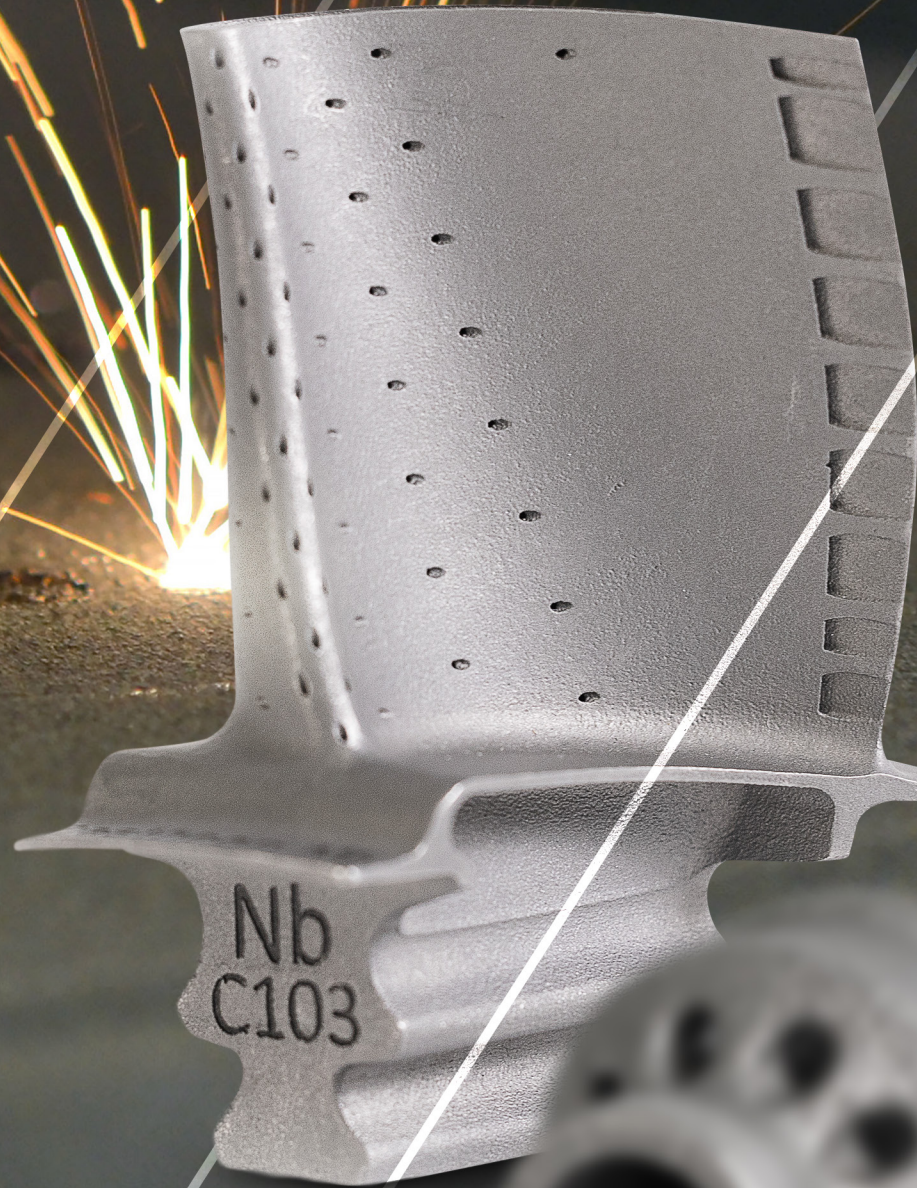


# Rising to the Challenge:

How Niobium C103  
is Paving the Way for  
Next-Generation  
Materials







# Abstract



In this eBook, we will delve into the world of **Niobium C103**, a refractory based alloy that has gained widespread recognition for its exceptional properties and versatile applications. We will begin by providing an overview of the history and development of Niobium C103, including its discovery and early applications in the aerospace industry. We will then explore its unique chemical and physical properties that make it an ideal material for high-performance applications, including its resistance to high temperatures, corrosion, and mechanical stress. Additionally, we will examine the various industries and applications that utilize Niobium C103, and its potential for future advancements in technology and engineering. Overall, this eBook aims to provide a comprehensive understanding of Niobium C103 and its impact on modern technology and industry.

