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Use of Beryllium for the VLT Secondary Mirror

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Abstract

REOSC has been selected for the design, manufacturing and integration of the four ESO Very Large Telescope (VLT) secondary mirrors (M2). The VLT secondary mirrors are 1.12 m lightweight convex hyperbolic mirrors made of Beryllium. Despite the VLT active optics correction capabilities, the use of a metal for the mirror structure implies specific manufacturing processes and associated design rules in order to ensure its dimensional stability during the telescope required life time.
This paper describes how the fabrication process of the VLT secondary mirror has been optimised in order to maximise the dimensional stability of its structure. The Beryllium properties are analysed in parallel with the mirror requirements, the choices for the manufacturing, at all levels, are presented. A short work progress is presented, with the achieved mirror properties.

Keywords : VLT, Beryllium, Nickel coating, lightweight mirror, material stability

1 Introduction

In 1994, REOSC was selected for the design and fabrication of the first VLT secondary mirror, with DORNIER as main contractor. DORNIER is in charge of the design and manufacturing of the four VLT M2 electromechanical units which support the mirror and actively control its position.
The VLT M2 is a 1.12 m diameter lightweight convex mirror, to be operated at in visible and infrared wavelengths. A chopping mode of the mirror is implemented for infrared observations, thus requiring low weight, low inertia, and high stiffness in order to meet the required dynamical performances of the mirror assembly. ESO has chosen Beryllium in order to meet those requirements.
The mirror and mounts are designed by REOSC, the mirror blank is provided by Brush Wellman (ELMORE, Ohio, USA), polished and integrated at REOSC.
This paper summarises the VLT M2 requirements, describes the design rules and manufacturing processes used to optimise the mirror performances. The current progress is presented as well.

2 VLT secondary mirror requirements

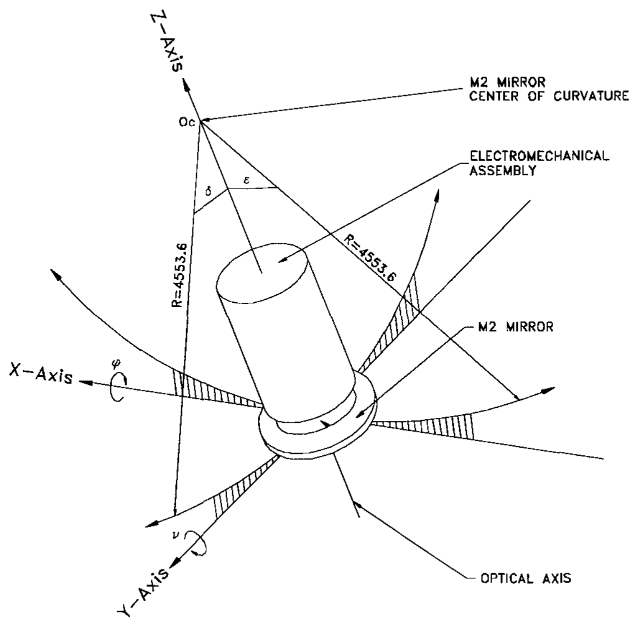
2.1 VLT secondary mirror description, mechanical requirements

The VLT M2 UNIT is an optomechanical system constituted by the M2 mirror and the Electromechanical Unit (EMU). The M2 mirror is a 1120 mm diameter convex hyperbolic lightweight mirror, supported on three attachment points by the VLT M2 electromechanical unit. The VLT M2 EMU controls the position of the mirror along five independent degrees of freedom for the following purposes (Fig 1):

