High Temperature Solutions
Furnace Operations & Repair

H.C. Starck
High Performance Metal Solutions
Our Commitment to Engineering Excellence

H.C. Starck Solutions’ complex product fabrication capability delivers superior quality with material consistency and product reliability. H.C. Starck Solutions achieves world class quality through continuous research of new products, development of engineering solutions, and continuous improvements in H.C. Starck Solutions’ manufacturing environment to deliver premium products for the most challenging applications.

Nearly 100 years of powder metallurgical experience is the cornerstone of H.C. Starck Solutions’ success in producing advanced technology metals for fast growing industries including aerospace, chemical processing, electronics, industrial, medical, and energy. As one of the world’s leading suppliers of molybdenum, tungsten, tantalum, niobium, and their alloys, H.C. Starck Solutions is at the forefront of creating solutions with next-generation materials and fabricating engineered components for a diverse spectrum of markets.

> Product Quality and Service
> Research and Development
> Manufacturing Excellence
> Reclamation and Recycling

Strategic Advantages of Working with H.C. Starck Solution

H.C. Starck Solutions understands market trends and the latest cutting-edge technologies are providing us the opportunity to create value added solutions for complex applications. In addition, our robust and sustainable, vertically integrated supply chain enables us to deliver high performance materials and products seamlessly to the marketplace. Paramount to H.C. Starck Solutions is securing materials from reliable sources. Our raw material procurement relies on the continuous expansion of our recycling activities and the fair, conflict-free and sustainable procurement of raw materials.

A recognized leader in refractory metal technology, H.C. Starck Solutions' knowledge and technical expertise benefit customers through joint collaborations with our dedicated team of research engineers. This collaborative effort facilitates new and improved product designs through a study of the product’s life-cycle. Extensive in-house state-of-the-art laboratory facilities with the latest in analytical tools, testing equipment, modeling and simulation software assist engineers in evaluating product performance. For example, innovative material solutions provide texture control thus enhancing the uniformity and performance consistency.

H.C. Starck Solutions offers exceptional customer care with sales and technical support.
Fabricating Products with High Temperature Materials

Fabricated product solutions from H.C. Starck Solutions service a wide spectrum of markets, industries and applications including vacuum heat treating, sintering, annealing, brazing, and all high temperature furnace applications in the medical, aerospace, defense and automotive industries.

As an example, heat treating large aerospace parts in vacuum furnaces, or running high volumes of production parts for brazing through controlled atmosphere furnaces, and annealing medical and aerospace products to critical specifications, all require high temperature materials with superior mechanical and physical properties.

Molybdenum, tungsten, niobium and alloys such as MoLa (molybdenum-lanthanum), TZM, MHC, and MoW (molybdenum-tungsten) are perfect for the heat treating and furnace markets. These high temperature refractory metals are characterized by their mechanical durability, high ductility and toughness, high thermal and electrical conductivity, low coefficient of thermal expansion, and excellent strength and stability at temperatures up to 2000 °C.

Customer specific furnace components and fixtures are uniquely designed and supplied by H.C. Starck Solutions. We machine and fabricate products from rod, plate, sheet, and foil.
Our high temperature refractory metal materials and components are utilized in furnace applications and supplied to OEMs, end-users, and aftermarket manufacturers. The major parts of the furnaces that utilize refractory metals are heating elements with their auxiliary components like hangers, supports and feed-throughs, and heat shields with their own auxiliary components like rivets, staples, and separators.

**H.C. Starck Solutions’ refractory materials serve the following furnaces:**

- High temperature furnaces in vacuum, reducing or inert atmospheres
- Chemical reaction furnaces in vacuum, air, or various atmospheres

**Industrial Furnace Operations**

- Annealing
- Brazing
- Heat Treating
- HIPing
- Melting
- Pre-heating for Metalworking
- Powder Processing
- Sintering
- Tempering
- MIM (Sintering/Debonding)

**Industries Served**

- Automotive
- Aerospace
- Defense
- Energy
- Medical
- Nuclear Fuel
- Crystal Growth
- Waste Treatment
Innovative Research and Development

Committed to the research and development of new products and materials, H.C. Starck Solutions has a renowned research staff dedicated to advancing metals technology. To benefit customers, we continually invest and upgrade our manufacturing and analytical capabilities. H.C. Starck Solutions evaluates the materials using characterization instrumentation complete with optical and electron microscopy and a complete chemical analysis lab. Advanced material modeling and simulation capabilities support the rapid development of new products and processes at H.C. Starck Solutions.