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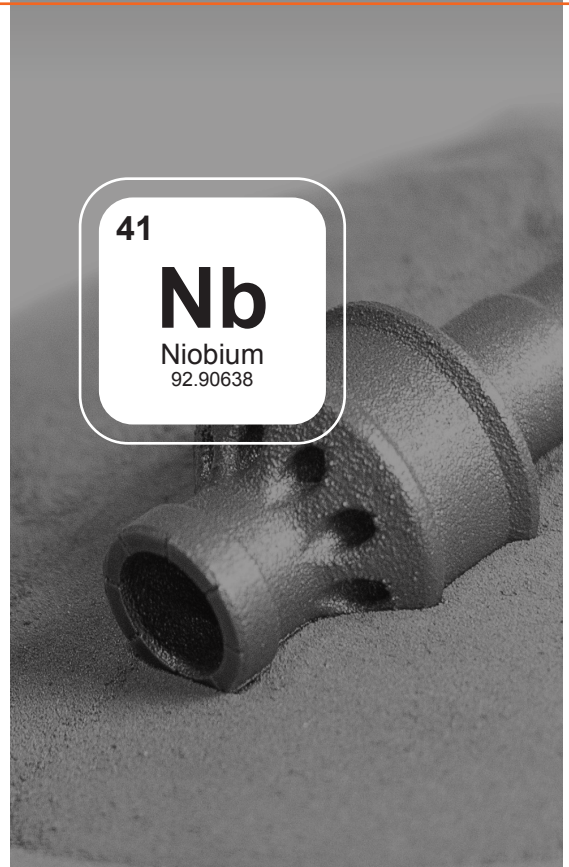
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## Introduction: What is Niobium?

**Niobium C103 is a high-performance alloy used in various industries for its excellent properties.**

The alloy is composed of 89% Niobium, 10% Hafnium, and 1% Titanium, enabling exceptional strength and performance at high temperatures. In addition to the high temperature characteristics, C103 offers attractive corrosion resistance in harsh environments. It is also highly resistant to corrosion in harsh environments, and able to withstand extreme temperatures. It is predominantly being used in uncooled rocket engine combustion chambers, thrusters, and uncooled nozzle extension sections (SpaceX Falcon's Merlin upper stage, Aerojet Rocketdyne's RL10 upper stage, Rocket Lab's Electron Rutherford upper stage).

