THERMAL PROCESSING FOR SPACE & ADDITIVE MANUFACTURING:

The Essential Guide

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EXECUTIVE SUMMARY

The Space Race 2.0 is well underway as private sector companies compete for opportunity in this next frontier. Advancements in tech and materials have the potential to take humankind further than ever before.

But in this race, it's not just a matter of who can find the greatest innovative solutions, but also make them ready for repeatable, scalable production.

In this guide, we'll cover how the latest advancements in additive manufacturing are shaping the future of space, and how heat treating is bringing these innovations to fruition.

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BEYOND A MAN ON THE MOON

Where Space is Heading

Throughout the 1950s and 1960s, the U.S. and Soviet Union (now the Russian Federation) were not only engaged in the relentless Cold War but also in another, otherworldly battle to master spaceflight and be first to step foot on the moon.

Today a new space race is underway, this time between private sector enterprises that aim to bring space programs to the masses—and a wide range of new technology is helping unlock our space potential.

Worldwide broadband and new methods of power generation are just some of the ways that industry visionaries are reimagining life on Earth to be better connected and sustainable. At the same time, advances in additive manufacturing are fueling the possibility of long-range human space expeditions.

And NASA is helping to orchestrate it all with the retirement of the ISS and sponsorship of three new commercial space stations.

Making Life on Earth Better, Safer, and More Connected

According to NASA, 95% of space missions in the next decade will stay in low Earth orbit (LEO) and geostationary orbit (GEO). That means the first wave of commercial activity in space will largely focus on making life on Earth better.

Several worldwide broadband satellites are already in orbit, offering more consistent, reliable internet signals around the globe. The Ukraine war has shown how global internet connection can provide an important lifeline.

Defense campaigns are using advanced satellite machine learning to improve asteroid and missile detection, along with revolutionary laser technology that has made intersatellite communication possible for the first time—and the travel of information faster.

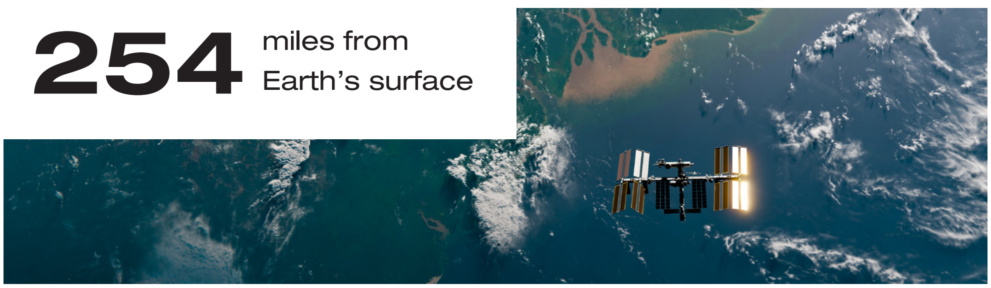
And to help make every future mission safe and successful, NASA is developing a scalable network of public GPS receivers for short-range space navigation.

ADDITIVE MANUFACTURING FOR SPACE

Even with space travel on the horizon, this industry still faces many challenges when it comes to sustaining human life off planet, a large one being manufacturing. Not only do we need the ability to replace mission-critical parts, but we also need to build new space infrastructure and accommodate growing space inhabitancy.

The ISS's current model relies on cargo resupply missions to deliver spare parts, those that aren't already stored in excess on the space station. Orbiting at only 254 miles from Earth's surface, astronauts usually go three months between shipments, which is a long time to wait when the part is needed now. On Mars, these ferry lead times would be impossibly long. This is one challenge that has kept us tied to single-planet life, and that OEMs are solving with additive manufacturing.

254 miles from Earth's surface



3D printing machines are a versatile, portable solution that requires significantly less machining than traditional manufacturing. Equipped with a 3D printer and alloy powder, travelers would be able to print near-net metal parts from virtually anywhere in the universe.

