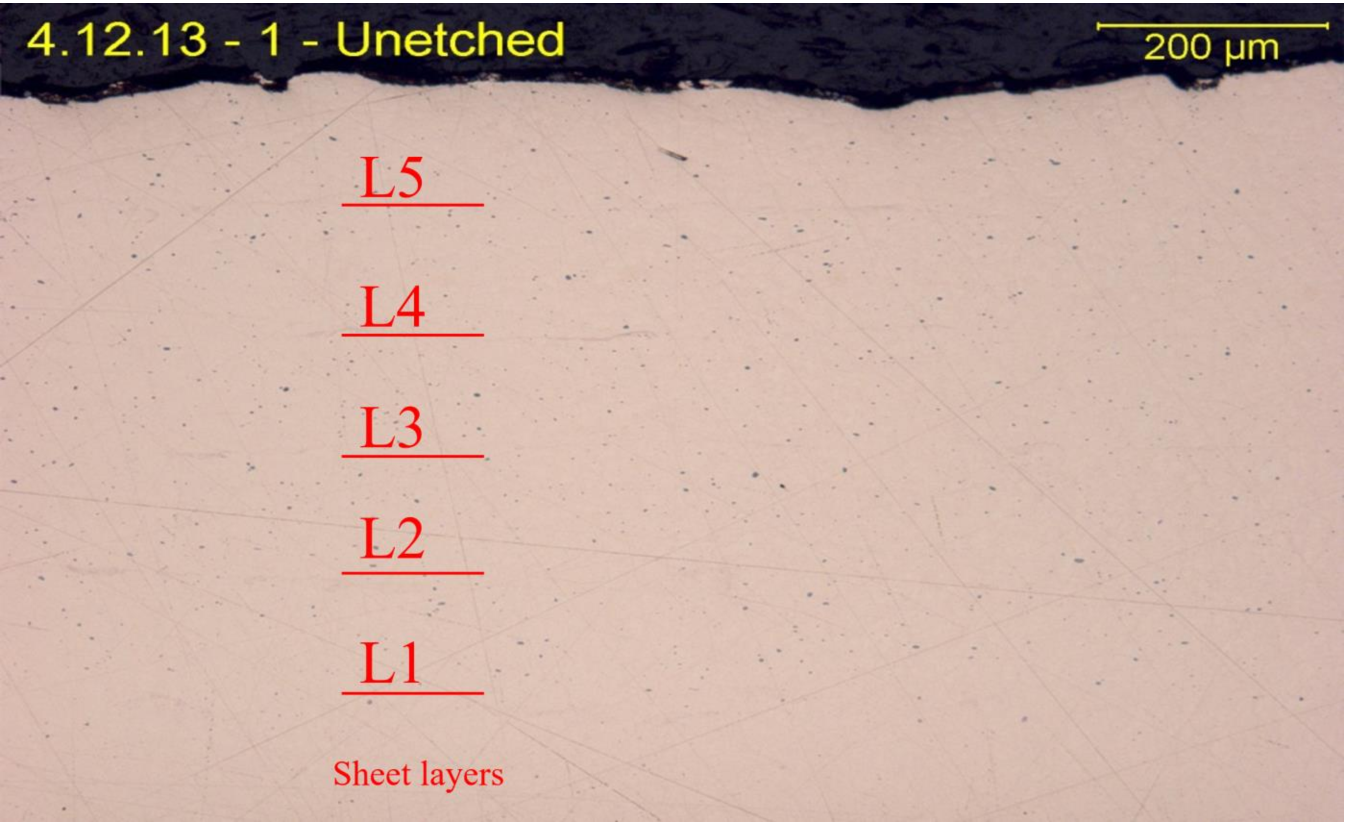
Whether welding with sheet or tapes, the general UAM process is the same. The sonotrode rolls across the material, bonding it to the layer below, in 1" strips at a time (or .5" strips for our smallest platform). The welding tool, or sonotrode, then continues to welding adjacent strips in a rastering pattern until the entire surface has been welded and all material is bonded to the underlying layer or material.

Each weld overlaps the adjacent weld so that there are no seams in the layers. Under high power ultrasonic fields, metal flow readily.

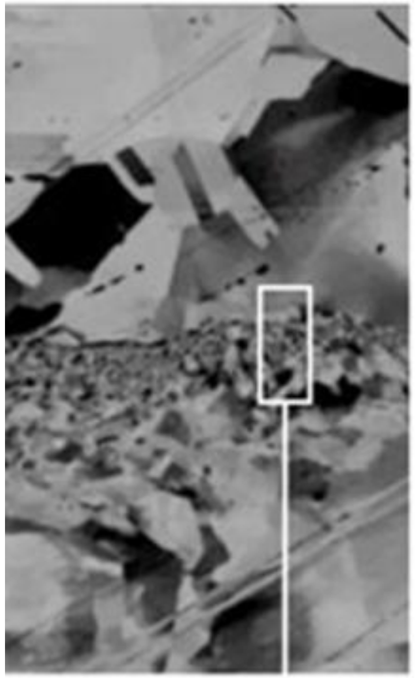
UAM material is built up layer after layer in Z creating solid metal.

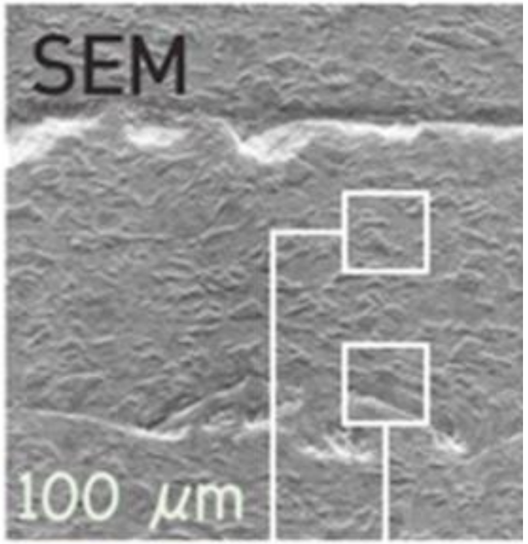
Metallurgy

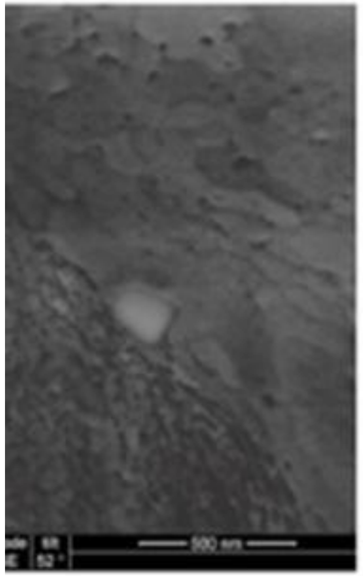
UAM's scrubbing action breaks up naturally occurring surface oxides, collapses asperities (microscopic ridges), and drives dynamic recrystallization at the tape-tape interface. In this process, new, much smaller grain structures are developed at the interface creating a bond between the two interfaces without any melting. As shown in the micrograph below, the outcome of building up metal foils of the same material results in a homogeneous structure, in which the layers are near impossible to observe optically.

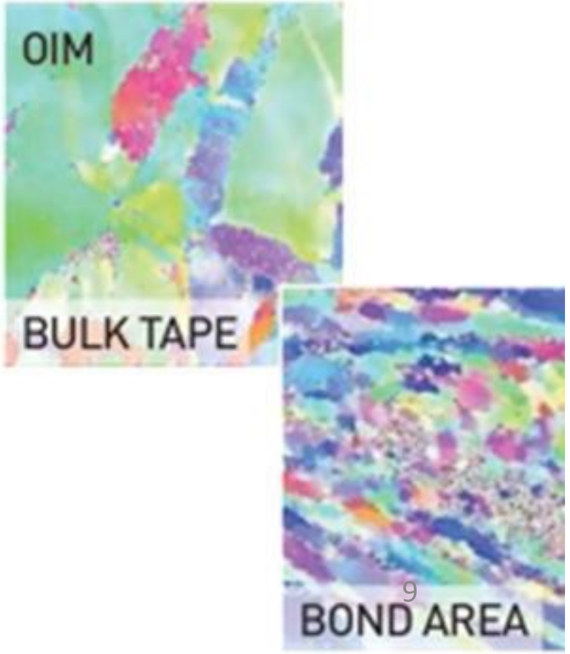


Dynamic Recrystallization

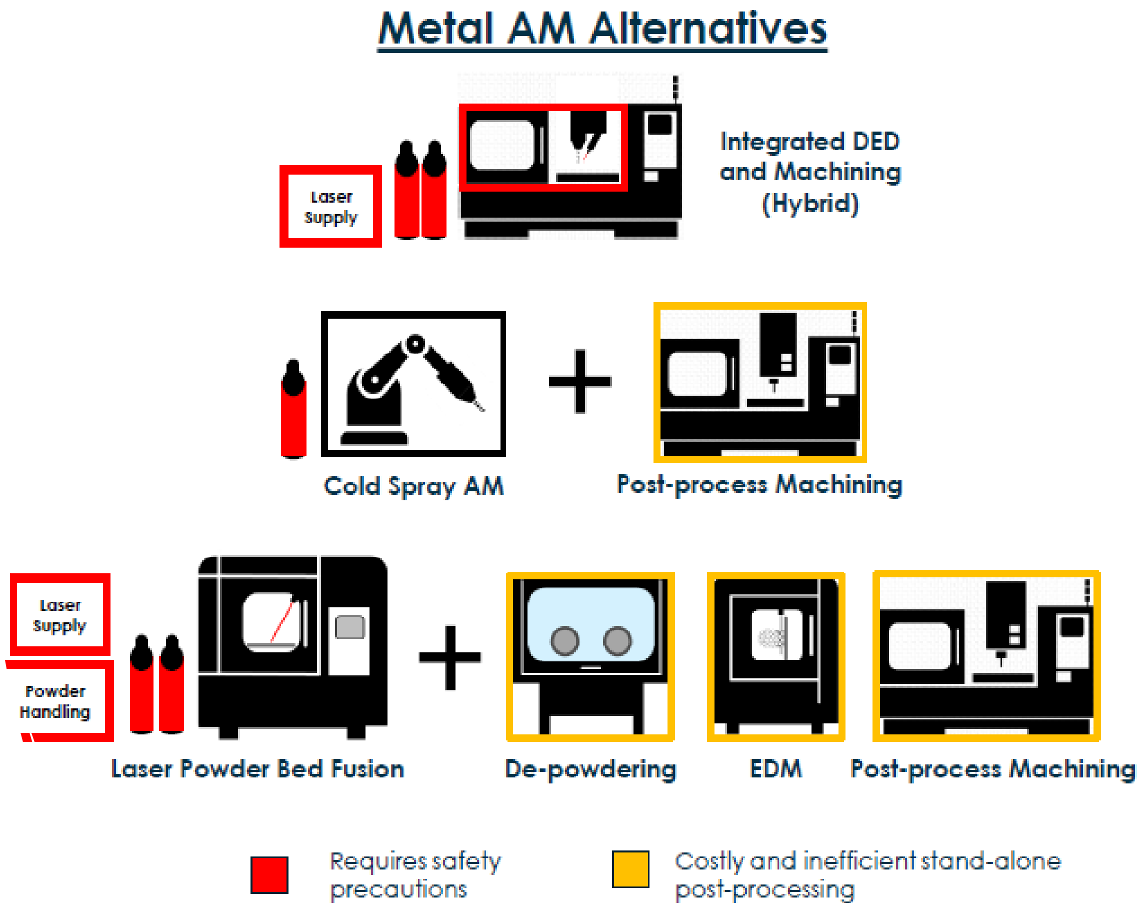








UAM Safety & Productivity



UAM is self contained and does not use lasers or powders. Commercial metal foil feedstock eliminates:

- Laser or EB safety enclosures
- Explosive powder handling equipment
- Expensive laser/EB power supplies and maintenance
- External Gasses
- Transfer time between systems (non-hybrid)

Only, basic CNC machining safety requirements are necessary for UAM, including hearing protection, safety glasses, abrasion resistant gloves, etc.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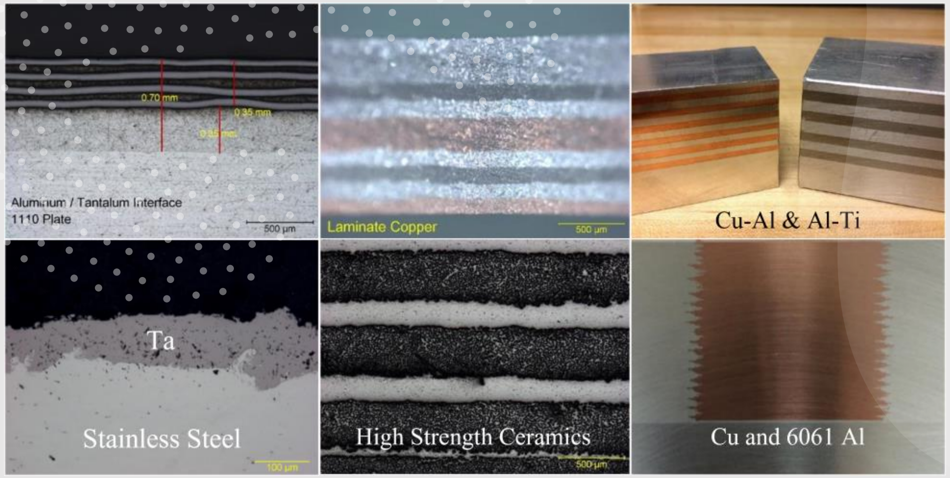
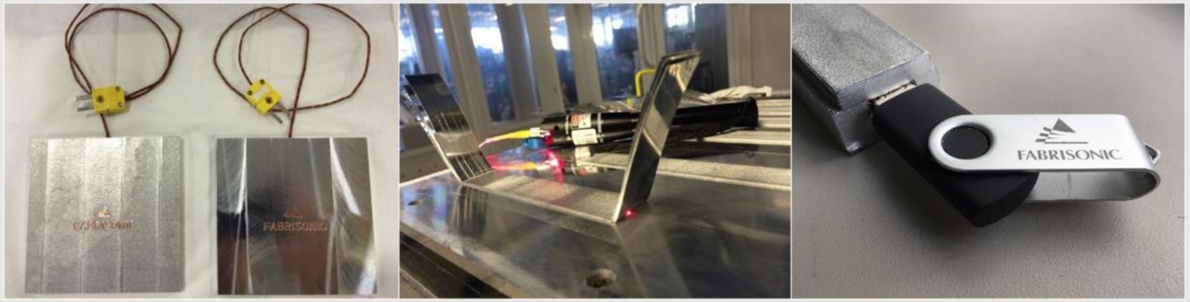
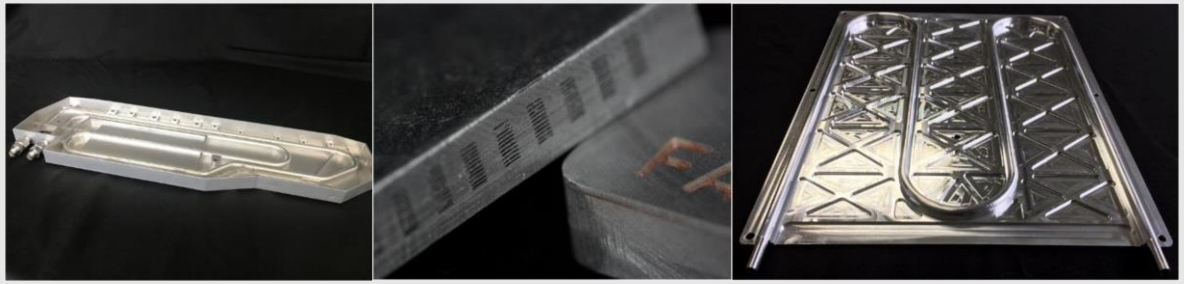
What Can UAM Do?







