International Conference on Space Optics—ICSO 2014

La Caleta, Tenerife, Canary Islands

7–10 October 2014

Edited by Zoran Sodnik, Bruno Cugny, and Nikos Karafolas

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International Conference on Space Optics — ICSO 2014, edited by Zoran Sodnik, Nikos Karafolas,
Bruno Cugny, Proc. of SPIE Vol. 10563, 105631J · © 2014 ESA and CNES
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2304207

ATHERMAL METAL OPTICS MADE OF NICKEL PLATED ALSI40

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I. ABSTRACT:

Metal optics is an inherent part of space instrumentation for years. Diamond turned aluminum (Al6061) mirrors are widely used for application in the mid- and near-infrared (mid-IR and NIR, respectively) spectral range. Aluminum mirrors plated with electroless nickel (NiP) expand the field of application towards multispectral operating instruments down to the ultraviolet wavelengths. Due to the significant mismatch in the coefficient of thermal expansion (CTE) between aluminum and NiP, however, this advantage occurs at the cost of bimetallic bending. Challenging requirements can be met by using bare beryllium or aluminum beryllium composites (AlBeMet) as a CTE tailored substrate material and amorphous NiP as polishable layer [1]. For health reasons, the use of beryllium causes complications in the process chain. Thus, the beryllium approach is subjected to specific applications only. Metal optics has proven to be advantageous in respect of using conventional CNC and ultra-precision fabrication methods to realize complex and light-weighted instrument structures. Moreover, the mirror designs can be effectively optimized for a deterministic system assembly and optimization [2]. Limitations in terms of dimensional stability over temperature and time are mainly given by the inherent material properties (figures of merit) of the substrate material in interaction with the polishing layer.

To find an optimal compromise, a thermal matched aluminum-silicon alloy (silicon contents ≈ 40 wt%) plated with NiP (AlSi40/NiP) was investigated in a joined project of the Max Planck Institute for Astronomy MPIA and the Fraunhofer Institute for Applied Optics and Precision Engineering IOF. The main tasks of the project were the minimization of the bimetallic bending, the development of reliable stabilizing and aging procedures, and the establishment of a proven fabrication method.

This paper describes fundamental results regarding the optimization of the athermal material combination. Furthermore, the developed production chain for high quality freeform mirrors made of AlSi40/NiP is pointed out. The capabilities of the material combination are demonstrated by the usage of three selected examples:

- Camera optics for cryogenic usage, part of the LUCI instrument for the Large Binocular Telescope
- Three Mirror Anastigmat (TMA) optics for the Polar Communication and Weather (PCW) Mission for the Space Technology Development Program of the Canadian Space Agency
- K-mirror system for image de-rotation operating at ambient temperatures (0° C - 15° C)

II. INTRODUCTION:

Demanding metal based mirrors for space applications as well as for astronomical instrumentation acting in the NIR and visual (VIS) wavelengths are characterized by the following typical optical specifications:

- Shape: aspheres, off-axis aspheres, freeforms e.g. biconic, anamorphotic
- Form deviation: 100 nm PV (peak to valley), 15 nm rms (root mean square) at a clear aperture (CA) size of 200 mm x 200 mm
- Micro-roughness: < 0.7 nm rms (2.5x magnification) , < 0.3 nm rms (40x magnification
- Cleanliness: 5/3 x 0.1 according to DIN ISO 10110
- Optical coating: protected silver, gold
- Coating qualifications: MIL-M-13508C 4.4.6 (adhesion), ISO 9022-2-14-04 (thermal stability), MIL-M-13508C 4.4.7 (humidity), and other tests

IOF has developed technologies and processes including diamond machining, post polishing, local figuring techniques, and optical coating to realize the above specifications on nickel plated aluminum (Al6061) mirrors. Thus, for example, the optics of the Jena-Spaceborne-Scanner JSS product line (developed by Jena-Optronik GmbH) is realised by a TMA telescope designed in aluminum [3], [4].

With respect to the system alignment and integration as well as in terms of weight- and temperature restrictions, a couple of boundary conditions have to be considered. Besides the realisation of the single optical element, the attention will focus more and more on the issues of:

- Well defined references for metrology and assembly
- Easy and reliable system alignment and integration
- Light-weighting
- Athermal design

Because of the excellent machinability and the wide variety of possible manufacturing technologies, metal substrates offer outstanding opportunities for novel approaches in respect to these issues. In a range of investigations it is clearly shown that the effort for system alignment and integration can be significantly reduced by the usage of well- defined references [5], [6]. References, which are easily feasible in metal substrates, are also a potential key for improving the metrology and the correction cycle of complex optical shapes [7].