Today, space manufacturing is additive manufacturing, and the future of commercial space is riding on the adoption of 3D printing.

THERMAL PROCESSING FOR ADDITIVE MANUFACTURING

OEMs and tiered suppliers who have embraced additive manufacturing are finding material advantages in the race to space. Many are ramping up production and seeking economies of scale. Others are exploring new and proprietary alloys that will yield stronger, longer-lasting parts.

However promising additive manufacturing is for space, the adoption of AM has still been limited due to the lack of standards for proprietary material and 3D printing applications. The R&D process for discovering these standards can be lengthy and expensive.

As a thermal processing partner, we're joining OEMs in the drive to bring AM into mainstream manufacturing with new industry standards and production-ready solutions that help achieve ROI.

RESEARCH & DEVELOPMENT FOR SPACE

A large portion of the industry research and development currently being conducted is focused on launch and propulsion. SpaceX, BlueOrigin, NASA, among others, are all looking for more efficient, reliable, and sustainable ways to launch into space.

In 2010, SpaceX's Falcon 9 became the first reusable rocket for orbital class launches, a giant leap for the commercialized space industry and a first step toward sustainability. The amount and cost of fuel it takes to deliver any payload to space also is driving many companies to explore alternative fuels and combustion methods.

As rocket science evolves, so do the parts. With every new development, heat treaters play an important role in discovering the processes and parameters needed to bring new parts up to spec. Those with flexibility of coach and custom cycles, along with full-cycle data reporting, offer a higher level of control and are especially vital for helping the industry progress.

Hot Isostatic Pressing, Space, and Additive

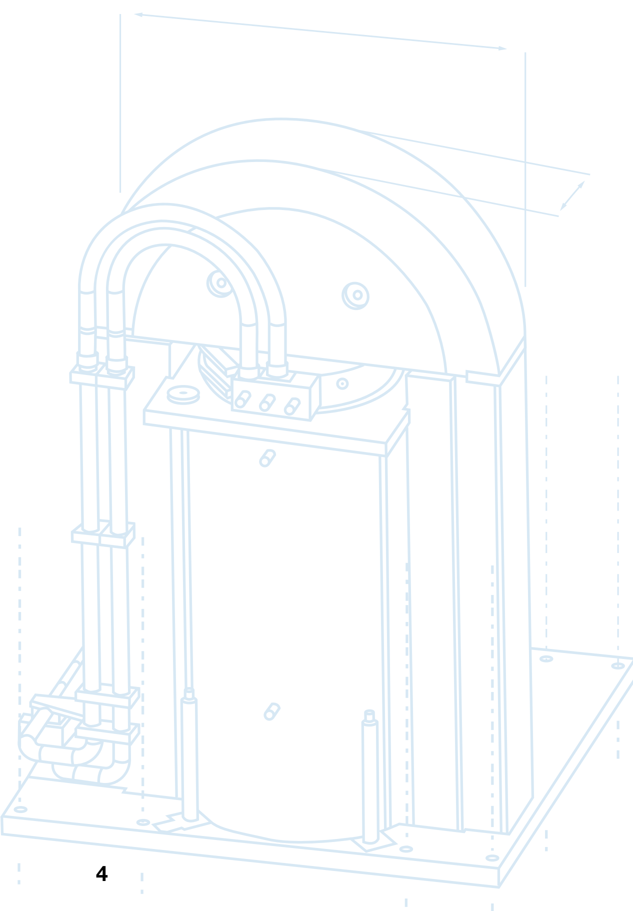
Hot isostatic pressing (HIP) combines high temperature and pressure to improve a part's mechanical properties and performance at extreme temperatures. The sealed HIP vessel provides uniform pressure to bring parts to 100% theoretical density with minimal distortion. The high level of control and uniformity has made HIP the gold standard for AM parts for space.

3D printed materials tend to have porous microstructures that can compromise part performance. HIP is the only process that's able to eliminate these pores without compromising the complex geometries and near-net dimensions that are achieved in the printing process.

