Glass Technology for the next generation X-ray optics: Report on polishing tests on Shell#4 with INAF-OAB Zeeko machine

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Scope of the document

The scope of the document is to report the activities performed on the Shell#4 in INAF-OAB after the breakage. After the breakage of the shell#4 in LT-Ultra, for opportunity reasons it has been decided to continue the polishing work on this shell instead of starting a new one from integration phase. Given that the resources to restart the grinding campaign in LT-Ultra were not available, the results to be presented in the Lynx trade off selection process were judged primary.

Change record

Issue	Description of changes	Date
1	First emission of the document	11-09-2018

Reference Documents

RD1	BCV report	TN2000_2
RD2	Marta M. Civitani, Stefano Basso, Mauro Ghigo, Joanna Holyszko, Giovanni Pareschi, Gabriele Vecchi, Giancarlo Parodi, Kiran Kiranmayee, Jacqueline Davis, Ron Elsner, Doug A. Swartz, "Lynx optics based on full monolithic shells: design and development (Conference Presentation)", Proc. SPIE 10699, Space Telescopes and Instrumentation 2018: Ultraviolet to Gamma Ray, 1069911 (10 July 2018); doi: 10.1117/12.2313541; https://doi.org/10.1117/12.2313541	
RD3	Civitani, M.M., Basso, S., Citterio, O., Holyszko, J., Ghigo, M., Pareschi, G., Parodi, G., Toso, G.Vecchi, G., “Thin fused silica shells for high-resolution and large collecting area x-ray telescopes (like Lynx/XRS),” Proc. SPIE 10399-31 (2017).	
RD4	Vecchi, G., et al., “A bonnet and fuid jet polishing facility for optics fabrication related to the E-ELT,” Mem. S.A.It. 86, 408 (2015)	
RD5	M. M. Civitani, J. Hołyszko, G. Vecchi, "Probing 3M™ Trizact™ abrasive pads in the polishing and super-polishing phase of Fused Silica", Proc. SPIE 10706, Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation III, 107063K (2018);	

Acronyms

BF: Best Focus
DC: Constant removal
FOV: Field-of-View
HEW: Half Energy Width
ISW: Invar Spoke Wheel
IP: Intersection Plane
MM: Mirror Module
MS: Mirror Shells
OOR: Out-of-Roundness
PTV: Peak-to-Valley
Rq: Root Mean Squared
RT: Ray-Tracing
σ: Interface Width (square sum of interfacial roughness and interfacial diffuseness)
SSD: Sub Surface Damage
SSS: Shell Support System
TBD: To Be Defined
T/M: Thermal-Mechanical
$\varnothing_{MIN}$: Exit pupil
$\varnothing_{MAX}$: Entrance pupil
WS: Wolter-Schwarzschild
W1: Wolter-I

INAF Istituto Nazionale di Astrofisica / (Italian) National Institute for Astrophysics
OAB Osservatorio Astronomico di Brera / Brera Astronomical Observatory

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1 Introduction

The development of Shell#4 started in 2013 on the basis of a standard Wolter-I design. In order to overcome the problems faced with Shell#7 and to reach sub arc-sec performances, the production flow of the shell has been partially modified and a final step with IBF was envisaged, as it could account the requested figuring accuracy. The polishing of the shell wasn't completed mainly due to lack of funds. The work on this shell has been restarted in 2017 thanks to a dedicated founding program of the Italian Space Agency (ASI). The summary of the activities and the final status of the shell are reported in [6]. The original SSS was composed of two rings made of Borofloat glass, hosting three couples of metallic connections. The stiffness of this structure was poor and deformations were induced on the mirror shells during the different fixation phases. An additional interface to the SSS was introduced in order to overcome this problem. This Invar Spoke Wheel (ISW) was designed to follow the manufacturing process of the shell (grinding, polishing, X-ray calibrations) up to the final integration in the spider. The increased stiffness of the system prevents the deformations on the shell, for example, when it is transferred from the lathe to the jig for x-ray calibration. The activities on the shell restarted from the grinding phase. As the OOR to be corrected was not that high, it has been decided to operate starting from the D20 grinding wheel, which guarantees an acceptable removal rate without degrading too much the micro-roughness. At the end of the grinding phase, as the metrology on the lathe is relatively simple, a bonnet polishing has been applied directly on the lathe in order to reduce the SSD. The lathe configuration was modified and a dedicated mixing device at controlled temperature was purchased for the slurry distribution. A mechanical interface has been prepared for the fixation of the Bonnet tools on the spindle. Unfortunately, the shell was broken due to a wrong carriage movement, during the metrological phase of the last run of bonnet polishing. The breakage passes through the shell height completely. An UV curing adhesive was used to fix the shell and the initial plans were changed. Due to the shell fracture, it was not possible to operate on all the shell, as the pitch tool could be damaged passing above the fracture. A limited test of the next polishing phases was carried out on an azimuthal portion of the parabolic section. Then the shell was dismounted from the lathe at the beginning of august 2017.

