Structural Materials

Beryllium

Among the light metals, beryllium is characterized by its out-standing combination of properties--low density (0.067 lb/in3), high strength (60 psi), good thermal properties, low cross-section, to thermal neutrons and high melting point (2300 °F). The use of beryllium has nevertheless been restricted by its poor ductility and low resistance to impact, as well as by factors of its toxicity and high cost.

Some of the properties of beryllium are summarized as follows:

1. **Density:** Beryllium "has a relatively low density of 0.067 lbs/in^3. This is slightly higher than the density of magnesium and about two-thirds that of aluminum.
2. **Modulus of Elasticity**: The modulus of elasticity of Beryllium high, being 3.1 x 10^4 kg/mm^2 (44 x 10^6 psi). This combined with its low density, makes it attractive as a light, but stiff, material.
3. **Tensile Properties:** The mechanical properties of beryllium are affected by the method of production. Hot-pressed beryllium has a room temperature ultimate tensile strength of around 60 Ksi with a ductility of 0.5 - 0.3%. Beryllium retains its strength at high temperatures; even at 600 °C, it has an ultimate tensile strength of about 25 Ksi. Above 250 °C, its ductility rises to a level in excess of 10%. The fatigue strength of beryllium is high, being in excess of 80% of the ultimate tensile strength. Its room temperature impact strength, however, is negligible and in this respect it performs more like a ceramic than a metal.
4. **Thermal Properties:** The melting point of beryllium is 2345 °F (1283 °C), and it is useful in some applications up to 1500 °F, far in excess of that of aluminum or magnesium and but close to stainless steel. Beryllium has a thermal conductivity of around 0.4 cal/cm^2/sec/°C/cm; of the commonly used aerospace materials only aluminum has a higher value.
5. **Nuclear Properties:** The thermal neutron absorption cross-section of beryllium is very low. 0.01 Barns per atom. On the other hand, the thermal neutron scattering cross-section has the relatively high value of 7 Barns per atom. Beryllium undergoes a (n,2n) nuclear reaction which generates neutrons and compensates for neutrons absorbed. Because of these properties, beryllium is an ideal nuclear reflector and is also useful as a moderator in nuclear reactors.
6. **Brittleness:** Cast beryllium is brittle and has essentially no elongation in tension. It could not be used for structural purposes unless all the stresses acting on it were well within the elastic limit or else were compressive. The relatively coarse grain size makes for difficulty in machining due to chipping or cracking. Extruded beryllium can have ductilities ranging from 2 to 50% elongation in specific directions depending on its fabrication history. It is clear that fabricated beryllium is to be preferred to cast metal from all standpoints except cost.

7. **Cost:** Beryllium is an expensive material. The price of beryllium depends largely on the quantities required and the complexity of the shape, and it is possible to provide only general indications of cost. Metallic beryllium powder sells for around $187 per kg. A hot-pressed block may be as much as three times this price after finish machining, and worked shapes even more expensive. These prices can be compared with those of steel, which costs about 12 cents per kg and aluminum at about 60 cents per kg.
8. **Toxicity:** Beryllium and its compounds are toxic materials. It can be dangerous in the form of finely divided particles and as powder or vapor, but is not dangerous as a solid material.

Applications of beryllium include the following:

1. **Nuclear:** Beryllium has long been recognized as a suitable material for use as a moderator and also as a reflector in nuclear reactors.
2. **X-Ray:** For many years almost the only application found for beryllium was in X-Ray windows. More recently, because of its superior transparency to electromagnetic radiation of low wave-lengths, including X-Rays, beta and gamma rays, and electron beams, beryllium is finding application in all forms of radiation devices used in medical, industrial, and scientific equipment.
3. **Optical:** Optics is another major application field for beryllium. Manufacturers find it attractive because of its mechanical, physical and thermal properties. Lightweight beryllium mirrors can offer weight savings from 6 to 40 times that of glass mirrors of equivalent optical performance.
4. **Thermal:** Beryllium's high specific heat and thermal conductivity make it applicable for use as a heat sink or a radiation shield. Heat shields have been used on both the "Mercury" and "Gemini" space capsules.
5. **Structural:** Applications of beryllium as a structural material in the space industry include the TACSAT 1 orbiting satellite, a project of the Hughes Aircraft Company. Beryllium was a natural choice to meet the stiffness requirements for the many cantilevered members of the TACSAT vehicle. The structural elements included the bearing and power transfer assembly, and the bicone antenna support. The structure was fabricated and tested and met all loading requirements with a weight savings of about 30%.

