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DIRECTLY POLISHED LIGHT WEIGHT ALUMINUM MIRROR

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ABSTRACT

During the last ten years, Astron has been a major contractor for the design and manufacturing of astronomical instruments for Space- and Earth based observatories, such as VISIR, MIDI, SPIFFI, X-Shooter and MIRI. Driven by the need to reduce the weight of optically ultra-stiff structures, two promising techniques have been developed in the last years: **ASTRON Extreme Lightweighting [1][2]** for mechanical structures and an improved **Polishing Technique for Aluminum Mirrors**. Using one single material for both optical components and mechanical structure simplifies the design of a cryogenic instrument significantly, it is very beneficial during instrument test and verification, and makes the instrument insensitive to temperature changes. Aluminum has been the main material used for cryogenic optical instruments, and optical aluminum mirrors are generally diamond turned. The application of a polishable hard top coating like nickel removes excess stray light caused by the groove pattern, but limits the degree of lightweighting of the mirrors due to the bi-metal effect. By directly polishing the aluminum mirror surface, the recent developments at Astron allow for using a non-exotic material for light weighted yet accurate optical mirrors, with a lower surface roughness (~1nm RMS), higher surface accuracy and reduced light scattering. This paper presents the techniques, obtained results and a global comparison with alternative lightweight mirror solutions. Recent discussions indicate possible extensions of the extreme light weight technology to alternative materials such as Zerodur or Silicon Carbide.

1. INTRODUCTION

Cryogenical optical earth- and space based instrumentation needs materials with demanding requirements on properties like weight, strength, stiffness, (thermal-) conductivity, manufacturability and cost. The increasing requirements on performance, tolerances and capabilities inspired institutes to develop and investigate new materials like CFC, SiC, C-SiC and other exotic materials. However, these techniques are often expensive and not always easily available or reliable for all applications. In addition, lack of heritage creates high risks while implementing these new techniques. Often Aluminum is chosen because of its heritage and the extensive knowledge of its properties, its reliable and predictable behavior, which is essential for monolithic cryogenic structures with complex accurate optical systems. Using one single material for both optical components and mechanical structure simplifies the instrument significantly: no mechanical compensation for differential thermal expansion is needed, uniform thermal expansion maintains the performance of the optical system which is very beneficial during instrument test and verification and makes the instrument insensitive to temperature changes.

Driven by the need to reduce the weight of optically ultra-stiff structures, while securing all advantages of using aluminum two promising techniques have been developed: **ASTRON Extreme Lightweighting [1][2]** for mechanical structures and an improved **Polishing Technique for Aluminum Mirrors**. Astron Extreme Lightweighting has been developed using the unique capabilities of modern design and milling techniques (CAD-CAM communication, 5 axle simultaneous milling). This development leads to weight reduction up to 95 % improving the Weight-Stiffness ratio.

The development of a polishing technique for Aluminum Mirrors was needed to manufacture cryogenic mirrors that combine high optical performance and low weight. Traditional Diamond turned mirrors show irregularities caused by the manufacturing process, the turning grooves cause severe scattering and the grating pattern could lead to undesired ghosts. Adding a nickel layer on a diamond turned surface would make polishing of the mirror easier, however it also introduces a bi-metal effect due to differential thermal expansion between nickel and aluminum. As a result the accuracy of such a mirror in a cryogenic environment could be far less accurate than specified. Making the mirrors very thick and solid would probably suffice to achieve a proper surface accuracy but would also introduce a serious amount of weight. Direct polishing of a lightweighted aluminum mirror surface would therefore be the best choice.

2. MATERIAL AND DESIGN TRADE-OFF

The cryogenic nature of (near-) infrared instruments puts special requirements on the thermal material properties. In the material trade-off the following parameters need to be considered: strength, elasticity, density, specific stiffness, manufacturability and cost. CTE (Coefficient of Thermal Expansion), CTE uniformity and CTE prediction and stability over different production batches, vacuum compliance, thermal conductivity and specific heath capacity for quick cooling are important as well. These parameters should be specified at cryogenic temperatures. The present material choice for mid-IR instruments built at Astron (VISIR, MIDI, MIRI, X-Shooter) is an aluminum alloy (e.g. 6061 or 5083) for the optics as well as for the opto-mechanical structure. The drive to reduce weight of the optics and opto-mechanics for earth based cryogenic instruments is to maintain and improve the stiffness of the optical system with an implicit effect on reduction of total instrument mass and cooling power and/or cooling time.