2 Polishing activities with Zeeko @INAF-OAB

At the beginning of 2018, the test activities restarted by means of the available equipment in INAF/OAB laboratories, with the aim of complete the figuring of an azimuthal segment of the shell#4. The Zeeko IRP1200 was used both for Bonnet polishing and both for the pitch polishing. A new set-up, based on the interferometry approach, was prepared for the metrology of the shell.

Given that the weight of the overall assembly (Shell + SSS + ISW) was about 80 kg, it has been decided to keep the ISW fixed on the Zeeko rotary table and move only the Shell in the SSS for the metrology. The connections between the ISW and the SSS were changed to spacers allowing a kinematic mount. In figure 1 is shown the spoke wheel on the Zeeko rotary table: this part remained fix on the machined and only the original SSS with new spacers were transported in the adjacent room for metrology.

Figure 1: (A) The invar spoke wheel fixed on the Zeeko with new interfaces spacers to allow kinematic repositioning. (B) The system to dismount the shell from the Zeeko.

2.1 Bonnet polishing configuration

In the past, IRP600 Zeeko machine was used to polishing the Shell#7. Even if the geometry of the new shell#4 is pretty similar, the mechanical constrains on this new IRP1200 Zeeko machine are different. Moreover, as the area to be polished was limited to an azimuthal segment, the set-up and the procedure had to be revised.

In general, the polishing of the internal surface shell is operated combining the rotation of the rotary table and movement of the arm, in vertical and radial direction to follow the conical angle of the surface. Moreover, the bonnet tool is driven on the surface with a precession angle. Given that the machine works on the dwell time, the tool path is generated from the Zeeko software, based on the geometry of the surface and of the error to be removed. Moreover, the tool patch follows the real relative alignment between the surface and the bonnet, in such a way that the applied offset is constant on the surface. The greater is the offset is applied toward the surface, the higher will be the removal rate. Given that the shell is thin and changes shape when pressed, the maximum allowable offset has been derived in terms of maximum radial allowable deformation. This corresponds to a maximum load, which was derived by mechanical simulations. Taking into account that some margin was taken due to the lack of experimental data on the glass strength, the velocity of the process could be higher in the future, when the data relevant to the material characterization will be available.

Due to the presence of the breakage on the shell surface, only an azimuthal section of the shell has to be figured. This kind of geometry is not considered in the options available in the Zeeko software. A reverse engineer approach was used in order derive, from the standard case of a complete revolution surface, the basic inputs for the process (like precession angle, commanded relative positions for the robotic arm path), which were used to generate a custom G-code for the operations. Probing the surface in different positions, the position and the alignment of the surface segment have been reconstructed and accounted for a constant offset application. The tool path was set to a raster scan, moving along rows, and starting from the top. The rotary table movement drove the scan of each row, with inversion of the motion at the edge of the azimuthal section. The passage between rows was handled in the same area. In the pre-polishing phase a constant removal was requested, so that the relative velocity between the surface and the tool was the same in all the area. The tool path for the pitch polishing was generated in a different way. A number of azimuthal positions have been randomly generated. In correspondence of each of them, the pitch tool was driven up and down along the vertical axis following the conical angle with radial corrections. The number of strokes, their amplitude and the position of the center of oscillation could be defined. The azimuthal scan are repeated back and forth a defined number of times. Given the randomization on the angles, each scan is independent from the previous one.

