PLANSEE

W-MMC

Tungsten-based metal matrix composites

The basis of intelligent technology

Plansee is the world's leading manufacturer of powder-metallurgically processed refractory and specialty metals. Based on our core competencies in the areas of high-performance materials, forward-looking applications, and technologies, we have manufactured products and components made from molybdenum, tungsten, tantalum, niobium, chromium and their alloys for 100 years.

Being a leader in technological innovation, we consistently strive to optimize materials and meet new mechanical, chemical and physical demands that arise from our clients' practical needs.

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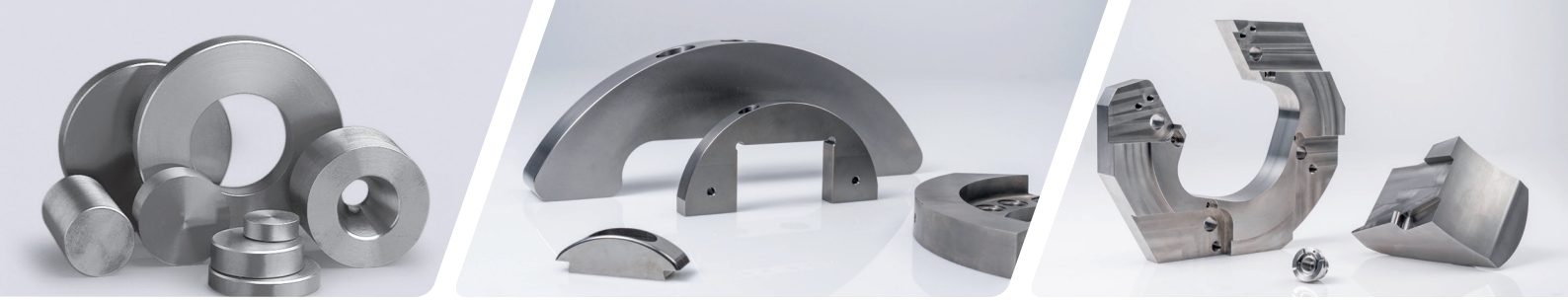


Overview of Plansee's W-MMC (Tungsten-based metal matrix composites)

Tungsten is considered a refractory metal. It has the highest melting point and the lowest vapor pressure of all metallic elements. It is also characterized by high density, a very high level of dimensional stability, and a uniquely low coefficient of thermal expansion.

Plansee specifically influences and complements these special properties of tungsten by combining it with other metals. The results are tungsten-based metal matrix composite materials, including tungsten heavy alloys (WHA) and tungsten copper composites, with unique properties: DENSIMET®, INERMET®, DENAL®, WCu and SPARKAL®.

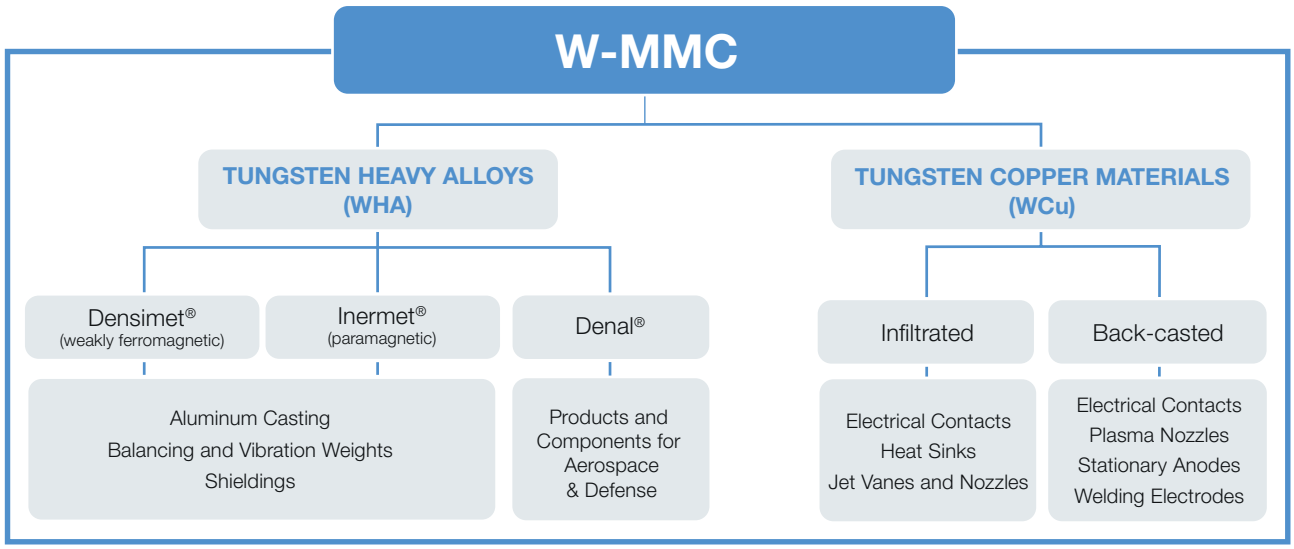


Figure 1: Material overview

Tungsten-based metal matrix composites offer a perfect combination of high densities and mechanical properties. A huge advantage is their good machinability.

