



High Performance Metal Solutions

# 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.

Spanning the globe with over 30 locations worldwide including Asia, Europe, and the Americas, H.C. Starck Solutions offers exceptional customer care with local sales and technical support. Our local presence coupled with multiple global manufacturing sites permits us to effectively respond to our customer's requests.

# 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, tantalum, 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.

- > **Furnace Assemblies**
- > **Flat Ribbed Heating Elements**
- > **Boats & Trays**
- > **Hot Zones**
- > **Furnace Racks**
- > **Heat Shields**



# Furnace Applications and Operations

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**

### 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 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.

### Metallurgical Laboratory

- > **Optical microscopy**
- > **SEM with EDS<sup>1</sup> and EBSD<sup>2</sup>**
- > **Mechanical testing**

### Extensive analytical capabilities

- > **IGA<sup>3</sup>**
- > **ICP<sup>4</sup>**
- > **GDMS<sup>5</sup>**



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.

Only the highest commercially pure powders are used.



### > 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

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

\* 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

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

## 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.

### > MoW Alloys

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

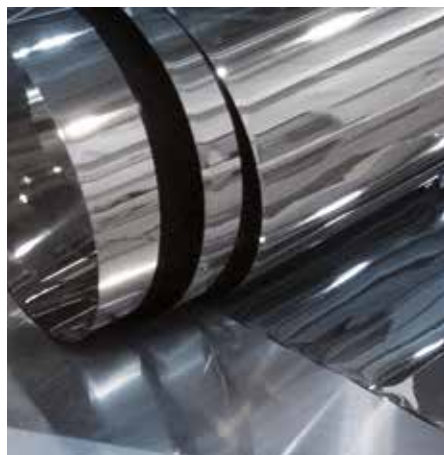
ODS MoLa contains lanthanum oxide (0.3 wt %, 0.6 wt. % and 1.1 wt. % lanthana) and is an oxide-dispersion strengthened material that contains a mixture of molybdenum with a very fine array or dispersion of lanthanum oxide particles.

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.



Molybdenum



Tungsten



Tantalum

## Tungsten Mill Products

### 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 and Alloy Mill Products – Powder Metallurgy

- > Pure tungsten (99.95 % minimum purity)

Form	Diameter/Thickness inches	mm	Width/Length
Plate	0.1875-1.0	4.8-25.4	24" (610 mm) max.; up to 10 feet
Sheet	0.0050-0.187	0.127-4.80	24" (610 mm) max.; 5 to 30 feet
Foil	0.0010-0.0049	0.025-0.12	1/8" - 6" (1525 mm); 30 foot max.

## Physical Properties – Molybdenum, Tantalum, and Tungsten

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



## Tantalum Mill Products

### Electron Beam Melting

- > Tantalum for high temperatures with stabilized grain structure.
- > Creep resistance properties for vacuum furnaces.

### Tantalum Plate, Sheet and Foil

Gauge Range	Type	Thickness >= 36" Wide and < 40"	Sheared Width < 36" Wide	Sheared Length <= 36" Wide <= 12" Length	Sheared Length <= 36" Wide > 12" Length
0.0050" - 0.0109"	Sheet	0.003	0.125	0.125	0.1875
0.0110" - 0.0159"	Sheet	0.004	0.125	0.125	0.1875
0.0160" - 0.0209"	Sheet	0.005	0.125	0.125	0.1875
0.0210" - 0.0309"	Sheet	0.006	0.125	0.125	0.1875
0.0310" - 0.0609"	Sheet	0.007	0.125	0.1875	0.1875
0.0610" - 0.0909"	Sheet	0.010	0.125	0.1875	0.250
0.0910" - 0.1109"	Sheet	0.014	0.125	0.1875	0.250
0.1100" - 0.1879"	Sheet	0.020	0.1875	0.250	0.375

Rectangular Flat Product Tolerances for TA130 (SGS) and Embossed Material  
(Embossed Material available from 0.0050" to 0.0150" only)

Tolerances are applied before the emboss process.