**Comprehensive applications laboratories**

**Thin Film Laboratory**
- Planar and rotary target deposition chamber
- Co-Sputtering capability, rapid composition optimization
- Thin film characterization physical and electrical

**Metallurgical Laboratory**
- Optical microscopy
- SEM with EDS and EBSD
- Mechanical testing

**Extensive analytical capabilities**
- IGA
- ICP
- GDMS

**Advanced Engineering and R&D groups**
- Recognized leader in refractory metals technologies
- Advanced engineers dedicated to machining and fabrication
- Hundreds of patents and technical publications

**Materials Processing Laboratory Research**
- Deformation process via rolling
- Cold (CIP) and Hot Isostatic Press (HIP) to study pressing and assisted sintering
- Thermal Treatment to study annealing and sintering processes

H.C. Starck Solutions also provides services for precharacterization of materials for customers; for example, performance of material after high temperature anneal.

1. Energy Dispersive X-Ray Spectroscopy
2. Electron Backscatter Diffraction
3. Interstitial Gas Analysis
4. Inductively Coupled Plasma (Mass Spectroscopy)
5. Glow Discharge Mass Spectroscopy
Powder Metallurgy and Vacuum Arc Cast Products

Both powder metallurgy and vacuum arc cast processing are employed by H.C. Starck Solutions to yield the highest quality products. Our alloys are designed for furnace applications with the highest temperature utilization capabilities.

**Molybdenum Products**

- **Powder Metallurgy (P/M)**
  Molybdenum is produced by compacting < 99.95 % pure powder into billets that are sintered and subsequently worked into finished wrought forms.

- **Vacuum Arc Cast**
  Products made by this process are available exclusively from H.C. Starck Solutions. Arc cast wrought products exhibit excellent workability, weldability, and good machining characteristics with lower oxygen, greater ductility and fracture toughness relative to powder metallurgy.

  In the vacuum arc melting process, 99.95 % minimum pure molybdenum powder with or without required additions is compacted, sintered, arc melted, and cast to produce an ingot weighing up to one ton. All these processes take place under vacuum.

**Molybdenum Mill Products – Powder Metallurgy**

<table>
<thead>
<tr>
<th>Form</th>
<th>Diameter/Thickness inches</th>
<th>mm</th>
<th>Width/Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Billets</td>
<td>1.250-30</td>
<td>32-762</td>
<td>Extruded</td>
</tr>
<tr>
<td>Forgings</td>
<td>*</td>
<td>3.2-213</td>
<td>Up to 50”/10,000 lbs.</td>
</tr>
<tr>
<td>Rod &amp; Bar</td>
<td>0.1250-8.4</td>
<td>3.2-213</td>
<td>8 - 25 ft</td>
</tr>
<tr>
<td>Plate</td>
<td>0.1875-2.0</td>
<td>4.8-50.8</td>
<td>24” (610 mm) max; 2 to 10 feet **</td>
</tr>
<tr>
<td>Sheet</td>
<td>0.0050-0.187</td>
<td>0.127-4.80</td>
<td>24” (610 mm) max; up to 200 feet</td>
</tr>
<tr>
<td>Foil</td>
<td>0.0010-0.0049</td>
<td>0.0254-0.12</td>
<td>1/8” to 12” (305 mm); Nominal 200 foot coils</td>
</tr>
<tr>
<td>Extruded Tube &amp; Shapes</td>
<td>*</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Submit size required for H.C. Starck quotation
** Inquire for thickness x length x width combinations