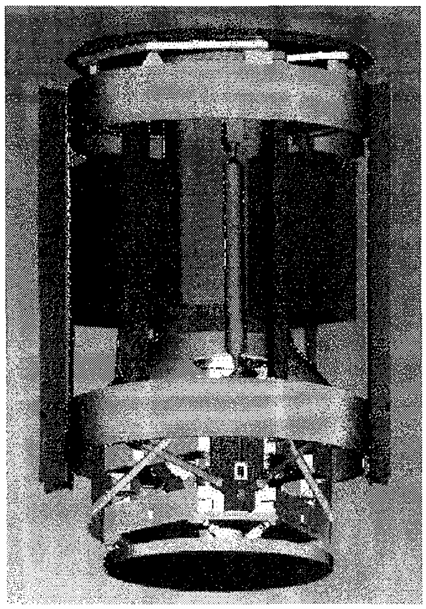
- Focusing : the position of the mirror can be adjusted in continuous mode or by discrete steps along the telescope axis with an accuracy of 1 µm.

- Centering : the mirror position can be adjusted in continuous mode or by discrete steps around its center of curvature, with a +/- 6 arcmin range and an accuracy of 1 arcsec.

- Tilt/chopping : the mirror position can be controlled around any axis perpendicular to the optical axis. The mirror tilt is used for field stabilisation and chopping modes. In field stabilisation mode, tracking errors of the telescope as well as image motion are corrected. The frequency range for field stabilisation is 0-10 Hz, with a maximum amplitude of 12 arcsec. In chopping mode, used for infrared observation, the mirror describes an angular motion ideally approaching a rectangular wave with a frequency up to 5 Hz, a maximum amplitude of 2 arcmin and an accuracy of 0.15 arcsec. The tilt axis follows the field rotation caused by the telescope altitude-azimuth mount.



Mirror position active control



CAD view of the M2 Unit

Figure 1 - M2 UNIT - (Courtesy ESO & DORNIER)

The achievement of the above performance requires a mirror low weight and low inertia, combined with a high stiffness.

The following table summarises the mirror mechanical requirements.

Mirror 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 Eigenfrequency	> 380 Hz
Mirror 1rst Eigenfrequency on three points	> 600 Hz

Table 1 - VLT secondary mirror mechanical requirements.

2.2 Optical requirements

2.2.1 Optical parameters

- Radius of curvature : - 4553.57 mm at 5°C (convex)
- Conic constant : -1.66926 (hyperbolic, with 75 μm aspherization)
- useful external optical diameter : 1116 mm
- useful internal optical diameter : 50 mm

The difference between the mechanical and optical diameters is 2 mm only along the mirror radius. The mirror defines the pupil of the telescope. Using classical polishing techniques, turned edge effects can hardly be avoided. The chosen solution is to add an overhang on the mirror contour and remove it by cutting after final polishing.
The edge cutting requires some care in order not tot produce high spatial frequency errors on the mirror surface, in order not to introduce stress in the mirror and in order not to separate the Nickel coating from the Beryllium. Edge cutting is discussed in paragraph 5.5.3.

2.2.2 Optical quality

The useful wavelength range of the Very Large Telescope extends from the near UV to 25 μm in the infrared. The optical quality is specified taking into account the M1 correction capability. Low spatial frequency terms can be subtracted from the overall wavefront error . In the telescope these low spatial frequency terms are dealt with an appropriate offset of the primary mirror support forces.

2.2.2.1 Passive mode.

All surface errors are included except curvature and conic constant errors. The optical quality of the M2 is measured without the active optics operation. The slope errors are limited to 0.7 arcsec RMS on the mechanical surface (approximately 0.2 arcsec RMS on the sky).

2.2.2.2 Active mode.

The optical quality in active mode specifies the minimum value of the peak signal in the long-exposure Point Spread Function after removal of the curvature and conic constant errors, and after removal of the sixteen first natural modes of the primary mirror.
The variation of the peak signal intensity of the telescope is defined using the « Central Intensity Ratio (CIR) ». The peak signal intensity variation due to the high spatial frequency errors of the M2 shall be less than 2% i.e. the CIR must be larger than 0.98.
The CIR is deduced from the interferograms and from finite element analysis by numerical calculations, the sampling rate for the interferogram acquisition is 250 points over a diameter.
The following example (Fig 2) shows the variation of the M2 CIR with the amplitude of three « bumps » on the M2 mechanical surface, located in front of mount attachments, with a spatial period of about a third of the mirror radius.