Table 1. Below some specific features of different materials when applied for optics and opto-mechanics. [5]

Material:	**Aluminum hard alloy**	**SiC types**	**Epoxy Carbon Composites**
stiffness/ mass (E/?)	high	(very) high	very high/varies
Strength/ mass (s/?)	high	high	high
CTE	high	Very low	Very low
Thermal Conductivity	moderate	low	low
Optics possible	Yes, proven	Yes, proven	Yes, in development
Cost	low	high	Initial high/ lower for series

Table 2. Some specific material properties [6] [7]

Material:	**Aluminum hard alloy**	**SiC types**	**Epoxy Carbon Composites (mono)**
E-mod [GPa]	68.9	450 (varies)	100 (varies)
Rho [kg/m^3]	2700	3000	1500
E/rho [N m/kg] x 10^6	25	150 (varies)	67 (varies)
CTE [mm/mm] x 10^{-6}	24	2.4	0.1
$E^{1/3}$/rho [N m/kg] x 10^6	1.5	2.6 (varies)	3.1 (varies)

The above specified numbers are just examples from one specific type of material or composite with a specific material orientation. The E/rho value is commonly used for materials to judge its specific stiffness: the stiffness per kilogram material. The specific stiffness E/rho is valid for massive one-dimensionally loaded structures. For material comparison of two-dimensionally loaded structures, like plates with distributed weight, a specific stiffness of $E^{1/3}$/rho should be applied **[8]**. An example of a two-dimensionally loaded structure is a mirror structure with its own weight. The difference between the specific stiffness of the materials is smaller for two-dimensional loaded structures.
Other parameters like lightweight techniques to reduce weight but also the design of stiff structures become more important. For lightweighting this is obvious; the higher the reduction of weight the lower the flexure (as long as manufacturing allows). For the design process the shape and location of ribs as well as the shape and position of the surfaces that create stiffness are important.

A mechanical engineer tries to design a cryogenic instrument of mono material to have a well defined overall shrinkage of the instrument. If this is the case, the *absolute value of the CTE* is less important, but what still remains is the *tolerance of the CTE* and *CTE uniformity*. The CTE values for Epoxy Carbon Composite look excellent in comparison with aluminum but the CTE is depending on the fibers. Variations in the fiber orientation can cause unpredictable behavior. This can vary by design, but also during production and it is difficult to control and to verify except for mass produced pipes, tubes and plates. For aluminum the CTE is large in comparison with some other high-tech materials, but the CTE-tolerance is excellent. The CTE is well known, well controlled and over several batches constant and reliable and qualified. We have a similar situation for the E-modulus: The E-modulus for the Epoxy-Carbon Composite is controlled by fibers. Changing the type, amount, orientation, production process and other parameters will influence the E-modulus significantly and can reduce the E-mod to values 10 times lower. For SiC types without fibers the E-mod is much better controlled, but still depending on several processes.

Today the approach and design philosophy is becoming more and more important in designing new opto-mechanical structures. The M7 mirror presented in chapter 3 has a rather classical lightweight design while in chapter 5 an extreme lightweighted mirror is presented, which is basically the same as M7, as far as diameter and optical accuracy is concerned, only the design strategy of the mirror is totally different and optimized for maximum stiffness combined with lowest mass. Still it's made out of aluminum and will be produced on a CNC milling machine, the same as the one used for M7. Designing optics and opto-mechanical structures can profit by adopting new machining strategies and set a next step in the evolution of instrument development and production. The evolution in production technology is continuously ongoing and mainly concentrated on monolithic complex design. For the next decade one should think about improved tolerances and lower roughness (more stiff machines), intelligent software for complex shapes and low cost production (24hours / 7days per week). This could make the extreme lightweight mirror technology and equivalent mechanical structure approach suitable for larger quantities and common use.

3. ALUMINUM POLISHING

For several years we experimented at ASTRON with polishing Aluminum 6061, and successfully manufactured flat optical mirrors used for Infra Red instruments like VISIR and MIDI and very flat interfaces for opto-mechanical structures for the 2K SPIFFI camera. Using Aluminum oxides and water it is possible to polish an aluminum surface reasonably well to certain extends, but the process is very sensitive for oxidizing and scratching. During the last four years we investigated several polishing techniques on small mirrors and finally modified and applied these methods on two a larger mirrors up to 200 mm in diameter before we made the decision to polish the 300 mm mirror for X-Shooter.