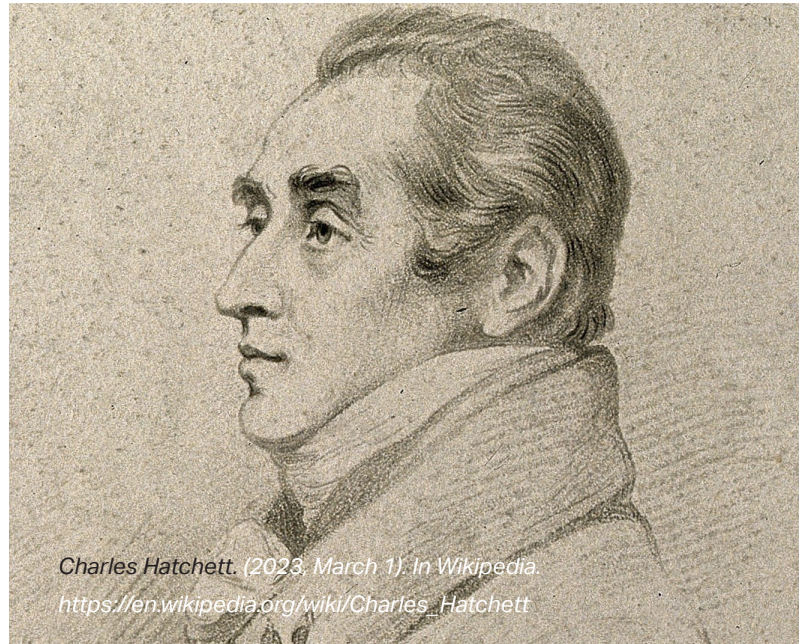


# Its History

## Niobium was first discovered in 1801

by English chemist Charles Hatchett, was initially thought to be a new element. It wasn't until 1846 that German chemist Heinrich Rose successfully isolated Niobium in its pure form and named it after Niobe from Greek mythology.

Following this discovery, Niobium's potential in various industries began to unfold. In the 1950s, the discovery of Niobium's superconducting properties marked a significant advancement, leading to its application in medical devices such as MRI machines. This period also saw the material's initial exploration in the aerospace and defense sectors, where its suitability for high-temperature applications was recognized. However, it was in the late 1980s that Niobium's use in steel alloys, particularly High-Strength Low-Alloy (HSLA) steel, became prominent. Its addition to steel significantly enhanced strength and toughness, marking a major step forward in metallurgy.



Charles Hatchett. (2023, March 1). In Wikipedia. [https://en.wikipedia.org/wiki/Charles\\_Hatchett](https://en.wikipedia.org/wiki/Charles_Hatchett)

## Discover more

about the obstacles involved in additive manufacturing refractory alloys through the expertise of Dr. Gao.

 [Read the Article](#)



During the first space race, the exceptional qualities of Niobium in extreme high-temperature environments came to the forefront. Both the US and USSR relied heavily on Niobium alloys, which were essential in applications requiring non-regenerative cooling systems or where high-temperature space structures had to endure rigorous conditions. Niobium's formability and resilience made it one of the most preferred refractory alloys for space applications. The late 20th century also witnessed a rise and fall in the interest in Niobium as a superconductor. Teledyne Wah Chang's investment in CBMM, the world's largest Niobium miner and producer, highlighted the potential of Niobium in this field. However, following the cancellation of a significant national project involving Niobium, Teledyne Wah Chang divested its ownership, a decision that would equate to a substantial financial loss in today's market.

The transformative impact of Niobium was further elevated with the advent of additive manufacturing (AM). The innovative work of Dr. Youping Gao, ADDMAN's Chief Scientist and Founder of Castheon, particularly in Laser Powder Bed Fusion (LPBF) technology, revolutionized the manufacturing processes. His contributions made it feasible to create complex Niobium structures that were previously unattainable with conventional manufacturing methods. This advancement opened new possibilities in various sectors, including the hypersonic field, showcasing Niobium's versatile and powerful applications in modern technology.





# What does Hypersonic Mean?

**A hypersonic vehicle** is a type of aircraft or missile that travels at extremely high speeds, typically above Mach 5 (five times the speed of sound).

Hypersonic vehicles are defined by their ability to sustain hypersonic speeds for an extended period of time, which requires advanced materials, propulsion systems, and thermal management.

Hypersonic vehicles are classified into cruise and boost-glide types. Cruise vehicles, exemplified by the X-15, rely on propulsion systems like scramjet and rotating detonation engines for sustained hypersonic flight, using atmospheric air for combustion. Boost-glide vehicles, on the other hand, use a rocket booster for initial acceleration to exoatmospheric altitudes, followed by a glide phase with reaction control and short-pulsed propulsion. This method, often reaching high hypersonic speeds, is similar to spacecraft reentry dynamics, as seen in the Space Shuttle reaching speeds up to Mach 25.



**The relationship between Mach and temperature** is that as an object travels at higher speeds (Mach numbers), the temperature of the object and its surrounding environment increases.