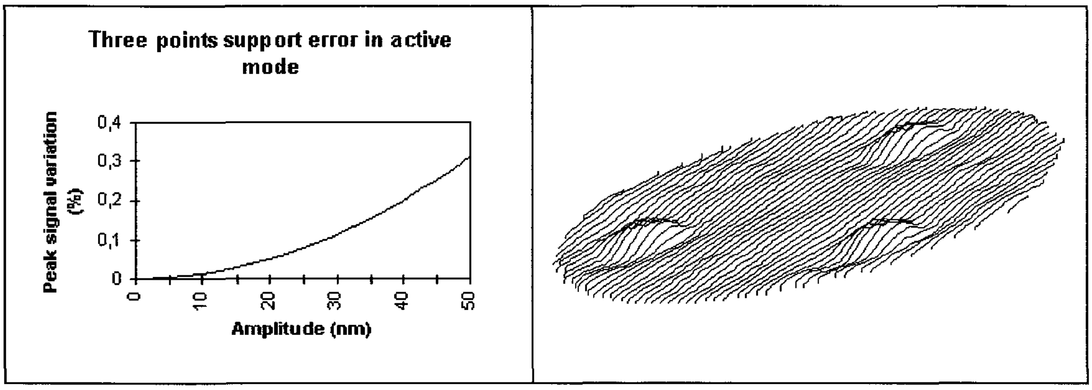


Fig 2 - Example of three mounts impact on CIR in active mode

The main concern for the mirror performance is to correctly evaluate the spatial frequency and the amplitude of the possible mirror figure changes induced by its potential material instability. Up to now, there is no way to accurately map the homogeneity of a Beryllium block after consolidation.

2.2.3 Micro-roughness

A structural Beryllium grade was used rather than an optical grade in order to increase the mirror mechanical performances. High accelerations are expected in case of earthquake, therefore a strong material is necessary. The mirror is Nickel plated to achieve the 2 nm micro-roughness requirement of the M2. The electroless Nickel used for plating is harder than bare Beryllium and more easily polished to a fine surface finish.
In operational conditions, the temperature range at the M2 level is 0°C to 15°C. This temperature variation may cause mirror figure changes by bimetallic effect between the Nickel layer and the Beryllium structure. The induced distortions are mainly low order aberrations such as focus and astigmatism. Nevertheless they induce internal stress in the mirror structure and in the Ni layer, a possible cause for dimensional instability. The Ni plating process is carefully defined to minimise these effects.

3 Beryllium properties

3.1 Mechanical and thermal properties

Beryllium has a high stiffness to weight ratio (164 GPa.cm^3/g), the highest found among the materials being used for optics manufacturing.
Beryllium has a Young modulous of 303 Gpa. A high Young Modulous is desired for increased mirror dynamical performances. Silicon carbide has a higher Young modulous than Beryllium, 420 Gpa for pure SiC, and 330 Gpa for Reaction Bonded SiC with 30% Si. Glasses have a relatively low Young modulous compared to Silicon Carbide and Beryllium.
Beryllium has a density of 1.85 g/cm^3. Glasses and ceramics used for mirrors manufacturing all have a density larger than 2.2 g/cm^3. Beryllium provides good flexibility for the design of a mirror with minimised weight and inertia.

3.2 Thermal properties

Beryllium has an anisostropic single crystal coefficient of thermal expansion (CTE). Section 3.3.1 deals with the stress induced in the material with temperature change and the associated dimension changes. The average coefficient of thermal expansion of Beryllium is 11.4 10^{-6}/K.
Beryllium has a high thermal conductivity of 220 W/mK and a high specific heat of 1820 J/kgK. The coefficient of thermal expansion to thermal conductivity ratio (α/K), defined as the coefficient of thermal distortion in permanent state, is 0.05 μm/W. The coefficient of thermal expansion to thermal diffusivity (α/D), defined as the coefficient of thermal distortion in transient state, is 0.2 $s.m^{-2}.K^{-1}$.
Table 2 presents the mechanical and thermal properties of Beryllium and other materials used for mirror substrates.