The development of the new technique started with samples of 20 mm diameter, made from Al 6061 T6, that were diamond turned and post polished using rather traditional methods (by hand, on pitch). The surface roughness measurements of the diamond turned samples showed a clearly higher surface roughness (1.57-1.80 nm Ra) and periodicity, caused by the DT process. The polished sample (0.59-0.90 nm Ra, figure 2) showed a fine randomly distributed pattern, partially caused by the polishing process, partially by the material structure.

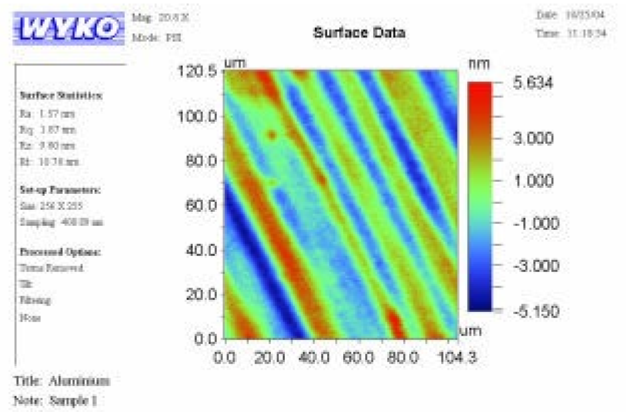

Fig. 1. Diamond turned sample, Ra= 1.57 nm.

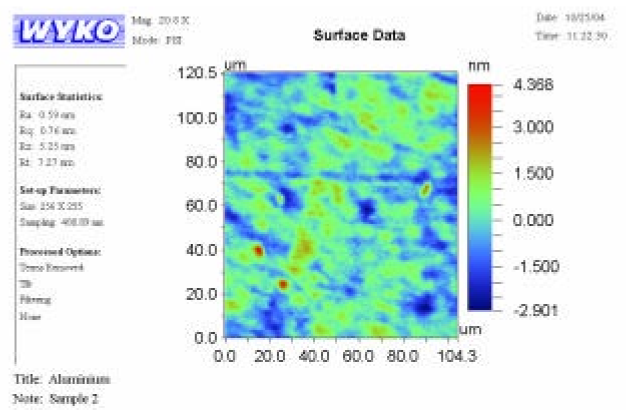

Fig. 2. Polished sample, Ra= 0.59 nm

Extending to larger diameters, we ordered flat and curved diamond turned samples of 70 mm diameter and 'scaled-up' the process. The diamond turned mirrors initially showed a roughness of more than 10 nm. By post-polishing one of these samples we reduced the roughness to better than 2 nm.

However, the forces that were generated by the polishing process became large and might have become a potential risk for manufacturing the mirrors. New experiments performed on a concave 200mm mirror, in the same time being used for testing how off-axis mirror segments could be stress-free mounted and polished, led to a method that could be scaled to 300mm and more. Instead of using aluminum oxides we used diamond slurries with 3 and 1 micron particles. During the experiments it appeared that temperature changes in the polishing environment have a large impact on the process. A clean and temperature controlled environment is essential for good results. The force of the polishing tool on the mirror is also an important parameter, as too much pressure will cause a grayish surface with lots of pits. Fine tuning off all parameters finally lead to a controllable polishing process where surface roughness values of 1 nm Ra and even less are achieved, despite the larger diameter, while the surface accuracy over the entire diameter could be brought easily well within 1 fringe (@ 633nm, see figure 3).

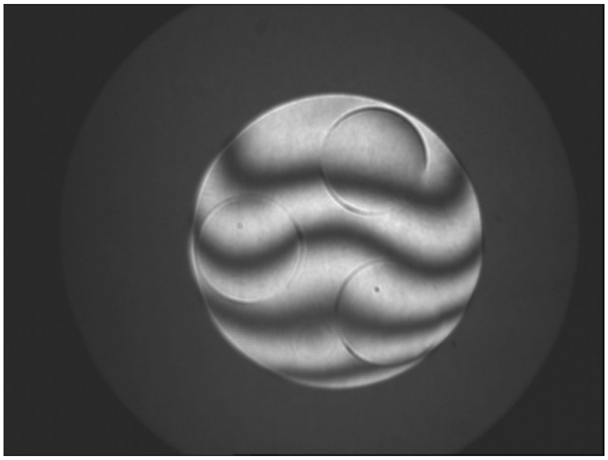

Fig. 3. Fringe pattern of the concave 200mm mirror after polishing (three segments visible).