**Molybdenum Mill Products – Vacuum Arc Cast**

- **Pure Molybdenum**
  (99.97 % minimum)
- **TZM**
- **MoW**

<table>
<thead>
<tr>
<th>Form</th>
<th>Diameter/Thickness inches</th>
<th>mm</th>
<th>Width/Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ingots</td>
<td>6-12</td>
<td>152-304</td>
<td></td>
</tr>
<tr>
<td>Forgings</td>
<td>Submit size required for H.C. Starck quotation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rod &amp; Bar</td>
<td>0.1250-6</td>
<td>3.2-152</td>
<td>24” (610 mm) max; up to 10 feet</td>
</tr>
<tr>
<td>Plate</td>
<td>0.1875-2</td>
<td>4.8-50.8</td>
<td>24” (610 mm) max; up to 200 feet</td>
</tr>
<tr>
<td>Sheet</td>
<td>0.0050-0.187</td>
<td>0.127-4.80</td>
<td>1/8” - 12” (305 mm); nominal 200 foot coils</td>
</tr>
<tr>
<td>Foil</td>
<td>0.0010-0.0049</td>
<td>0.0254-0.12</td>
<td></td>
</tr>
</tbody>
</table>
Molybdenum Alloys

> **TZM Molybdenum Alloy**
TZM (0.50 Ti, 0.08 Zr, balance Mo) is consolidated by either the P/M or vacuum arc-casting processes.

The titanium and zirconium carbides increase strength and creep resistance at elevated temperatures.

TZM molybdenum alloy also permits higher service temperatures without loss of toughness in comparison to pure molybdenum.

Arc cast material resists abrasion and is widely used for injection molding nozzles.

> **H.C. Starck Solutions’ MoW alloy**

Offering the only commercially available arc cast molybdenum and tungsten alloy with 70 wt. % Mo and 30 wt. % W, H.C. Starck Solutions’ MoW alloy has demonstrated excellent service life in handling high purity molten zinc (99.99 % Zn).

Our Mo 75 wt. % and W 25 wt. % alloy has also been made via the P/M method for use as heat shields in furnaces.

> **MHC Alloy**

MHC (1.2 % Hf, 0.1 % C) contains hafnium carbide, which is consolidated by the P/M process.

The high recrystallization temperature, high strength, low thermal expansion, and high thermal conductivity makes it ideally suited for die applications, particularly for brass extrusion.

> **ODS MoLa Alloys**

ODS MoLa contains lanthanum oxide (0.3 wt %, 0.6 wt. % and 1.1 wt. % lanthana) and is an oxide-dispersion strengthened material that contains a mixture of molybdenum with a very fine array or dispersion of lanthanum oxide particles.

ODS MoLa has extraordinary resistance to recrystallization, improved ductility, and high-temperature formability.

These materials are applied in environments requiring dimensional stability and strength at temperatures above the capabilities of either pure molybdenum metal or TZM alloy.
**Physical Properties – Molybdenum, Tantalum, and Tungsten**