Beryllium's Unique Properties
Comparative Typical Properties of Beryllium to Other Metals

Beryllium's Advantages

- Lowest stiffness/ Weight Ratio of any Metal
- Very low Specific Heat at Cryogenic Temperatures
- High Thermal Conductivity
- Very Low Neutron Capture Cross Section
- Very High Sound Velocity
- Very High Modulus Elasticity
- Very High Specific Heat at Normal and Elevated Temperatures
- Very Low Specific Gravity
- Low Electrical Resistivity
- High Melting Point

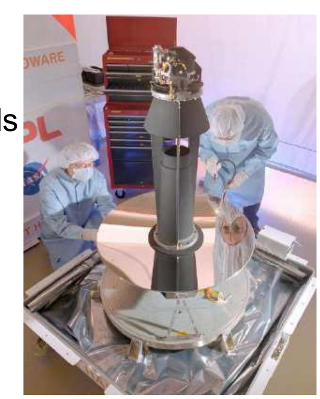
Properties	Beryllium		Magnesium Alloys	Aluminum Alloys	Titanium Alloys	Steels
Density (lb/in^3)	-	0.066	0.066	0.101	0.164	0.286
Melting Point(°F)	-	2350	1100 to 1200	900 to 1200	2700 to 3000	2500 to 2800
Specific Heat (Btu/lb ft/ft^{2}hr-°F	RT 500°F 1000°F	0.42 0.56 0.65	0.25 0.26 0.26	0.22 0.25 0.30	0.13 0.14 0.17	0.14 0.15 0.15
Thermal Conductivity ((Btu ft/ft^{2}hr-°F	RT 500°F 1000°F	105 80 56	80 - 40	100 - 50	4.5 5.5 7.5	9 11 13
Linear Coefficient Of Thermal Expansion (in./in./°F x 10^{-6}	RT 500°F 1000°F	6.5 7.5 8.5	15 16 17	12.5 14.0	5 5.5 5.75	6.0 to 9.5
Electrical Resistivity (microhm/cm)		4.1	10	5.7	150	70
Modulus of Elasticity (psi x 10^6	RT 500°F 1000°F	44 39 26	6.0 5.0	10.3 7.0	16 14 9	30 26 23
Typical Ultimate Tensile Strength (Wrought Forms) (psi x 10^3	RT 500°F 1000°F	80[(1)] 62 34	34[(2)] 15	76[(3)] 24	170[(4)] 125 40	200[(5)] 175 135

[1]SR-200 cross-rolled sheet
[2]HM-21-8A
[3]7075-T6 sheet

Health and Safety

Handling Beryllium in solid form posses no special health risks. Like many industrial materials. Beryl-ilum containing materials May pose a health risk if rec-ommended safe handling practices are not followed. Inhalation of airborne beryllium may cause a serious lung disorder in susceptible individuals. The Occupational Safety and Health Administration (OSHA) has set mandatory limits on occupational respiratory exposures. Read and follow the guidance in the Material Safety Data Sheet (MSDS) Before working with this material. For Additional information on safe handling practices or technical data on beryllium, contact Brush Wellman Inc – Electrofusion Products.