1 inch = 25.4 mm

### Tantalum Bar, Wire, and Rod

Size	Coiled Length	Straight Length	Diameter Tolerance +/-	Coil Length Tolerance +/-	Straight Length Tolerance	Straightness Deviation max.
0.025" - 0.0299"	supplied by weight	N/A	0.00075"	10% (wt)	N/A	N/A
0.030" - 0.0599"	supplied by weight	N/A	0.001"	10% (wt)	N/A	N/A
0.060" - 0.0899"	supplied by weight	36" to 60"	0.0015"	10% (wt)	+0.125" - 0	0.0625" per ft.
0.090" - 0.1249"	supplied by weight	36" to 60"	0.002"	10% (wt)	+0.125" - 0	0.0625" per ft.
0.125" - 0.1869"	supplied by weight	36" to 60"	0.003"	10% (wt)	+0.250" - 0	0.0625" per ft.
0.187" - 0.3749"	supplied by weight	36" to 60"	0.004"	10% (wt)	+0.250" - 0	0.0625" per ft.
0.375" - 0.4999"	N/A	36" to 60"	0.005"	N/A	+0.250" - 0	0.0625" per ft.
0.500" - 0.6249"	N/A	36" to 55"	0.007"	N/A	+0.250" - 0	0.0625" per ft.
0.650" - 0.7499"	N/A	36" to 55"	0.008"	N/A	+0.250" - 0	0.0625" per ft.
0.750" - 0.9999"	N/A	36" to 55"	0.010"	N/A	+0.250" - 0	0.0625" per ft.
1.000" - 1.3749"	N/A	25" to 55"	0.015"	N/A	+0.250" - 0	0.0625" per ft.
1.375" - 1.9999"	N/A	25" to 55"	0.020"	N/A	+0.250" - 0	N/A
2.000" - 2.4999"	N/A	12" to 55"	0.030"	N/A	+0.250" - 0	N/A
2.500" - 6.0000"	N/A	up to 55"	*	N/A	+0.250" - 0	N/A

1 inch = 25.4 mm

### Product in Annealed Condition

- > Longer lengths are available in the unannealed condition
- > Ends are sheared through 0.3749" diameter
- > Ends are saw cut at 0.375" and above
- > Straightness deviation of machined rod is 0.0625" per foot maximum

# 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

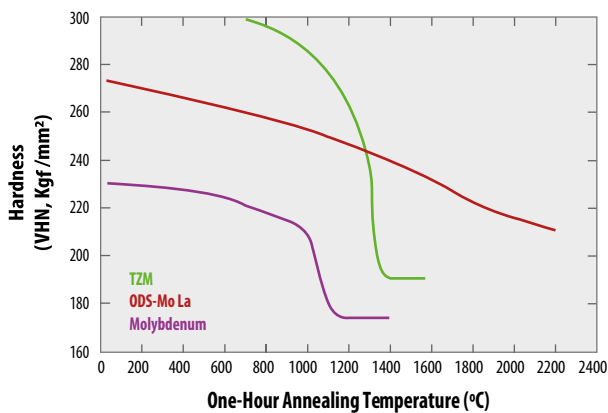
### > Tungsten (W)

#### Benefits:

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

## Molybdenum

### Hardness versus Anneal Temperature



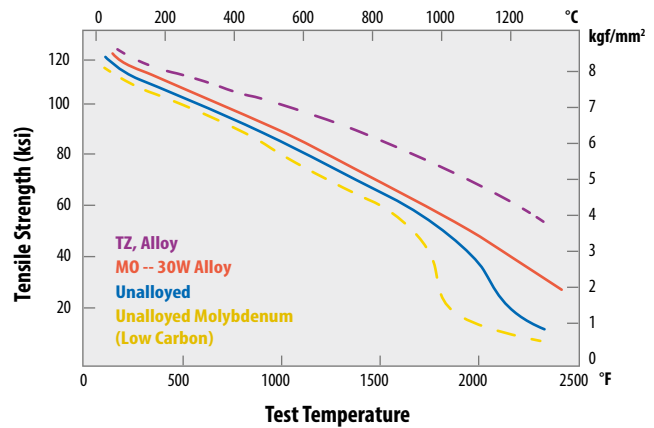
### > Tantalum (Ta)