Benefits of HIP for space parts:

- Greater resistance to impact, wear, and abrasion
- Improved performance at extreme temperatures
- Better fatigue resistance
- Improved ductility

We've found that aerospace HIP recipes for traditionally casted parts are a great starting point for many novel space applications that don't yet have industry spec and standards. Starting with existing recipes opens the opportunity to do initial coach cycles with other parts, which can reduce the upfront cost of R&D before going to unique cycles for optimization.



For this process, our Cleveland division is equipped with a Quintus QIH-122 HIP vessel, which is specially modified with additional thermocouples to track every variable of HIP. Robust cycle data reports provide an efficient path forward in the iterative R&D process and toward production-ready development.

Some commercial heat treaters don't have the level of data or dynamic cycle offerings like this and will only run HIP coach cycles with set parameters. Without custom cycles, it's impossible to push the boundaries of what's possible.

Your R&D Fueled by Data and Automation

The technology and techniques used in heat treating today have become just as innovative as the materials and parts being created for space applications. Suppliers that drive innovation and push boundaries within their own specialty are better equipped to support your own research and development efforts.

At Paulo, we're setting a new standard with automated process controls, advanced data collection, and batch tracking that allows us to deliver a new level of efficiency and precision to heat treating—and help OEMs like you sharpen your edge in the race to space.

Paulo...

Proprietary software that tracks every step to ensure your parts are delivered on spec and on time.

Paulo Universal Batch System automatically adjusts temperature and atmospheric conditions according to your part's recipe.

HIP vessels have been modified to have 9 thermocouples, allowing for more control and data collection.

Paulo offers both coach and custom HIP cycles.

VS

Other Heat Treaters...

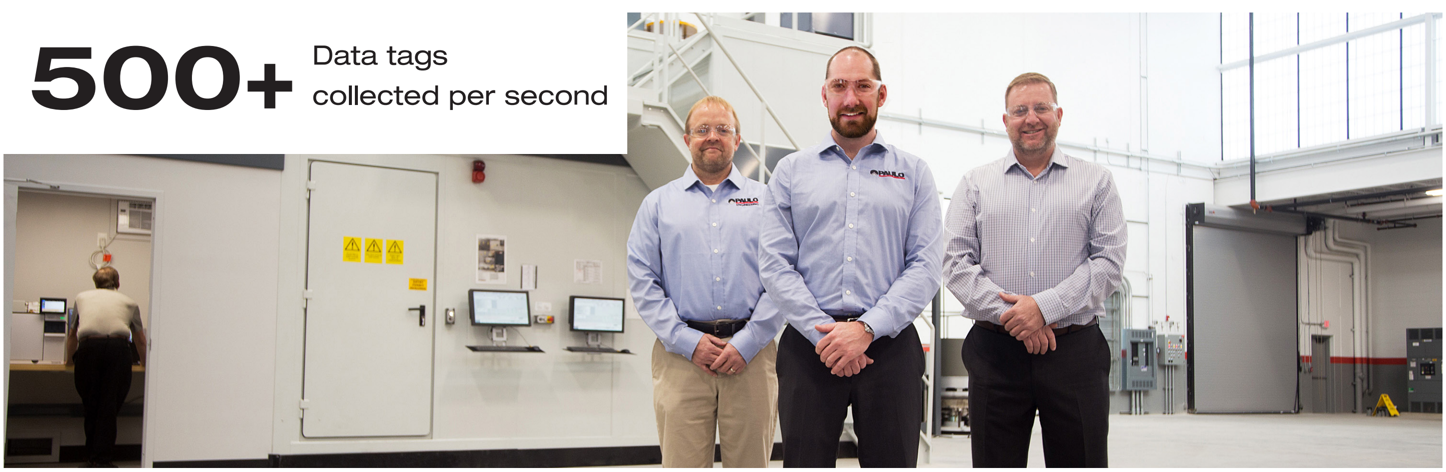
Less sophisticated part tracking used by some competitors can lead to unplanned delays.