4. X-SHOOTER M7

In 2006 we started the production of the optical components for the Near Infra Red arm of X-Shooter **[4]**, a spectrometer built for the VLT in Chile. The mirror blanks were manufactured in-house, using a 5-axis milling machine, and followed an elaborate heat treatment process which was used in order to minimize global deformation by aging in time. The process consists of CNC milling the component with an oversize of 1mm, followed by solution treatment and down- and up-hill quenching for full recrystallization of the material (Aluminum T6 treatment). In a second CNC milling step the component is milled to the final size, with only some extra material on the optical surface, followed by aging. A third CNC Milling step reduces the oversize on the optical surfaces to only a few tens of micrometers, followed by several thermal cycles. This procedure should limit internal stress deformations of the optical surface to only a few nanometers, even at cryogenic temperatures **[3] [4]**. Also subsurface damage caused by milling must be removed prior to polishing. This was done with a pre-polishing step, comparable with grinding, using 30 micron Aluminum oxide.

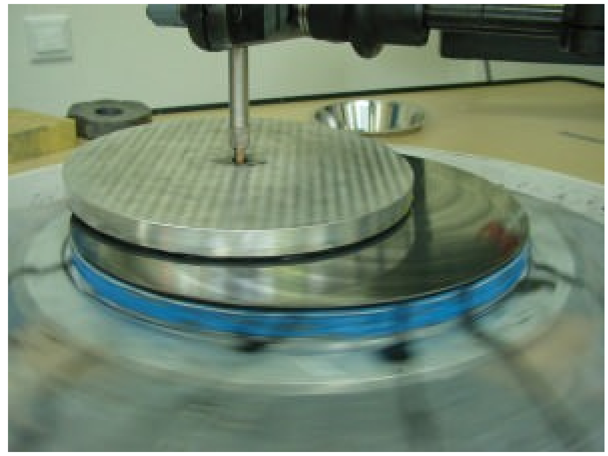

Fig. 4. M7 during a polishing session, mirror face up. The polishing tool on top has a 5 mm thick layer of specially prepared polishing pitch.

After each session, the shape and radius of the mirror was checked with the interferometer. Following the process that was used for the 200mm test mirror, the M7 was polished within the specified 0.5 wave surface accuracy while having a surface roughness of 1 nm Ra. After cleaning and removing the protection tape at the back of the mirror blank we discovered that the slightly *elastic* protection tape had bent the mirror blank in one direction, causing 0.5 wave of astigmatism. Nevertheless the results are satisfying with room for improvement in the future. This mirror is used in the Near Infra Red domain, but the optical quality is sufficient for visual wavelengths as well.

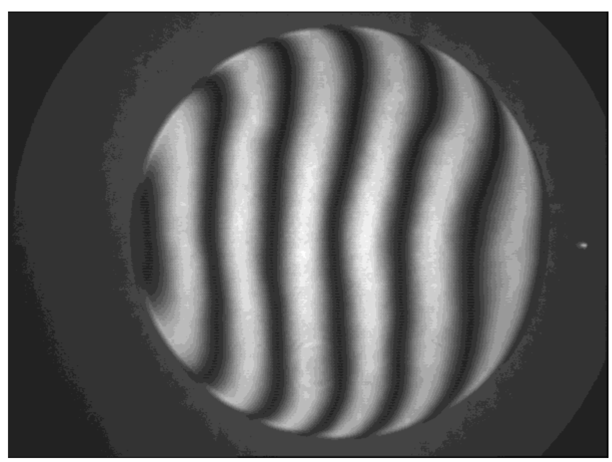

Fig. 5. Fringe pattern of M7 after polishing, showing less than 1 fringe surface error over the entire 300 mm diameter

One of our concerns was a possible effect of the lightweight rib-structure on the back of the mirror. The 300 mm diameter mirror needed to be lightweight in order to reduce the total mass of the instrument as much as possible. Pockets at the back side of the mirror (see picture below) resulted in a 65 % mass reduction of the mirror. The face sheet thickness was 9 mm. Because the side-effects of polishing the mirror were not yet known there was some doubt whether the rib-structure could become visible after polishing the mirror, reducing the optical performance of the mirror. Interferometric measurements after polishing however didn't show any serious traces of this print-through, which feeds the idea that combined with the used polishing technique the face sheet thickness of future lightweight mirrors could be reduced seriously while still maintaining a high level of surface quality. Polishing experiments on a smaller test mirror for MIRI (JWST), where the thickness of the face sheet was only 3 mm, confirmed this, paving the way towards extreme lightweight mirror developments.