This showed that metal optics provide a great deal of freedom for opto-mechanical design approaches and that electroless nickel as a polishing layer on Al6061 enables high quality mirror surfaces. But the CTE mismatch between the aluminium substrate and electroless nickel involves too much limitation on the operating temperature range and leads to a special effort regarding the temperature management of the instrument. Athermal designs for nickel plated Al6061 mirrors in particular for optical systems working under cryogenic conditions are hardly practicable. To overcome this constraints and by keeping the benefits of metal substrates, a novel material combination was introduced by the MPIA and Fraunhofer IOF. The basic idea is the utilization of a silicon particle reinforced aluminum material with approximately 39-43 wt% silicon as a bulk material [8]. The material matches the CTE of the electroless nickel polishing layer with 1×10^{-6} K^{-1} in between the manufacturing tolerance of the materials. It can be tailored by adjusting the silicon content of the bulk material as well as by modifying the phosphorous content of the NiP layer [9]. Fig. 1 depicts the mirror structure consisting of the AlSi bulk material, NiP polishing layer and the optical reflector coating with protection layer.

To determine the possibilities and limitations of the new approach, the project addressed the following key issues:

- Measurement of the CTE according to the material composition
- Optimization of the CTE matching
- Investigation of the material microstructure
- Development of reliable stabilizing and aging procedures
- Verification of the material combination for cryogenic usage
- Implementation of a manufacturing chain for high quality metal mirrors made of AlSi40/NiP

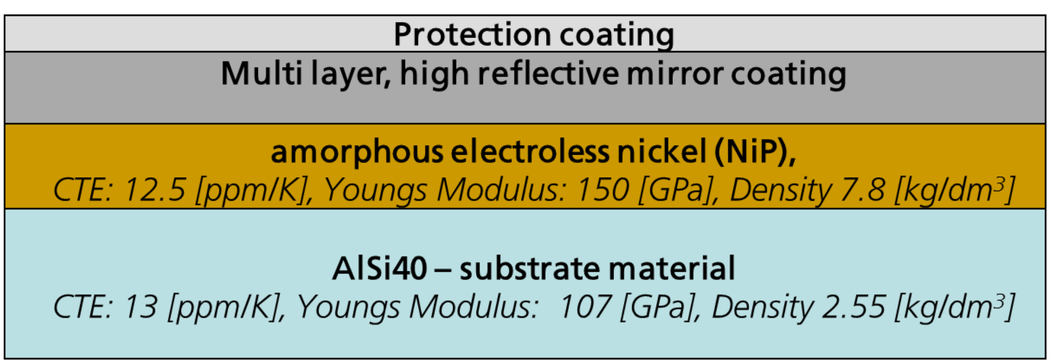

Fig. 1. Layout of a nickel plated AlSi40 mirror.

III. INVESTIGATIONS

A. CTE matching

The knowledge of the thermal expansion of the aluminum bulk material and the NiP polishing layer is one essential precondition for the realization of an athermal mirror characteristics. The CTE as a function of the percentage of silicon and as a function of the percentage of phosphorous in the NiP layer, respectively, are of particular interest. Therefore, a CTE measurement method based on a low-temperature dilatometer (NETZSCH DIL 402 C) was developed. The reproducibility of the developed CTE analyses is $\pm$ 0.15 $\times$ 10^{-6} K^{-1}.

The left section of Fig. 2 shows the determined trend of the CTE ranging from -185 °C to 100 °C for electroless nickel layers with increasing phosphorous contents. A higher phosphorous concentration leads to a lower CTE of electroless nickel. NiP layer that are suitable for diamond turning and post polishing vary between 11 wt% and 13 wt% phosphorous content. Within these limits, the CTE are in a tolerance of < 0.5 $\times$ 10^{-6} K^{-1} [9], which is verified experimentally. In principle, the CTE of electroless NiP can be manipulated and tailored to a target value during the plating process by controlling the deposition parameters. As a part of the project, a controlled plating process was implemented to ensure the fabrication of NiP samples with defined phosphorous contents. Furthermore, measurement methods for determining the phosphorous contents were investigated and adapted.