Beryllium in Optics



- One of the lightest and stiffest metals
  - CTE is higher than that of vitreous mirror materials
  - High specific stiffness and thermal diffusivity
  - Be it an outstanding choice for mirrors when very low areal densities are desired, as for space applications or for chopping mirrors on ground telescopes
  - Beryllium is extremely expensive

- Beryllium mirrors cannot be cast
  - Metal loses its strength during the melting process
    - Uneven, dual (large and small) grain structure develops during solidification.
  - To achieve highest strength Be must have a fine-grained structure
  - Most Be is produced by the powder metallurgy process
  - Powder technology is needed to compensate for the anisotropic thermal coefficient of expansion of the hexagonal crystalline structure of Be
  - Isotropic properties are achieved by randomly orienting the particle grains
  - Bond particles solidly together by applying pressure and heat
  - Accomplished by putting Be powder in a mold, then heating it to about 900 $^{\circ}$C while compressing it by vacuum or pressure (1000 atmospheres)
  - Known as vacuum hot pressing (VHP) and hot isostatically pressing (HIP)
  - With current tank size limitations, the largest piece of beryllium that can be produced is approximately 2 m in diameter, with a maximal length of 2.5 m

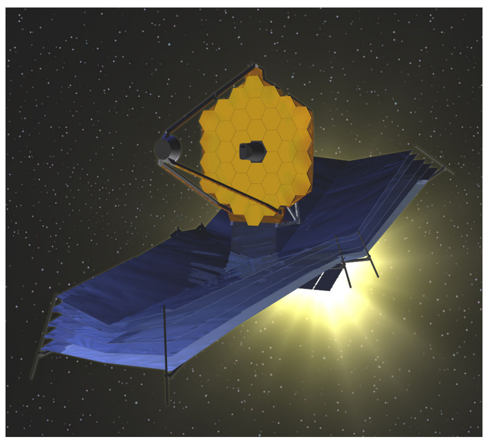
Fast aspheric surfaces up to 1.2 meters in diameter have been ground and polished by Tinsley to 0.02 waves (HeNe) RMS with surface roughness as low as 15 A RMS (filtered to below 30 micron features)

- Beryllium can be light weighted by machining with conventional mills and lathes
  - Precautions must be taken to prevent very small beryllium particles, less than 10 μm in size, from becoming airborne and therefore potentially respirable
  - Inhalation of beryllium dust can result in beryllosis, which is potentially fatal
    - There is no such danger during polishing because it is a wet process.

- Through variation in particle size, distribution, BeO content, and temperature, it is possible to produce a variety of Be grades with different properties.

- For IR applications, the best choice is the Brush-Wellman O-30 grade, which takes a good polish with a residual microrough-ness of around 25 Å
- Such mirrors can be used bare (without optical coating)
- The O-30 grade also has the advantage of posessing very homogeneous thermal and mechanical characteristics thanks to the use of specially calibrated spherical powder grains
- For improved polish quality, such as that needed for UV or visible applications, Be can be plated with electroless nickel, a nickel-phosphorus alloy.
  - CTE of Ni and Be are well matched, these mirrors are usable over a wide temperature

James Webb Space Telescope (JWST)



Titanium

The density of Titanium is roughly 55% that of steel. Titanium alloys are extensively utilized for significantly loaded aerospace components. Titanium is used in applications requiring somewhat elevated temperatures. The good corrosion resistance experienced in many environments is based on titanium's ability to form a stable oxide protective layer. This makes titanium useful in surgical implants and some chemical plant equipment applications.

Unalloyed (commercially pure) titanium can be found in two crystallographic forms:

- Hexagonal close-packed (hcp) or alpha (α) phase is found at room temperature
- Body centered cubic (bcc) or beta (ß) phase is found above 883 °C (1621 °F)

The control of alpha (α) and beta (ß) phases through alloying additions and thermomechanical processing is the basis for the titanium alloys used by industry today. It is also the primary method for classifying titanium alloys. Titanium alloys are categorized as either alpha (α) alloys, beta (ß) alloys, or alpha+beta (α+ß) alloys. Some common titanium alloys are listed below according to these categories.