Figure 2 shows that the robotic arm of IRP1200 fits the shell#4 with a margin of a few millimeters. Nevertheless, the working condition is very safe, as the approaching and the departure phase are based on the same G-code, which drives the polishing. The movements of the robotic arm are given in terms of positions and orientations in the machine system reference. Once checked a first time, the operations can be realized automatically. This is a very safe condition with respect to the procedure adopted on the lathe, where the movements at the beginning and at the end of the machining had to be commanded in manual way. The breakage of the shell#4 occurred during one of these phases.

In the past activities with IRP600 Zeeko and in bonnet polishing phase experienced on the lathe, the R40 Bonnet tool was used in the figuring. It guarantees a good removal rate with a footprint of around 1 Centimeters Square. Given the different sizing of the robotic arm of the IRP1200 Zeeko machine, the usage of the R40 bonnet became impossible. A smaller bonnet (R20) was the only possibility to fit the size of shell (figure 3). The removal rate of the R20 is a factor four lower with respect to R40, with a considerable increase of the polishing time. Due to mechanical interference, the standard precession angle (20° with respect to the vertical) was not implementable and an alternative configuration was used. The precession angle was reduced to 10° and set in horizontal with respect to the surface. In general, the lower is the precession angle, the lower is the expected micro-roughness. As a drawback, the removal rate is lower. With a further reduction of a factor two due to the lower precession angle, the process was a factor eight slower. In figure 4 the bonnet tool final configuration in the shell is shown. In figure 5 the polishing configuration adopted on the parabolic and hyperbolic side are reported.

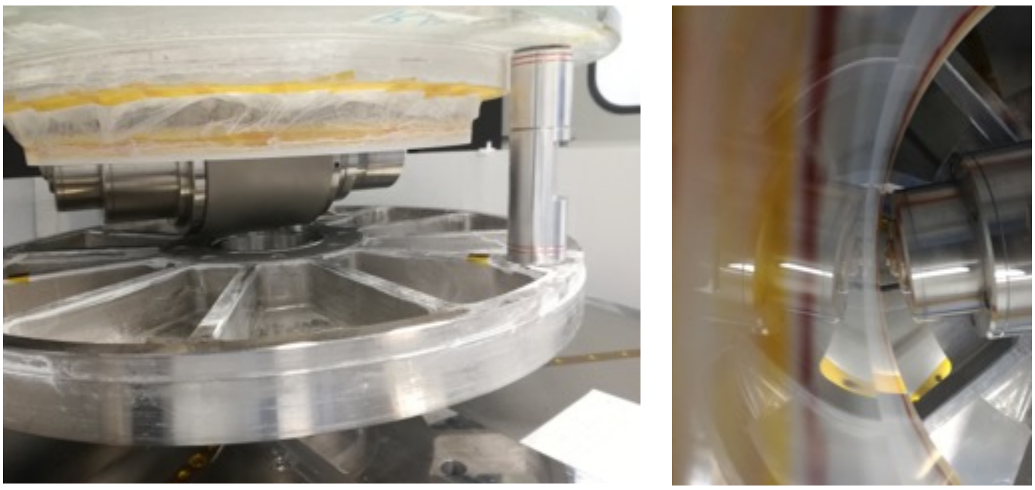

Figure 2: The Zeeko IRP 1200 fit the shell configurations for few millimeters.