UAM Can do a LOT of things, but core applications include:

-Bonding dissimilar metals

-Embedding sensitive electronics and sensors

-Creating complex internal geometries

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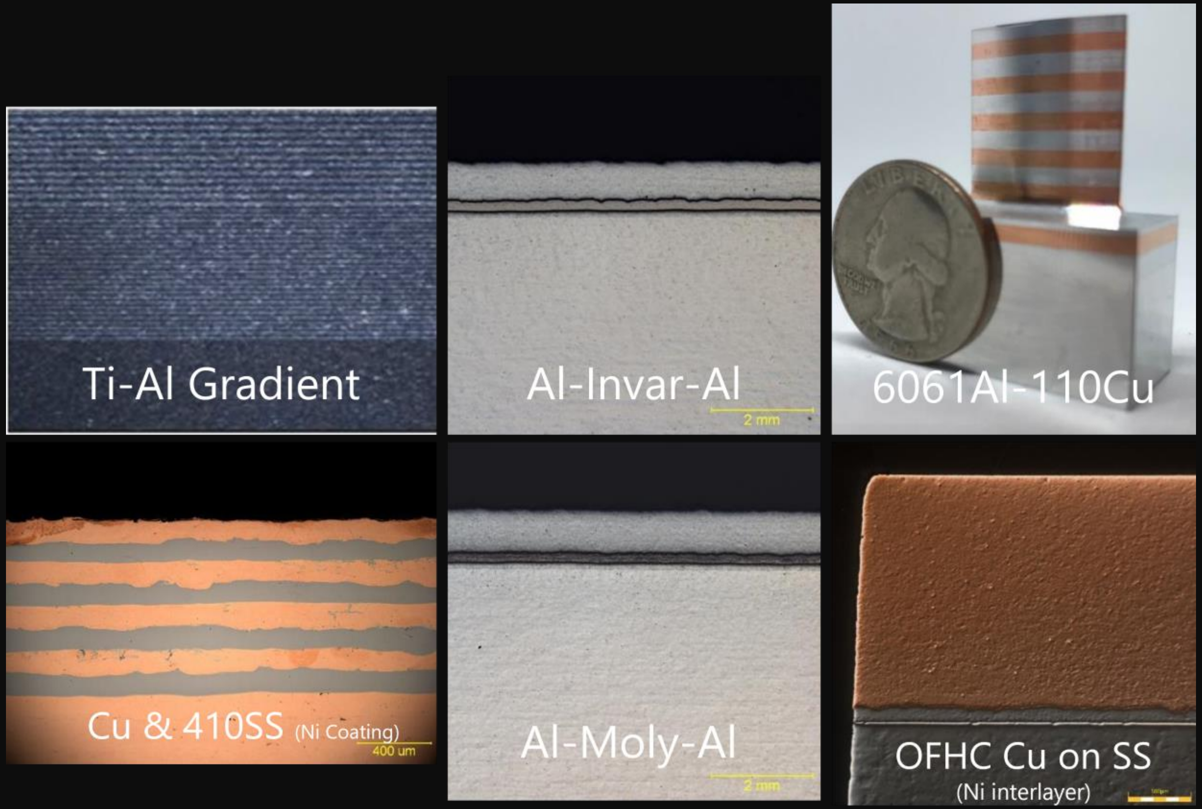
Designing for Multi-Material Parts

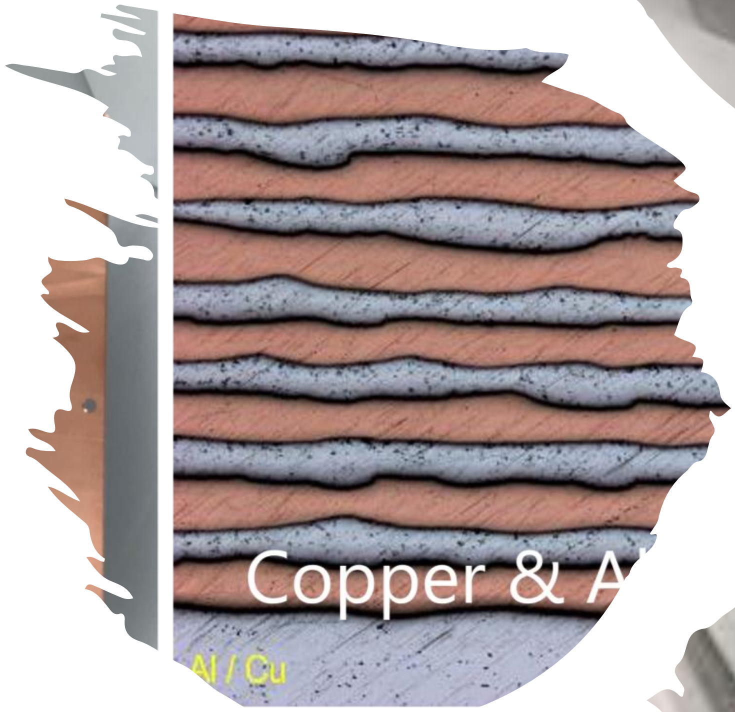
One of the key core applications of UAM is printing dissimilar metal parts. Fusion (melting) based 3D printing processes struggle to join different metals. As welders know, welding (melting) two different metals together often creates unwanted properties in the new alloy created, such as loss of ductility and porosity. UAM, however, is a solid-state additive process, and no melting of the metals occurs. This allows UAM to join different metals together without the unwanted consequences that result from other metal 3D printing processes.

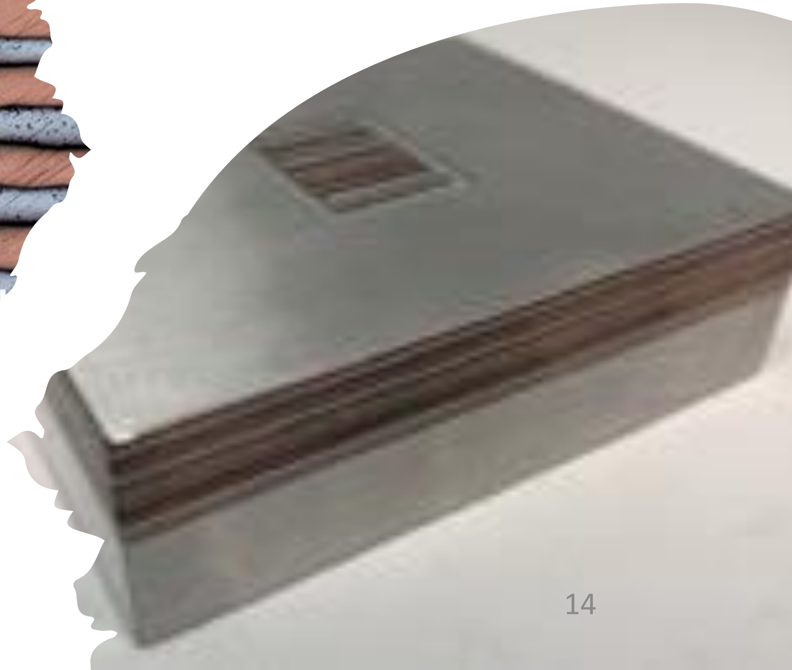


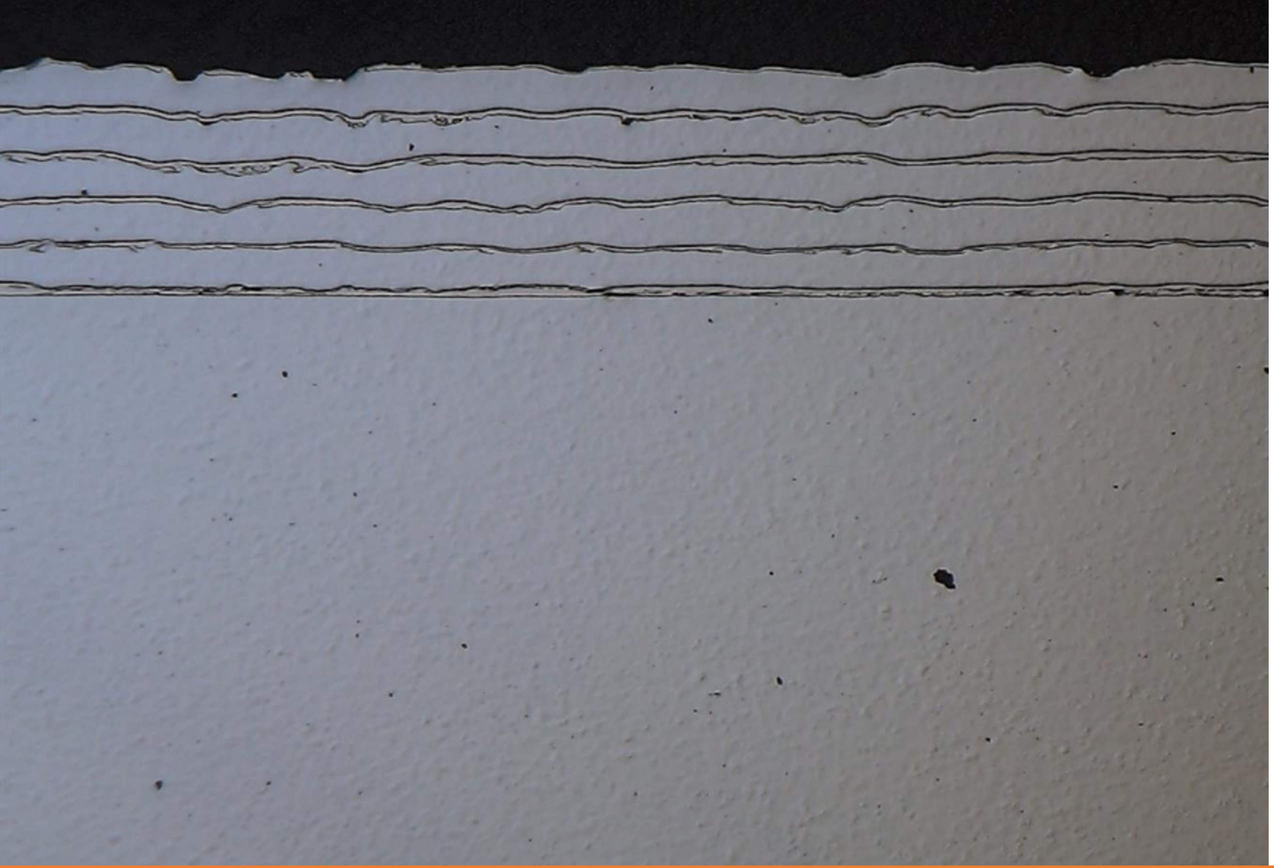
Designing for Multi-Material Parts

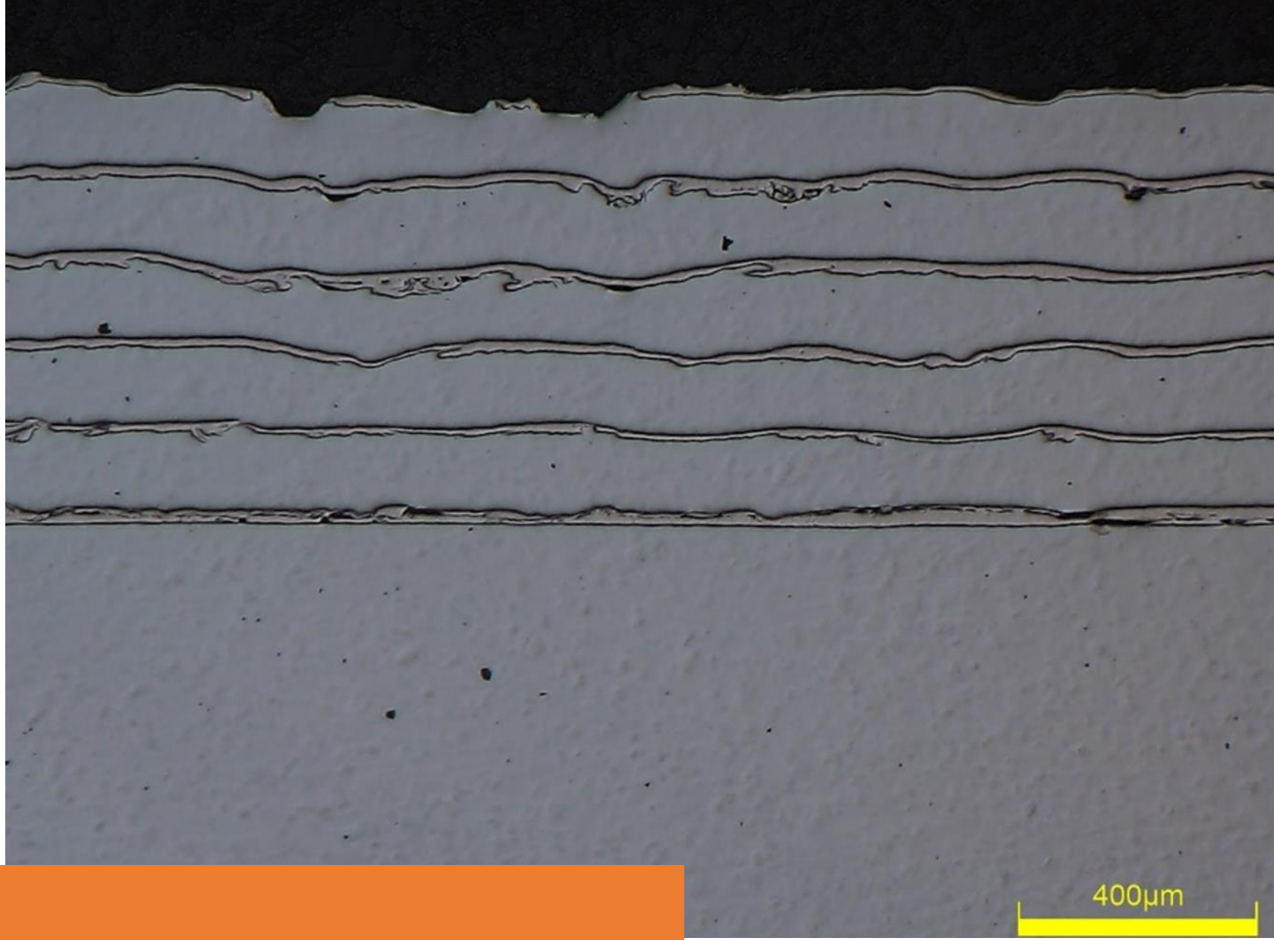
‘Traditional’ 3D printing promises engineers freedom of geometry – the ability to print complex geometries not possible with other methods. UAM extends this to freedom of material. For example:

- Can the mass of your part be reduced by using aluminum for structure but integrating high conductivity copper at critical areas (such as cooling channels)?
- Can your electronics enclosure also be a radiation shield by printing a combination of aluminum, tantalum and titanium in a layered fashion?
- Could you leverage a gradient of thermal expansion to reduce cyclic thermal strain by combining aluminum, invar, and molybdenum?