Alpha and near alpha alloys	Alpha + Beta alloys	Beta alloys
Ti-2.5Cu	Ti-6Al-4V	Ti-13V-11Cr-3Al
Ti-5Al-2.5Sn	Ti-6Al-6V-2Sn	Ti-8Mo-8V-2Fe-3Al
Ti-8Al-1V-1Mo	Ti-6Al-2Sn-2Zr-2Cr-2Mo	Ti-10V-2Fe-3Al
Ti-6242	Ti-3Al-2.5V	Ti-15-3
Ti-6Al-2Nb-1Ta-0.8 Mo	Ti-8Al-1Mo-1V	
Ti-5Al-5Sn-2Zr-2Mo		

Alpha alloys commonly have creep resistance superior to beta alloys. Alpha alloys are suitable for somewhat elevated temperature applications. They are also sometimes used for cryogenic applications. Alpha alloys have adequate strength, toughness, and weldability for various applications, but are not as readily forged as many beta alloys. Alpha alloys cannot be strengthened by heat treatment.

Beta alloys have good forging capability. Beta alloy sheet is cold formable when in the solution treated condition. Beta alloys are prone to a ductile to brittle transition temperature. Beta alloys can be strengthened by heat treatment. Typically beta alloys are solutioned followed by aging to form finely dispersed particles in a beta phase matrix.

Alpha + beta alloys have chemical compositions that result in a mixture of alpha and beta phases. The beta phase is normally in the range of 10 to 50% at room temperature. Alloys with beta contents less than 20% are weldable. The most commonly used titanium alloy is Ti-6Al-4V, an alpha + beta alloy. While Ti-6Al-4V is fairly difficult to form other alpha + beta alloys normally have better formability.

Alpha + beta alloys can be strengthened by heat treatment. When strengthening alpha + beta alloys the components are normally quickly cooled from a temperature high in the alpha-beta range or even above the beta transus. Solution treatment is then followed by aging to generate an proper mixture of alpha and transformed beta. Heat treatment is dependent on the cooling rate from the solution temperature and can be affected by the size of the component.