This phenomenon stems from the object's movement through the air, resulting in compression of the air in its path and consequent heating. At hypersonic velocities, this compression heating can cause the air temperature to surge to thousands of degrees. NASA classifies an aircraft as hypersonic when it significantly

## What is the relationship between Mach and temperature?

surpasses the speed of sound. Typically, hypersonic aircraft achieve speeds exceeding 3,000 mph and a Mach number (M) greater than five ( $M > 5$ ). To account for re-entry aerodynamics, a high hypersonic regime is defined at Mach numbers greater than 10 ( $M > 10$ ).<sup>1</sup>

In the realm of high-speed aircraft, air friction induces intense heating at the leading edge. For example, an object traveling at Mach 5 can encounter surface temperatures of approximately 1,000 degrees Celsius.

The maximum temperature a Mach vehicle can reach varies based on the specific vehicle and flight conditions. However, during sustained hypersonic flight, hypersonic vehicles can endure temperatures well exceeding 1,500 degrees Celsius (2,732 degrees Fahrenheit) at their leading edges.



Refractory Thruster

The necessity for such extraordinary speeds and components capable of withstanding these extreme temperatures presents formidable technical challenges for engineers and scientists in the development of hypersonic vehicles.

Addressing these challenges entails enhancing materials and propulsion systems, advancing thermal management techniques, and ensuring the safety and reliability of these vehicles.

At Castheon, we've harnessed the potential of refractory alloys, notably Niobium C103, by integrating it with Additive Manufacturing (AM), particularly utilizing Laser Powder Bed Fusion (LPBF) technology. This method is enabling efficient and swift manufacturing of Niobium C103 components that can operate effectively in the high-temperature realm of hypersonics.