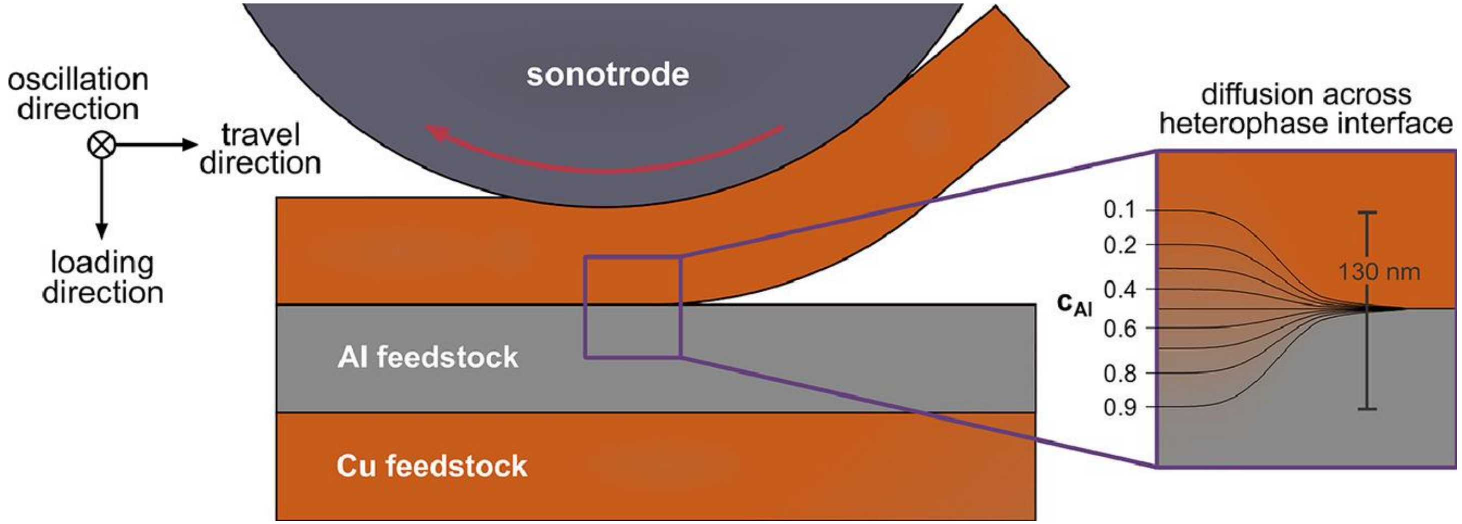




Designing for Multi-Material Parts

Interlayers are often used to improve bonding between harder materials. For example, Al 1100 and Ni 200 are common interlayers used when bonding materials such as SS 316 or other harder alloys. A thin interlayer (usually 0.001” thick) can enable combinations of Inconel's, high strength steels, and even refractory metals all in one component.

Designing for Multi-Material Parts



General Consideration:

UAM is most amenable bonding soft metals to other soft metals, and soft metals to hard metals. This is due to the fact that the UAM process relies on plastic deformation for bonding.

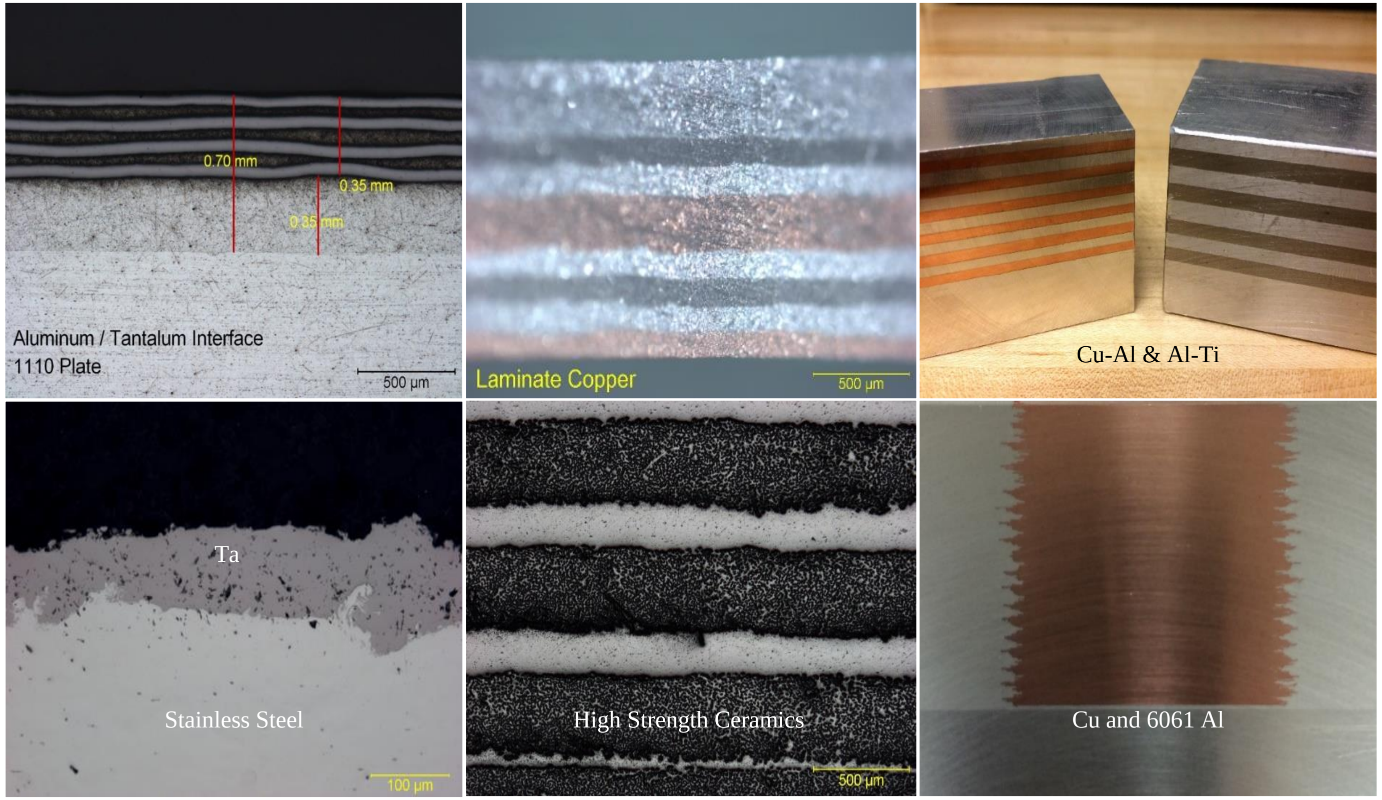
Considerations for Multi-Material Parts

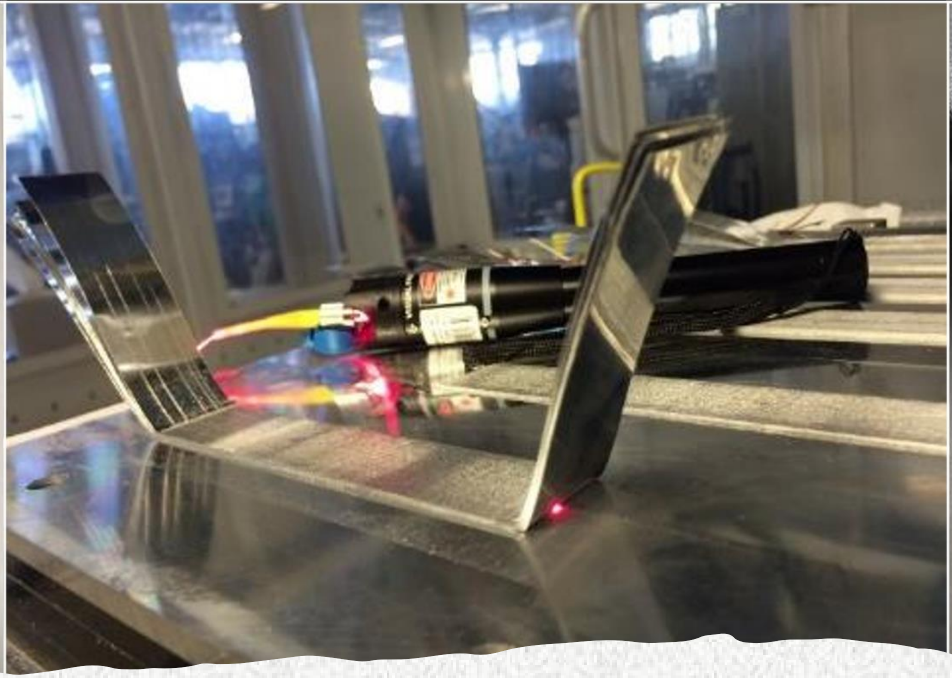
Designers should consider the following when designing multi-material parts:

-Use Environment: Dissimilar metals held at high temp in operation can diffuse into one another creating undesirable alloys. Dissimilar metals in liquids require attention to corrosion.

-CTE mismatch of the metals: cycling at temperature extremes can cause stress

-Hardness of the metals: two hard metals are difficult to weld via UAM unless a softer interlayer is possible (e.g., Al 1100 or Ni 200)





Designing for Embedded Sensors

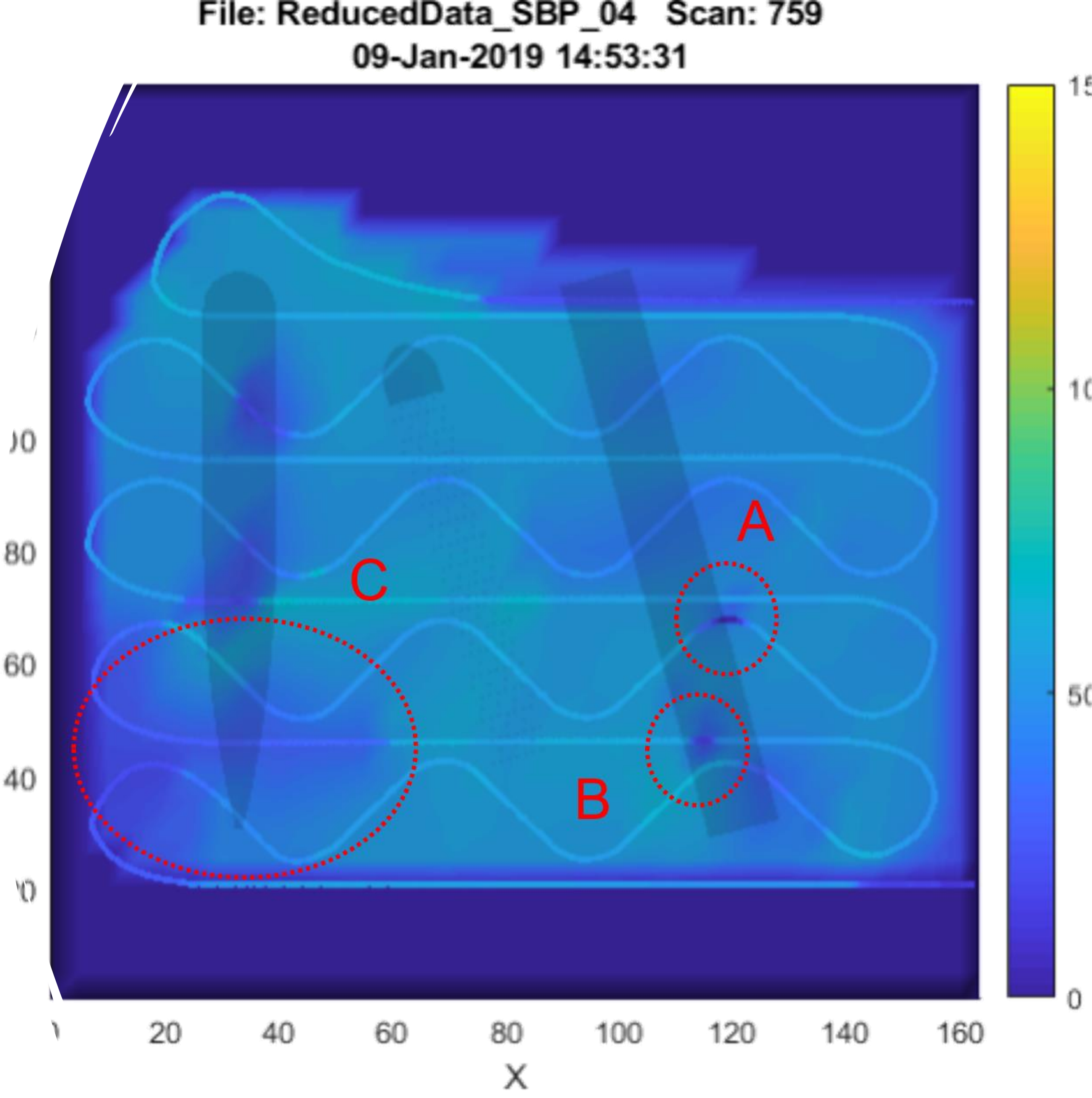
Because UAM welds occur at low temperature, the UAM process can be used to embed critical sensors and electronics into metal parts. These sensors include: strain gauges, thermocouples, fiber optics, circuit boards, RFIDs, etc. The process of embedding each of these types of sensors or electronics varies, but each can be fully encapsulated into a metal part or component using the UAM process.

Designing for Embedded Sensors

Why?

Embedding sensors and electronics allows engineers to collect in situ data, enables continuous health monitoring of components while in operation, and protects sensors and electronics from caustic and damaging environments.

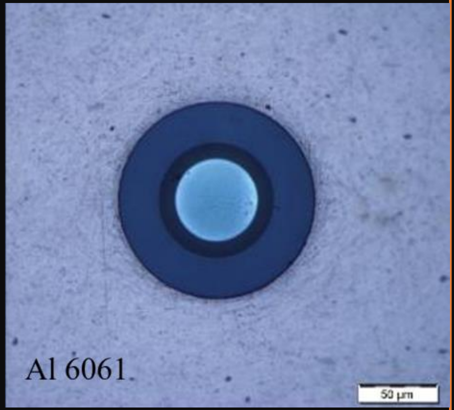
In the example to the right, a sensor was embedded into the baseplate of a LPBF machine, to monitor strain during the 3D printing process. This can assist engineers and printers in identifying failure of a part during the build process, as well as to better understand the strain experienced in the part during the build.



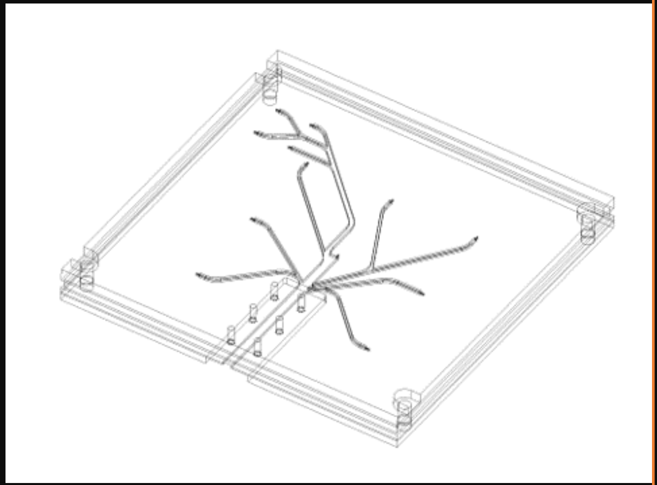
Designing for Embedded Sensors

Usually, during the UAM process, a channel or pocket is milled and the sensor is placed in the channel or pocket. Then, layers of foil are built over the sensor to embed the sensor and create the rest of the part. Because metal flows under ultrasonic activity, sensors such as thermocouples or fiber optics are often fully encapsulated by the material welded via UAM.