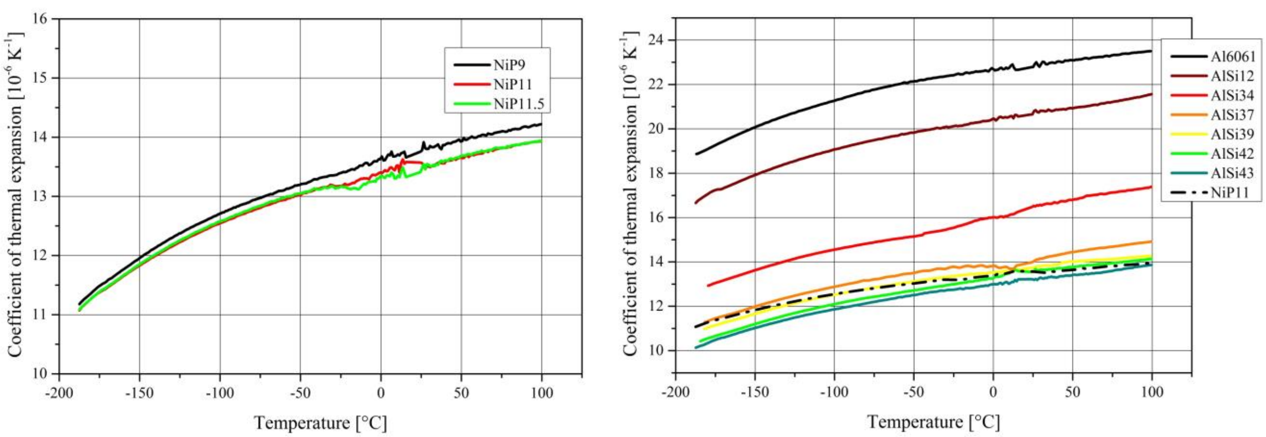

Fig. 2. Coefficient of thermal expansion for NiP layer with different phosphorous content (left) and for AlSi materials with different silicon content (right).

The right part of Fig. 3 illustrates the dependency of the CTE from the silicon content of relevant aluminum materials. A difference of 1 wt % silicon of the aluminum-silicon material tends to result in a decrease of the averaged CTE of 0.2 $\times$ 10^{-6} K^{-1} in a temperature range from -185 °C to 20 °C. An aluminum-silicon material with 39 wt% Si exhibits the closest CTE matching with the NiP layer, containing 11wt% P. In that case the averaged CTE difference is < 0.1 $\times$ 10^{-6} K^{-1}. The measurements highlight that aluminum-silicon systems with a silicon content between 37 wt% and 44 wt% match the CTE of standard NiP plating below 1.5 $\times$ 10^{-6} K^{-1}. Hypereutectic aluminum-silicon alloys like AlSi40 are manufactured by rapidly solidification processes. Typical tolerances for such industrial proven technologies are $\pm$ 2 wt% Si. Via a pointed selection of the raw material, the CTE difference to the polishing layer can be easily reduced to 1 $\times$ 10^{-6} K^{-1} or less.

B. Application of AlSi40/NiP at cryogenic temperatures

LUCI is a NIR-spectroscopic utility with camera and integral-field unit for extragalactic research as a part of the instrumentation for the Large Binocular Telescope (LBT). The LUCI optics works across the 0.9-2.5 μm spectral range under cryogenic conditions. While some of the mirrors of the instrument can be adequately manufactured by diamond turning of Al6061, the mirrors for the camera optics are more challenging and were realized with AlSi40/NiP. Figure 3 shows the all AlSi40-design of the LUCI camera, including the aspherical primary (CA = 127 mm in diameter) and the aspherical secondary mirror (CA = 27 mm in diameter). The required surface irregularity within the clear aperture is < 150 nm PV and the specified surface roughness is < 5 nm rms. Furthermore, all periodic surface structures due to diamond turning processes must be polished out. A local figuring technique is strongly required to meet the desired specifications and to provide an opportunity to correct mirror deformations caused by mounting effects at cryogenic temperatures. Nickel plated metal optics provide this possibility.