Commercial and semi commercial grades and alloys of titanium

	Tensile Strength (min)		0.2% yield strength (min)		Impurity limits, wt % max					Nominal composition, wt %				
Designation	**MPa**	**Ksi**	**MPa**	**Ksi**	**N**	**C**	**H**	**Fe**	**O**	**Al**	**Sn**	**Zr**	**Mo**	**Other**
Unalloyed grades														
ASTM Grade 1	240	35	170	25	0.03	0.10	0.015	0.20	0.18	…	…	…	…	…
ASTM Grade 2	340	50	280	40	0.03	0.10	0.015	0.30	0.25	…	…	…	…	…
ASTM Grade 3	450	65	380	55	0.05	0.10	0.015	0.30	0.35	…	…	…	…	…
ASTM Grade 4	350	80	480	70	0.05	0.10	0.015	0.50	0.40	…	…	…	…	…
ASTM Grade 7	340	50	280	40	0.03	0.10	0.015	0.30	0.25	…	…	…	…	0.2Pd
Alpha and near alpha alloys														
Ti Code 12	4480	70	380	55	0.03	0.10	0.015	0.30	0.25	…	…	…	0.3	0.8Ni
Ti-5Al-2.5Sn	790	115	760	110	0.05	0.08	0.02	0.50	0.20	5	205	…	…	…
Ti5Al-2.5Sn-ELI	690	100	320	90	0.07	0308	0.0125	0.25	0.12	5	2.5	…	…	…
Ti-8Al-1Mo-IV	900	130	830	120	0.05	0.08	0.015	0.30	0.12	8	…	…	1	IV
Ti-6Al-2Sn-4Zr-2Mo	900	130	830	120	0.05	0.05	0.0125	0.25	0.15	0.15	6	4	2	…
Ti-6Al-2Nb-ia-0.8Mo	790	115	690	100	0.02	0.03	0.0125	0.12	0.10	6	…	…	1	2Nb,1Ta
Ti-2.25Al-1ISn-5Zr-.1Mo	1000	145	900	130	0.04	0.04	0.008	0.12	0.17	2.25	11.0	5.0	1.0	0.2Si
Ti-5Al-5Sn-2Zr-2Mo(a)	900	130	830	120	0.03	0.05	0.0125	0.15	0.13	5	5	2	2	0.25Si
Alpha-beta alloys														
Ti-6Al-4V(b)	900	130	830	120	0.05	0.10	0.0125	0.30	0.20	6.0	…	…	…	4.0V
Ti-6Al-4V-ELI(b)	830	120	760	110	0.05	0.08	0.0125	0.25	0.13	6.0	…	…	…	4.0V
Ti-6Al-6V-2Sn(b)	1030	150	970	140	0.04	0.05	0.015	1.0	0.20	6.0	2.0	…	…	0.75Vu,6.0V
Ti-8Mn(b)	860	125	760	110	0.05	0.08	0.015	0.50	0.20	…	…	…	…	8.0Mn
Ti-7Al-4Mo(b)	1030	150	970	140	0.05	0.10	0.013	0.30	0.20	7.0	…	…	4.0	…
Ti-6Al-2Sn-4Zr-6Mo©	1170	170	1100	160	0.04	0.04	0.0125	0.15	0.15	6.0	2.0	4.0	6.0	…
Ti-5Al-2Sn-2Zr-4Mo-4Cr(a)(c)	1125	163	1055	153	0.04	0.05	0.0125	0.30	0.13	5.0	2.0	2.0	4.0	
Ti-6Al-2Sn-2Zr-2Mo-2Cr(a)(c)	1030	150	970	140	0.03	0.05	0.0125	0.25	0.14	5.7	2.0	2.0	2.0	2.0Cr,0.25Si
Ti-10V-2Fe-3Al(a)(c)	1170	170	1100	160	0.05	0.05	0.015	2.5	0.16	3.0	…	…	…	10.0V
Ti-3Al-2.5V(d)	620	90	520	75	0.015	0.05	0.015	0.30	0.12	3.0	…	…	…	2.5V
Beta Alloys														
Ti-13V-11Cr-3Al©	1170	170	1100	160	0.05	0.05	0.025	0.35	0.17	3.0	…	…	…	11.0Cr, 13.0V
Ti-8Mo-8V-2Fe-3Al(a)(c)	1170	170	1100	160	0.05	0.05	0.015	2.5	0.17	3.0	…	…	8.0	8.0V
Ti-3Al-8V-6Cr-4Mo-4Zr(a)(b)	900	130	830	120	0.03	0.05	0.020	0.25	0.12	3.0	…	4.0	4.0	6.0Cr.8.0V
Ti-11.5Mo-6Zr-4.5Sn(b)	690	100	620	90	0.05	0.10	0.020	0.35	0.18	…	4.5	6.0	11.5	…

(a) Semicomercial alloy, mechanical properties and composition limits subjects to negotiation with suppliers. (b) Mechanical properties given for annrealed condition may be solution treated and aged to increase strength (c) Mechanical properties given for solution treated and aged condition, alloy not normally applied in annealed condition. Properties may be sensitive to section size and processing (d) Primarily a tubing alloy; may be cold drawn to increase strength.