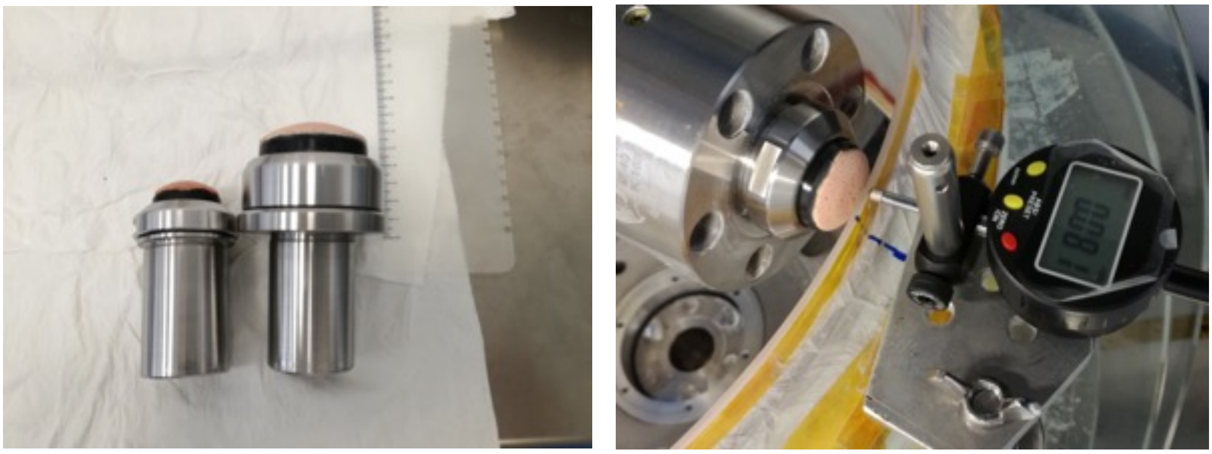

Figure 3: (A) The comparison between Bonnet tool R20 and R40. (B) The procedure to determine the offset to be applied.

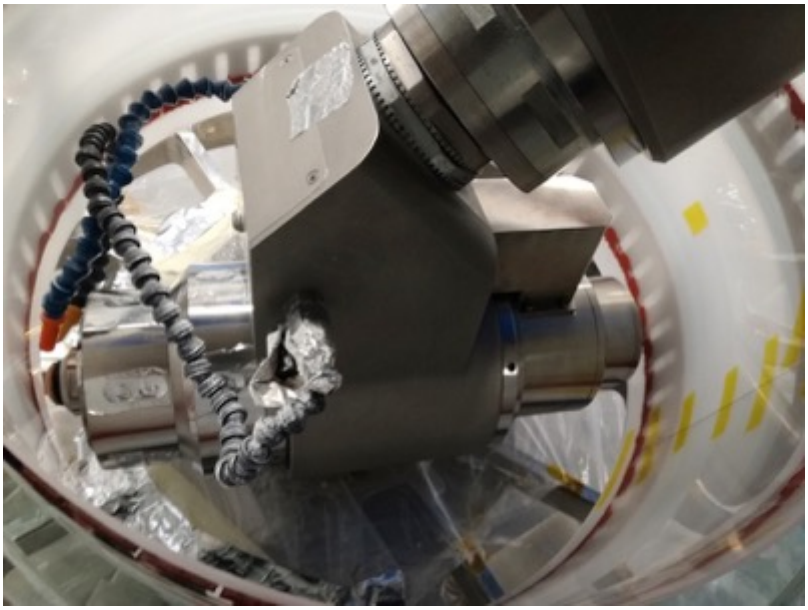

Figure 4: The Zeeko IRP1200 equipped with the Bonnet R20 is used @INAF/OAB to polish an azimuthal segment of the shell#4. Given the relative size of the shell and of the robotic arm, the accommodation of the shell was not simple. The precession angle is reduced to 10° and set in horizontal direction. In this way the shell fits with few millimeters margin. The breakage occurred on the lathe is visible on the right

Figure 5: Configuration for polishing activity with Bonnet tool R20 on the shell#4. On the right, the set-up used on Parabolic side, on the left the protective system implemented on Hyperbolic side to prevent slurry sputtering outside the shell.

2.2 Pitch tool smoothing configuration

The smoothing procedure has been used with the same process tested on the lathe. A pitch tool with a layer of Trizact 3M has been fixed with bi-adhesive (Figure 6). The linear stage, used on the lathe to allow the high frequency oscillations of the pitch tool, is too heavy to be mounted on the Zeeko robotic arm. So, the pitch tool movement was driven directly by the Zeeko carriages (Figure 7). As a consequence, taking a minimum margin on the maximum carriage velocity, the resulting oscillation frequency is a factor 10 lower. Therefore, the results achieved in this configuration should be scaled for temporal assessment considerations. The length of the stroke has been increased to 5 cm and the length of abrasive area reduced to 80 mm.