Right: A sensor embedded via UAM, fully encapsulated.



Right: Smart baseplate design



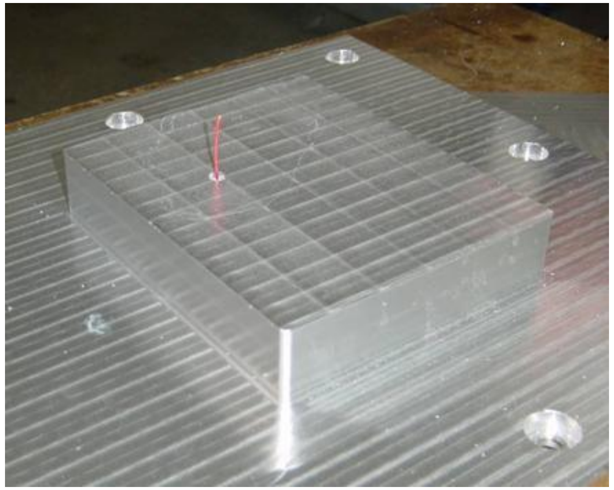
Right: Thermocouples are embedded into a LPBF build plate. First, channels are milled and thermocouples are placed in the channels. Then layers of foil are ultrasonically built up in Z, until the part is built to height and then profiled out.

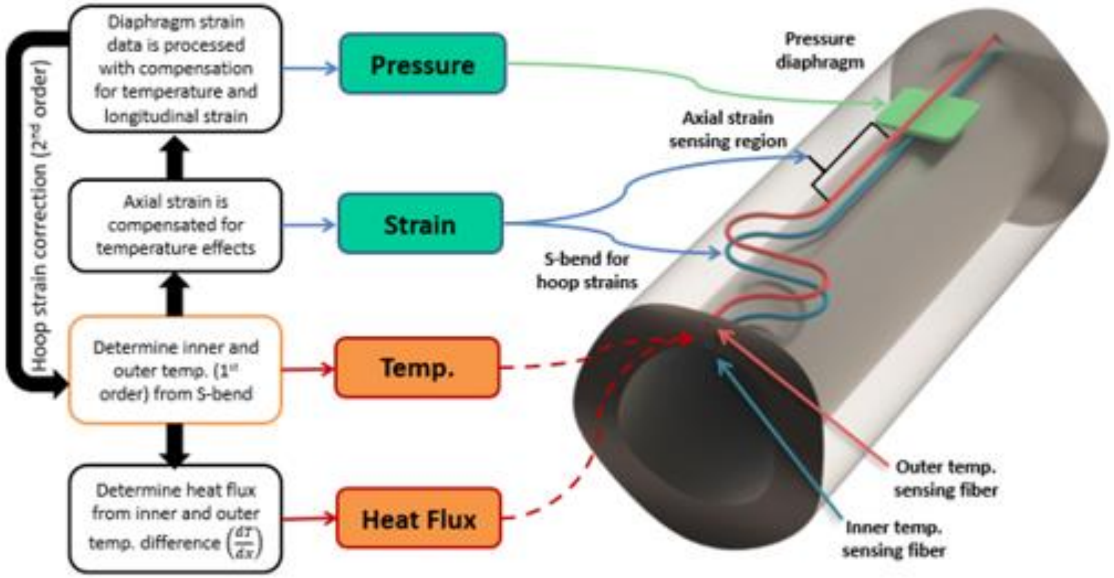
Designing for Embedded Sensors

The ability for UAM to fully embed sensors into metal components opens up a new world for engineers to design "smart" parts, able to give real-time data, feedback, and health monitoring. Additionally, engineers can protect and shield components from caustic environments or other detrimental environments, including radiation.

What would you like to embed to make your components *smart*?

A circuit board embedded into a fully dense metal housing providing shielding.

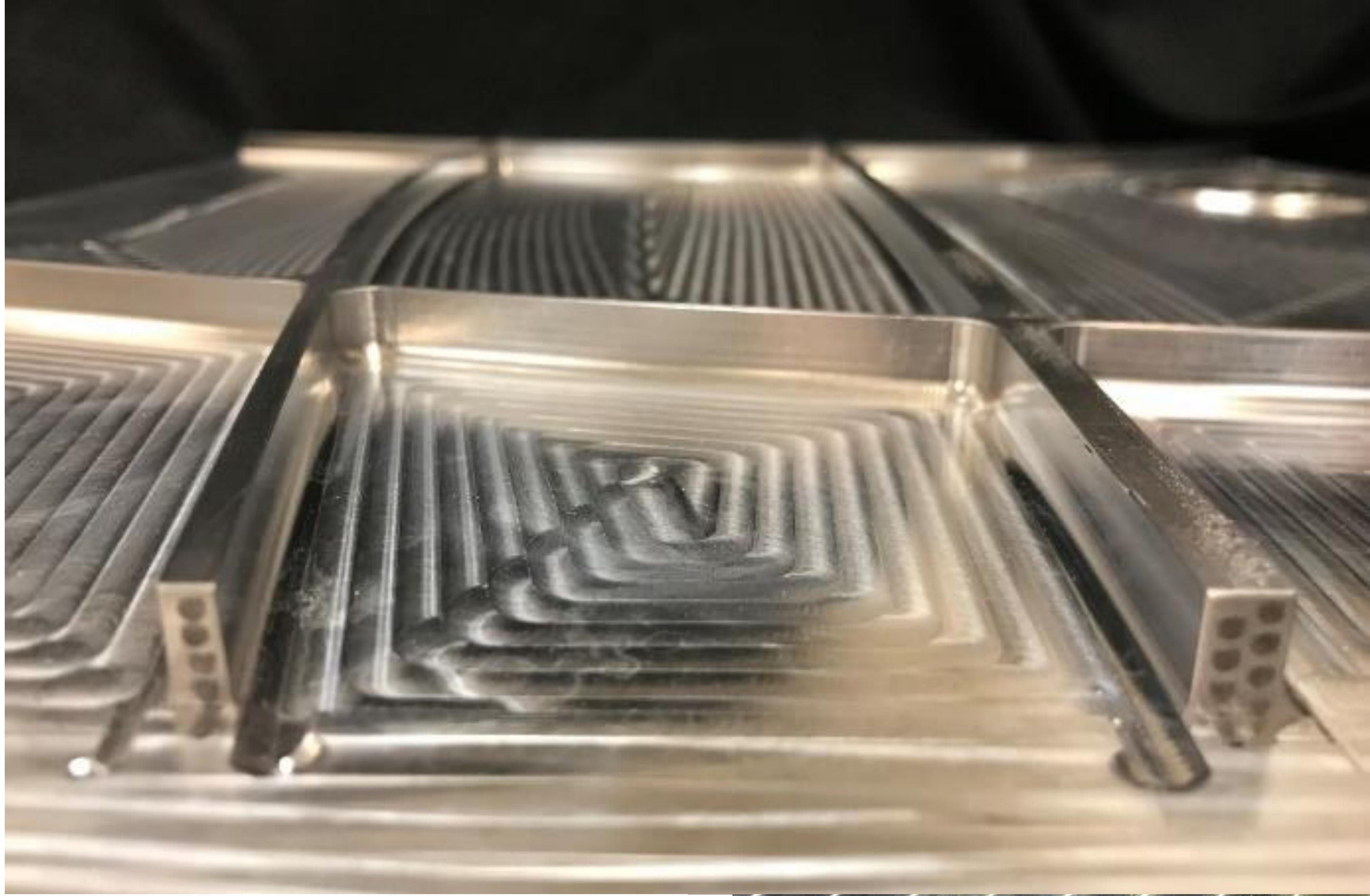


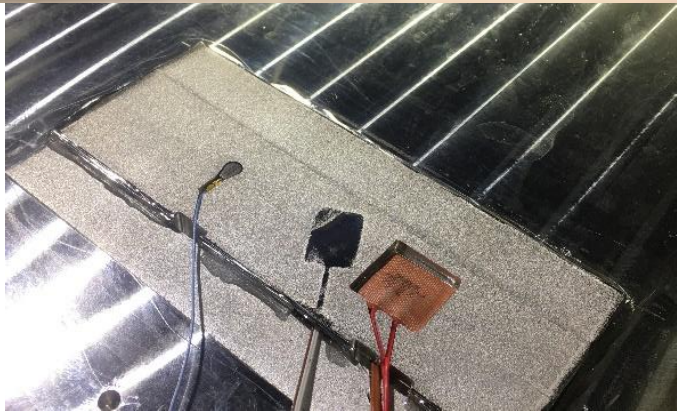


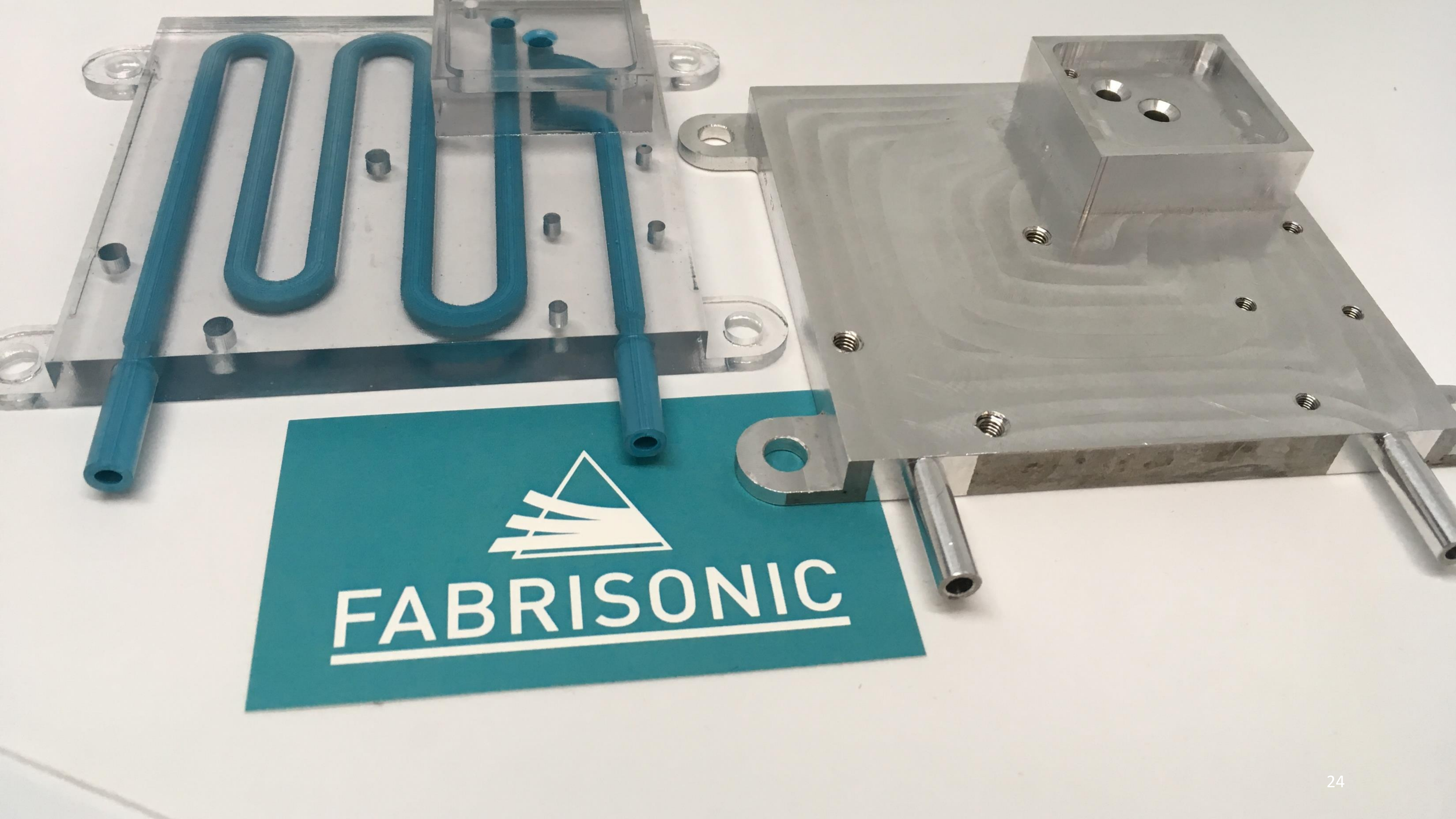
A pipe with embedded sensors designed to provide real-time data on strain, temperature, pressure, and heat flux.

Other things that UAM can embed:

- MMC tape or fibers
- Electrical wiring
- Carbon nano-tubes
- RFIDs
- Resistance heaters or heater cartridges
- Connectors
- Accelerometers
- Fiber Optic Bragg Gratings



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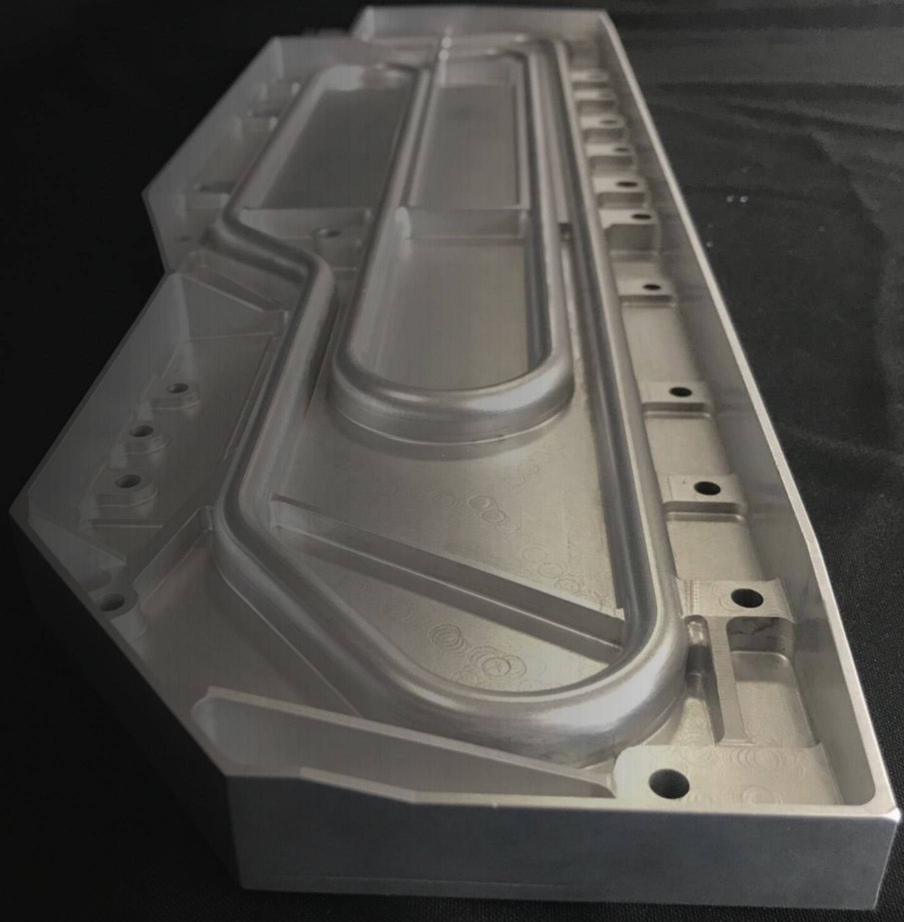
Designing for Complex Internal Geometries

Whether to move fluids, route cables, or to lightweight structures, many components benefit from or require internal passageways or channels. UAM provides engineers and designers with the ability to design and create channels and passageways into metal components and fully encapsulate these features. These passageways can be fully hermetic and can withstand high burst pressures.