	Preferred	Beryllium I220 H	SiC RB (30%Si)	ZERODUR	SiC/Al	Al
Density ρ (g/cm^3)	Low	1.85	2.89	2.53	2.91	2.70
Young Modulous E (GPa)	High	303.4	330	91	117	68
Spécific modulous E/ρ (Gpa.cm^3/g)	High	164	114	36	40	25
Coefficient of thermal expansion α (10^{-6}/K)	Low	11.4	2.4	0.1	12.4	22.5
Thermal conductivity k (W/m K)	High	220	155	1.6	123	167
Specific heat Cp (J/kg K)	High	1820	670	810	800	900
Thermal diffusivity D (10^{-6} m^2/s)	High	64.3	80	0.76	53	69
Coeff. of thermal distortion α/k (μm/W) (steady state)	Low	0.05	0.02	(0.06)*	0.10	0.13
Coeff. of thermal distortion α/D (s/m^2/K) (transient state)	Low	**0.18**	**0.03**	**(0.13)***	**0.23**	**0.33**

*** ZERODUR has a near zero coefficient of thermal expansion that makes it not comparable using the coefficients of thermal distortion.**

Table 2 - Beryllium mechanical and thermal properties

3.3 Potential sources of Beryllium instability[1]

The dimensional instability of a Beryllium substrate is linked to :

- the homogeneity of the CTE and of the mechanical properties in the material,
- the plastic behaviour of Beryllium, characterised by its microyield strength and microcreep strength,
- the amount of internal stress in the substrate.

3.3.1 Inhomogeneity of the Be coefficient of thermal expansion and mechanical properties

Beryllium has an anisotropic hexagonal single crystal structure, with a 37 % CTE difference between crystal axis and basal plane. A powder consolidation process is used rather than a crystal growth process to randomise the CTE distribution in Be blanks and guarantee the good homogeneity of the mechanical properties.
The powder characteristics and the consolidation method influence the homogeneity. Even if the CTE distribution is randomised, the CTE anisotropy of the grains generates internal stress at their boundary. For the 15°C operational temperature range of the VLT, the theoretical maximum amount of induced stress at the grains boundary is 6.7 Mpa[1]. This theoretical average amounts to 2 Mpa due to grain distribution[1].

3.3.2 Plastic behaviour. Microyield strength

Like all metals, Be is subject to plastic deformation under stress. The Be microyield strength is linked to the substrate fabrication history. It depends on the powder grain size and geometrical properties, on the chemical composition and on the consolidation process.
The process of microyielding occurs, at least in the early stages, by movement of dislocations. Anything that pins or prevents dislocation movement increases microyield strength. The amount of dislocations in grains depends on the powder fabrication method. The dislocations are more readily pinned with a small grain size.
A prestrain will increase the microyield strength[1], but strain can also induce residual stress and increase the sensitivity to microcreep. Microyielding or microcreeping will occur when external load is applied, the applied stress and the residual stress being additive.
Annealing decreases microyield strength and decreases residual stress.

3.3.3 Micro-creeping.

The microcreep strength, as for the microyield strength, is linked to the chemical composition, powder characteristics, and consolidation process. As seen in section 3.3.2 it also depends whether the material has been prestrained or not. Microcreep amplitude is proportional to the size of the stressed area, is time dependent and behaves according to an Arrhénius law. Micro-creeping deformations occur at the early stage of the load application.
It is especially taken into account for the design of the mount interfaces : mounts are attached to the mirror by clamping, the design of mount attachments is made in order to concentrate the induced stresses in a small area, far from the optical surface. The mounts are integrated before polishing.