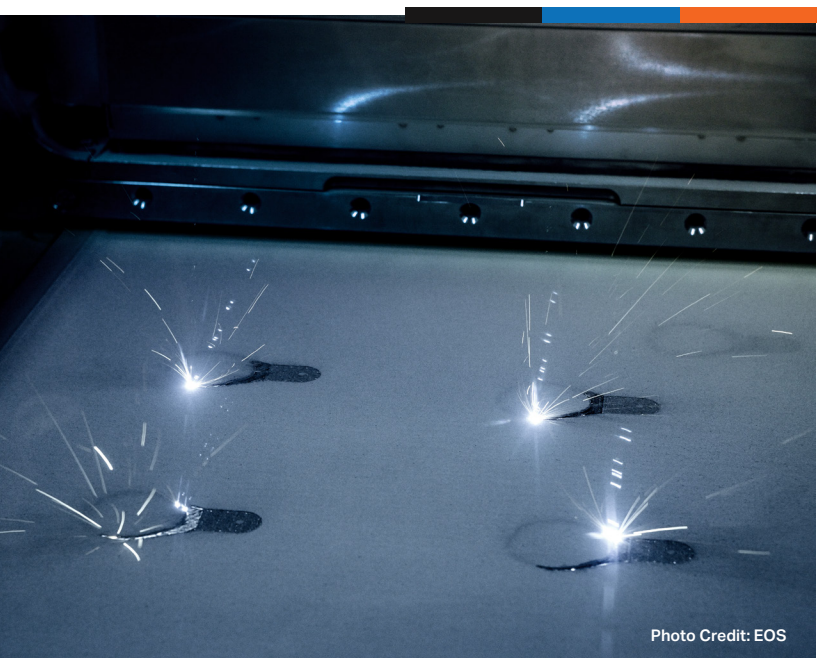


Photo Credit: EOS

## What is LPBF?

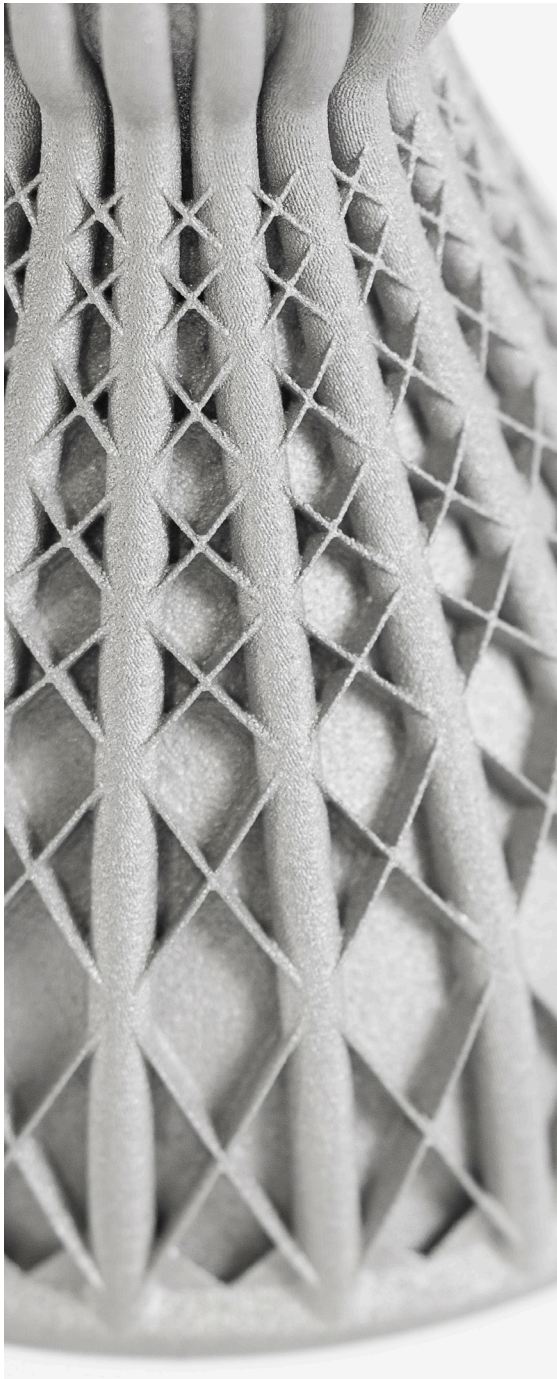
**Laser Powder Bed Fusion (LPBF)** is a type of additive manufacturing process that uses a laser to melt and fuse together layers of metal powder to create a three-dimensional object.

The LPBF process begins with a thin layer of metal powder being spread across a build platform. A high-powered laser beam is then directed at the powder, selectively melting and fusing the powder particles together to create a solid layer, essentially a welding process. The build platform then moves down by a small increment, and the process is repeated, layer by layer, until the desired object is created.

<sup>1</sup>www.grc.nasa.gov



# Unlocking the Power of Niobium C103 and LPBF



## Niobium C103: Bridging the Gap in Structural Material

Refractory metals constitute a class of metallic elements known for their exceptional resistance to heat and wear. These metals boast high melting points, nearly twice that of superalloys. But ironically, they also have poor oxidation resistance aside for a few extremely expensive elements such as Iridium in the extended refractory family. Additionally, their inherent hardness and heat resistance pose challenges in fabrication.

Presently, there is no ideal alloy meeting the criteria of elevated temperature tolerance (2,000-3,300°F), strength, oxidation resistance, reasonable fabricability, and cost-effectiveness for large-scale industrial use as structural materials. Consequently, Niobium C103 emerges as a leading candidate, serving as a crucial structural material for high-temperature applications.

This alloy exhibits a comparatively low density compared to other refractory metals. Notably, it stands as the sole tri-elemental refractory alloy consistently manufactured on an industrial scale, underscoring its significance as a high-temperature structural material, despite its modest strength.

## Why Combine C103 and Additive Manufacturing (AM)?

Incorporating Niobium C103 into the realm of Additive Manufacturing has revolutionized the utilization of refractory materials, addressing previous limitations related to fabricability, oxidation resistance, and creep performance. AM introduces unparalleled shape-producing capabilities, enabling the creation of intricate designs and complex geometries while significantly improving the properties and overall performance of the materials.