UAM Process for Internal Geometries

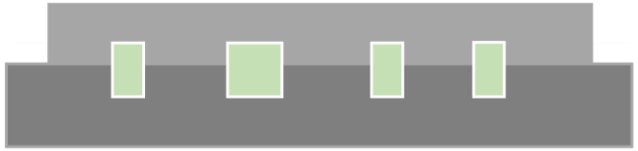
Step 1: Weld baselayers of foil onto baseplate (not to scale)

Step 2: Mill desired geometry into the plate

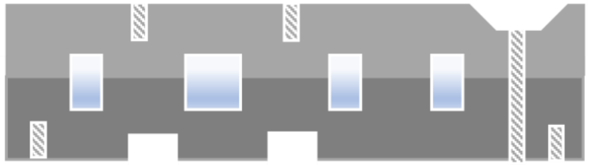
Step 3: Apply support material and allow to cure

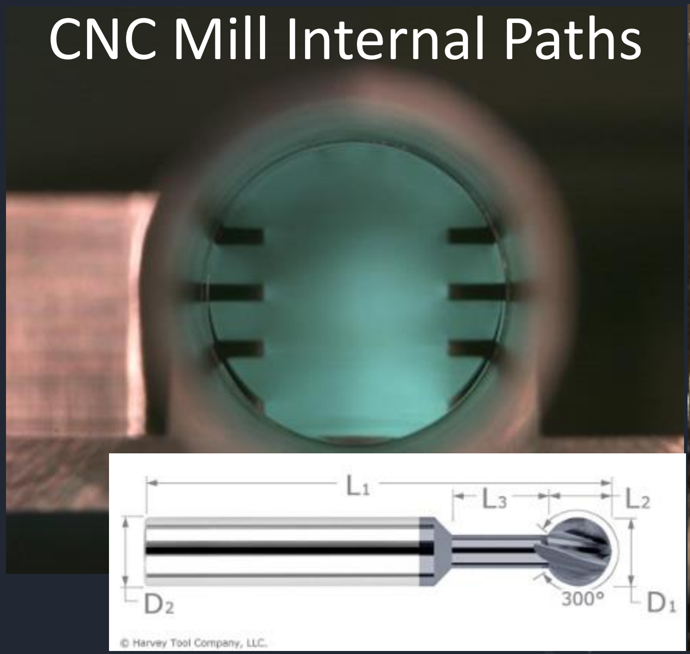
Step 4: Face-mill the material at the height necessary to achieve desired channel depth

Step 5: Weld capping layers to desired wall thickness



Step 6: Flush support material and mill remaining features and holes (as necessary)

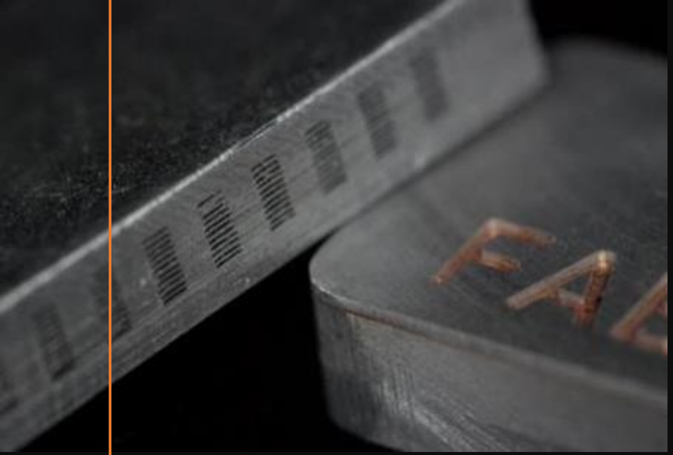


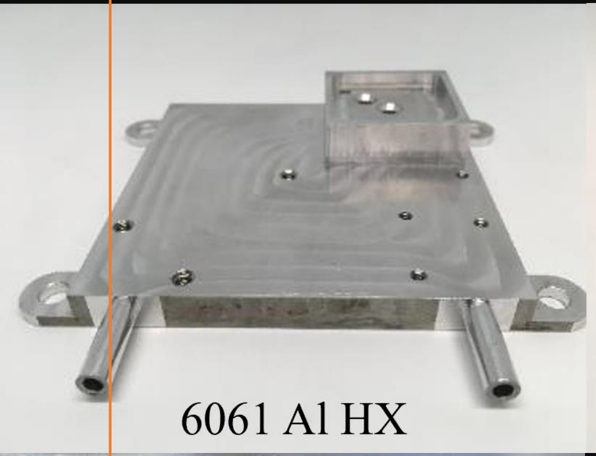


Designing for Complex Internal Geometries

Components that often benefit from UAM are heat exchangers. Although, many other types of parts with internal channels and geometries can be made with UAM.

Similar to embedded sensors, parts with internal geometries begin with a metal baseplate. Then, channels are milled. The UAM process then adds material above the channels, fully encapsulating the channels. Once the part is built to the desired height, the part is the profiled out using the CNC capabilities of the UAM machine. Parts can be further lightweighted by removing unnecessary material via milling.





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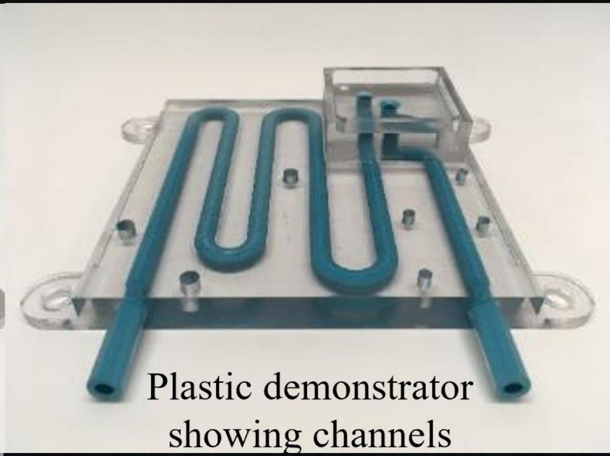
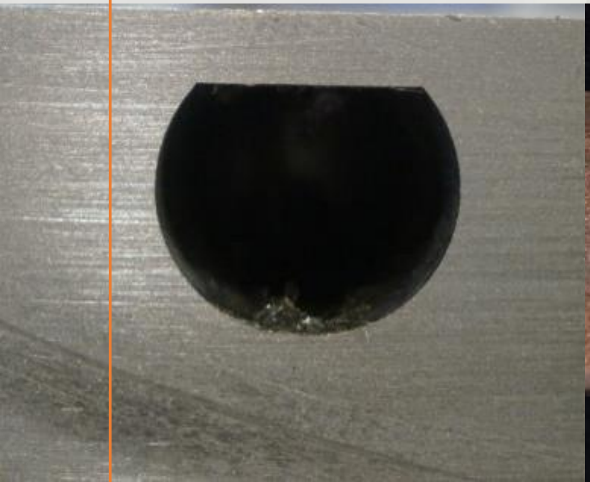


Plastic demonstrator showing channels



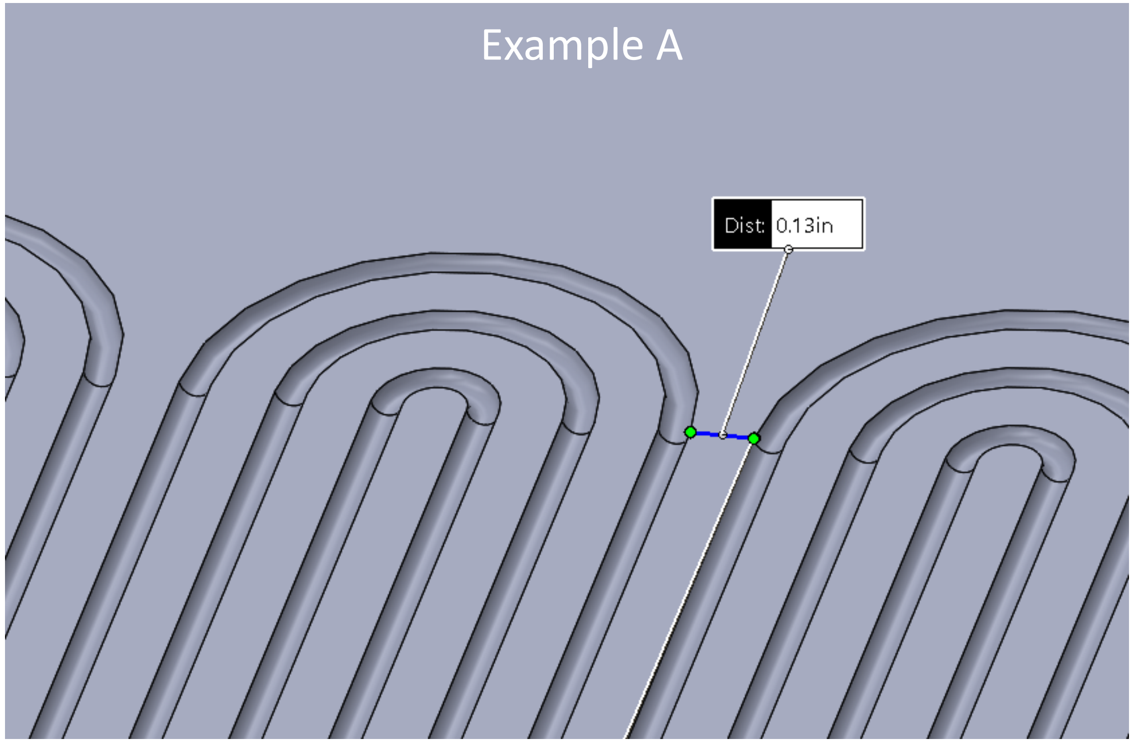
Designing for Complex Internal Geometries

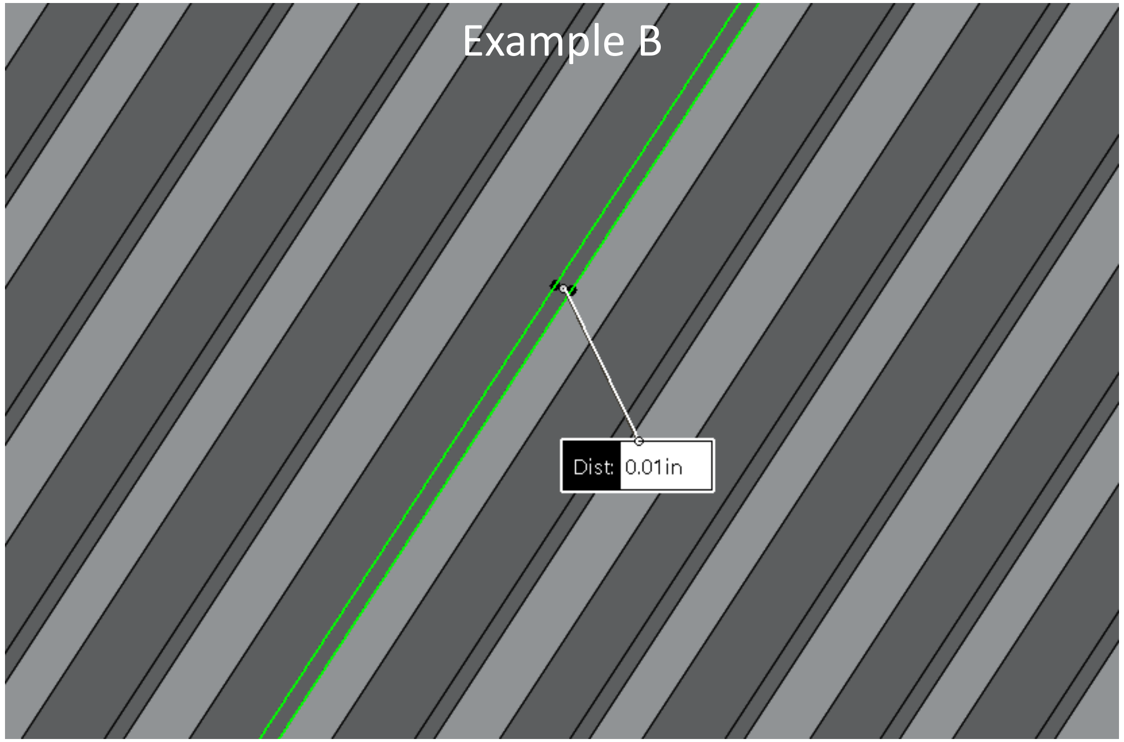
- Channels can be as small as 0.005” and as large as 0.750” wide.
    - Intermediate walls between channels should be 0.100” or thicker.
- Channels can be deep, but high aspect ratios may create problems for bonding through vibration.
- Channels will have a CNC surface finish, unlike other 3D printing processes (e.g., LPBF).
- Channels may be curved.
- Because of the UAM process, channels will be mostly round, with a flat top.
- Channels may also be finned.

How do Fabrisonic engineers Design for UAM?

Design for UAM: Wall thickness and aspect ratio

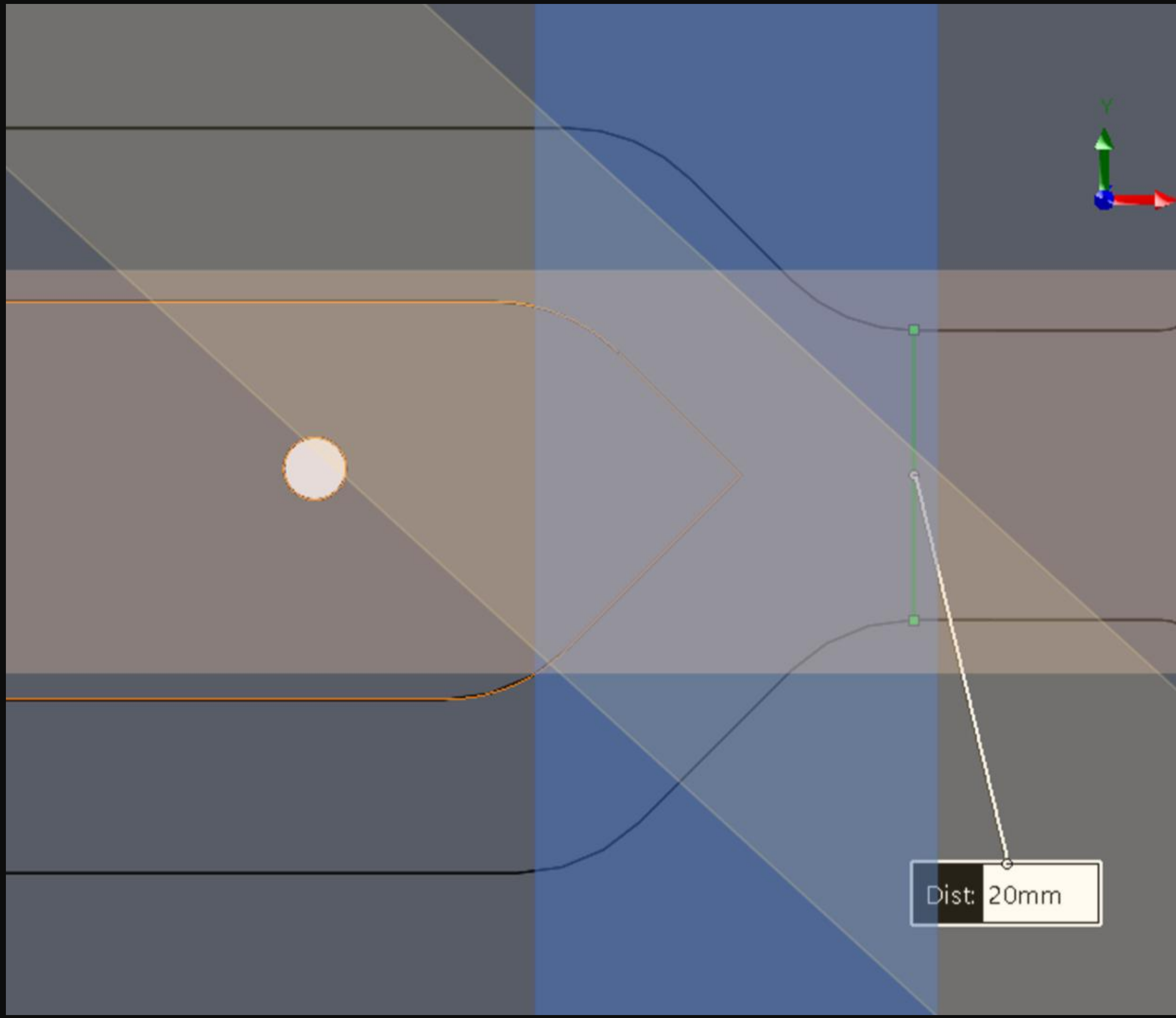
The examples below depict two different wall thickness and aspect ratio situations. Example A depicts a part with a wall thickness of 0.130", whereas Example B depicts a part with a wall thickness of only 0.010". Example A walls have an aspect ratio (W/H) of 13:3, whereas Example B has an aspect ratio of 1:5. Example A is more amenable to UAM due to the greater contact area the walls provide, and the better aspect ratio of the walls. The walls of Example B are at risk of deforming under the force of the sonotrode.