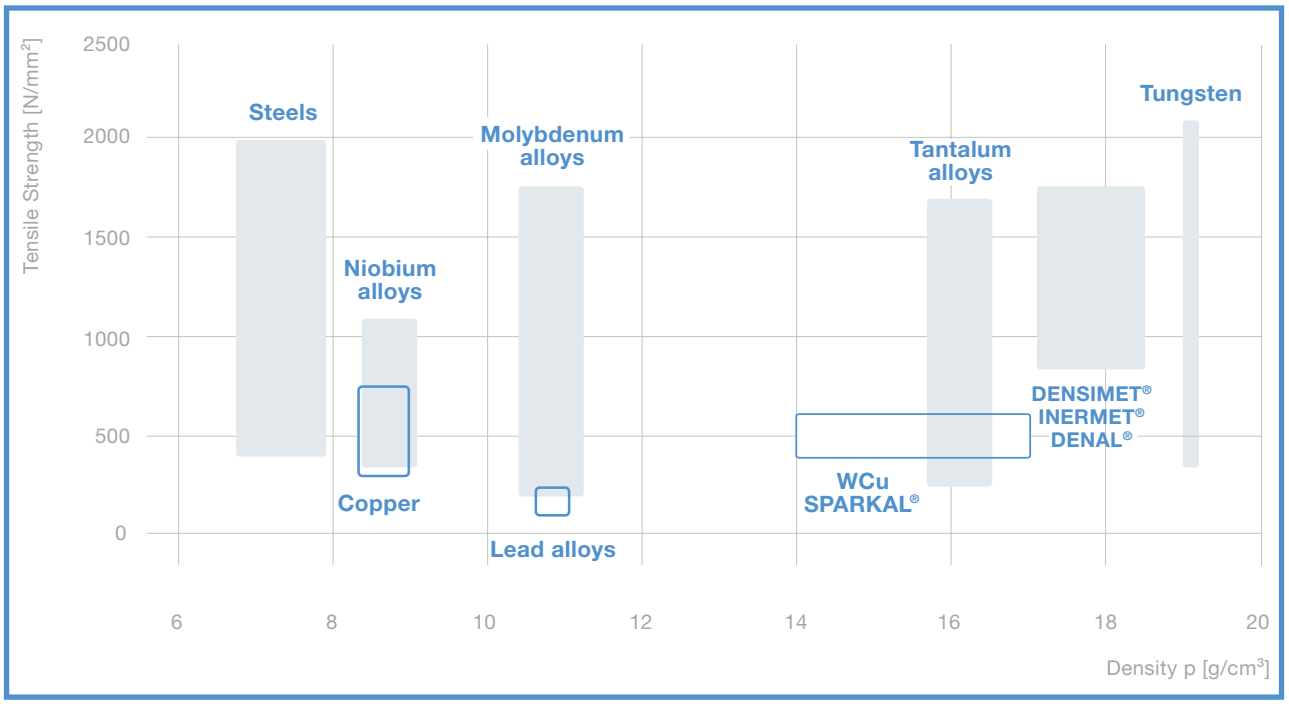


Figure 2: Strength of materials

Customized solutions and R&D support

We produce our tungsten-based metal matrix composite materials by powder metallurgical processes. This technology gives us the flexibility to specifically adapt the microstructure of the materials during the manufacturing process. As a result, we can supply materials whose properties are optimized to the customer's specific applications. Additionally, a wide range of material compositions is possible, such as the production of the contact material tungsten carbide-silver (WCAg).

An experienced team of research and development experts at several locations works with our customers on customized solutions. We simulate the behavior of materials in manufacturing and application processes, research the chemical and physical processes, and test our findings in specific trials in close coordination with our customers. Our R&D center is fully integrated within our production operation and guarantees maximum flexibility and efficiency. Together we are capable of responding to our customers' individual needs and meeting their ever-increasing requirements.

Our mission is to remain one step ahead in the development of the highest quality materials and to offer our customers real competitive advantages.

PLANSEE

Range of materials for standard products

Material	Designation	Chemical composition [%] W	Remainder	Nominal density	ASTM-B-777/07 Class
Weakly ferromagnetic					
DENSIMET® 170	D170	90	Ni, Fe	17.0	1
DENSIMET® 176	D176	92.5	Ni, Fe	17.6	2
DENSIMET® 180	D180	95	Ni, Fe	18.0	3
DENSIMET® 185	D185	97	Ni, Fe	18.5	4
DENSIMET® 188	D188	98.5	Ni, Fe	18.8	
DENSIMET® D2M	D2M	90	Ni, Mo, Fe	17.3	
Paramagnetic					
INERMET® 170	IT170	90	Ni,Cu	17.0	1
INERMET® 176	IT176	92.5	Ni,Cu	17.6	2
INERMET® 180	IT180	95	Ni,Cu	18.0	3
DENAL®	high characteristics swaged	92	Ni, Fe, Co	17.6	
DENAL®	high characteristics swaged, Co-free	91.7	Ni, Fe	17.55	
DENAL®	high characteristics	91	Ni, Co	17.5	
WCu	WCu10	90	Cu, (Ni)	17.1	
WCu	WCu15	85	Cu, (Ni)	16.4	
WCu	WCu20	80	Cu, (Ni)	15.5	
SPARKAL®	SPARKAL® X	75	Cu	14.8	
SPARKAL®	SPARKAL® X FIN	80	Cu, Ni	15.6	

In addition to the standard materials listed above, we offer a wide range of customized materials. Our material experts would be pleased to assist you and develop the optimal material combination for your particular requirements.

Guidelines for material selection

Correct material selection requires knowledge of the application. Important criteria may be:

- Physical properties
  (e.g. density, shielding behavior against radiation, thermal conductivity, thermal expansion coefficient, melting point, electrical conductivity, burn-off resistance, magnetization)
- Mechanical properties
  (e.g. strength, fracture toughness, elongation, creep behaviour)
- Chemical properties
  (corrosion and oxidation resistance)
- Ease of working
  (machinability, formability, weldability)

With suitable material compositions and manufacturing processes, a variety of properties can be achieved based on tungsten.

