Use of Beryllium for the VLT secondary mirror

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This synopsis presents a summary of the article "Use of beryllium for the VLT secondary mirror", published in SPIE Vol.2857 in November 1996. This paper discusses the advantages of using beryllium for active and adaptive optics mirrors of large ground-based system, like the Very Large Telescope (VLT). It also describes the various steps of the mirror manufacturing process. This article is about the VLT secondary mirror, but is can be related to any projects requiring a low weight, low inertia and high stiffness mirror, such as space or military application projects.

Introduction

The European Southern Observatory Very Large Telescope is located at the Cerro Paranal Observatory in Chile, at 2635m altitude. Therefore, it structures and optical components must operate in a specific environment. The secondary mirror (M2) is part of the active optics system of VLT. Its motion helps correcting the wavefront from distortion due to the environment. Thus, the secondary mirror has to meet the following specifications.

VLT secondary mirror requirements

The M2 assembly is made of the secondary mirror, and the electromechanical unit (EMU). Table 1 summarizes how the EMU controls the mirror position:

Table 1 : Description of M2 motion

Positioning	Degree of freedom	Range	Frequency	accuracy
focus	Translation along z-axis			1 µm
centering	Rotation around the center of curvature	± 6 arcmin		1 arcsec
Tilt (field stabilization)	Rotation about X and Y axis	12 arcsec max	0 – 10 Hz	
chopping	Rotation about X and Y axis	2 arcmin max	Max 5 Hz	0.15 arcsec

The following tables give the mirror mechanical and optical requirements:

Table 2 : mechanical requirements

Mechanical diameter	1120 mm
Mirror assembly (M2 + mounts + cell) weight	≈ 50 kg
Mirror weight	≈ 42 kg
Mirror assembly inertia	<4.0 $N.m^2$
Mirror assembly first eigen-frequency	>380 Hz
Mirror first eigenfrequency on three points	>600 Hz

Table 3 : optical requirements

Radius of curvature	-4553.57 mm at 5°C
Conic constant	-1.66926 (hyperbolic with 75 µm aspherization)
Useful external optical diameter	1116 mm
Useful internal optical diameter	50 mm
Useful wavelength range	Near UV to 25 µm
Temperature range in operating condition	0°C to 15°C
Slope errors (passive mode)	0.7 arcsec rms on mechanical surface
Central Intensity Ratio (CIR) (active mode)	>98%
Micro-roughness	< 2nm

In passive mode, all surface errors are considered, except curvature and conic constant errors. In active mode, the criterion is based on the minimum value of the peak signal, measured in the long exposure Point Spread Function. Curvature, conic constant, and the sixteen first natural modes of the primary mirror errors are removed. However, it is difficult to evaluate errors due to the instability of the Beryllium substrate.

Discussion of Beryllium properties

The main advantages of beryllium are its high specific stiffness, high Young's modulus, and low density. Therefore, a mirror made of beryllium can stand high acceleration in case of an earthquake; it has better dynamical performances, and is lighter than mirrors made of usual glass. However, beryllium Coefficient of Thermal Expansion (CTE) is quite high, compared to other materials. The following table compares mechanical and thermal properties of beryllium with other materials used for mirrors substrate:

Table 4 : comparison of mechanical and thermal properties of various optical materials

	preferred	Beryllium I220 H	SiC RB (30% Si)	Zerodur	SiC/Al	Al	BK7
Density ρ (g/cm³)	Low	1.85	2.89	2.53	2.91	2.70	2.51
Young Modulus E (GPa)	High	303.4	330	91	117	68	82
Specific stiffness E/ρ (GPa.cm³/g)	High	164	114	36	40	25	33
CTE α (10^{-6}/K)	Low	11.4	2.4	0.1	12.4	22.5	7.1
Thermal conductivity λ (W/mK)	High	220	155	1.6	123	167	1.114
Specific heat C_P (J/kg.K)	High	1820	670	810	800	900	858
Thermal diffusivity D (10^{-6}m²/s)	High	64.3	80	0.76	53	69	0.548
Coefficient of thermal distorsion α/λ (µm/W) (steady state)	Low	0.05	0.02	0.06	0.10	0.13	6.37
Coefficient of thermal distortion α/D (s/m²/K)	Low	0.18	0.03	0.13	0.23	0.33	12.96

For large ground based, active optics telescope application, mirrors should be very stiff, have a high Young's modulus, and be light-weighted. Glasses have a lower Young's modulus than Beryllium and Silicon Carbide. Beryllium has the highest specific stiffness, and the lowest density.