Titanium and titanium alloy product characteristics and typical applications

Alloy	Guaranteed minimum room-temperature tensile strength: Ultimate ksi	Yield, ksi	Processing Characteristic: Resistance to cracking during forging	Sheet forming Rating	Weld-ability Rating	Heat treatable To high strength?	Harden-ability, section depth in.	Typical Applications
Unalloyed	50 65 80	40 55 70	Excellent	Excellent	Excellent	No	Not Harden-able	Hydraulic control valve, gyro-wheel structure, fittings, attach brackets, welded-duct halves, complex tube shapes, heat pump channel, skin-stringer structures
Ti-5Al-2.58n	120	115	Fair to good	Fair	Excellent	No	Not harden-able	Transmission and gear housing, jet-engine-compressor case assembly and stator housing, droop leading edge in boundary-layer control system and duct structure
Ti-5Al-1Mo-IV	130 to 135	120 – 125	Fair	Fair	Good	No	Not harden-able	Jet-engine compressor blades, discs and housings, gryo-scope gimbal housing, inner skin and frame for jet-engine nozzle assembly, experimental sheet-stringer structures, bulkhead forgings
Ti-6Al-4V	130 Age Hardenable to 180	120 170	Good	Good	Fair to good	Yes	1	Jet-engine compressor blades, discs, etc, landing-gear wheels and structures, fasteners, brackets, fittings, pressurebottles, primary and secondary sheet stringer structures, frames, fire-walls, stiffeners, gussets, and ducts
Ti-6A1-6V-2Sn			Good	…	Poor	Yes	2	Fasteners and air intake control track, experimental structural forgings
Ti-13V-1lCr-3Al	125 to 130 Age Hardenable to 175	120 -125 165	Fair	Excellent to Fair	Fair to poor(a)	Yes	7	Structural forgings, primary and secondary sheet-stringer structures, skins, frames, brackets, fittings, fasteners, tension-torsion rotor straps and specialty uses
Ti-2.25Al-11Sn 5Zr-1Mo).2Si	125 to 130 Age Hardenable to 175	120 -125 165	Fair to good	…	…	Yes	2	Jet-engine compressor blades. Discs, wheels, and spacers, airframe, fasteners
Ti-4Al-3Mo-IV	130	120	Good	Good	Fair to Good	No	Slightly hardenable	Jet engine compressor blades. Discs, wheels and spacers, compressor case assemblies, airframe skin components
Ti-4Al-3Mo-IV	125 Age Hardenable to 180	115 155	Good	Good	Fair to good	Yes	…	Airframe components

(a) Welds are generally not heat treated because of embrittling reactions. Source: Titanium Alloys Handbook, MCIC-HB-02, R.A. Wood and R.J. Favor, Metals and Ceramic Information Center, Columbus, OH 1972.

Ti-3Al-2.5V - Mechanical Properties

Typical Mechanical Properties			
Temp °C (°F)	**Tensile Strength MPa (ksi)**	**Yield Strength MPa (ksi)**	**% Elongation in 50mm**
Cold worked and stress-relieved			
R.T.	895 (130)	760 (110)	19
150 (300)	785 (114)	640 (93)	17
250 (480)	715 (104)	585 (85)	15
Annealed			
R.T.	655 (90)	560 (72)	29
150 (300)	565 (82)	455 (66)	25
250 (480)	490 (71)	380 (55)	23

Table A

Creep and Stress-Rupture Data for Titanium Alloys (5)

Alloy	**Stress to 1.0% Creep in 1000 hrs. at 250°C (482°F)**		**Stress to Rupture in 1000 hrs. at 250°C (482°F)**	
	MPa	**ksi**	**MPa**	**ksi**
CP Grade 1	90	13	103	15
CP Grade 2	103	15	117	17
CP Grade 3	131	19	138	20
Ti-3Al-2.5V (Grade 9)	400	58	421	61
Ti-0.3Mo-0.8Ni (Grade 12)	221	32	297	43

Key to Tables B, C, and D	
A	Annealed
CW	Cold Worked, Unannealed
CWSR	Cold Worked, Stress-Relief Annealed
SCT	Subcooling and Tempering
STA	Solution Treated and Aged