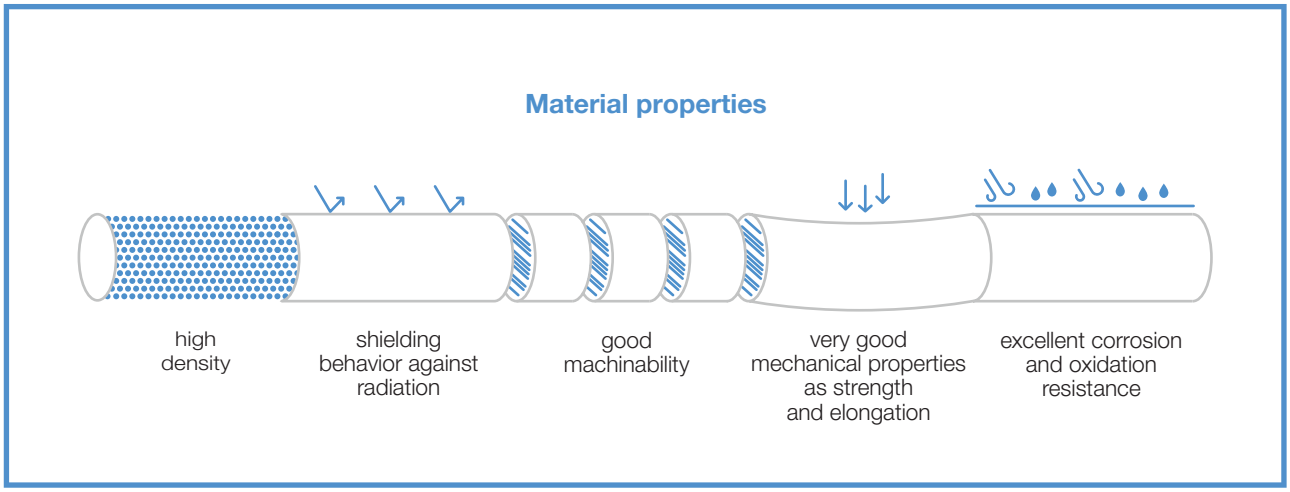


Figure 3: Properties of W-MMC

Plansee has developed several different composite materials with various property profiles. Each material features a special combination of properties and is therefore unique and unlike any other material. The advantages of our most frequently used materials are:

DENSIMET® and INERMET®

Plansee DENSIMET® and INERMET® composite materials are tungsten heavy alloys with a high tungsten content (> 90%) and a NiFe or NiCu binder phase. DENSIMET® and INERMET® tungsten alloys are distinguished by their particularly high density. Combined with their ability to absorb radiation as well as their outstanding mechanical properties and machinability, they are the ideal materials for a wide range of applications, such as in the aerospace field, the automotive industry, medical engineering and the construction industry.

Densimet® and Inermet® exhibit the following properties:

- High density of 17.0 to 18.8 g/cm³ (similar to pure tungsten)
- Better machinability compared to pure tungsten
- Inexpensive manufacture of complex products and components
- High Young's modulus and excellent mechanical properties
- High absorption capacity for X-rays and gamma rays
- Safe in terms of health and environment

DENSIMET® alloys also offer excellent strength and ductility, while another clear advantage of INERMET® lies in its non-magnetic characteristics.

DENAL®

DENAL® is the brand name used for defense-related products. DENAL® is usually a customized material with a very high compromise between high strength and ductility for various applications such as penetrator materials for penetration requirements.

WCu and SPARKAL®

Tungsten-copper combines a high level of temperature resistance – one of tungsten's most important benefits – with the excellent electrical and thermal conductivity of copper.

WCu exhibits the following properties:

- Excellent arc resistance
- Outstanding electrical conductivity
- High strength
- Good machinability
- Very good thermal conductivity
- Low thermal expansion

Due to the special composition of the chemical ratio, properties can be optimized according to requirements in terms of electrical conductivity, thermal conductivity, coefficient of thermal expansion and burn-off rate. One of these special compositions is the SPARKAL® – material – developed to meet the requirements of electrical discharge machining (EDM), SPARKAL® electrodes offer a number of advantages over conventional electrode materials.

Available products and standard dimensions

We offer standard products from stock in our Plansee Online-Shop. Please contact us for other dimensions and individual geometries. We will be pleased to help.

DENSIMET® D176		
Rods	Ø 6 – 62 mm	Length: 320 – 700 mm
SPARKAL® X		
Rods	Ø 8 – 90 mm	Length: 230 – 350 mm
Square bars	Ø 8 × 8 – 50 × 50 mm	Length: 350 mm
Plates	3 × 75 – 25 × 75 mm (thickness × width)	Length: 350 mm
SPARKAL® X FIN		
Tubes	Ø 0.5 – 6 mm	Length: 175 mm
Rods	Ø 0.5 – 6 mm	Length: 175 mm

We like to make life easy:

A quick and simple ordering process and clearly outlined pricing – directly on your screen. Rods, bars, blocks, tubes and plates as well as other Plansee products are available in configurable dimensions at **www.plansee.com/shop**

For more dimensions or customized products to meet your special needs – please visit **www.plansee.com** or contact us directly at **support@plansee.com**. Our sales team is looking forward to hearing from you.

Production process

Plansee products made from tungsten-based MMC are manufactured using powder metallurgy. All stages of production, from the powder to the finished product, satisfy Plansee's quality standards, exceeding ISO 9001 requirements.

Production process of tungsten heavy alloys

In order to manufacture DENSIMET® and INERMET®, mixtures of powdered metals are pressed and liquid-phase sintered to obtain a dense and solid material. The sintered product can be supplied as a semi-finished product such as plates and rods, as a near-net-shape product, or as a finished product according to the customer's drawings. If desired, our DENSIMET® and INERMET® components can undergo shaping and heat-treatment techniques to meet specific application requirements.

Plansee DENSIMET® and INERMET® materials comply with the AMS-T-21014, the AMS 7725 rev E, and the ASTM-B-777-99 (MIL-T-21014) specifications.