3.3.4 Internal stress

The internal stress is composed of balanced compressive and tensile stresses in the material.
The internal stresses are described as microscopic stress and macroscopic stress (residual stress).
Microscopic stress is mainly located at the grain boundary, it results from the CTE anisotropy of the Be crystal.
The residual stress results from material processing : consolidation, machining, heat treatment, grinding, plating, polishing. It is minimised by annealing, thermal cycling or acid etching. These operations are performed at all manufacturing steps. They all result in a dimensional change which needs to be minimised.

4 VLT secondary mirror manufacturing

4.1 Substrate manufacturing

4.1.1 Beryllium grade

The substrate is produced by Brush Wellman (Elmore, Ohio, USA). The Beryllium powder can be produced by impact grinding, ball milling or attrition. Impact ground powder is more equiaxed than ball milled or attrited powder, it has less tendency towards crystallographic orientation during consolidation.
Among the several impact ground powder grades available, I220 H and I250 H have improved microyield strength, microcreep strength, and homogeneity. I220 H was chosen : its cost is lower than I250H, it has a higher powder packing density that makes it more predictable in Hot Isostatic Pressed blanks.

4.1.2 Consolidation process

The Be powder can be consolidated by Vacuum Hot Pressing (VHP), Cold Isostatic Pressing (CIP), or Hot Isostatic Pressing (HIP).
Vacuum Hot Pressing is a uniaxial process, which results in a tendency for the grains to take a given orientation during consolidation. Hence the grades produced by VHP are anisotropic and have less dimensional stability than HIP'ed ones.
Cold Isostatic Pressing is used to produce near net shape substrates. The mechanical properties of CIP'ed blocks are lower than HIP'ed ones. CIP is best suited for serial applications.
Hot Isostatic Pressing (Fig. 3) produces isotropic material, in combination with higher mechanical properties. Near net shape structures can also be produced by HIPing.
I 220 H Be grade is produced from impact ground powder by HIPing. The following table presents the minimum specifications of the substrate :

Density	99.7 % of theoretical density
Ultimate tensile strength, MPa	455
Yield strength (0.2 % offset), MPa	350
Elongation, %	2.0
Micro-yield strength, MPa	42
Maximum grain size, µm	15

Table 2 - I220H Beryllium grade specifications

4.2 Substrate machining

The blank is machined at LOCKHEED MARTIN Beryllium (Tallevast, Florida, USA) down to a 80 % lightweight ratio. The final weight of the VLT M2 after machining is 39.4 kg.
Internal surface stress and subsurface damage are released by acid etching after rough machining. The residual stress is released by an appropriate heat treatment. Another acid etching step is performed after final machining to remove surface stress. Figure 4 shows the mirror during machining and at finished state.

4.3 Mirror grinding

The bare Beryllium blank is ground by TINSLEY Lab. (Richmond, California,USA) down to +/- 10 microns with respect to the theoretical asphere.
Thermal cycles are performed before rough and intermediate grinding. Once the mirror is ground, acid etching is performed on the optical surface, followed by thermal cycling. Thereafter the mirror is fine ground, and a last thermal cycling ends the grinding process.

4.4 Mirror nickel plating

The mirror electroless Ni plating is performed by LOCKHEED MARTIN Beryllium. The Nickel coating needs to be properly done in order not to affect the mirror stability. The instability may be caused by :

- the instability of the Nickel layer,
- the CTE mismatch with Beryllium.

4.4.1 Stability of the Electroless Nickel plating

The stability of the electroless Nickel plating is linked to the homogeneity of the layer properties and to the amount of stress in the cladding.

The homogeneity of the coating is controlled using appropriate plating procedures. Coating internal stress is produced with temperature changes, a bimetallic effect occurs because of the CTE mismatch with the Beryllium substrate.
The temperature used for the post-plating heat treatment also plays a role. The heat treatment is performed in order to improve adhesion, to change the Ni from anamorphous to polycrystalline substrate (Ni_3P), which is more stable. The transformation produces a shrinkage of the coating with associated residual stress. The stress produced depends , in addition to the heat treatment temperature, on the coating thickness and phosphorous content.