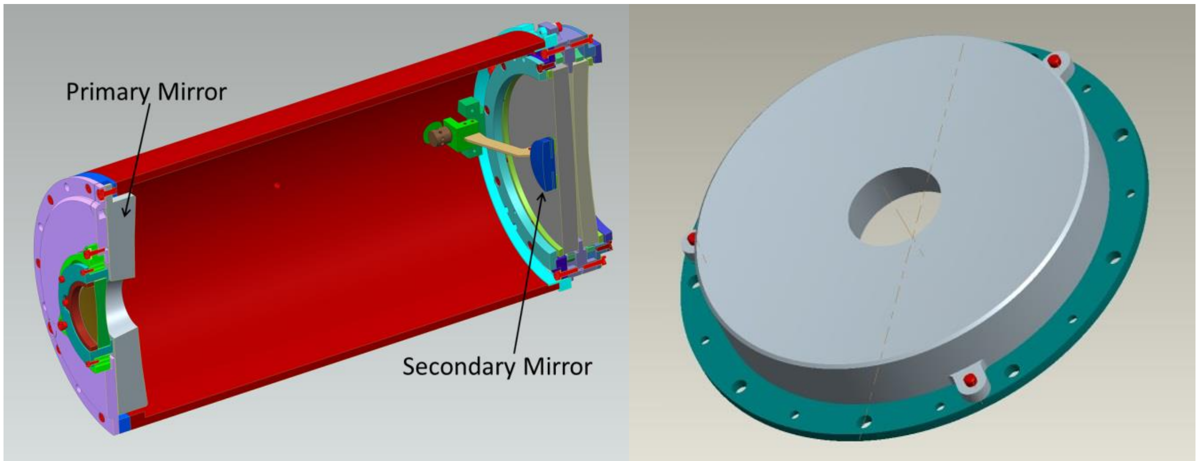

Fig. 3. Mechanical layout of the LUCI camera-optics (left) and of the primary mirror assembled on a mounting plate (right).

To verify the application of the AlSi40/NiP material combination, a FEM analysis in respect to the bimetallic deformation and the introduced stress were carried out. The simulations assume an averaged CTE in a temperature range from -185 °C to 20 °C of 12.8×10^{-6} K^{-1} for AlSi40 and 12.5×10^{-6} K^{-1} for NiP, respectively. Youngs -modulus are given by E = 107 GPa for AlSi40 and E = 150 GPa for NiP by assuming a layer thickness of 100 µm. The FEM model implicates an isostatic mounting of the mirrors and a homogeneous temperature change by 218 K as loading condition. Figure 4 illustrates the stress condition inside the NiP layer and the deformation due to the remaining bimetallic bending for the primary mirror. Compared to an Al6061 bulk material plated with 50 µm NiP, the simulated bimetallic bending is reduced by a factor of about 25. The secondary mirror exhibits similar results.

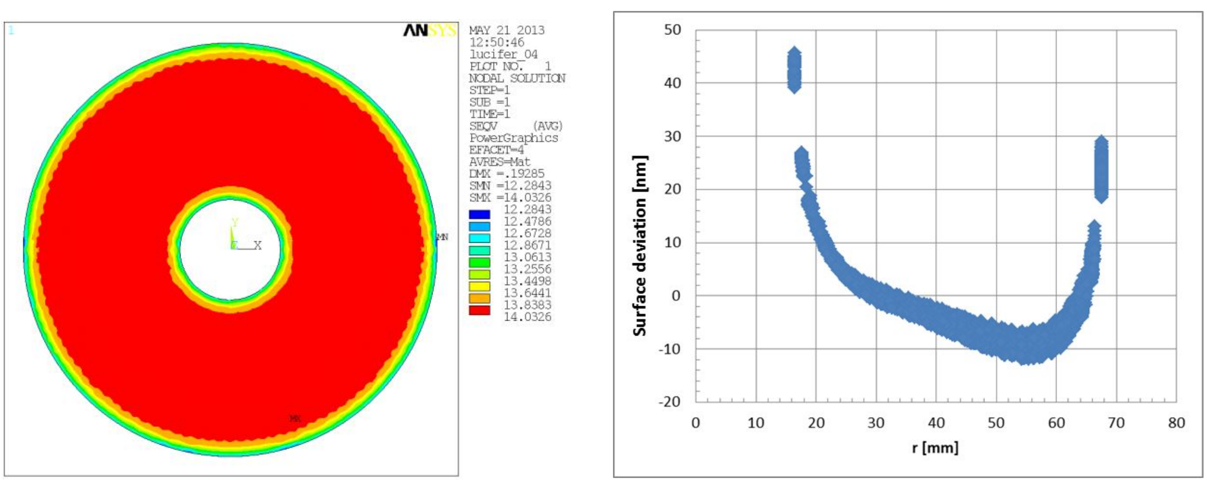

Fig. 4. Left: stress condition inside the NiP layer; Right: remaining form deformation (cross section) after removal of focus, z-shift, and intrinsic expansion of the mirror substrate.