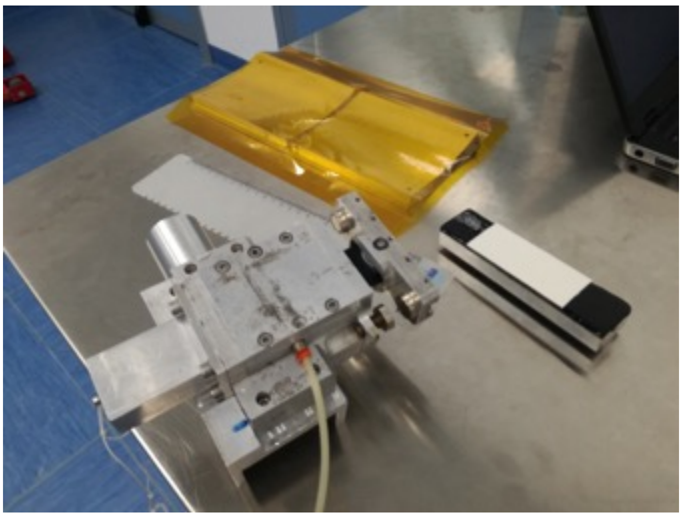

Figure 6: Pitch tool configuration for the polishing on the Zeeko machine.

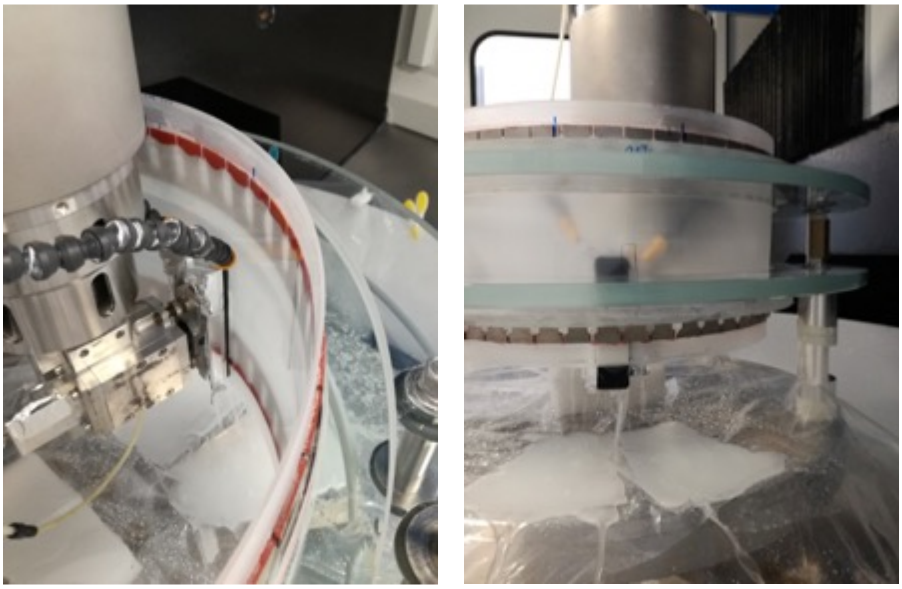

Figure 7: The pitch tool equipped with TRizact 3M^{TM} is fixed on the robotic arm of the Zeeko machine and the vertical carriage movement has been used to move the tool up and down.

3 Results

The list of the polishing run performed is reported in table 1.

RUN N#	SURFACE	TOOL	TIME (HOURS)	OFFSET
1	par	r20	5	150 micron
2	par	r20	5	150 micron
3	par	r20	5	150 micron
4	par	r20	5	150 micron
1	hyp	r20	5	150 micron
2	hyp	r20	5	150 micron
3	hyp	r20	5	150 micron
4	hyp	r20	5	150 micron
5	hyp	r20	5	150 micron
6	hyp	r20	5	150 micron
7	hyp	r20	5	150 micron
8	hyp	r20	5	150 micron
9	hyp	r20	3,5	150 micron
10	hyp	r20	3,5	150 micron
11	hyp	Tr1:80x3.5	1	5 mm
12	hyp	Tr1:80x3.5	5	5 mm
13	hyp	Tr1:80x3.5	5	5 mm