4.4.2 CTE mismatch

The Nickel CTE mismatch with Beryllium induces differential thermal expansion between the mirror structure and the coating, affecting the mirror figure.
The resulting distortion produces low order aberrations (mainly focus and astigmatism). The high frequency errors caused by bi-metallic effect are linked to the homogeneity of the Ni layer, of the chemical contents and of the mechanical properties. The coating and the Be structure must have homogeneous mechanical and thermal properties.

The electroless nickel is an alloy composed primarily of nickel and phosphorous. The phosphorous content influences the CTE of the coating[2]. For the VLT secondary mirror, the phosphorous content is set to achieve a coating CTE value of 11.5 10^{-6} /K to 12.0 10^{-6} /K, against 11.4 10^{-6} /K for the Be substrate.

The CTE varies with the external temperature[2]. With a 0°C to 15°C temperature range for the VLT, CTE variation of the Nickel coating is about 0.5 10^{-6} /K (CTE increases with the temperature).
The CTE decreases as the temperature of the post-plating heat treatment is increased[2].

4.4.3 Ni plating process

A compromise is found for the phosphorous content, the plating thickness, the post-plating temperature, to achieve low residual stress level, and CTE of the coating close to the Beryllium one.
The plating process is monitored by controlling the bath temperature, pH, Phosphorous and Nickel content. The mirror orientation in the bath, the gaseous sparging, the mechanical agitation are optimised as well.
The amplitude of the mirror distortion is minimised by plating both optical and back mirror surfaces.
The stress in the Ni layer is measured during the plating process by test strip methods in order to achieve a 0 +/- 10 Mpa in the layer on the back surface, and 40 +/-7 Mpa on the front face. After removal from the mirror surface from polishing, the stress in the front face will be approximately the same as in the back.
The goal for the amplitude of the distortions due to the bi-metallic effect is 0.5 µm peak to valley (mainly focus) if a good CTE matching is obtained.

4.5 Mounts integration - Mirror polishing - Edge cutting

4.5.1 Mounts integration

The fixation devices of the mirror are attached before polishing because they are the main stress contributors at the mirror level.
The design of the attachment points at the mirror level is done in such a way that the stress induced is located in a small area, as far as possible from the optical surface.
The mounts integration is followed by thermal cycling in order to smooth and stabilise the stress at attachment points. The cycles are calculated in order to reach locally the Be microyield strength. A permanent strain occurs, the microyield strength increases locally, but the microcreep strength decreases. However microcreep has been considered for the mounts design. Microcreep induced by the mounts integration occurs at the early stages of polishing and is then not taken into account.

4.5.2 Polishing - Stress relief

The stress in the front face Ni layer is naturally reduced during polishing. However, additional thermal cycles are performed during figuring to gradually decrease the amount of residual stress :

- One after rough polishing, when the shape of the mirror is smooth enough to perform interferometric measurement.

The thermal and dimensional stability of the mirror will be quantified for the first time at this step. The results will be available in October, 1996.

- A second one is performed during an intermediate polishing as a proof test for the mirror stability and to check the convergence of the stress relief process.

- A third one is performed during final polishing.

Additional thermal cycling may be performed during polishing, depending on the convergence of the residual stress relief.

4.5.3 Edge cutting

Edge cutting process is done by wire electro-discharge machining (EDM). This process induces a very low amount of stress in the cut area, its impact is very local, it has a good accuracy.
The stress redistribution in the mirror after edge cutting depends on the amount of residual internal stresses, on the homogeneity of the material properties and on the volume of material removed. The induced deformations should be minimised, with low order aberrations.
The edge has been designed in order to minimise the volume of material to be removed, and to limit the surface of the cut area. The ring removed is 7 mm thick, has a 1120 mm internal diameter and a 1142 mm external diameter. Qualification tests are performed on samples in order to optimise :

- the machining parameters, such as power, speed, wire diameter, in order to limit impact of the EDM, and to avoid Ni layer seperation,
- the choice of a maskant for the mirror optical protection,
- the way to protect the cut area and the Ni/Be interface after cutting.