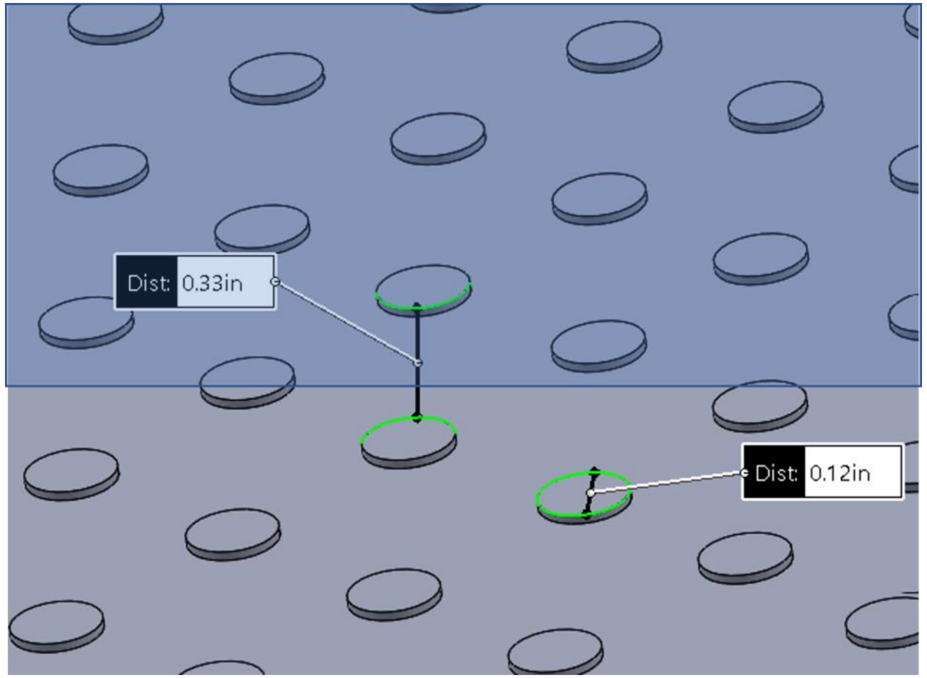




Design for UAM: Channel Size and Voids

- Because the UAM welder has a width of approximately ~1”, it is ideal that 50% of the welding surface area contact stiff material. Depending upon various factors, this surface contact area percentage can be lower or higher. In this example part, various weld strategies are depicted by the blue strip. In the parallel weld strategy (light orange), only a small portion of the welder is in contact with stiff material when welding over the 20mm wide channel. In the perpendicular weld strategy (blue), the welding tool must also deal with the 20mm wide channel, which will cause bonding issues to foil layers above the channel. In the angled weld strategy (light yellow), the welder also has challenges maintaining contact with stiff material.
- Solutions for designers could be:
  - Reduce channel width and increase channel depth to maintain the same flow rate and/or pressure.
  - Include support walls within the channels to increase surface contact area, provide resistance against the welding tool, and decrease the gap that the sonotrode must cross.



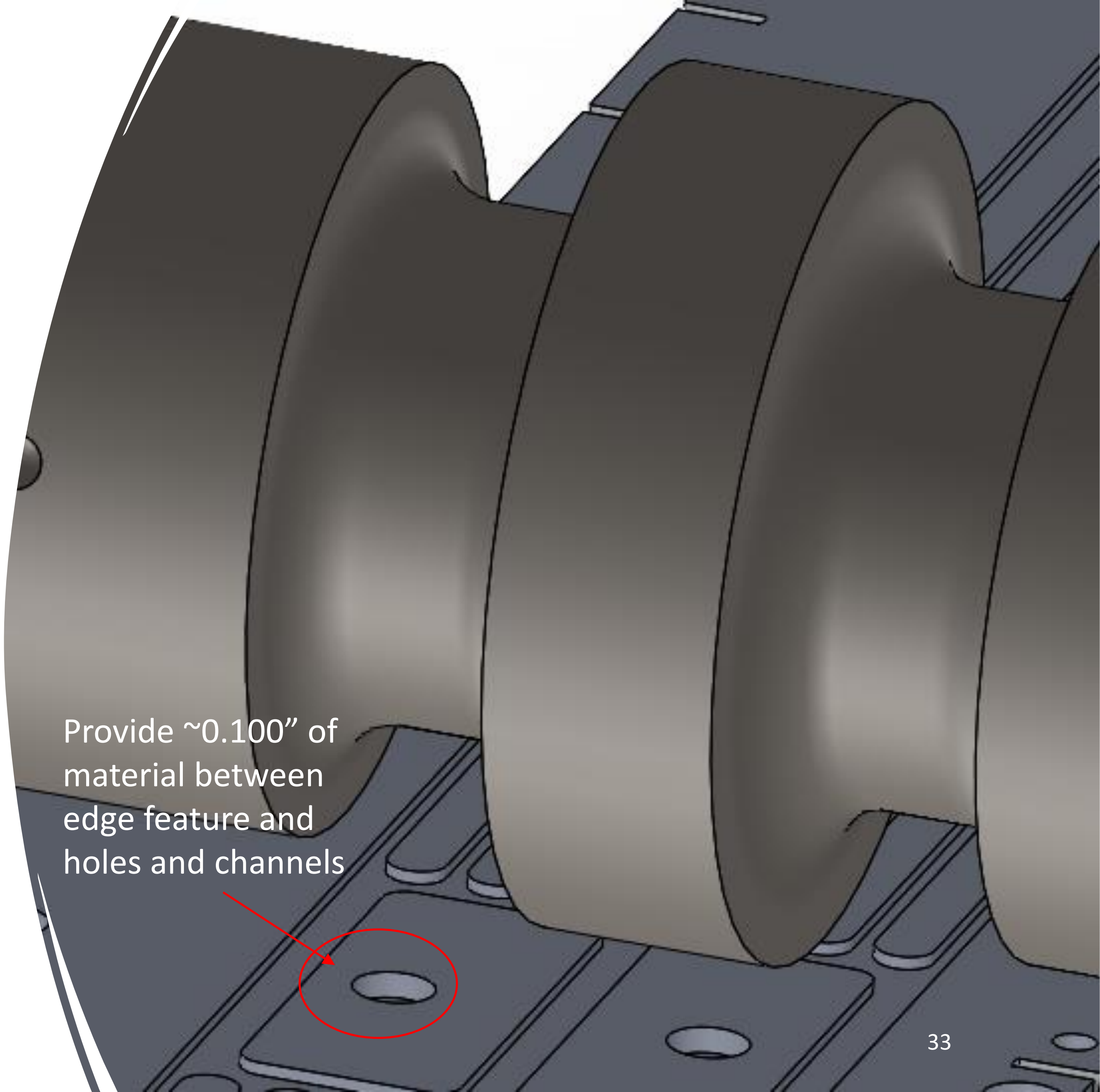


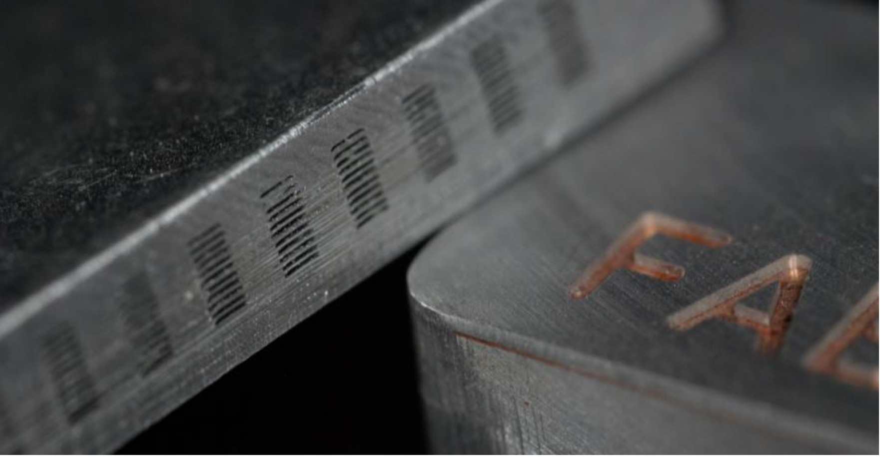
Design for UAM: Surface Area Contact

Surface area contact is critical for the UAM process. Walls, pillars, and other features provide resistance against the UAM sonotrode to enable the sonotrode to bond foil material to the underlying material. Insufficient stiffness has a negative effect on bonding. Ideally, the 50% of the welding tool is in contact with stiff material. In this example, pillars are design into the part for thermal effect; however, as can be seen by the light blue strip representing a weld path, less than 50% of the sonotrode would be in contact with stiff material. The aspect ratio of the pillars is amenable to the welding process; however, ideally these pillars would be closer together or more densely packed to provide resistance against the sonotrode.

Design for UAM: Leak Paths

In general, to achieve an extremely low leak rate, designers should include ~0.100” of material between any channel and another channel, between a channel and the edge of a part, or between a channel and another feature/void (e.g., a bolt hole or through hole).





General Consideration: Foil Thickness

- Foil thickness and number of layers: 0.005” to 0.006” foil layers are ideal for UAM. Thinner layers (down to 10um thick foil) and thicker layers (up to 0.020” thick) are possible, depending on the metal/alloy and how many layers are required.
- Very thin foils (≤0.100”) may rip or tear due to the surface roughness of the welding sonotrode and the ultrasonic scrubbing action.
- Thicker foils absorb the energy required for bonding.
- Harder materials generally require thinner foils, softer materials are amenable to thicker foils.

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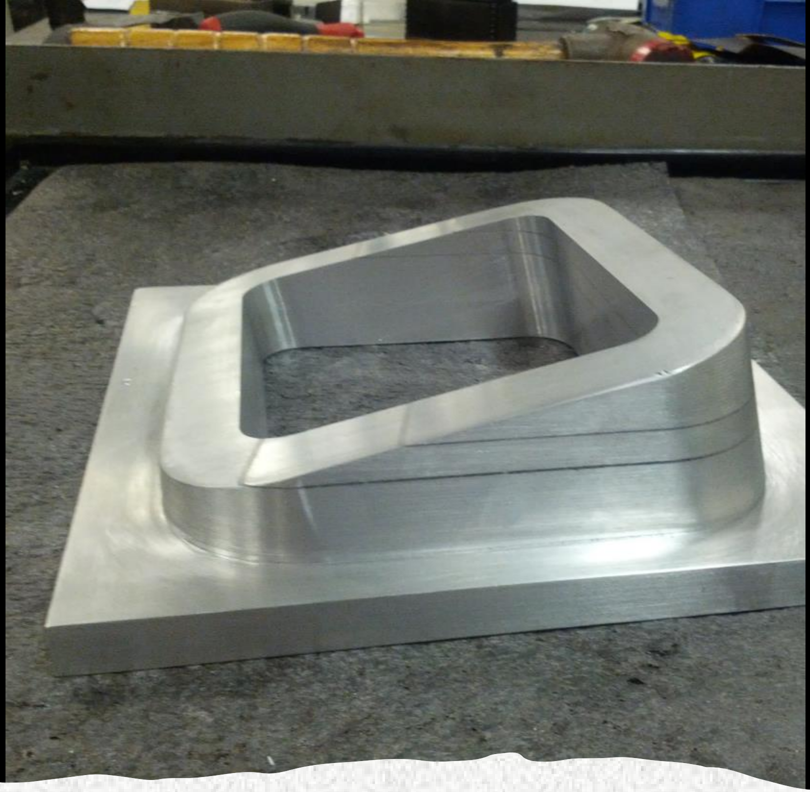
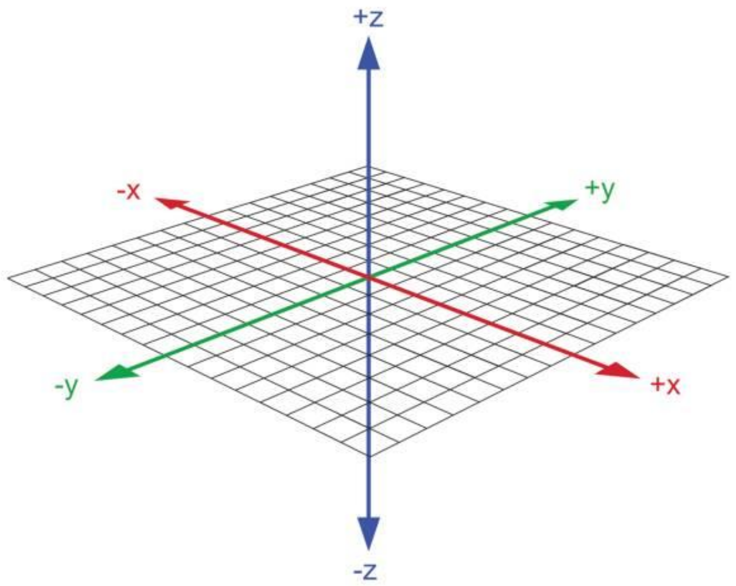


General Consideration: X, Y, & Z Build Envelope

UAM is not constrained in X and Y, except by the build envelope of the UAM machine. Our in-house machines are capable of building up to 72” x 72” (X and Y).

The Z direction is the most expensive direction. Additionally residual stresses build up in parts the more layers are welded. Generally, we try to minimize Z build height. Printing for thick parts can be offset by starting with a thicker baseplate, and only building UAM material to create the geometry that REQUIRES 3D printing. This saves time and material (foil) in the process.