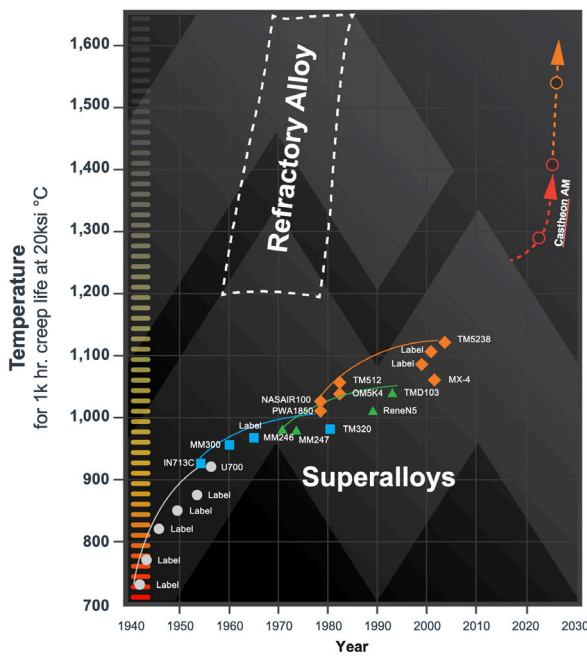
Through LPBF, Castheon has significantly enhanced the alloy's producibility in diverse shapes, amplifying its strength and resistance to creep, all while effectively mitigating grain boundary oxidation. These improvements in strength, creep resistance, and oxidation prevention, especially at elevated temperatures, were achieved through the formation of well-dispersed oxides and skillful engineering of grain boundaries without altering the alloy's composition, maintaining compatibility with the existing supply chain.

These heightened AM material properties broadened the application spectrum of the alloy to reach the 3,300°F range, resulting in a substantial enhancement of performance and reliability in rocket engine operations.

Refractory metal AM being a relatively recent capability is a standout innovation in this domain of Niobium C103 AM. Compared to traditional high-temperature materials, the C103 AM components exhibit remarkable cost efficiency, being an order of magnitude more cost-effective and faster to manufacture, all while displaying superior strength and durability at hypersonic temperatures, illustrated in Figure 1. Figure 1 provides a comparative view of temperature characteristics between superalloys and refractory materials. These cost, lead-time, performance, and advantages directly result from the AM process.

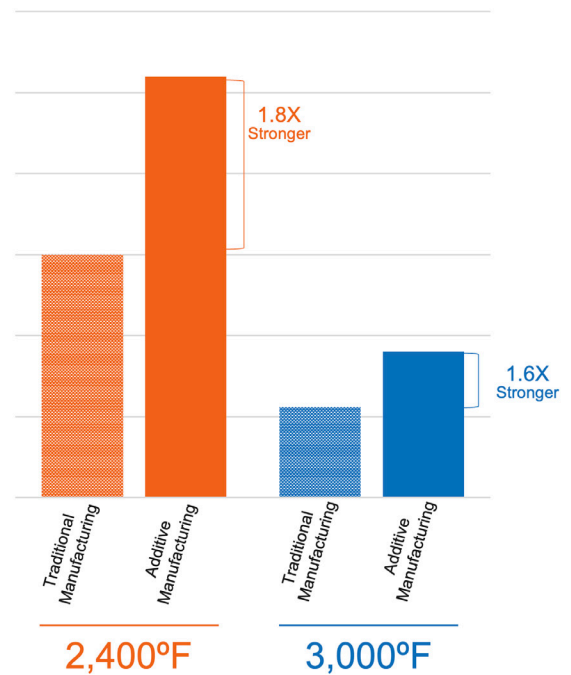
What truly sets C103 AM apart is its adept utilization of the distinctive physics of AM, resulting in Niobium C103 parts with significantly enhanced strength and durability at elevated temperatures compared to parts fabricated from C103 plate or bar-stock, as depicted in Figure 2. This achievement stems from the meticulous optimization of these advantages during C103 AM development, marking a significant advancement in this alloy.