However, Beryllium has a crystallic structure, meaning that its CTE is not homogeneous. In practice, thermal expansion of Beryllium is not the same over the entire mirror, and this induces internal microscopic stress. The maximum theoretical thermal stress is 6.7 MPa at the Beryllium grains boundary, for the 15°C operating range of the VLT. On average, the induced stress is 2 MPa.

In addition, specific fabrication techniques of Beryllium substrate must be carefully applied in order to minimize microyield stress, and residual stress. It comes from various steps of the manufacturing process, such as consolidation, machining, heating, grinding, plating, and polishing. Furthermore, the mirror is clamped to the mechanical mount, which induces additional stress. The mechanical mount must be designed in such a way that this stress is applied on a small area, far from the useful optical surface. Stress provokes deformation of the metal, and must be avoid.

VLT secondary mirror manufacturing

The substrate is made of I220 H Beryllium powder. This substrate has the best homogeneity, microyield and microcreep strength. Its cost is lower, and its behavior during processing is more predictable than other type of Beryllium powder substrate. The powder is consolidated with Hot Isostatic Pressing (HIP) technique.

This process produces an isotropic substrate, with higher mechanical properties than other techniques. HIP also allows production of near net shape structures.

Table 5 : I220 H Beryllium grade specifications

Density	99.7 % of theoretical density
Ultimate tensile strength	455 MPa
Yield strength (0.2% offset)	350 MPa
Elongation	2%
Microyield strength	42 MPa
Maximum grain size	15 µm

The machining process has been qualified on a test mirror made of Beryllium, in parallel of the M2 blank.

After machining, M2 weights 39.4 kg. Heat treatment is applied to remove residual stress. Internal surface stress, and subsurface damage are released by acid etching.

Grinding process is a combination of acid etching and thermal cycling, from -40°C to 100°C. After grinding, the Beryllium blank departure from the theoretical asphere is ± 10 µm.

Then the mirror is Nickel coated. The Nickel layer allows the achievement of 2 nm micro-roughness requirement. However, it has to be carefully plated in order to avoid instability of the Nickel layer, and CTE mismatch with Beryllium. These defaults would result in residual stress and mirror distortion, adding mainly focus and astigmatism errors. Thus, Nickel coating and Beryllium substrate should have homogeneous thermal and mechanical properties. The coating layer is a nickel and phosphorous alloy. The coating CTE is between $11.5\ 10^{-6}$/K and $12.0\ 10^{-6}$/K, with variation of $0.5\ 10^{-6}$/K for the operating temperature range of the VLT. The alloy CTE is comparable to the Beryllium CTE value: $11.4\ 10^{-6}$/K.

At this point, the mirror is attached to the mechanical mount. Indeed, polishing the mirror after integration in the mount will remove stress generated by the fixation devices. Thermal cycling is performed in order to reduce the stress at fixation points.

Then, polishing process associated with thermal cycles, gradually decrease residual stress.

Eventually, the mirror’s edge is cut, because the edge figure is higher than the rest of the mirror, due to polishing technique. This step is critical, because the mirror must not be damaged by this process. The wire Electro-Discharge Machining (EDM) allows material removal with good accuracy, and very low amount of stress. This edge cutting process is defined after many tests on sample. These tests were performed in order to optimize the machining conditions (power, speed, wire diameter of the EDM), the optical surface protection, and the Ni/Be interface at the cut area after edge cutting.

Control tests are performed throughout the entire manufacturing process. In the end, M2 is tested with a 250 mm diameter, Nickel plated mirror.

Conclusion

This report explains the advantages of using Beryllium for VLT M2, based on its mechanical and thermal properties. The remarkable particularity of Beryllium is its high specific stiffness. A mirror made of Beryllium is then light-weighted, but stiff, and has a high resonant frequency. Hence, Beryllium is used for space application (i.e. for the James Webb Space Telescope), and for systems requiring good dynamic, like adaptive optics mirrors. However, its thermal properties are not optimum, and Zerodur is preferred for large telescope primary mirror segments.
A description of the mirror manufacturing process is also given in detail. This information is useful for any optomechanical engineer, working on mirrors for astronomy and space application.

References:

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