After manufacturing the mirrors according to the process chain described in the following section, the surface deviation of the mirrors where measured under ambient (22°C) temperature. The primary mirror shows a surface deviation of 62.5 nm PV (see Fig. 5). The secondary mirror was realized with 82.6 nm PV over the entire surface. The micro-roughness of both elements is < 2 nm rms. The mirrors where characterized under cryogenic temperature (-180°C) applying the mounting conditions of the final instrument situation. During subsequent warm-cold cycles, both mirrors exhibit reproducible results. However, mounting effects still lead to figure deformation. The secondary mirror fulfills the required specification (< 150 nm PV @ -180°C) including the described effects. Restricted space conditions lead to a suboptimal decoupling of the primary mirror and a typical low order form deviation (astigmatism, trefoil) due to the mounting forces. The measured deformation determined under cryogenic temperature, was used as an input error map in an additional sub aperture finishing process by Magnetorheological Finishing (MRF). After refiguring, the surface form error of the primary mirror was measured with 147 nm PV @ -180°C in its final mounting configuration.

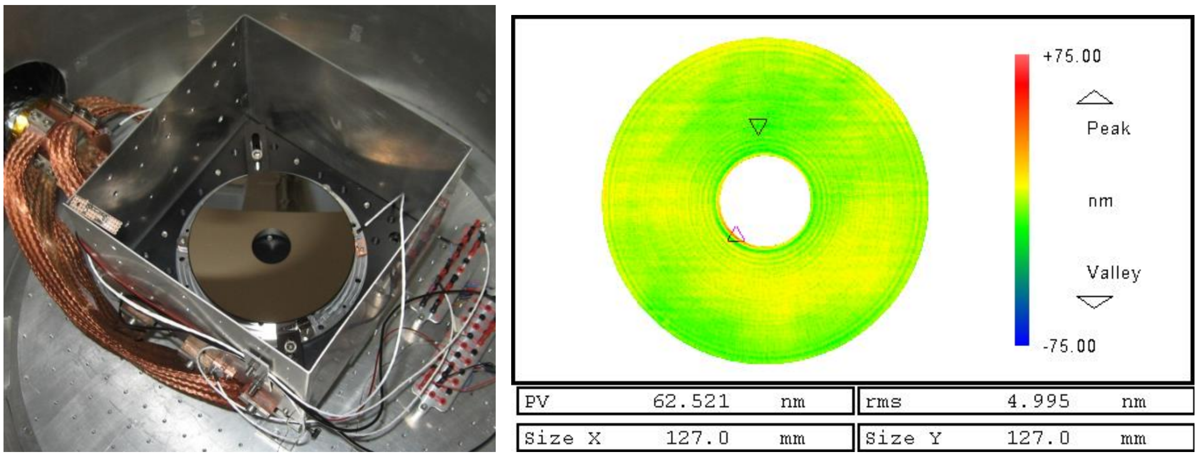

Fig. 5. Left: primary mirror mounted in the dewar for cryogenic characterization; Right: form deviation of the primary mirror after completion of all manufacturing steps @ ambient (22 °C) temperature.

C. Process chain for large freeform mirrors

One of the project aims is to adapt and enhance the fabrication processes for the specific requirements of the novel material combination and to furthermore, establish manufacturing techniques to realize freeform mirrors. Freeform shapes are of increasing importance for design and accordingly for performance reasons. Sometimes, one is forced to handle off-axis mirrors as freeforms during manufacturing, because their sizes in combination with their off-axis distance can easily exceed the limitations of ultra-precision turning machines in terms of diameter or maximum slope. This means that the off-axis segment is transformed in an “on-axis” freeform for all manufacturing steps, e.g. diamond turning, post polishing, as well as for metrology. During system integration, the retransformation is done by the usage of precise references. This is particularly the case for the TMA metal optics for the PCW space mission. The working wavelength range of the PCW instrument covers the NIR as well as the VIS spectral range down to 440 nm.

Fig. 5. Metal optics for the PCW Mission: primary mirror (left), secondary mirror (center), tertiary mirror (right), with AlSi40 as substrate material and electroless nickel (NiP) as polishing layer.