#### Benefits:

- High temperature refractory, ductile at room temperature even after high temperature exposure, and creep resistance

## Molybdenum

### Tensile Strength versus Temperature



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

## FLAT PLATE

### > Molybdenum (Mo, MoLa, TZM, W, and Ta Alloys)

**Application: Hearth plates, pusher furnace carriers**

#### Benefits:

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

## FABRICATIONS

### > FURNACE RACK (Mo, MoLa, TZM, W, and Ta)

**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, and Ta)

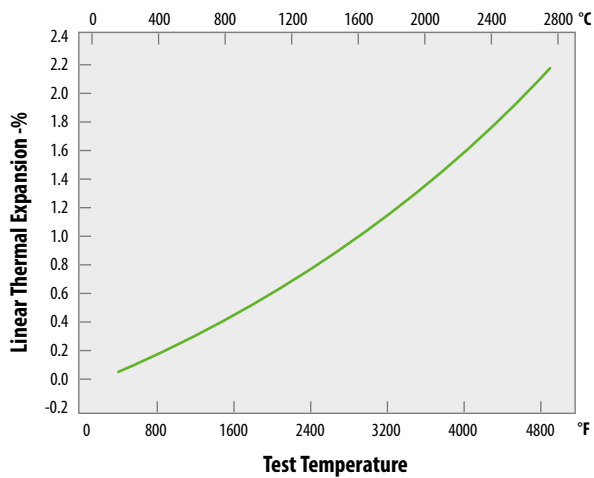
**Application: High temperature furnace shielding and heating elements**

**Benefits:**

- Developed per Print:  
Roll Forming: 60" long x 0.040" thick max. x mill width
- Cut or formed to desired shape

**Molybdenum**

**Thermal Expansion versus Temperature**



> **FURNACE BOATS and TRAYS (Mo, MoLa, TZM)**

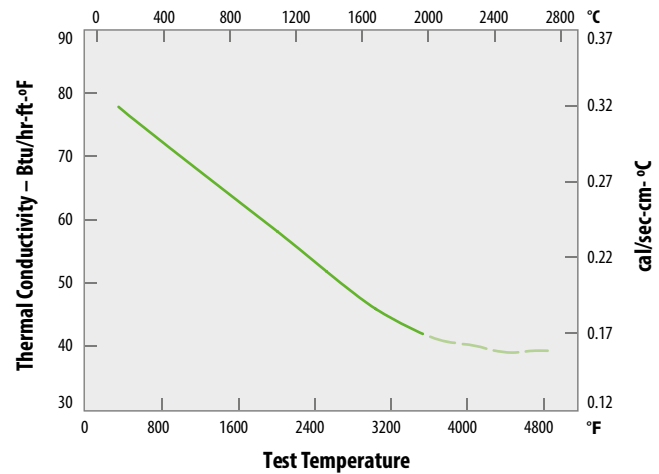
**Application: High temperature furnace boats, powder sintering, nuclear fuel processing, furnace support fixtures**