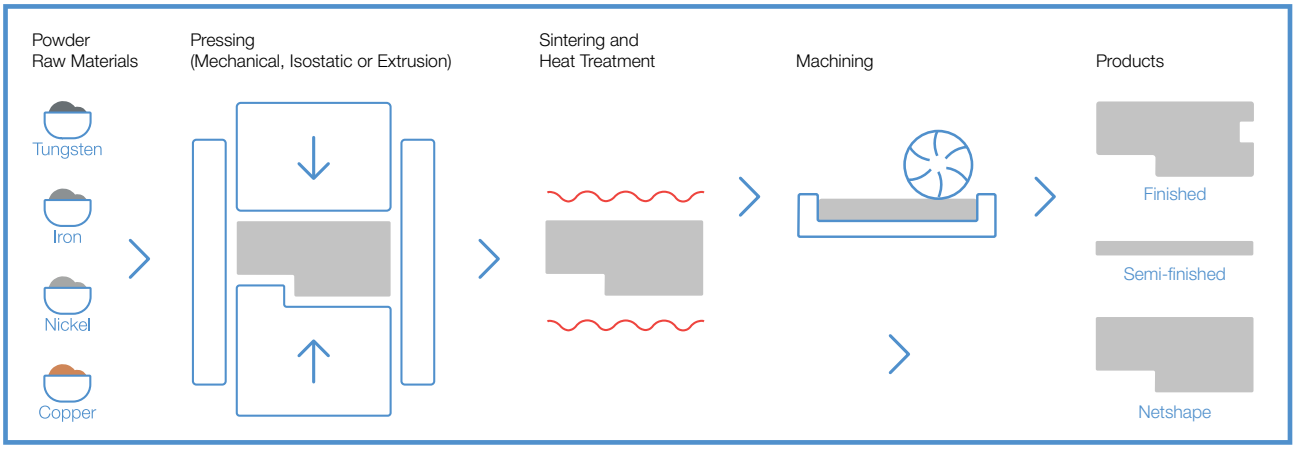


Figure 4: Manufacturing process of DENSIMET® and INTERMET® products

DENAL® is an advanced range of tungsten heavy alloys suited for kinetic energy ammunition penetrators. It is produced in a specific manufacturing process that includes forging, which allows the material to reach very high levels of mechanical characteristics. DENAL® is available in the form of round bars in several different lengths and diameters, which directly influences the penetration properties against targets. Suitable for medium and large caliber ammunition specifications, DENAL® is also available in a Co-free version, which takes into account environmental conditions from certain customers. DENAL® mechanical properties can be adapted to customer specifications, creating the best compromise between industrial efficiency and resistance to extreme conditions in a single product.

Production process of WCu materials

WCu materials are also manufactured from metal powder. All stages of production from the powder all the way to the finished product are carried out in-house and all satisfy Plansee's quality standards, which exceed the provisions of ISO 9001:2000 and AS/EN/JISQ 9100.

The essential step of manufacturing WCu products, such as SPARKAL® EDM electrodes, is infiltration:
During a two-stage manufacturing process, first a porous sintered base is fproduced from tungsten, and then the open pores are infiltrated with the liquefied copper. After sintering, the product can be machined to individual customer requirements.

This approach, leaves the properties of the individual components unchanged. An inspection under the microscope verifies that, the properties of each of the components main intact. At the macroscopic level, however, the properties of the individual components are combined. For example, the new material may have modified thermal conductivity and thermal expansion values.

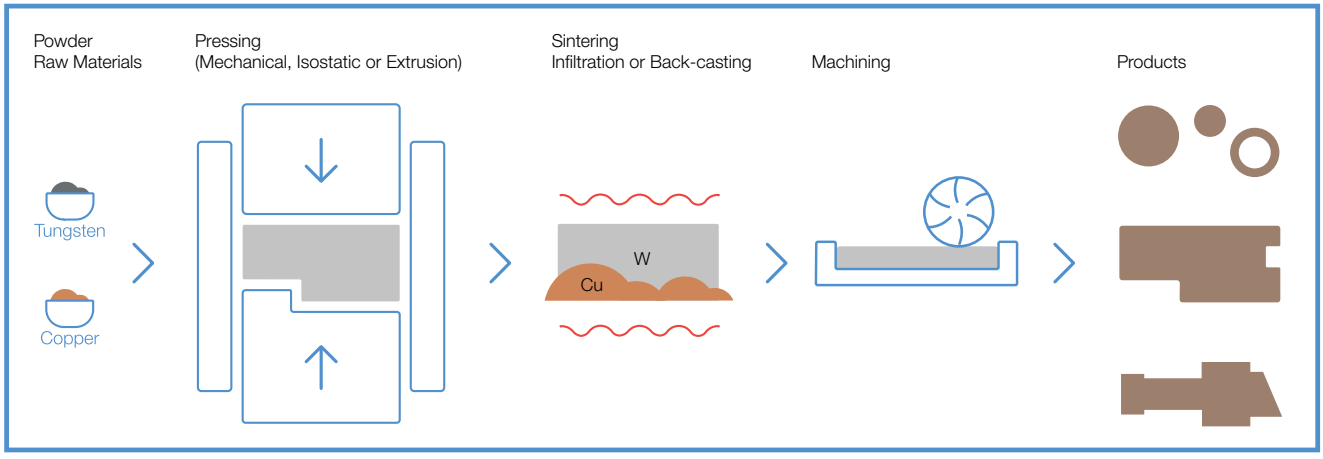


Figure 5: Schematic representation of the manufacturing process of WCu products and SPARKAL®

Another production approach is back-casting:
Back-cast materials simultaneously combine the material properties of two different material components. During this process, the materials themselves are retained in their original state and are only bound at a thin junction. The metals are fused in a mold to form a bond measuring just a few microns. Unlike welding and soldering techniques, this method guarantees a 100 % connection and ensures optimal thermal conduction.

Creating the future responsibly – since 1921

As early as 1921, Plansee chose to specialize in the powder metallurgical production of refractory metals – a recognized green technology.

When we produce and process our materials, we strive to minimize the impact on the environment. We are always mindful of material utilization, energy consumption, and emissions. Our near-net-shape manufacturing process, allows us to achieve high output. This results in lower waste and saves resources.