RUN N#	SURFACE	TOOL	TIME (HOURS)	OFFSET
14	hyp	Tr1:80x3.5	6	5 mm
15	hyp	Tr1:80x3.5	6	5 mm
16	hyp	Tr1:80x3.5	6	4 mm
17	hyp	Tr1:80x3.5	6	4 mm
18	hyp	Tr1:80x3.5	6	4 mm
19	hyp	Tr1:80x3.5	18	4 mm
20	hyp	Tr1:80x3.5	24	4 mm
21	hyp	Tr1:80x3.5	6	4 mm
22	hyp	Tr1:80x3.5	6	4 mm
23	hyp	Tr1:80x3.5	24	4 mm
24	hyp	Tr1:80x3.5	24	4 mm
25	hyp	Tr1:80x3.5	4,27	4 mm
26	hyp	Tr1:80x3.5	17,5	4 mm
27	hyp	Tr1:80x3.5	4,27	4 mm
28	hyp	Tr1:80x3.5	17,5	4 mm
29	hyp	Tr1:80x3.5	4,27	4 mm
30	hyp	Tr1:80x3.5	17,5	4 mm
31	hyp	Tr1:80x3.5	24	4 mm

3.1 Micro roughness evaluation

The micro-roughness has been evaluated with MFT 10x on the scale of 1 mm (see figure 8). The rms and the PtV of the micro-roughness maps acquired on 1 mm scale are reported in Figure 18. The values correspondent to the last run of Bonnet polishing were around 12 nm rms. This is an improvement with respect to the pre-polishing operated on the lathe (when the process converged to around 25 nm rms due to the slurry density deposition) and it is mainly due to the reduction of the waviness on the mid-frequencies scale. 47 hours were spent in total for this pre-polishing phase. The polishing with the Trizact converged quite rapidly in terms of micro-roughness. In the figure the rms is halved in one hour and then arrives to around 2 nm in 6 hours total. The process converges to around 1 nm rms in 17 hours.

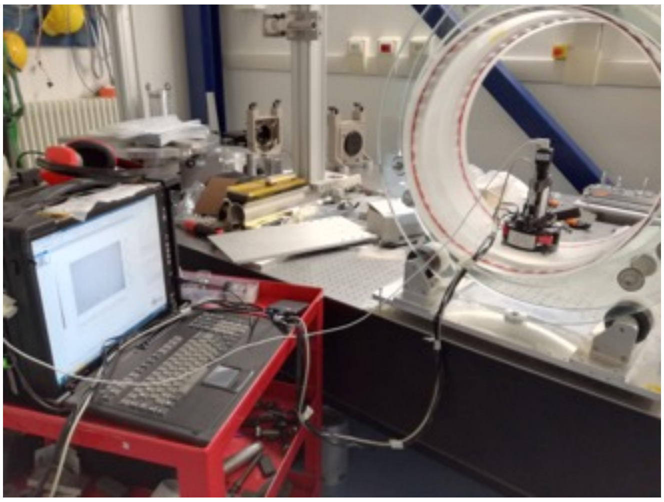

Figure 8: MFT measurement configuration

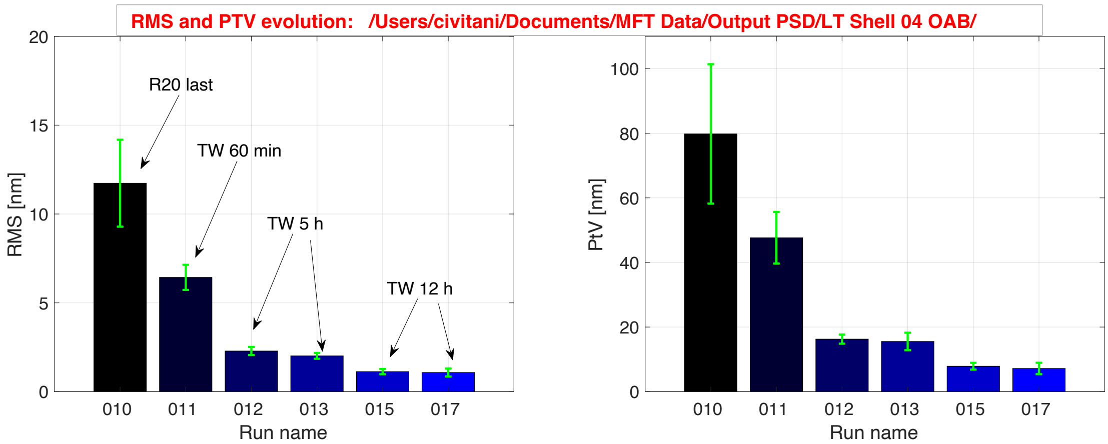

Figure 9: MFT 10x measurements results in terms of rms and PtV during the TRizact polishing phase. First data is relevant to the status of the segments after the last Bonnet polishing run. After around 20 hours the process converge to around 1 nm rms.