General Consideration: X, Y, & Z Strength



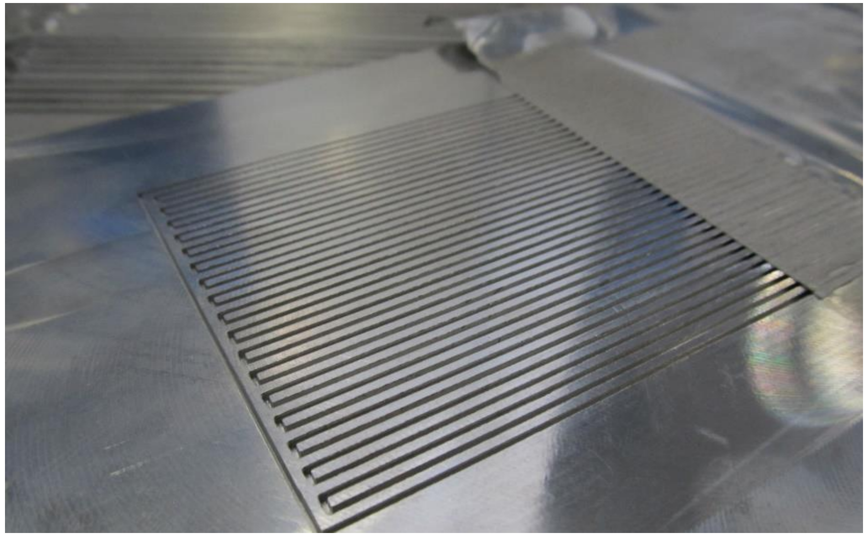
Because UAM uses monolithic foil sheets, the strength of a part in X & Y is the same as the incoming feedstock. Material properties do not change. UAM does lose some strength in Z (~20% debit), due to the nature of the bonds and the possible inclusion of oxides that remain at the interface. Engineers should consider this when designing a part for UAM; however, changes can be made in parts to design around this.

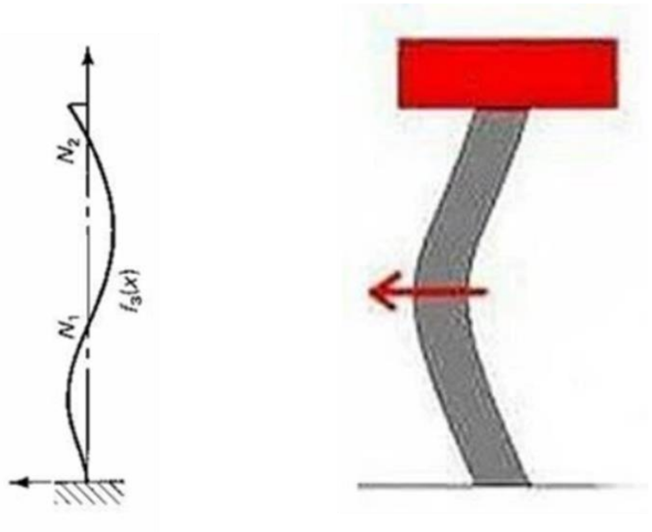
General Consideration: Stiffness

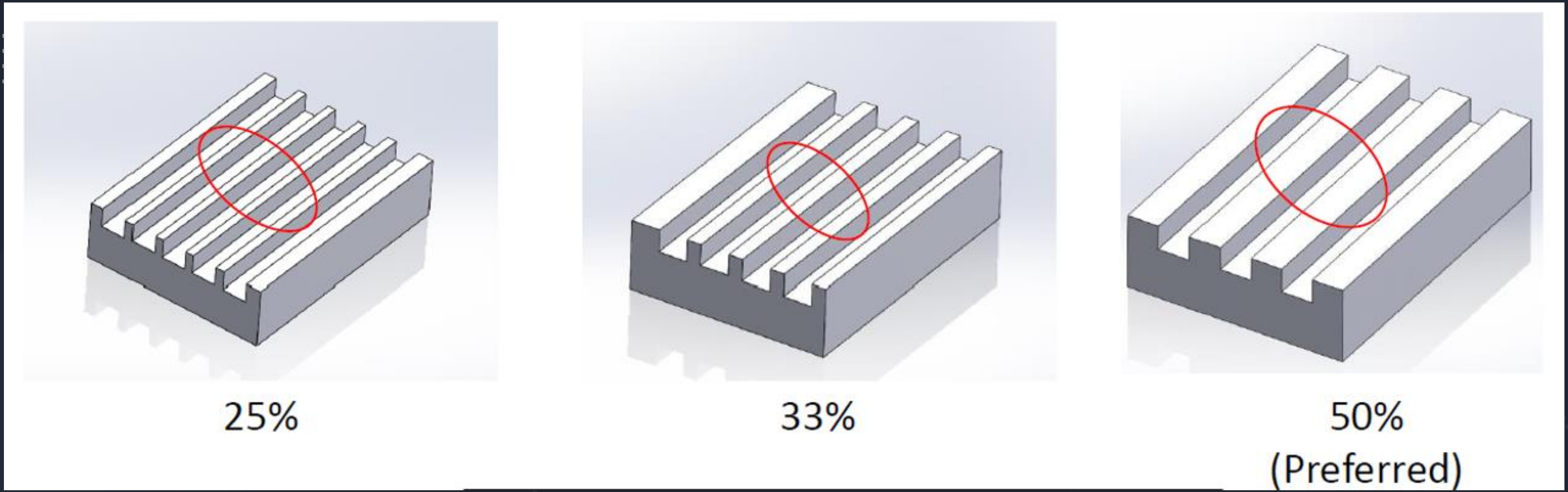
Stiffness is a critical factor for UAM. Walls and columns that are too small do not provide sufficient stiffness for the UAM process to bond effectively, and may also cause buckling or fracturing of the thin wall/column due to the downforce of the welder or resonance from the ultrasonic vibrations.

Stiffness is also a requirement for fixturing parts and baseplate material.

The stiffer the material and/or fixturing, the better the results with UAM.







General Consideration: Contact Surface

When welding material over channels, a good rule of thumb is that 50% of the welding horn is contacting underlying stiff material (e.g., a wall or column). Depending on various factors (material, geometries, welding parameters), this ratio can decrease.

What UAM is not good for

Organic structures and lattice structures

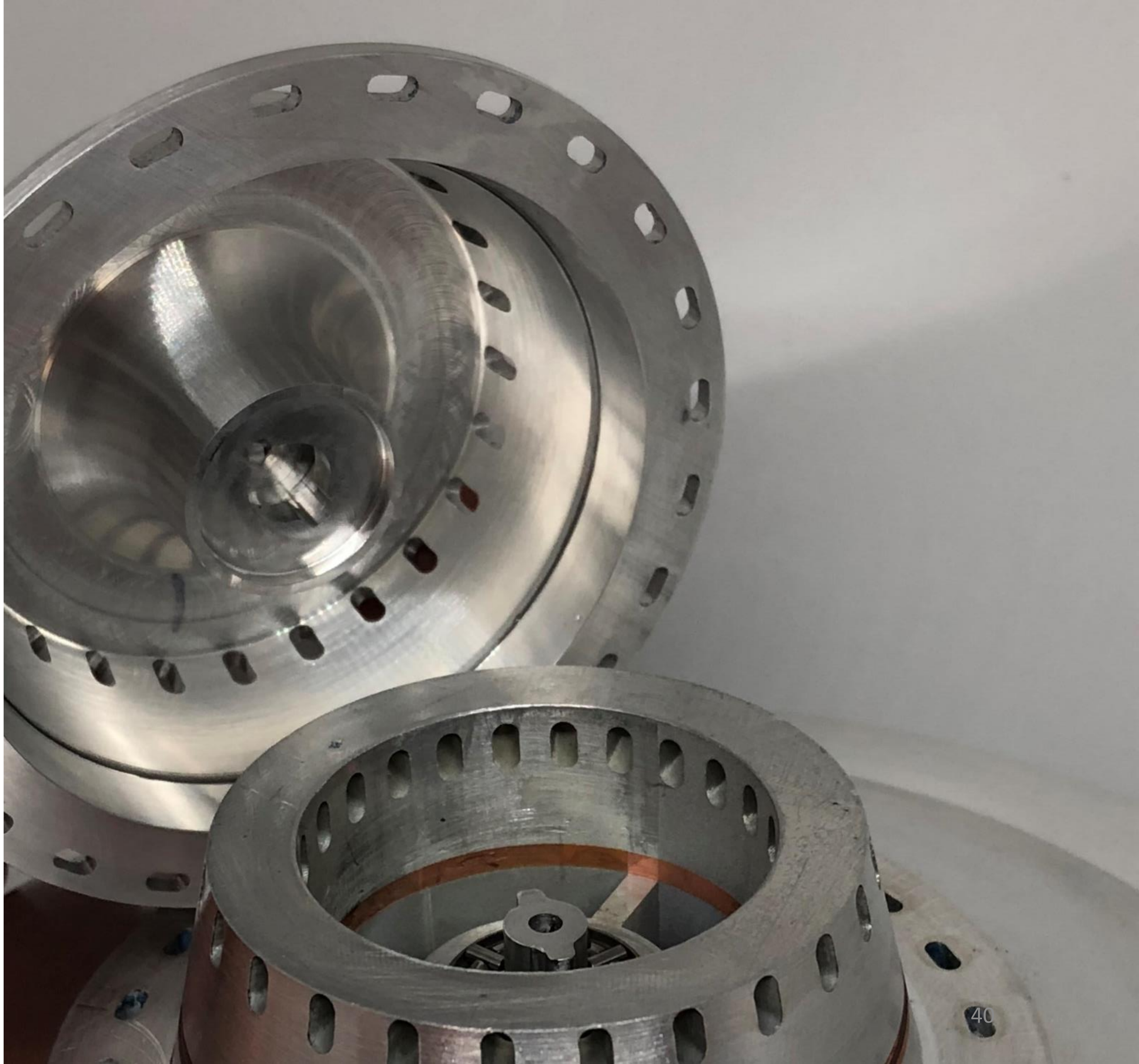
Building large parts completely out of UAM (e.g., large rocket nozzles)

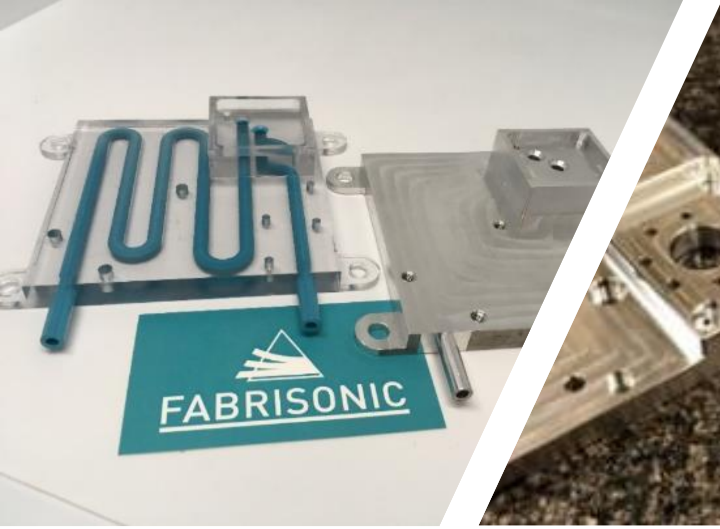
Refractories and extremely hard metals

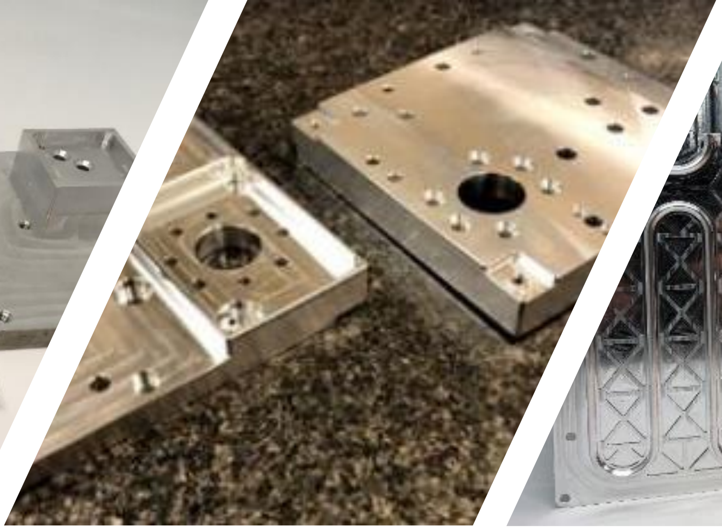
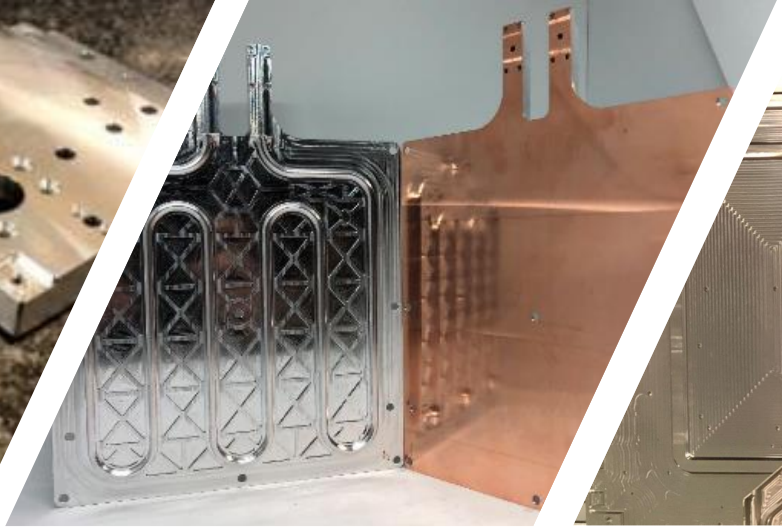
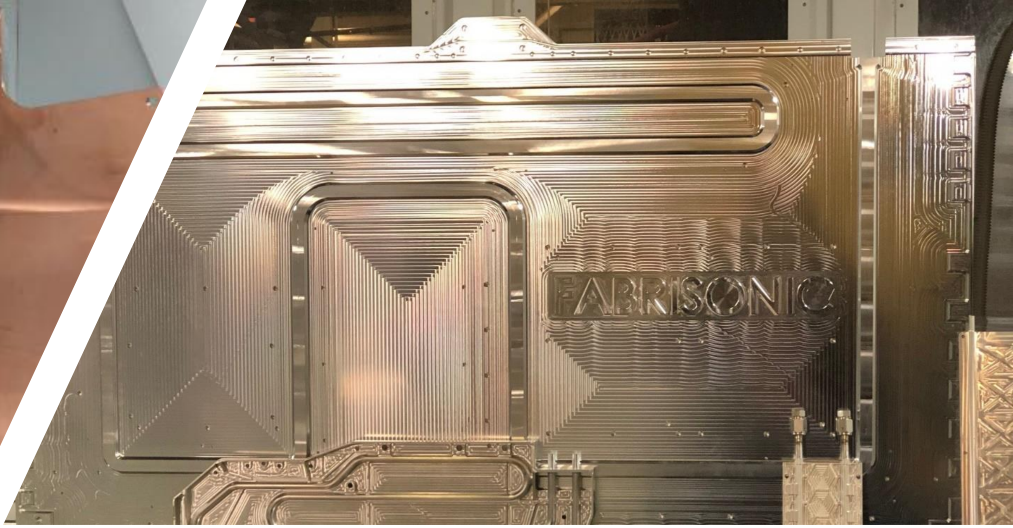
Metals with high lubricity (lead, silicon, etc)