The standards we adhere to are summarized in our Environmental and Quality Guidelines.

Raw materials from conflict-free sources

As one of the world's leading manufacturers of refractory metals, we bear great responsibility. We are especially concerned that the raw materials we procure are sourced responsibly and exclusively from conflict-free sources. As a result, we go to great lengths to ensure that we do not source or use any raw materials from socially, ethically or ecologically questionable sources.

Sustainability is a constant watchword in our purchasing policy. We only select suppliers that comply with rigorous procurement guidelines and our Supplier Policy.

Suppliers not only have to demonstrate that raw materials meet our strict quality requirements. They must also unreservedly respect human rights, labor laws, and international trade law, and provide proof that their raw materials come from "conflict-free" sources and meet strict environmental requirements. We participated in a pilot study conducted by the Organization for Economic Cooperation and Development (OECD) and have implemented the "Due Diligence Guidance for Responsible Supply Chains of Minerals from Conflict-Affected and High-Risk Areas“.

In its audit, the audit committee of the Responsible Business Alliance (RBA) and the Global e-Sustainability Initiative (GeSI) confirmed that Global Tungsten & Powders (GTP) in Towanda - a Plansee Group company – sources tungsten in compliance with the Responsible Minerals Assurance Process (RMAP). For Plansee's customers, the certificate provides independent proof that the Plansee Group procures its tungsten from responsible sources.

Consistent recycling throughout the entire process

Plansee attaches great importance to using resources as sparingly as possible throughout the production process. Near-net-shape production therefore plays a crucial role. Still, production waste and return materials cannot be completely avoided. These are chemically and thermomechanically processed for reuse in the company's own recycling facilities.

At the same time, the environment is not the only consideration. There are also good economic reasons for re-using these so-called "secondary raw materials":

- Security of supply
- Careful use of natural resources

Our in-house team of scientists is constantly fine-tuning the adopted methods and processes and ensures that only top-quality powder is obtained. In the case of tungsten, in particular, a large proportion of the material requirements is covered by recycling. The input material to the recovery process consists of sintered hard tungsten carbide scrap as well as soft scrap such as powders and grinding sludge, and other secondary raw materials with a tungsten content of 60 % or more. To enable us to reprocess as much waste material as possible, we have long-term take-back agreements with many of our customers.

Machining of W-based MMC

Machining of DENSIMET® and INERMET®

Turning	
Tools	CERATIZIT Maxilock S / CERATIZIT Maxilock N
Indexable inserts **H 216 T / H 10 T / AMZ / H 210 T**	Code –23P / –25P / –25Q / –27 / –42 positive cutting geometry, sharp cutting edges
Cutting speed [m/min]	60 – 140
Feed [mm]	0.05 – 0.3
Cutting depth [mm]	≤ 6
Coolant	Emulsion
Use CERATIZIT milling tool systems Maximill and solid carbide end mill cutter with positive cutting edges of the following geometry:	
Rake angle **Front clearance** **Hard metal grade**	+10° – +25° 0° – +15° H 216 T / H 10 T / AMZ
End mills micrograin K10 uncoated	DIN 2535
Cutting speed [m/min]	70 – 150
Feed/Tooth [mm]	0.03 – 0.15
Coolant	Dry
Drilling	
Hard metal grade	Finest grain K10 uncoated
Drilling diameter	< 18 mm
Drill	HSS or CERATIZIT solid carbide twist drill
Cutting speed [m/min]	HM: ≥ 30 / HSS: 8 – 15
Drilling diameter	≥ 18 mm
Drill	Short hole drill
Cutting speed [m/min]	HM: 30 – 60
Indexable inserts	WCGT Grade CTWN415 / XOMT Grade SR226
Cutting speed [m/min]	30 – 60
Feed [mm]	0.03 – 0.1
Coolant	Emulsion
Tapping	
Tools	VA nitrided taps with straight flutes and a tensile strength of 1400 N/mm^2
Coolant	Cutting oil

Machining of WCu

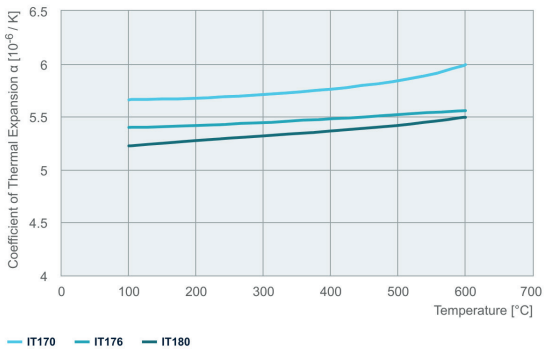
Milling	
Hardmetal grade	ISO K10-K20 / H216T / H10T; TiN coating possible
Tools	End milling cutter K10; DIN 2535HB, uncoated
Rake angle	8° – 12°
Clearance angle	7° – 12°
Approach angle of the main cutting edge	45°
Cutting speed	80 – 100 m/min
Feed	0.03 – 0.15 mm/rev
Condition of machining	Emulsion
Grinding	
Centerless grinding	Grinding wheels made of corundum in the hardness K, L, M
Grain	40 – 60 with intermediate structure
Binder	Resine binder
Cutting speed	28 – 32 m/sec.
Infeed	0.02 – 0.1 max.
Lubrication	Emulsion
Drilling	
	Through holes
Drill	High speed steel with Co (8%)
Tip angle	120° – 130°
Clearance angle at the main cutting edge	10°
Clearance angle at the periphery	8° – 10°
Cutting speed	12 – 20 m/min
Lubrication	Emulsion
	Counter bores
Drill	Hardmetal (grade ISO K10-K20)
Tooling geometry	as for high speed steel
Cutting speed	35 – 40 m/min
Lubrication	Emulsion
Coolant	Emulsion
Tapping	
Hardmetal grade	ISO K10-K20 / H216T / H10T / TSM20 / AMZ
Tools	Maxilock S/N
Inserts	Code –23P / –25Q / –27 / –42
Rake angle	6 – 8°
Clearance angle	7°
Cutting speed	60 – 100 m/min depends on dimension of the electrode
Feed	0.05 – 0.3 mm/rev
Lubrication	Emulsion