<table>
<thead>
<tr>
<th>Physical Properties</th>
<th>UNIT</th>
<th>Molybdenum</th>
<th>Tantalum</th>
<th>Tungsten</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical Commercial Purity</td>
<td>ASTM</td>
<td>99.95 %</td>
<td>99.9 %</td>
<td>99.95 %</td>
</tr>
<tr>
<td>Specifications</td>
<td>B-386</td>
<td>B-364</td>
<td>B-760</td>
<td></td>
</tr>
<tr>
<td>Density</td>
<td>g/cc</td>
<td>10.2</td>
<td>16.6</td>
<td>19.3</td>
</tr>
<tr>
<td></td>
<td>lbs/cu inch</td>
<td>0.369</td>
<td>0.600</td>
<td>0.697</td>
</tr>
<tr>
<td>Melting Point</td>
<td>Celcius</td>
<td>2623</td>
<td>3017</td>
<td>3422</td>
</tr>
<tr>
<td></td>
<td>Fahrenheit</td>
<td>4753</td>
<td>5463</td>
<td>6192</td>
</tr>
<tr>
<td>Boiling Point</td>
<td>Celcius</td>
<td>4612</td>
<td>5425</td>
<td>5644</td>
</tr>
<tr>
<td></td>
<td>Fahrenheit</td>
<td>8335</td>
<td>9797</td>
<td>10211</td>
</tr>
<tr>
<td>Typical Hardness</td>
<td>DPH (Vickers)</td>
<td>230</td>
<td>200</td>
<td>310</td>
</tr>
<tr>
<td>Thermal Conductivity @ 20 ºC</td>
<td>W/m*K</td>
<td>138</td>
<td>57.5</td>
<td>173</td>
</tr>
<tr>
<td>Coefficient of Thermal Expansion @ 25 ºC</td>
<td>μm/m*K</td>
<td>4.8</td>
<td>6.3</td>
<td>4.5</td>
</tr>
<tr>
<td>Electrical Resistivity @ 20 ºC</td>
<td>nΩ-m</td>
<td>53.4</td>
<td>131</td>
<td>52.8</td>
</tr>
<tr>
<td>Electrical Conductivity</td>
<td>% IACS</td>
<td>34</td>
<td>13.9</td>
<td>31</td>
</tr>
<tr>
<td>Tensile Strength MPa</td>
<td>Ambient</td>
<td>825-1380</td>
<td>240-283</td>
<td>700-3400</td>
</tr>
<tr>
<td></td>
<td>500 ºC</td>
<td>240-586</td>
<td>172-310</td>
<td>924</td>
</tr>
<tr>
<td></td>
<td>1000 ºC</td>
<td>138-207</td>
<td>90-117</td>
<td>350-525</td>
</tr>
<tr>
<td>Modulus of Elasticity GPa</td>
<td>Ambient</td>
<td>311</td>
<td>186</td>
<td>407</td>
</tr>
<tr>
<td></td>
<td>500 ºC</td>
<td>283</td>
<td>172</td>
<td>379</td>
</tr>
<tr>
<td></td>
<td>1000 ºC</td>
<td>269</td>
<td>152</td>
<td>345</td>
</tr>
</tbody>
</table>

**Powder Metallurgy**

> Pure tungsten metal powder is pressed and sintered into an ingot for hot and cold rolling.

> The material is 99.95 % minimum pure tungsten and is normally supplied as-rolled or cut to shape parts.

**Tungsten Mill Products – Powder Metallurgy**

> Pure tungsten (99.95 % minimum purity)

<table>
<thead>
<tr>
<th>Form</th>
<th>Diameter/Thickness inches</th>
<th>Width/Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plate</td>
<td>0.1875-1.0</td>
<td>4.8-25.4; 24&quot; (610 mm) max.; up to 10 feet</td>
</tr>
<tr>
<td>Sheet</td>
<td>0.0050-0.187</td>
<td>0.127-4.80; 24&quot; (610 mm) max.; 5 to 30 feet</td>
</tr>
<tr>
<td>Foil</td>
<td>0.0010-0.0049</td>
<td>0.025-0.12; 1/8&quot; - 6&quot; (1525 mm); 30 foot max.</td>
</tr>
</tbody>
</table>
Fabricating and Machining: Center of Excellence

FLAT SHEET

> Molybdenum (Mo), MoLa and TZM Alloys

Benefits:
- High melting temperature refractory, lower cost than Tungsten, creep resistance, and high temperature mechanical properties

> Tungsten (W)

Benefits:
- Highest melting temperature refractory, creep resistance, and high temperature mechanical properties

Molybdenum

Hardness versus Anneal Temperature

![Hardness Graph](image)

Molybdenum

Tensile Strength versus Temperature

![Tensile Strength Graph](image)

Typical Tensile Properties for indicated Products (5/8 inch Diameter bars)

FLAT PLATE

> Molybdenum (Mo, MoLa, TZM, W Alloys)

Application: Hearth plates, pusher furnace carriers

Benefits:
- High melting temperature, creep resistance, high temperature mechanical properties

FABRICATIONS

> FURNACE RACK (Mo, MoLa, TZM, W)