Table B

Ultimate Tensile Strength Comparison of Aerospace Materials

Material	**Condition**	**psi**	**(MPa)**
AM 350 Steel	SCT 850	206,000	(1419)
Ti-6Al-4V	STA	160,000	(1102)
Ti-15V-3Cr-3Al-3Sn	Aged	135,000	(930)
Ti-6Al-4V	A	134,000	(923)
Ti-3Al-2.5V	CWSR	132,000	(909)
21-6-9 Steel	10% CW	130,000	(896)
21-6-9 Steel	A	111,000	(765)
304 SS	CW	100,000	(689)
Ti-3Al-2.5V	A	90,000	(655)
304 SS	A	85,000	(586)
CP Titanium Ti-70	A	80,000	(551)

Table C

Yield Strength Comparison of Aerospace Materials

Material	**Condition**	**psi**	**(MPa)**
AM 350 SS	SCT 850	173,000	(1192)
Ti-6Al-4V	STA	145,000	(999)
Ti-15V-3Cr-3Al-3Sn	Aged	125,000	(861)
Ti-6Al-4V	A	126,000	(868)
Ti-3Al-2.5V	CWSR	115,000	(792)
21-6-9 SS	10% CW	115,000	(792)
Ti-3Al-2.5V	A	72,000	(579)
CP Titanium Ti-70	A	70,000	(482)
304 SS	CW	70,000	(482)
21-6-9 SS	A	64,000	(441)

Table D

Elevated Temperature Tensile Properties Comparison

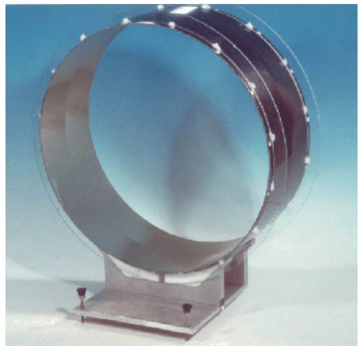
		Test Temp.		Ultimate		Yield		
Alloy	**Condition**	**°F**	**°C**	**psi**	**(MPa)**	**psi**	**(Mpa)**	**% Elong.**
CP Ti	A	R.T.	R.T.	75,000	(520)	48,700	(336)	36
		392	200	46,100	(318)	25,400	(175)	59
		662	350	33,200	(229)	16,600	(114)	58
		932	500	19,000	(131)	12,300	(85)	78
Ti-3Al-2.5V	A	R.T.	R.T.	94,500	(651)	86,500	(596)	30
		392	200	72,600	(500)	61,900	(426)	30
		662	350	63,600	(438)	52,200	(360)	29
		932	500	46,200	(318)	35,800	(247)	50
Ti-3Al-2.5V	CWSR	R.T.	R.T.	131,900	(909)	116,100	(800)	20
		392	200	108,600	(748)	92,600	(638)	17
		662	350	97,700	(673)	80,000	(336)	16
		932	500	65,400	(451)	48,700	(336)	51

Silicon Carbide

Silicon carbide (SiC), also known under the trade name Carborundum, is one of the hardest synthetic materials.

- Excellent thermal diffusivity
- High specific stiffness
  - One of the best materials for dynamic applications such as chopping secondary mirrors

- Bare SiC has good reflectance at EUV wavelengths, for which it is difficult to find suitable reflective coatings



SiC 60 cm X-ray mirror

- There are several methods of production
    - Some that produce pure SiC, and others that produce a matrix of SiC with other materials, usually elemental C or Si
    - Among the pure SiC forms chemical vapor deposition (CVD) is most often used for mirror blanks
        - Gaseous chemicals react on a heated surface (often graphite) to form solid crystalline materials. The process is relatively slow but results in 100% dense, high purity (99.9995%) beta silicon carbide. The beta SiC is cubic with the benefit of isotropic properties.
        - The graphite mandrel that is subsequently leached away.
        - The CVD SiC process allows near net shape mirrors to be directly produced with integral ribs and a thin face sheet for lightweight mirrors.
        - Lightweight mirrors as large as 1.5 m have been made with CVD SiC.
        - The extreme hardness and low porosity of CVD SiC allow for very smooth surfaces to be produced
        - Hardness makes material removal, figuring and polishing time consuming and difficult
        - Diamond is the only abrasive that can be used
        - Grinding & polishing with diamond grit leaves a surface roughness < 5 Å
        - Mirrors with complex shapes and ribbed backing structures can be produced by a two-step process in which the facesheet is deposited in the first CVD operation, then the backing ribs are deposited in a second furnace run