Physical and mechanical properties, corrosion behavior

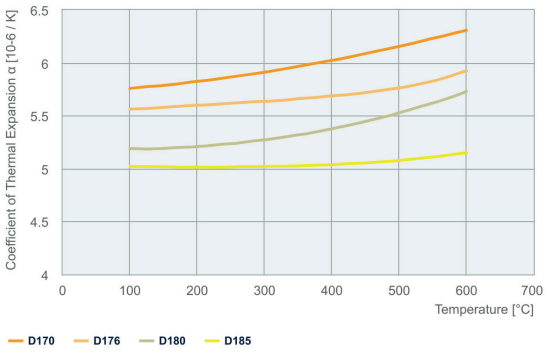
Properties of DENSIMET® and INERMET®:

Physical properties – typical values

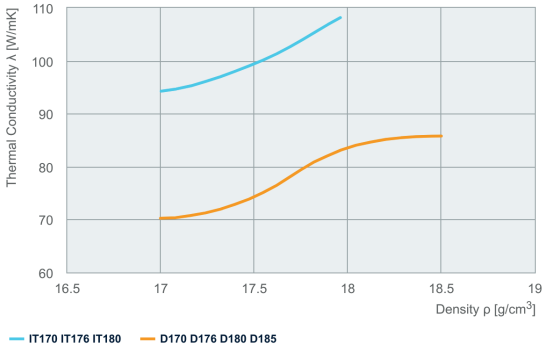
Coefficient of thermal expansion INERMET®



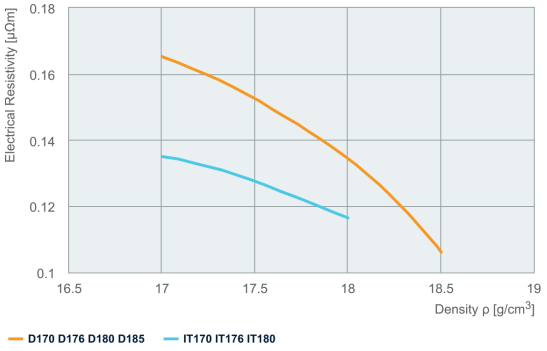
Coefficient of thermal expansion DENSIMET®



Thermal conductivity DENSIMET® and INERMET



Electrical resistivity DENSIMET® and INERMET®



Mechanical properties – typical values

	D170	IT170	D176/W	IT176	D180	IT180	D185
Young's modulus E [GPa]	340	330	360	350	380	360	385
Modulus of rigidity G [GPa]	140	125	145	135	150	140	160

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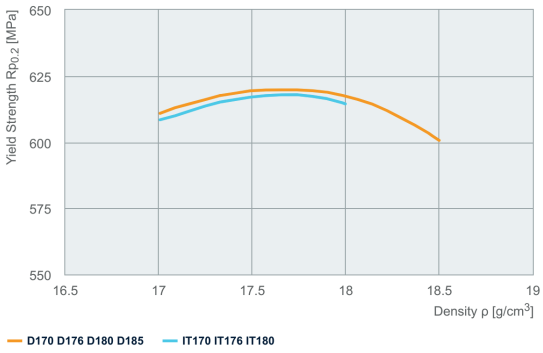
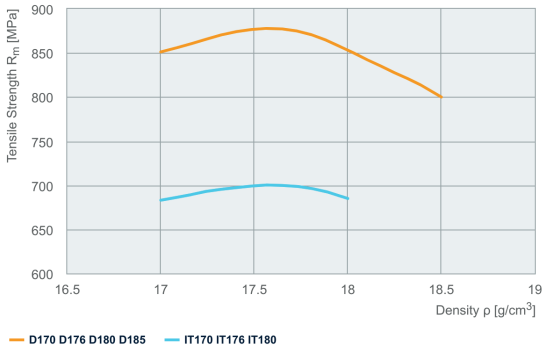
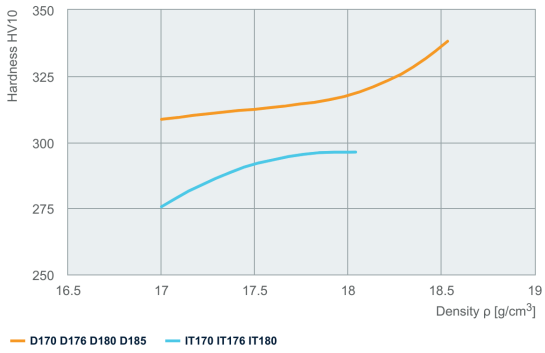
Yield Strength DENSIMET® and INERMET®