Application: High temperature furnace fixtures

Benefits:
- Developed per Print: Sheet length x width and plate length x width are main constraints on design
- Support product in high temperature furnaces
- High melting temperature, creep resistance at elevated temperatures
- Chemical resistance (Ta)
> ROLL FORMED PRODUCT
(Mo, MoLa, TZM, W)
Application: High temperature furnace shielding and heating elements
Benefits:
- Developed per Print:
  Roll Forming: 60" long x 0.040" thick max. x mill width
- Cut or formed to desired shape

> FURNACE BOATS and TRAYS (Mo, MoLa, TZM)
Application: High temperature furnace boats, powder sintering, nuclear fuel processing, furnace support fixtures
Benefits:
- Cut or formed to desired shape

**Molybdenum**
**Thermal Expansion versus Temperature**

<table>
<thead>
<tr>
<th>Test Temperature (°C)</th>
<th>Linear Thermal Expansion (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-0.2</td>
</tr>
<tr>
<td>400</td>
<td>0.0</td>
</tr>
<tr>
<td>800</td>
<td>0.2</td>
</tr>
<tr>
<td>1200</td>
<td>0.4</td>
</tr>
<tr>
<td>1600</td>
<td>0.6</td>
</tr>
<tr>
<td>2000</td>
<td>0.8</td>
</tr>
<tr>
<td>2400</td>
<td>1.0</td>
</tr>
<tr>
<td>2800</td>
<td>1.2</td>
</tr>
</tbody>
</table>

**Molybdenum**
**Thermal Conductivity versus Temperature**

<table>
<thead>
<tr>
<th>Test Temperature (°C)</th>
<th>Thermal Conductivity (Btu/hr-ft-°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>30</td>
</tr>
<tr>
<td>400</td>
<td>40</td>
</tr>
<tr>
<td>800</td>
<td>50</td>
</tr>
<tr>
<td>1200</td>
<td>60</td>
</tr>
<tr>
<td>1600</td>
<td>70</td>
</tr>
<tr>
<td>2000</td>
<td>80</td>
</tr>
<tr>
<td>2400</td>
<td>90</td>
</tr>
<tr>
<td>2800</td>
<td>100</td>
</tr>
</tbody>
</table>
> **BENT AND ROLLED PIECES – Brackets and Shielding**  
(Mo, MoLa, TZM, W)

**Applications:** Furnace heating elements, shield brackets, support fixtures, hangers, fasteners, and baffles

**Benefits:**
- Developed per Print:
  Mo, MoLa, TZM up to 0.5" thick  
  W up to 0.125" thick
- Customize other thicknesses per customer request
- Furnace support structures
- Can be cut or formed to desired shape

> **HOT ZONES (Mo, W)**

**Application:** High temperature outer furnace shielding

Used to insulate the outer walls of the furnace from higher temperatures within the furnace. Hot zones may become brittle after repeated temperature exposure due to recrystallization.

**Benefits:**
- Developed per Print:
  Common Joining Methods for fabricating: Wire staples, pins, wire nuts, rivets (Mo & W)
  Common Spacers: Coiled wire spacers, rod or ribs (Mo & W)
- Can also include stainless steel in outer layers, if application
- Can be cut or formed and assembled to desired shape

---

**Molybdenum Specific Heat versus Temperature**

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Specific Heat (cal/g °C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.05</td>
</tr>
<tr>
<td>800</td>
<td>0.09</td>
</tr>
<tr>
<td>1600</td>
<td>0.11</td>
</tr>
<tr>
<td>2400</td>
<td>0.13</td>
</tr>
<tr>
<td>3200</td>
<td>0.15</td>
</tr>
<tr>
<td>4000</td>
<td>0.15</td>
</tr>
<tr>
<td>4800</td>
<td>0.15</td>
</tr>
</tbody>
</table>