A final qualification step will be performed on a ϕ 250 mm Ni plated test mirror. The test mirror is made of the same material than the M2, and has undergone the same manufacturing process used for the mirrorr.

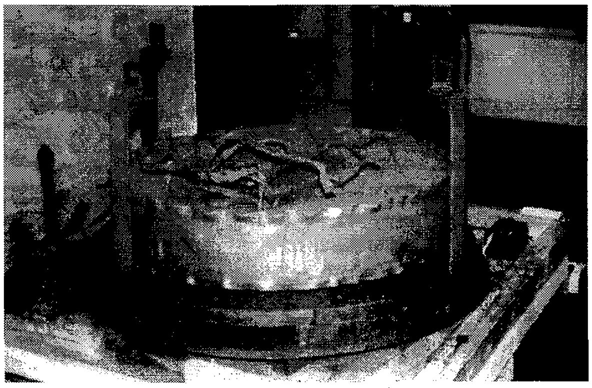
5 Current status

The blank has been HIP'ed, machined and ground and is now in Nickel plating. The mechanical and thermal properties of the blank have been measured, the first data about the blank dimensional stability have been obtained during grinding.

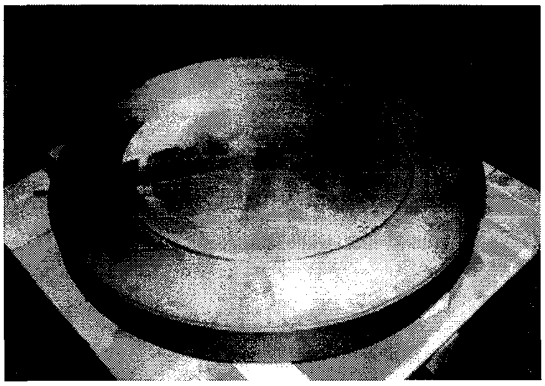
5.1 Substrate manufacturing

Figure 3 shows the Beryllium billet of the first VLT M2 mirror after consolidation by HIP'ing by Brush Wellman. The properties of the substrate matches well the specifications.
The measured microyield strength of the VLT secondary mirror substrate ranges from 82.7 Mpa to 124.8 Mpa., i.e. twice better than specified.
The final density is 1.8618 g/cm^3 , approximately 100 % of theoretical, against 99.7 % specified.
For the chemistry, all elements are well under the maxima specified.
The average grain size is 4.3 μm, well below the maximum of 15 μm specified. The small grain size is the primary reason for the high microyield strength.

The CTE measurement have confirmed the blank homogeneity : the average CTE between 0°C and 60°C ranges from 11.2 10^{-6} /K to 11.4 10^{-6} /K (measurement accuracy of +/- 0.1 10^{-6}/K), in all directions, at three different locations in the blank.