Tensile Strength DENSIMET® and INERMET®

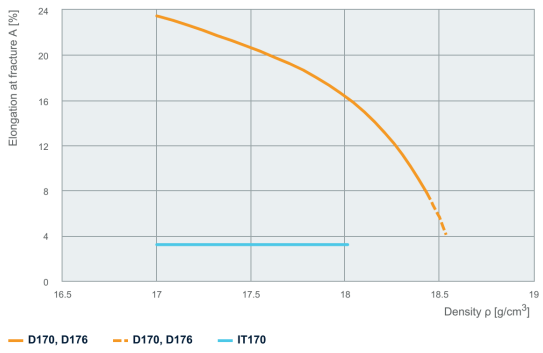


Hardness HV10 DENSIMET® and INERMET®

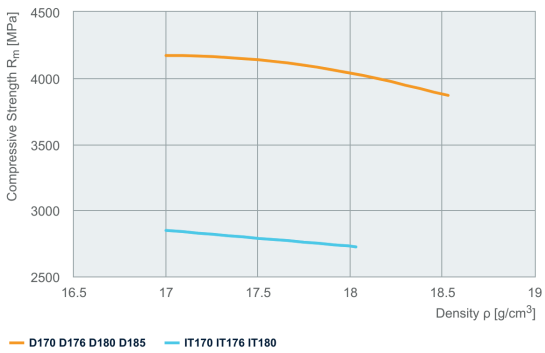


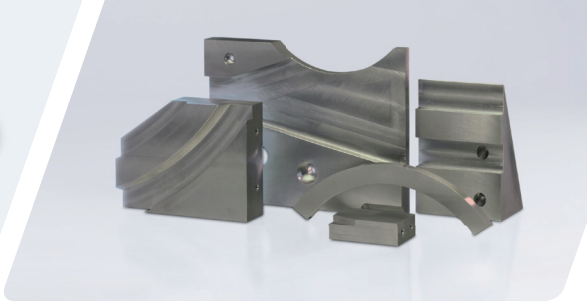
Hardness HB30 DENSIMET® and INERMET®

Elongation at fracture DENSIMET® and INERMET®



Compressive Strength DENSIMET® and INERMET®

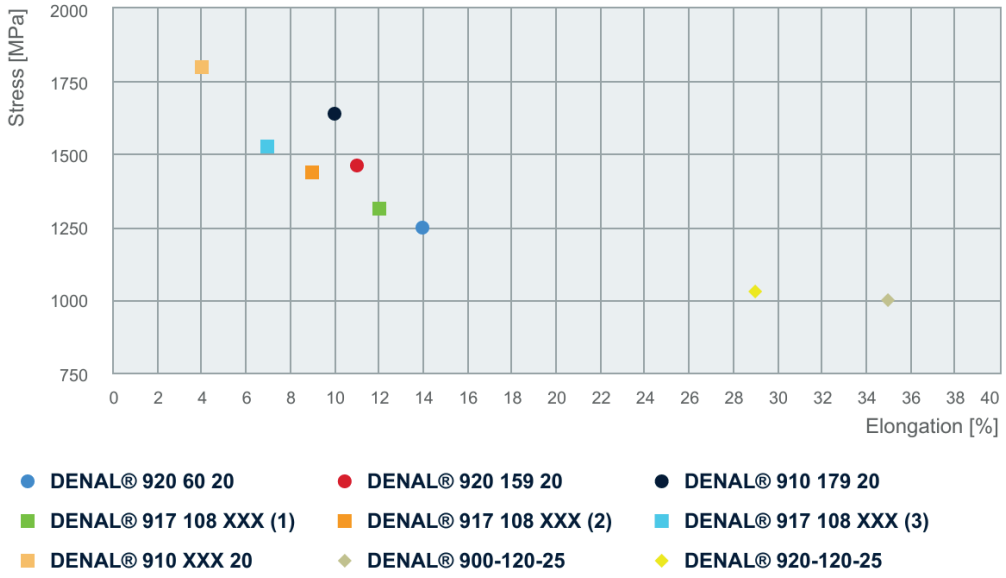



Properties of DENAL®

Material	Density	Y 0.2 Yield strength [MPa] Av. / Min.	UTS Tensile strength [MPa] Av. / Min.	A% Elongation [%] Av. / Min.	K (5x5) Charpy test [J/cm²] Av. / Min.
DENAL® - high characteristics swaged					
DENAL® 920 60 20	17.6	1250 / 1180	1250 / 1180	14 / 9	100 / 60
DENAL® 920 159 20	17.6	1460 / 1400	1460 / 1400	11 / 8	150 / 100
DENAL® 910 179 20	17.5	1640 / 1600	1640 / 1600	10 / 7	100 / 60
DENAL® - high characteristics swaged, Co-free					
DENAL® 917 108 XXX (1)	17.55	1280 / 1220	1315 / 1255	12 / 8.5	170 / 105
DENAL® 917 108 XXX (2)	17.55	1410 / 1350	1435 / 1375	11 / 7	150 / 70
DENAL® 917 108 XXX (3)	17.55	1510 / 1450	1525 / 1465	8 / 5	60 / 30
DENAL® 910 XXX 20	17.5	1800 / 1720	1800 / 1720	4	-
DENAL® - high characteristics					
DENAL® 900-120-25	17.2	700	1000	35	300
DENAL® 920-120-25	17.6	720	1030	29	150

UTS Tensile strength of DENAL® (average values)



- DENAL® 920 60 20
- DENAL® 920 159 20
- DENAL® 910 179 20
- DENAL® 917 108 XXX (1)
- DENAL® 917 108 XXX (2)
- DENAL® 917 108 XXX (3)
- DENAL® 910 XXX 20
- DENAL® 900-120-25
- DENAL® 920-120-25

Properties of WCu

Physical and mechanical properties – typical values

Material [wt%]	Density at 20°C [g/cm³]	CTE at 20°C [ppm/K]	TC at 20°C [W/mK]
WCu10	17.1	6.4	195
WCu15	16.4	7.3	215
WCu20	15.5	8.3	235

Properties of SPARKAL®

Physical and mechanical properties - typical values depending on geometry and product dimensions

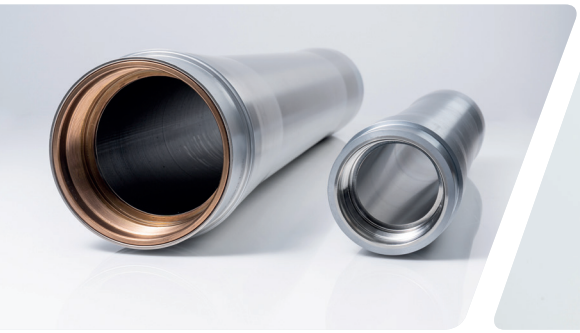
	SPARKAL® X	SPARKAL® X FIN
Chemical composition (%)	W 75 Cu 25	W 80 CuNi 20
Density (g/cm³)	14.8	15.6
Hardness (HV 5)	240	270
Electrical conductivity (% IACS)	40	20
Electrical resistance (µΩ cm²/cm)	4.3	8.4
Modulus of elasticity (MPa)	250.000	280.000