To realize a diffraction limited optical performance, local figuring and polishing techniques are essential. The three mirrors of the TMA require a surface shape deviation of less than 45 nm rms each and a surface micro-roughness of less than 1 nm rms. The off-axis primary mirror with a CA of 260 mm in diameter and the tertiary mirror with a CA of 320 mm in diameter were handled and fabricated as freeform mirrors [10].

The manufacturing of ultra-precise AlSi40/NiP metal optics depends on a multiple-stage and deterministic production chain. Manufacturing processes, metrology, and the assembly of the freeform mirrors give a variety of feedback information that has to be carefully considered during the opto-mechanical design phase. Special attention has to be paid to the thermal treatment and aging procedures to provide dimensional stability over time and temperature [11]. Table 1 summarizes the main manufacturing steps of the used production chain.

Table 1: Manufacturing steps for the PCW freeform mirrors.

Step		**Main issues**	**Test / Tools**
Opto-mechanical design		- Ensuring optical function - Manufacturing related design - Data transformation, retransformation due to references - Ensuring deterministic system assembly	- Finite element analysis regarding dimensional stability, gravity - Ray tracing - Design and manufacturing Know-How
Pre-shaping CNC		- Achieving tolerances < ±10 µm	- Coordinate measurement technology (CMM) vs. CAD model
Thermal treatment / aging		- Providing dimensional stability	- Specialized procedure for substrate material - Thermal treatment and cycling
Shaping (diamond machining of the substrate)		- Achieving tolerances < 5 µm on all critical surfaces - Shape irregularity < 3 µm PV inside CA - Micro-roughness < 10 nm rms inside CA	- CMM vs. CAD model - Interferometer + CGH - White light interferometry
Plating NiP		- Homogeneous polishing layer, no defects - Phosphorous content 11 % - 13%	- Visual inspection - Chemical analysis on samples
Thermal treatment / aging		- Providing dimensional stability	- Specialized procedure for substrate material + NiP - Thermal treatment + cycling
Shaping (diamond machining of the polishing layer)		- Achieving tolerances < 5 µm on all critical surfaces including references - Shape irregularity < 3 µm PV inside CA - Micro-roughness < 10 nm rms inside CA	- CMM vs. CAD model - Interferometer + CGH - White light interferometry
Correction cycle	Freeform metrology	- Shape characterization with measurement accuracy < λ/10 PV - Prevent alignment errors	- Interferometer + CGH using alignment features
	Local figuring (MRF)	- Shape irregularity < 40 nm rms inside CA - Micro-roughness < 3 nm rms inside CA	- Interferometer + CGH, white light interferometry
Polishing, smoothing (CCP)		- Micro-roughness < 1 nm rms inside CA - Reducing mid spatial frequency errors - Cleanliness < 3x0.1 @ 50 mm	- Atomic force microscopy - White light interferometry - Visual inspection
Optical coating (sputtering)		- High reflectivity (λ: 430 nm to 14500 nm) - Durability for space conditions	- Reflectivity measurement - Coating validation regarding adhesion, temperature change, humidity, thermal vacuum, irradiation

Table 2 shows the final results of the realized TMA mirrors after completion of all manufacturing steps including optical coating. The mirrors were successfully integrated in the PCW breadboard system by ABB Canada.

Table 2: Manufacturing results for the PCW mirrors made of nickel plated AlSi40.

Mirror	Shape	CA in diameter	Final form deviation rms	Micro-roughness (2.5x magnification) rms	Micro-roughness (40x magnification) rms
Primary	Concave, off-axis	247.4 mm	25.7 nm	< 0.7 nm	< 0.3 nm
Secondary	Convex, on-axis	31.5 mm	11.0 nm	< 0.7 nm	< 0.3 nm
Tertiary	Concave, off-axis	318.4 mm	20.7 nm	< 0.7 nm	< 0.3 nm