Manual controls traditionally used by other heat treaters leave room for human error and out-of-spec conditions.

Out-of-box HIP vessels have only 6 thermocouples, which means less data and more unknowns when it comes to part specs.

Most heat treaters offer only coach cycles for HIP.

500+ Data tags collected per second



OTHER PROCESSES FOR SPACE PARTS

After HIP, parts will sometimes need a secondary thermal process. This is often a solution and age, or vacuum. Based on the application, we'll use existing aerospace recipes and advanced metallurgical knowledge to guide early decision-making processes in R&D.

Vacuum, Solution & Age, Anneal, Stress Relieve

Vacuum treatments are used to help combat the internal stress from 3D printing, HIP, and previous thermal processing. The controlled environment uses a combination of gas and temperature to heat and cool parts at a specified rate to reduce their likelihood of cracking in service.

Solution and age using an argon gas quenchant is an especially common process for treating space parts. Since homogeneity of the part is vital for strength, we use computer-controlled vacuums that ensure uniformity. Our proactive PCIS software tracks every part and every cycle variable, adjusting as needed to make sure every part is brought up to spec the first time.

High-Pressure Heat Treatment (HPHT)

High pressure heat treating combines HIP and solution treating into a single step. This eliminates an entire thermal cycle, which can help prevent further stress and sometimes results in superior material properties. Combining these processes also improves turnaround time and significantly reduces a part's time in the supply chain.

Vacuum Brazing

In traditional machining, vacuum brazing is used for part joining to create intricate part geometries. However, additive manufacturing can achieve geometric complexity without the need to join several components together. This ability to print a near-net shape has eliminated much of the need for vacuum brazing for space.

However, there are some traditionally machined parts that do require brazing for space applications including cooling jackets and cooling plates.

SPACE PARTS REQUIRING THERMAL PROCESSING

The future of space travel requires parts that can not only perform under high levels of mechanical pressure and extreme temperatures, but are durable enough for long-range and repeat missions. Heat treatment is a critical step in preparing rocket engine components, among others, for commission.

Since the inception of NASA's Space Shuttle Program, Paulo has treated countless integral components for launch and propulsion, along with many parts currently in orbit on the International Space Station. And today we process many parts for private-sector innovators who are developing equipment for repeated use and advanced application.

Space parts that are most commonly heat treated include:

- Volutes
- Turbine manifolds
- Bearing houses
- Fuel inlets
- Housings, support housings
- Bearing supports
- Turbo components

MATERIALS USED IN SPACE PARTS

In this still-nascent industry, new materials and applications are being explored every day as companies look for an advantage in the race to space. Proprietary alloy blends bring unique properties and promising potential in the push for stronger, faster, longer-lasting parts. But with unique properties comes the need for unique heat treating processes.

Partnering with the right commercial heat treater is essential for efficiently finding a production-ready process and bringing these great innovations to life.

High-performance superalloys commonly used for space include:

- Inconel 718, 625
- Aluminum (Al F357)
- Titanium (Ti-6Al-4V)
- Hastelloy C22

Adapting Alloys for AM

Finding new opportunities within existing alloys like this is a highly efficient way to gain material advantage in today's race to space. Inconel 718, a championed space alloy, was originally used as a premier casting material before being adopted for AM.

This nickel-based material features an extremely high tensile and yield strength that makes it ideal for components taking on a high mechanical load in extreme environments ranging from combustive to cryogenic—making this a natural material to adopt for space in the early days of 3D printing.

Because casting and 3D printing both result in similar porous microstructures, the heat treating process used for Inconel castings could also be adapted.

GO FOR LAUNCH

OEMs who are leading the race to commercial space are using additive manufacturing to push the boundaries of what conventional wisdom says is possible, and they're setting the new standard for metal part production through strong alliances with commercial partners.

3.5M lbs of thrust to escape Earth's gravity

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