HIP can after pressing

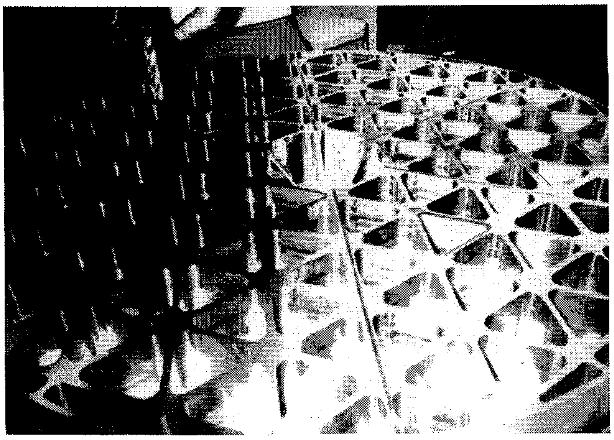


Be billet after HIP can residual removal

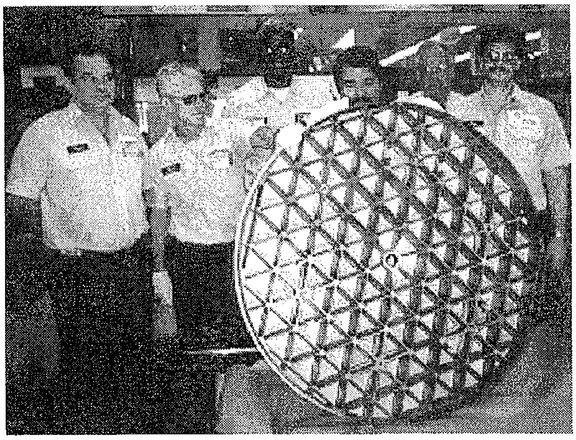
Figure 3 - Mirror blank Hot Isostatic Pressing

5.2 Machining

Figure 4 shows the VLT M2 blank during and after machining at LOCKHEED MARTIN Beryllium. That phase was carefully defined in order to minimise the stress induced in the blank during machining, and relieve the residual stress. The removal rates used were carefully defined. A heat treatment was performed after rough machining, during 4 hours at a 780°C temperature. The maximum distorsion evidenced after heat treatment was about 60 μm, a good first data about the blank stability. The blank was acid etched during and after machining to remove surface stress. The acid etching was used to carefully control the mirror weight as well.
Specific procedures have been established for the machining of the mount interfaces. The mounts design necessitates the machining of undercuts through the structue walls. Machining tools and parameters were qualified on a Beryllium test mirror made in parallel with the M2 blank.



Rough machining



After finish machining

Figure 4 - VLT M2 secondary mirror machining

5.3 Grinding

The grinding is performed by TINSLEY Labs. That phase is finishing as that paper is written. Acid etching and thermal cycles were performed from -40°C to 100°C in order to remove the residual stress induced during grinding. The first results about the blank stability were obtained at that step. Thermal cycles were performed from -40°C to 100°C. The power changed approximately 2 microns over the last 3 thermal cycles. It changed <.5 microns during the last cycle, almost in the measurement noise. The meaurements were performed using a profilometer, with an accuracy of about 1 micron peak to valley. Theses preliminary results are very promising, the blank looks very stable.
The radius of curvature is 1.2 mm from the nominal, the achieved profile is 5 microns peak to valley from the theoretical one. The VLT M2 blank is now being prepared for Nickel plating.

6 Conclusion

Beryllium was selected and used for the manufacturing of the VLT secondary mirrors. Progresses made in the understanding and control of the fabrication process result in a better confidence in the area of dimensional and thermal stability than previously observed with Beryllium optics.
Beryllium grades with improved homogeneity, microyield strength and microcreep strength have been developed. The impact of Beryllium processing - machining, grinding, polishing - on thermal stability is minimised using appropriate procedures. Nickel plating of Beryllium is optimised to achieve a very good CTE mismatch and a very low amount of residual stress. A structural Beryllium grade (I-220H) was selected for its better microcreep and microyield strengths compared to an optical grade (I-70H).
A lot of investigations have been done to establish a manufacturing process to overcome the intinsic instability of Beryllium substrate. A series of control steps have been included to constantly monitor the performance of the blank (measurements prior and after annealing, test mirror, test strips,...), in order to achieve the required results for each of the manufacturing steps, a good convergence during grinding and polishing, a low stress before edge cutting and an adequately low risk of instability during the lifetime of the mirror.
The blank production is currently ending with the Nickel plating. The polishing will start in September, 1996. Accurate results concerning the mirror stability will be available at the end of the year. They will be presented in a next paper.

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