**Development of Metal with Durability at High-Temperature Through Time**



**Figure 1** Illustrates the step change improvement in performance at high temperatures delivered by C103 AM and refractory alloys. The leap in durability at high temperatures far exceeds the gradual pace realized by Superalloys.

**Strength Improvement of Additively Manufactured Niobium C103 at Hypersonic Relevant Temperatures**



**Figure 2** Strength benefits of C103 AM compound and multiply at hypersonic temperatures. Optimization of C103 AM into Super C103 AM will deliver even higher performance.

# Material Science

## Material Characteristics:

- **Ideal for Extreme Temperature Environments**
- **Non-Ablative**
- **High Thermal Conductivity**  
(Ideal for managing high heat fluxes in passive or active thermal management systems)
- **Relative Low Density**  
(Compared to other refractory metals, stiffened metallic envelope)
- **Exceptional Properties at Operational Temperature**  
(Strength, creep, impact resistant)
- **Overall Manufacturing Maturity**  
(Inspectable, reworkable, welding/joining, integration, complex shapes/sharp leading edges)
- **Life Cycle Cost** (AM metallic solutions offer cost advantages over high temperature composites and complex assemblies)

**Figure 3**  
Utilizing polarized 3D metallography, defect-free materials with a dense, desirable microstructure and appropriate grain size are analyzed. At 25x magnification (4 mm x 3 mm), the method allows for accurate grain counting, essential for rapid development and quality assessment.

**Figure 4**  
Following a 2-hour exposure at 2,900°F, wrought Nb C103 exhibits abrupt grain growth, in stark contrast to the 3D printed Nb C103, which maintains grain stability under identical testing conditions.

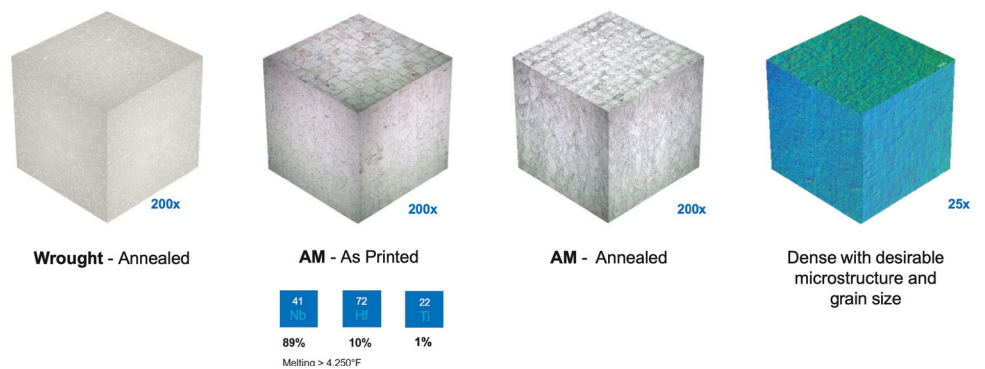
## AM vs Wrought:

Castheon's 3D-printed Niobium C103 boasts material characteristics that surpass those of traditional wrought materials due to a combination of key improvement mechanisms. ("Wrought" implies a forging process and ought to serve as the benchmark for comparing traditional metal fabrication methods to metal AM). Firstly, by precisely controlling the rapid solidification inherent to the LPBF process, this refractory metal maintains its integrity even under extreme conditions. This precise solidification process aids in creating complex grain boundaries which are stable when subjected to elevated temperatures (Figure 4). Additionally, the LPBF process allows for the creation of evenly distributed ODS/CDS (Oxide Dispersion Strengthened/Carbide Dispersion Strengthened) structures, featuring highly stable carbides and oxides like HfO<sub>2</sub> and HfC.

Castheon's robust and proprietary LPBF process consistently delivers exceptional results across multiple powder sources, batches, and printer platforms, as evidenced by over 270 cycles of M14 and M18 testing and proven space flight success. These advancements collectively make Castheon's 3D-printed Niobium C103 a superior choice, outperforming wrought materials in various critical aspects.