D. Usage of defined references

Metal optics are practically predestined for the consequent usage of references for metrology, alignment, and assembly. References, realized in the same setup as the optical surfaces by ultraprecise diamond machining, exhibit shape and position tolerances of less than 3 µm and a few arc seconds, respectively. The example of the de-rotator assembly of the GRAVITY instrument for the Very Large Telescope Interferomter (VLTI) of the European Southern Observatory (ESO) shows that this advantage can be reasonable used for the AlSi40/NiP material combination. The de-rotator (working temperature: 0°C - 15°C) consists of a K-mirror assembly (AlSi40/NiP) and a mounting flange (AlSi40) integrated in a rotation stage made of stainless steel (Fig. 6). Besides the manufacturing of the mirrors with a figure accuracy of 30 nm rms and a micro-roughness of 2 nm rms, the main challenge of the de-rotator system is the positioning of the mirrors relative to each other and to align the rotation axis relative to the axis of symmetry in Tx, Ty, Tz as well as Rx, Ry. The positioning of the mirrors was carried out according to the tight manufacturing tolerances, with the exception of the rotation in Y of the prismatic mirror. This degree of freedom was aligned. The de-rotator assembly was characterized under interferometric observation of the system wave front in double pass during rotation. Finally, a mirror tip-tilt error (Rx, Ry) of 7.5 arcsec and an alignment of the rotation axis vs. symmetry axis of 10 µm in lateral shift and of 8 arcsec in tip-tilt (Rx, Ry) were achieved.

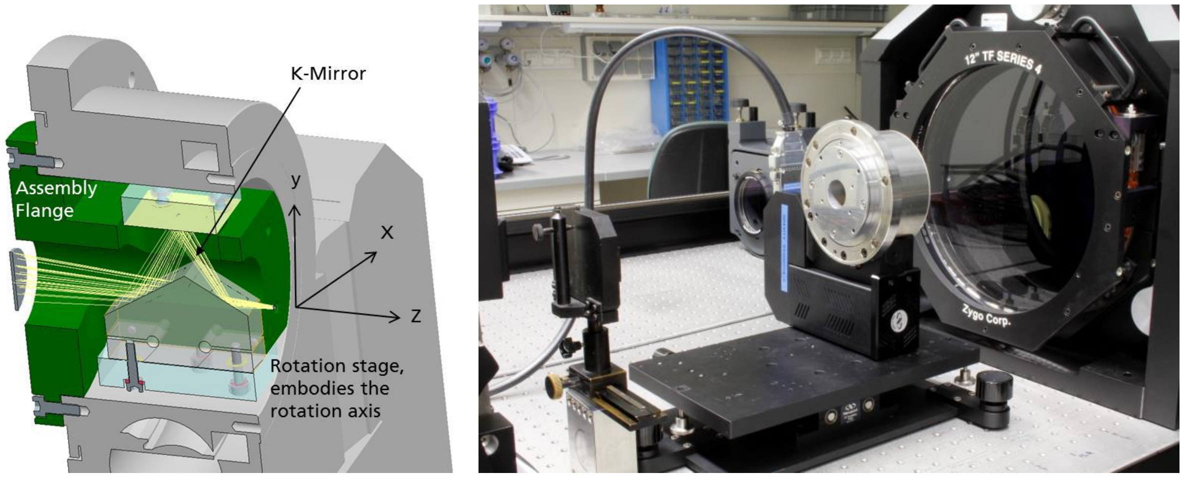

Fig. 6. Left: de-rotator with K-mirror assembly; Right: interferometric test setup for system alignment

III. CONCLUSION:

The thermal expansion properties of silicon particle reinforced aluminum material as a mirror bulk material and electroless nickel as a polishing layer for metal optics were investigated in the temperature range of -185 °C to 100 °C. It could be demonstrated that the CTE of both materials can be tailored to 1×10^{-6} K^{-1} or less. The resulting minimized bimetallic bending and the increased specific stiffness open up a significantly wider working temperature range compared to nickel plated Al6061 solutions. The deformation characteristics under the influence of thermal gradients as well as deformations introduced by mounting forces still need to be considered carefully. The possible application of AlSi40/NiP under cryogenic condition was demonstrated.

Well-developed technologies including diamond machining, local polishing and figuring techniques, and optical coating can reasonably be applied on nickel plated AlSi40 mirrors and structure elements made of AlSi40. Results are confirmed by realizing high precision TMA mirrors for the PCW space mission. Reference strategies for minimizing the system alignment and assembly effort were successfully applied on a de-rotator system. Current activities are focusing on additive manufacturing processes to realize extreme light-weight structures in aluminum substrates.

ACKNOWLEDGEMENTS

The research is supported by the Max-Planck-Gesellschaft and the Fraunhofer Gesellschaft under the "Research and Innovation Pact".

The metal optics for the PCW space mission was realized under a subcontract from ABB Canada.

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