**Benefits:**

- Cut or formed to desired shape

**Molybdenum**

**Thermal Conductivity versus Temperature**

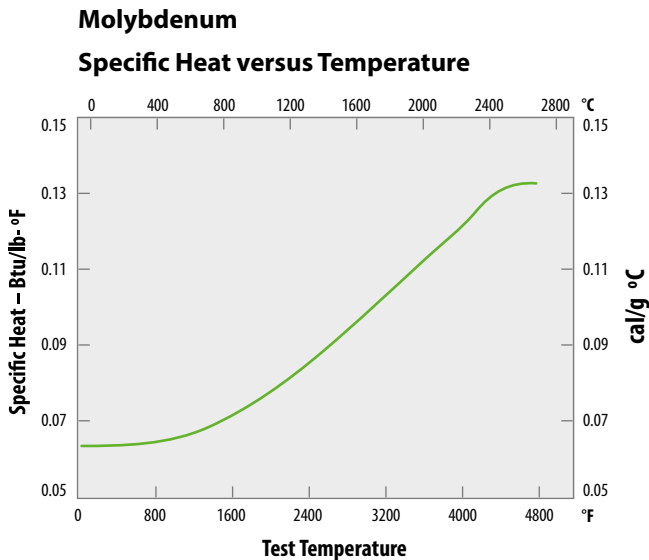


> **BENT AND ROLLED PIECES – Brackets and Shielding**  
(Mo, MoLa, TZM, Ta, W)

**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



> **HEATING ELEMENT (Mo, MoLa, TZM, Ta, 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
- Ta remains ductile after high temperature exposure

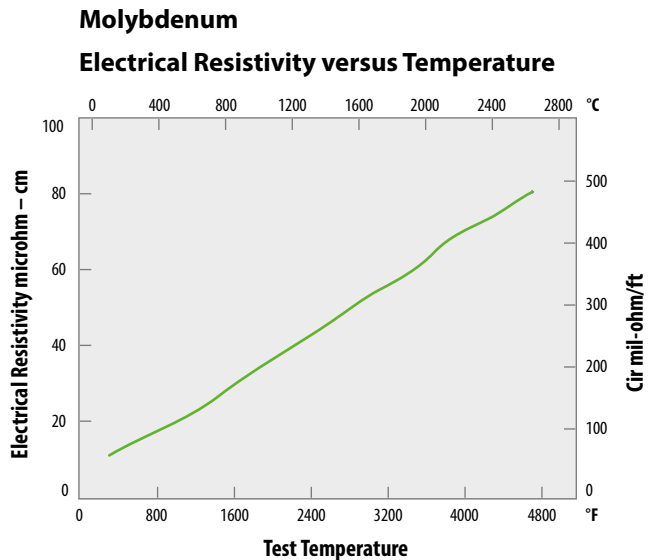
> **HOT ZONES (Mo, W, Ta)**

**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

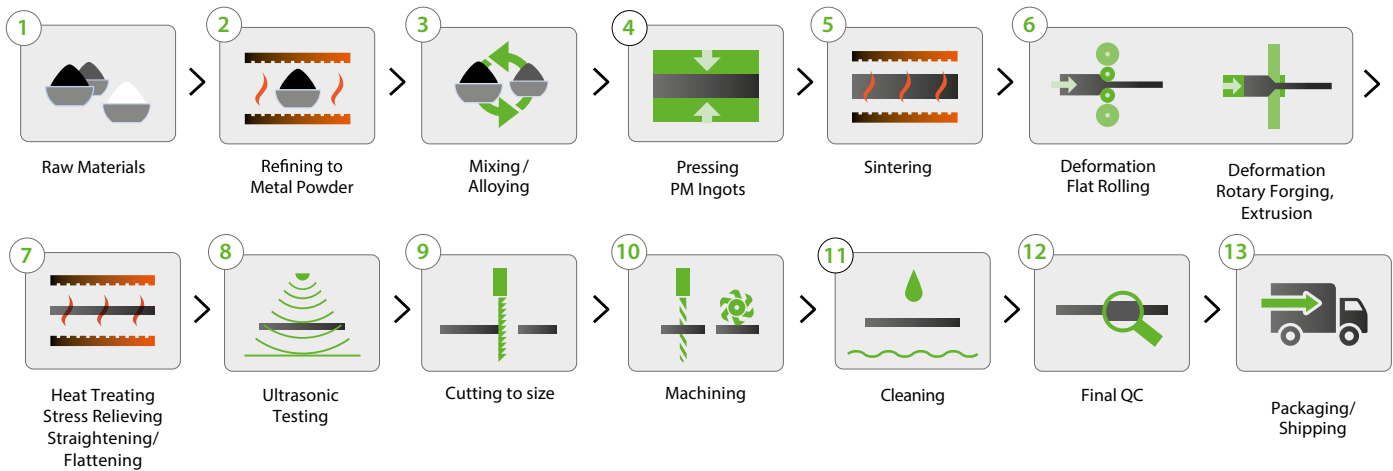


- W, Mo, and Ta can operate in vacuum or inert gas atmospheres
- W, Mo, and MoLa cannot be used in air atmosphere
- Ta cannot be used in hydrogen atmosphere
- Ta is used in Ta-lined furnaces to prevent chemical contamination