Other Plansee high-performance materials

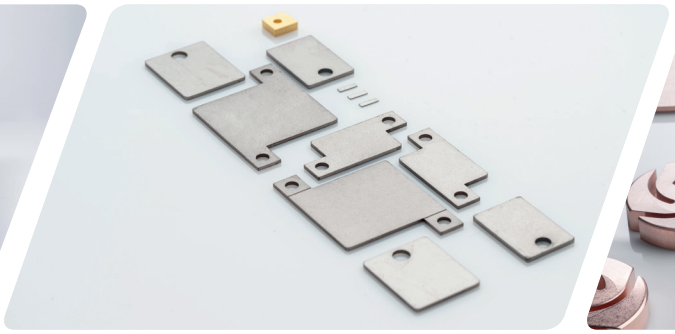
Based on our many years of experience in the field of powder metallurgy, we supply a wide range of products made from high performance materials. In addition to tungsten-based metal matrix composites, Plansee is also a leading producer of:

- Molybdenum and Mo alloys
- Tungsten and W alloys
- Tantalum and Ta alloys
- Copper-Chromium
- Niobium
- Sputter materials for hard coating

Selection of Plansee products made of high-performance materials:



Sputtering targets

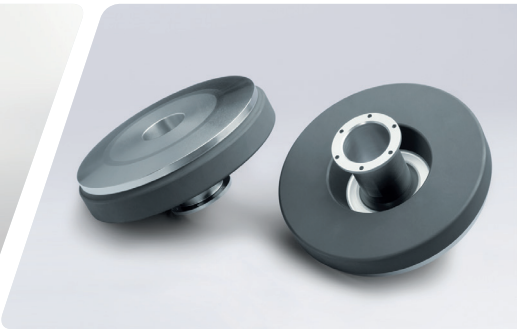


Thermal management components

CuCr contacts

Glass melting electrodes

Mo spray wire

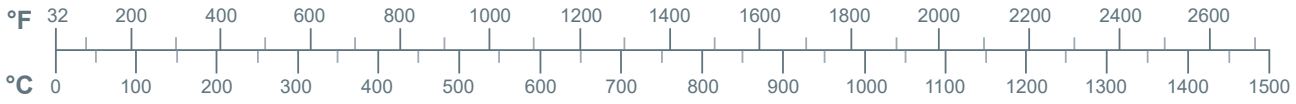


X-ray rotary anodes

Conversion of units

Table 10

Property	SI Unit	Conversation factor	
Area	m^2	1 in^2	= $6.4516 \cdot 10^{-4}$ m^2
		1 ft^2	= $9.2903 \cdot 10^{-2}$ m^2
Density	kg/m^3	1 lb/in^3	= $2.76799 \cdot 10^4$ kg/m^3
		1 lb/ft^3	= 16.0185 kg/m^3
Energy	J = N • m = W • s	1 Btu	= $1.05506 \cdot 10^3$ J
		1 cal	= 4.184 J
		1 eV	= $1.6022 \cdot 10^{-19}$ J
Force	N = kg • m/s^2	1 lbf	= 4.4482 N
Length	m	1 in	= $2.54 \cdot 10^{-2}$ m
		1 ft	= $3.048 \cdot 10^{-1}$ m
Mass	kg	1 lb	= $4.5359 \cdot 10^{-1}$ kg
Power	W = J/s	1 Btu/hr	= $2.93071 \cdot 10^{-1}$ W
		1 hp	= $7.457 \cdot 10^2$ W
Pressure (Stress)	Pa = N/m^2	1 atm	= $1.01325 \cdot 10^5$ Pa
		1 lbf/in^2 (psi)	= $6.89476 \cdot 10^3$ Pa
		1 lbf/ft^2	= 47.8803 Pa
		1 mbar	= 10^2 Pa
		1 N/mm^2 (MPa)	= 10^6 Pa
		1 torr	= $1.33322 \cdot 10^2$ Pa
Specific heat by mass	J (kg • K)	1 cal/(g • °C)	= $4.1868 \cdot 10^3$ J/(kg • K)
		1 Btu/(lb • °F)	= $4.1868 \cdot 10^3$ J/(kg • K)
Temperature	K (Kelvin)	x °C = (x + 273.15) K y °F = (y • 0.5556 + 255.37) K °F in °C: (°F – 32) • 5/9 = °C °C in °F: (°C • 9/5) + 32 = °F	
Thermal conductivity	W/(m • K)	1 kcal/(m • hr • °C)	= 1.163 W/(m • K)
		1 Btu/(ft • hr • °F)	= 1.73073 W/(m • K)
Volume	m^3	1 in^3	= $1.63871 \cdot 10^{-5}$ m^3
		1 ft^3	= $2.83168 \cdot 10^{-2}$ m^3



For further information on Plansee semi-finished products and formed parts made of Mo and Mo alloys, please visit our website **www.plansee.com** or contact your Plansee partner.

Close to the customer – our global network

Plansee manufactures and markets its products worldwide. Production sites in Europe, the USA, Japan, India, China, and Korea as well as a global network of sales subsidiaries and sales partners enable outstanding customer service and product quality delivered by local teams. Stronger than any alliance and more diversified than single producers, Plansee is the most reliable source for high-performance components made of refractory metals.

For more information and local contacts, please visit our website:

www.plansee.com

Plansee SE
Metallwerk-Plansee-Str. 71
6600 Reutte
Austria
Telephone: +43 5672 600 0
E-Mail: info@plansee.com

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