Plastics and polymers

Case Studies

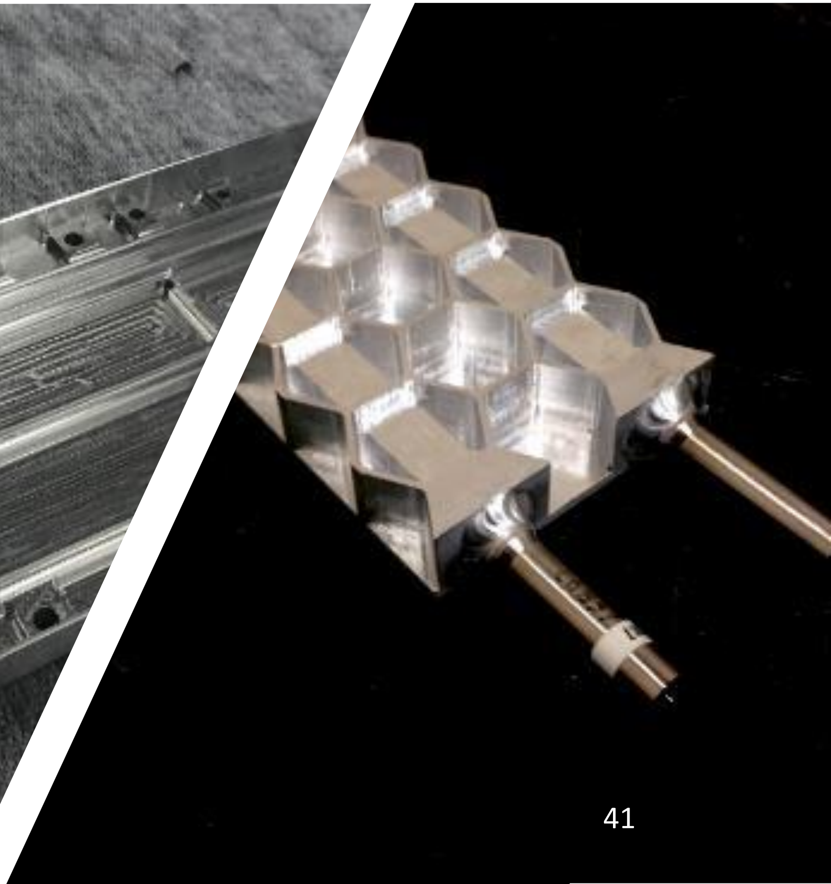




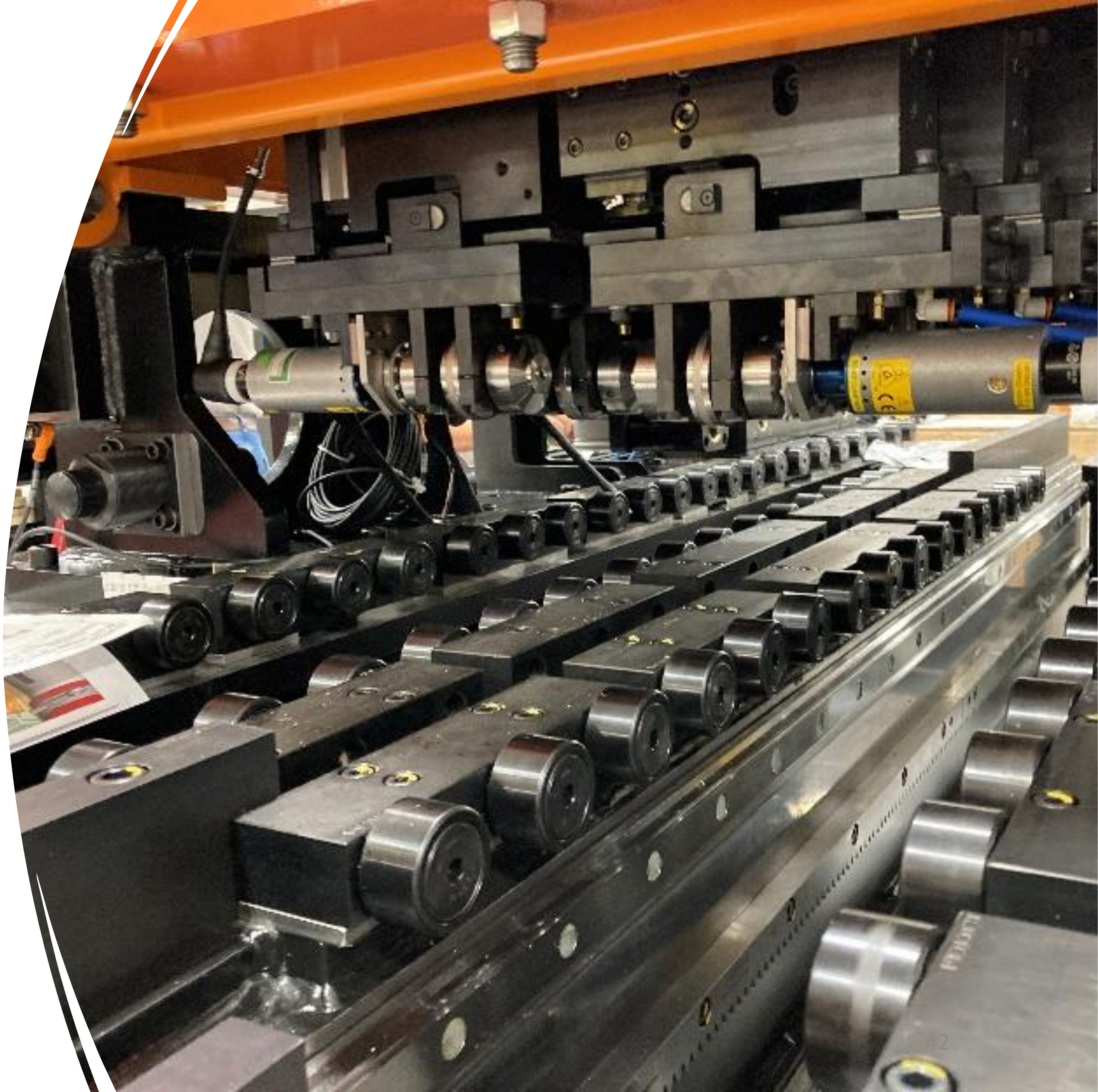
Heat Exchanger Examples

Fabrisonic has made numerous heat exchangers and cold plates for commercial and governmental customers. These heat exchangers have passed rigorous testing requirements, and have include multi-materials and embedded sensors in addition to incorporating complex internal geometries for fluid flow.

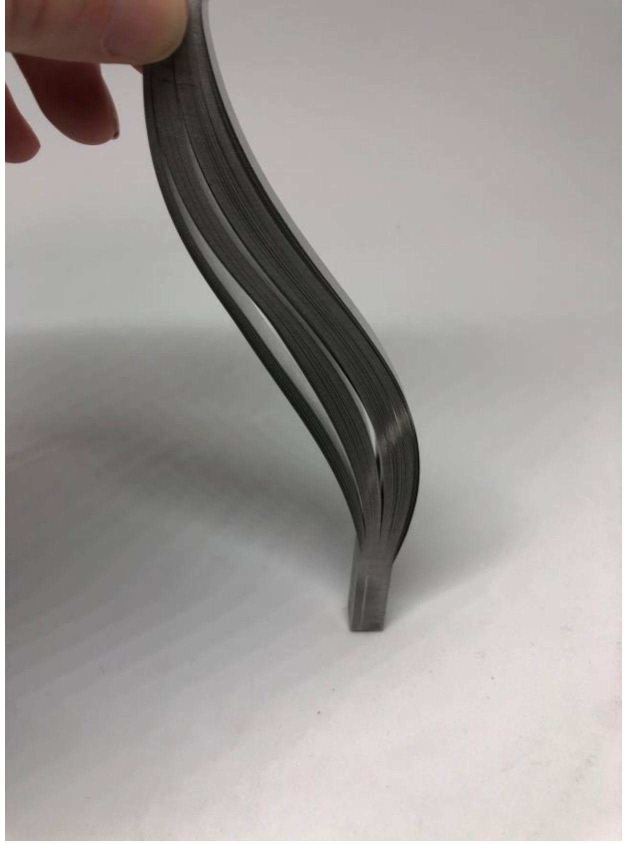



Electrification

Starting in 2020, Fabrisonic partnered with a mid-western electric vehicle (EV) battery manufacturer to produce battery bus bars using UAM technology for a large EV manufacturer. By designing and building custom UAM machines, Fabrisonic enabled the EV battery manufacturer to produce more than 23 million parts in 2023 alone. UAM technology increased production by 200% and decreased manufacturing costs by 45%. UAM's high weld rate, ability to bond dissimilar metals, and ability to embed sensors, enables engineers to create high-production electrical components at lower cost for the EV industry.





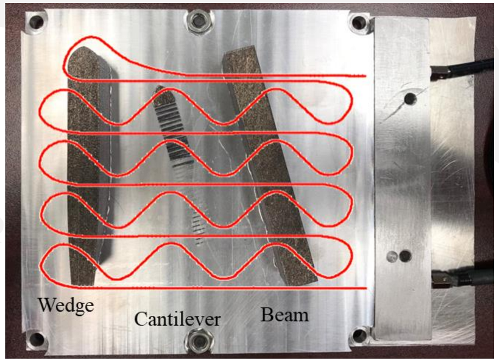


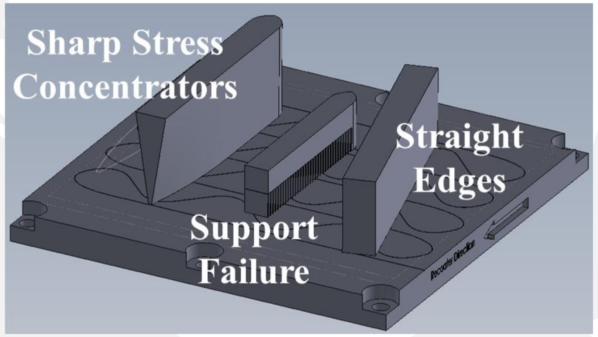

Thermal/Electrical Management

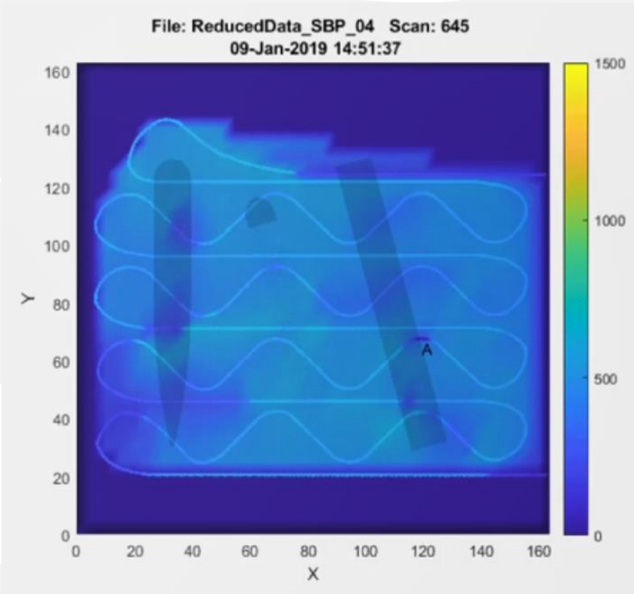
Fabrisonic has manufactured numerous shunts, or thermal straps, designed to be solid material on each end and flexible (unwelded) material in the middle. This allows for flexibility and effective management of thermal and electrical conductivity. These shunts can be made out of aluminum, copper, or other materials as necessary.

Smart Build Plates

UAM has produced "smart" build plates for other 3D printing machines (e.g., LPBF), to enable engineers to collect data during the powder printing process. Embedded thermocouples, fiber optics, and accelerometers have enabled customers to measure strain, temperature, and re-coater blade hits during the build process to understand failure modes and the ways in which part geometries and printing parameters affect build quality.

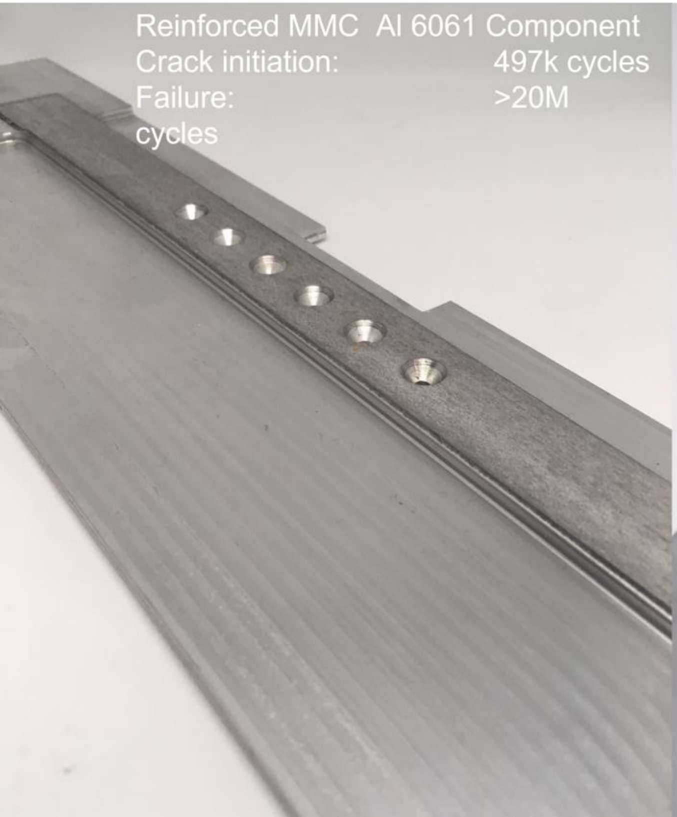






Selective Reinforcement

Reinforcing metals and alloys using ceramic fibers and other materials can significantly improve strength and reduce risk of failure due to fatigue. In one trial, a reinforced MMC fatigue sample demonstrated fatigue resistance with 5x the performance against a unreinforced Al 6061 test sample, and resisted failure with more than 20x the performance of the unreinforced sample.



FAQs

How do you keep material from extruding into channels?

This depends on the channel width, material thickness and stiffness. In some cases, channels are thin enough, and the foil is thick enough that extrusion is unlikely. However, in cases in which we need to protect against extrusion, or to provide some resistance force against the welder, we employ a proprietary support material, which is water soluble, into the channels prior to welding layers over top. We then flush that material out of the part after completing final machining operations.

Can you UAM onto round parts?

We do have the capability of printing onto cylinders and other round parts by using our rotary welding apparatus. Our largest UAM machine does also have limited 5-axis welding capabilities.

What tolerances can be achieved?

Because UAM technology is integrated into CNC platforms, tolerances are as good as CNC machining. Usually, tolerances as good as 0.001” or better are achieved in most parts we make for customers.

FAQs Continued

Are UAM seals hermetic?

UAM can produce hermetic seals. Heat exchanger and other components have passed helium leak tests down to 10^{-9} std. cc/sec.

Can UAM parts be heat treated and/or HIP'd?

Yes, however, engineers should consider CTE mismatch and/or possibilities for diffusion to occur if parts are made from multi-materials.

For more information, contact info@fabrisonic.com