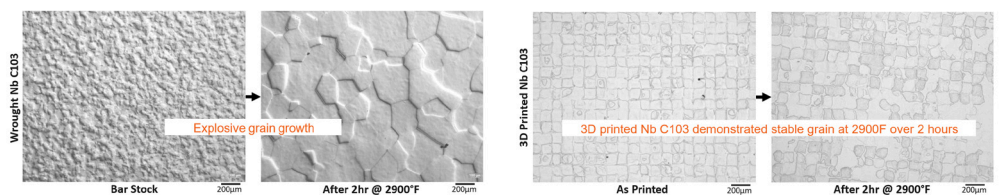
## Nb C103 Microstructure Comparison Wrought vs AM LPBF

Figure 3



## AM vs Wrought

Figure 4







## Why is Castheon so invested in the 3D Printing of refractory alloys?

Castheon is deeply committed to the advancement of 3D printing technology for refractory alloys, driven by several compelling factors. Foremost among them is the remarkable high-temperature performance displayed by these metals, surpassing even the capabilities of superalloys, as illustrated in Figure 1. Our additive manufacturing endeavors have successfully mitigated numerous challenges inherent in traditional refractory alloys, including poor creep resistance, inadequate oxidation resistance, and insufficient strength, thereby expanding their potential applications.

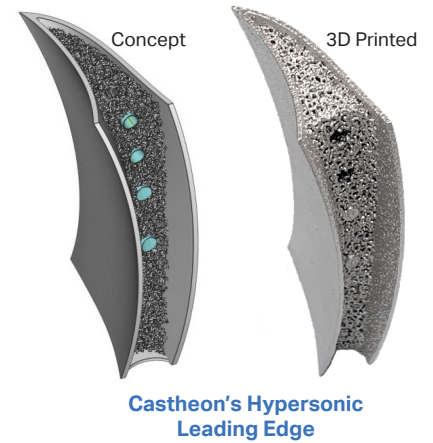
We believe these metals will have a significant role in the future of our hypersonic missiles and defense systems and offer advantages in terms of cost and performance. By developing new ways to process and fabricate these materials, Dr. Gao and his team are helping to pave the way for the next generation of hypersonic missiles and defense systems.

**Furthermore, AM reduces material waste, streamlines the production process, and decreases the overall cost of manufacturing.**

Dr. Youping Gao and the team at Castheon have been at the forefront of developing innovative approaches to overcome the challenges associated with the 3D printing of refractory alloys, enabling them to push the boundaries of what is possible in the field.

By investing in this technology, Castheon is positioned to revolutionize the manufacturing of high-performance components for aerospace, energy, and other demanding applications.





## Conclusion

Additive manufacturing offers an efficient and effective approach to utilizing refractory alloys, leading to significant cost savings. By employing AM techniques, the buy-to-fly ratio is improved, eliminating the need for costly machining processes. Additionally, AM utilizes a common feedstock size, reducing lead time for production and AM offers superior material properties. These advancements enables refractory alloys to be effectively employed in extreme environment applications. The strength, creep resistance, and oxidization resistance of AM-produced refractory alloys experience a quantum leap compared to their wrought counterparts. Moreover, through structural design incorporating heat pipe techniques, such as porous or solid structures and phase change materials, engineering goals can be achieved with refractory materials. The utilization of AM allows for the production of complex-shaped refractory metals that were previously challenging to manufacture.

### CHECK OUT THIS ARTICLE FROM SME ABOUT ADDITIVE FOR AEROSPACE

#### RAMPTing up

"When you print these materials, they typically become both stronger and harder than their wrought or forged equivalents," he said. "The laser promotes the creation of a supersaturated solid solution with fantastic properties, ones that cannot be achieved otherwise. When you combine this with AM's ability to generate shapes that were previously impossible to manufacture, it presents some very exciting possibilities for the aerospace industry." - Dr. Youping Gao

 [Read the Full Article](#)





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