# Refractory Metal Production Processes

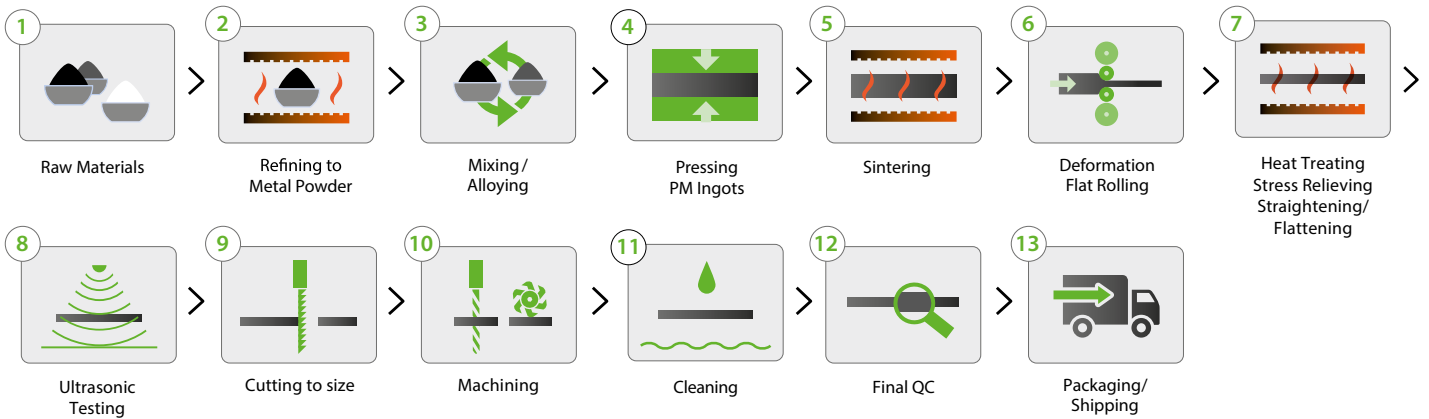
## Molybdenum Process

- > 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



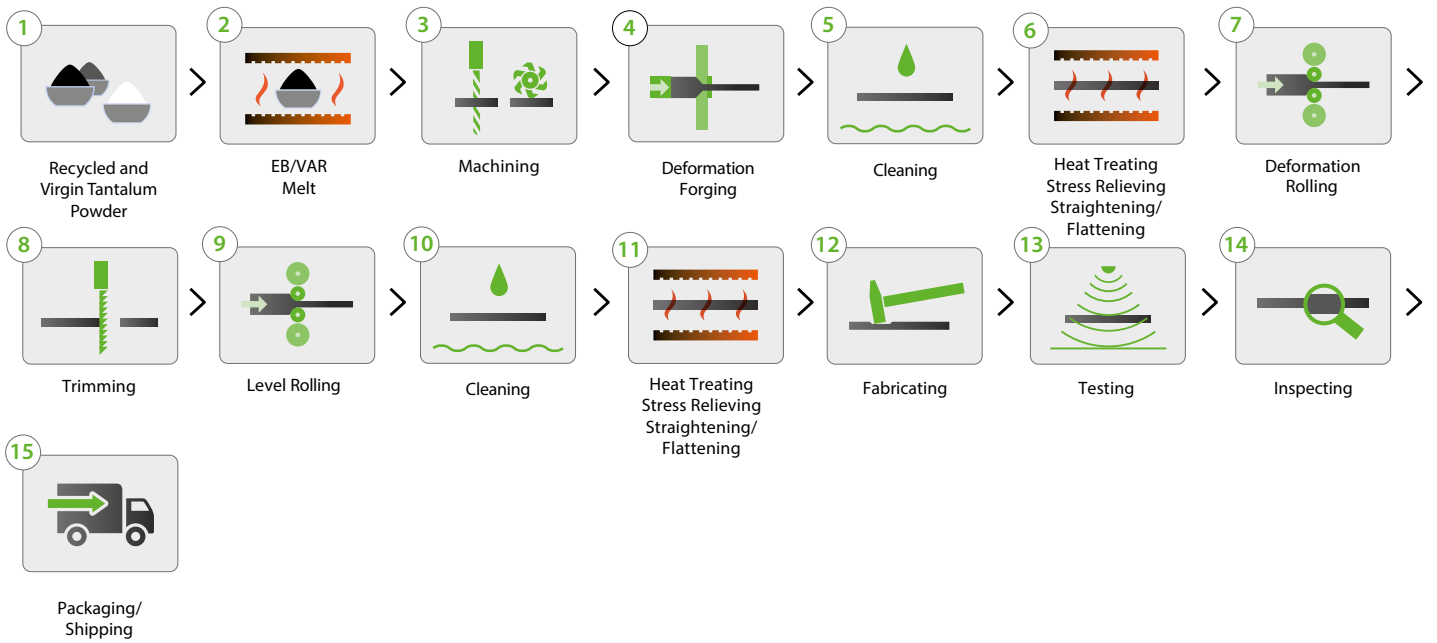
## Tungsten Process

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



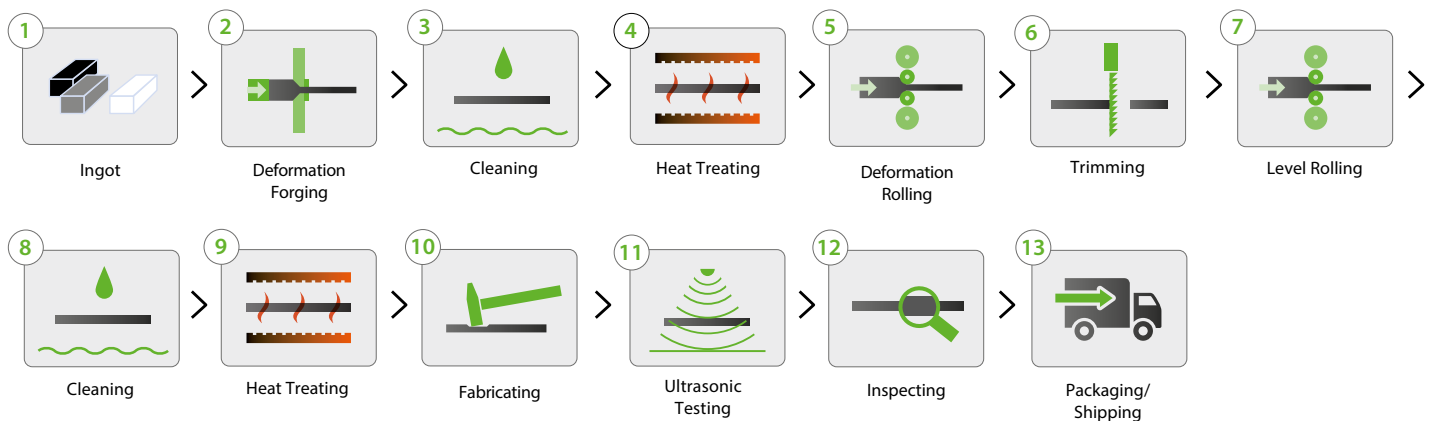
### Tantalum Process

- > Competitive costs
- > Leading edge in R&D and technology
- > Forging expertise – consistent grain size and texture control
- > Electron beam (EB) melting – control purity to precise levels
- > Vacuum Arc Re-melting (VAR)



### 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 the 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.



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