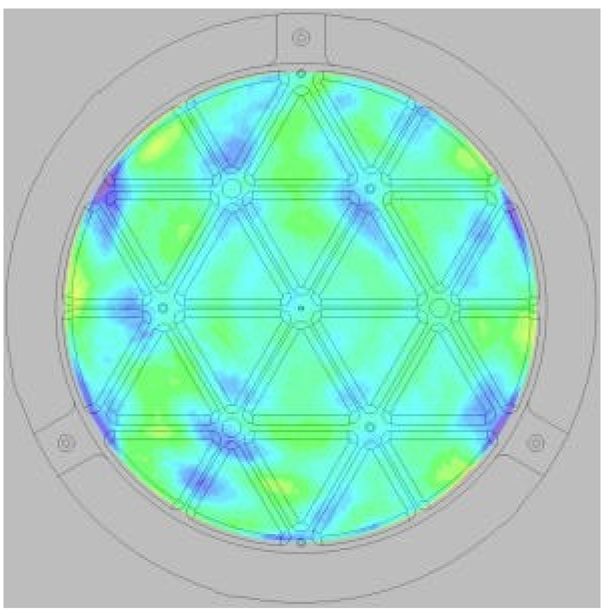

Fig. 6. Residual irregularities of the 300 mm M7 layered on a mechanical drawing of the back of the mirror. The relation between light weight pockets and print through is visible but insignificant: Residual irregularities are in the range of 4nm RMS, while surface roughness is still around 1 nm (Ra). The OPD map (created with Intelliwave) shows the remaining irregularities, with tilt, focus, astigmatism, symmetric and asymmetric subtracted.

5. STUDY: EXTREME LIGHTWEIGHT MIRROR

With print-through not being a critical issue when polishing a thin face sheet, as demonstrated by M7 and the MIRI mirror, it is finally possible to significantly reduce the face sheet thickness thereby lowering the mass of the mirror. So far the trade-off of applying ASTRON Extreme Lighweighting in optical parts was negative as the mass reduction was limited in comparison to the conventional techniques due to the high percentage of mass residing in the face sheet. Now the face sheet is thinner, applying Extreme Lightweighing makes sense as the percentage of mass reduction and increase in global stiffness is now much higher. This technique allows for a closed back mirror with very thin internal ribs and back sheet (1 to 0.3 mm) increasing global stiffness without adding much weight. Therefore replacing diamond turning with polishing not only improves optical properties but also allows for a lighter mirror with a better stiffness-to-weight ratio.

Currently at ASTRON a study is ongoing to investigate the amount of mass reduction and increase in stiffness that is achievable using this lightweighting approach while taking the X-shooter M7 mirror specification as a starting point. With the experience of the design and production of the Balance Arm for the X-shooter project **[4]**, this alternative lightweighting technique can be tuned for an optical part, using only the back side as an entrance surface and at the same time leaving a complex internal rib structure (see Fig. 7), from a fine distributed rib structure supporting the optical face sheet for local stiffness via a wider distribution of medium sized pockets to a main structure for global stiffness, all in one mirror model.

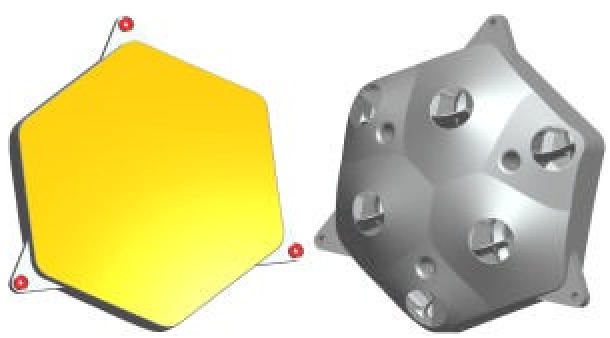

Fig. 7. Front and back view of study model based on the X-Shooter M7

A thin face sheet demands a high density local rib structure which in turn adds mass due to the many corners that have rounds in the model left by the milling tool. In such an extreme lightweighted structure these rounds make up for a significant amount of mass, therefore the goal was to implement a hexagonal rib distribution, i.e. a 120 degree corner angle, for both global and local stiffness so as to keep the additional material to a minimum. However, using a small entrance hole to mill away a large internal volume by its nature leads to an internal rib design based on a spherical coordinate system instead of the normal Cartesian one, i.e. a conical or radial local rib orientation. Combining hexagonal, conical and radial ribs leads to four, five and six sided cells, with angles ranging from 120 to as low as 60 degrees, which was accepted as a compromise (see Fig. 8).