**Molybdenum Electrical Resistivity versus Temperature**

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Electrical Resistivity (µhm cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.05</td>
</tr>
<tr>
<td>800</td>
<td>100</td>
</tr>
<tr>
<td>1600</td>
<td>200</td>
</tr>
<tr>
<td>2400</td>
<td>300</td>
</tr>
<tr>
<td>3200</td>
<td>400</td>
</tr>
<tr>
<td>4000</td>
<td>500</td>
</tr>
<tr>
<td>4800</td>
<td>500</td>
</tr>
</tbody>
</table>

---

> **HEATING ELEMENT (Mo, MoLa, TZM, W)**

**Application:** Heating element for high temperature furnaces

**Benefits:**
- Can be cut or formed and assembled to desired shape
- Used as heating medium in the furnace
- W and Mo can operate in vacuum or inert gas atmospheres
- W, Mo, and MoLa cannot be used in air atmosphere
Refractory Metal Production Processes

Molybdenum Process
- Uniform gauge control
- Controlled flatness
- Precision machining (5 Axis)
- Laser and Water Jet cutting
- Riveting
- In-house expertise for extrusion and rotary forging
- Copper and nickel cladding of Molybdenum

Tungsten Process
- Fully integrated supply chain
- Controlled flatness
- Water jet cutting
- In-house expertise in rolling operations
- Uniform gauge control
Niobium Process

- In-house expertise in forging, rolling, machining, cutting and fabrication
- Expertise in thermal processing
- Chemical, mechanical, and microstructure monitoring in-house
- Consistent grain size and texture control
H.C. Starck Solutions’ Secure Material Supply Chain

H.C. Starck Solutions’ Responsible Supply Chain Management System (RSCM) contributes to its reliable and secure supply chain through the procurement of raw materials that ensures efficient and competitive purchasing. RSCM helps to avoid sourcing from conflict regions in the world or from suppliers that do not act in line with environmental and social sustainability. The RSCM system fulfills all requirements of a management system standard required by ISO and has been confirmed by the external auditor, Bureau Veritas.

H.C. Starck Solutions is one of the first companies to pass a second consecutive audit under the Conflict-Free Smelter (CFS) Validation Program introduced in 2010. The program, created and driven by the electronics industry, is being recognized and adapted by many metal industries determined to eliminate unethical sources of raw material from their supply chains. The term “conflict minerals” applies to minerals (including tantalum, tin, tungsten and gold) that have originated in conflict regions where production and trade is closely connected with ongoing abuse of human rights.

In addition to securing a conflict-free raw material supply chain, H.C. Starck Solutions reclaims spent materials for our customers. A recognized leader in Green Technology, H.C. Starck Solutions is a founding member of the Center for Resource Recovery and Recycling (CR3) coalition. H.C. Starck Solutions was also awarded the Sony “Green Partner” certification, one of the best established programs of its kind, and is a gold standard of the electronics industry. H.C. Starck Solutions’ treats sound environmental standards, robust supply chain, energy efficiency and recycling as foundational pieces of our strategy.
The conditions of your use and application of our products, technical assistance and information (whether verbal, written or by way of production-realizations), including any suggested formulations and recommendations, are beyond our control. Therefore, it is imperative that you test our products, technical assistance and information to determine to your own satisfaction whether they are suitable for your intended uses and applications. This applicable specific analysis at least must include testing to determine suitability from a technical as well as health, safety, and environmental standpoint. Such testing has not necessarily been done by H.C. Starck Solutions. All information is given without warranty or guarantee. It is expressly understood and agreed that the customer assumes and hereby expressly releases H.C. Starck Solutions from all liability, in tort, contract or otherwise, incurred in connection with the use of our products, technical assistance and information. Any statement or recommendation not contained herein is unauthorized and shall not bind H.C. Starck Solutions. Nothing herein shall be construed as a recommendation to use any product in conflict with patents covering any material or its use. No license is implied or in fact granted under the claims of any patent. Properties of the products referred to herein shall as general rule not be classed as information on the properties of the item for sale. In case of order please refer to issue number of the respective product data sheet. All deliveries are based on the latest issue of the product data sheet and the latest version of our General Conditions of Sale and Delivery.

The values in this publication are typical values and do not constitute a specification.