- Reaction-bonded SiC is ceramic casting process
    - Silicon carbide grains are mixed with water and binding agents to form a slurry
    - Cast into a sacrificial mold and then freeze dried to remove the water
    - Sintered to form a porous alpha SiC structure
    - A high temperature process burns off the mold material, fuses the grains together, and permits infiltration of the voids with molten Si to form a solid structure

        - 100% dense structure consisting of a bonded network of SiC (70-85%) with isolated regions of free Si (15-30%)
    - The reaction bonding process has shrinkage of less than 0.5%
    - Produces very good material properties
        - Specific stiffness is not as high as the CVD form
        - It is difficult to polish reaction-bonded SiC to a surface finish better than about 20 Å, so overcoats of pure silicon or CVD SiC are sometimes applied to provide a readily polishable surface
        - It is possible to cast reaction-bonded SiC into complex shapes, including honeycomb sandwich structures with continuous front and back sheets

- A SiC matrix can be produced by infiltrating molten Si into a shaped mass of chopped carbon fibers, which react to form SiC.
    - Known as C/SiC (pronounced seasic)
    - Before infiltration, complex shapes including honeycomb sandwich structures can be formed by machining and joining
    - The amount of C fiber remaining in the matrix can be tailored
        - Allows some control of the toughness of the material
        - The main drawback of infiltrated SiC is that it needs to be clad with a more polishable material if a fine polish is required

- SiC is extremely hard
    - Polishing time is much longer than with traditional materials
- CVD process tends to generate high internal stresses
    - Detrimental to deterministic figuring
- SiC is brittle
    - Lightweight SiC mirrors are extremely fragile
- Currently, the maximum size for SiC mirror blanks using these methods is about 1 m in diameter.

Silicon carbide has potential as a mirror substrate material. It has highly desirable mechanical and thermal properties and can achieve an excellent surface finish. Of the four different manufacturing processes for SiC, CVD SiC has the best overall performance and the reaction bonded SiC is a close second. The porosity of the sintered and hot pressed SiC make them less suitable for the mirrors.

Stiffness & Specific Stiffness

- For large telescopes mass is important and mirrors are usually designed to minimize mass
    - On the ground, gravity is the dominant factor
        - Deflection of the mirror must controlled
    - In space, a minimum natural frequency is usually the criterion in order to withstand acoustic loading during launch and satisfy operational constraints in orbit

- Inherent stiffness of the substrate material has a significant effect on the suitability of the finished and installed mirror
  - A more rigid material with low density tends to resist deformations due to polishing, mounting, gravity, and vibration during operation

- Whatever the shape and internal structure of the blank and the characteristics of its supporting system, a general rule applies:
  - Deflection under self-load and fundamental frequency are a function of the ratio of stress to strain (Young modulus), E, to the density of the material, ρ. This ratio, which is a characteristic of a given material, is called ***specific stiffness***:

$$\text{specific stiffness} = \frac{E}{\rho}$$

    The higher this ratio, the less the deflection and the higher the fundamental frequency

  - A large number is desirable
  - Denser materials tend to be more rigid, so that, for most structural materials, this ratio does not vary greatly
    - There are significant differences, especially in the case of composite materials
    - Be and SiC lead the list
    - Cer-Vit and Zerodur have the highest values for the nonmetals

	Density	Young's modulus	Specific stiffness
	ρ (g/cm^3)	E (GPa)	(Gpa cm^3/g)
Borosilicate	2.2	63	29
ULE	2.2	68	31
Zerodur	2.5	91	36
SiC (CVD)	3.2	466	186
Be	1.85	300	162
Al	2.7	70	26

Stiffness values of various materials.