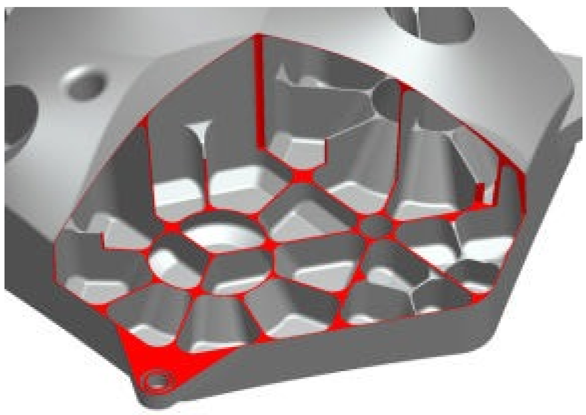

Fig. 8**.** Inside rib distribution of extreme lightweighted study model based on the X-Shooter M7.

Radial ribs were cut off near the pocket centre to achieve an equal cell span and to further reduce mass. With the emphasis on the mirror back structure, only simple mounting features were added. Off course in a final mirror design the mounting features should be integrated with the global rib configuration.

To be able to reach all the inside material directly behind the back side surface, the centre axis of every pocket no longer can be perpendicular to a plane, as in the X-shooter Balance Arm, but orients perpendicular to roughly a sphere, effectively comprising the back side of conical surfaces. In combination with a certain minimum rib height on the circumference of the mirror, the centre height of the mirror is raised to around 100 mm, equal to 1/3 of the diameter. When scaling up the mirror, this ratio would roughly stay the same. The upper mirror diameter is an estimated 1 meter but highly depends on polishing techniques, available milling tools and details of the internal design: ASTRON Extreme Lightweighting *is only possible* when optimizing the design for manufacturing, starting from concept design until adding the last round feature to the model.

Local deformation due to the polishing forces and gravity was leading in deciding which combination of sheet thickness and cell span was allowable, using the performance values of the original M7. A sheet thickness of 2 mm and an inscribed circular span between 23 to 29 mm was eventually chosen, based on print through, achievable internal round dimensions and, above all, the possible negative effects of residual stresses in the material, an often overlooked aspect of (thin walled) highly accurate parts, especially in cryogenic application.

With the reduction of mass from 44 kg/m^2 to 24 kg/m^2 for the same local deformation and the added closed back side reducing global deformation by 29% for a given weight and overall height [2], and improved optical performance using polishing, it is clear that the use of aluminum as a mirror material in cryogenic application can be extended, still being a conventional and proven alternative to other exotic materials. The extremely light weighted design has a 19% higher eigen frequency compared to a traditional lightweight design of the same mass.

Currently alternative design and manufacturing methods are under investigation to reduce the height to diameter ratio of the mirror. Another interesting approach would be to integrate the optical surface into the main support structure enabling a monolithic multiple mirror unit to further reduce weight, increase stiffness and improved overall accuracy of the instrument.

6. EXTREME LIGHTWEIGHTING IN ALTERNATIVE MATERIALS

Applications for the extreme light weighting technique are not limited to aluminium. Recent discussions indicate possible extensions of this technology to other materials, such as Zerodur or Silicon Carbide. In fact it is possible to use extreme light weighting in any isotropic material that can be shaped by CNC milling.

Expected weight savings, increased eigen frequencies and reduction of deformation of the optical surface are in the same range as discussed for the aluminum mirror. In case of silicon carbide the extreme light weighting of the backside must be completed before sintering, while polishing the front side is completed after sintering. The large number of internal ribs at the back side of the mirror allows for a thinner face sheet, while maintaining an easy polishing process and reducing risk of print trough by the ribs.

7. CONCLUSIONS

Modern design and milling techniques combined with traditional materials with well known properties still allow for improvements that make them competitive to more advanced new materials and concepts. This paper presents results obtained in studies that combine the extreme lightweight strategies with newly developed optical polishing techniques. A method is described how we can approach that process and partial tests have been presented.

In summary:

- Aluminum can be polished to visual wavelength specifications.
- Studies indicate that this process is applicable for Extremely Lightweighted Aluminum mirrors.
- Aluminum mirrors and opto-mechanical structures will evolve over coming decade and can compete with high-end material solutions like SiC or Epoxy composites in performance, on cost, risk and lead-time.
- The CTE for cryogenic instruments is less important, the tolerance of the CTE is dominant for selection of material. The CTE tolerance of aluminum grades is extremely small, reliable and predictable.

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