3.2 Interferometry set-up for mid-frequencies evaluation

The longitudinal profiles have been measured with Zygo interferometer. The set-up is shown in figure 10. The collimated beam passes trough a cylindrical lens and reflected with a flat mirror at 45° before hitting the surface of the shell. This kind of metrology is feasible, in dependence of the amplitude and the amount of mid-frequencies present on the surface. In particular, during the first part of the smoothing, it returns only qualitative assessments. A new system, which combines the Out-Of-Roundness profilometer measurements with an optical probe and longitudinal scan acquired with the interferometer, is under study and could be build starting from the available equipment.

With respect to the mid-frequencies smoothing, in the current configuration, the time scale is quite long. The fringes pattern during the measurement with the interferometer of one of the last polishing run is reported in figure 11 (left). The mid-frequencies features are localized in the edges of the considered segment. The reconstructed error map is shown in figure11 (center), colour map is in nanometres. The evolution of one profile extracted from the maps corresponding to the last four polishing runs is shown in Figure 11 (right). The smoothing effect is visible but the process is not completed. As each of these runs lasts 24 hours, the convergence of the process is at the moment still quite slow. The low frequency error is almost stable for the most part of the area. Given that the micro-roughness level is already sufficiently low, in the next weeks a first trial of ion beam figuring will be tried with the aim of verifying that the shell mounting scheme, the set-up and first evaluations on the problems which could arise from the generated heat and from the back-sputtering. Then, the figuring of the segment will be completed, with respect to the mid-frequencies smoothing and to the final correction of low frequency errors with the ion beam. In figure 12 the status of the azimuthal segment before the IBF is shown.

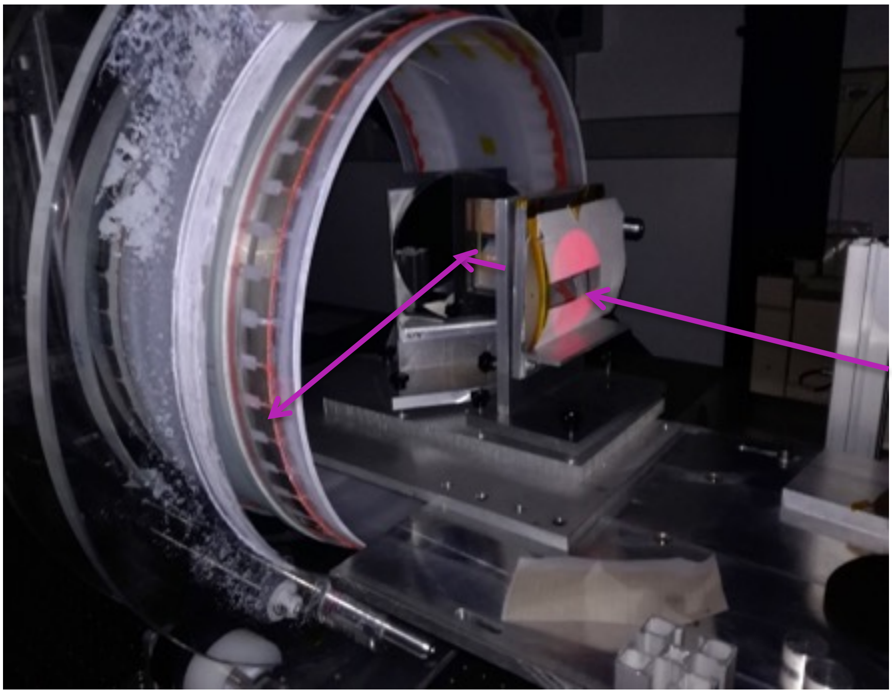

Figure 10: The metrological set-up used at INAF/OAB to control the smoothing process during the polishing.

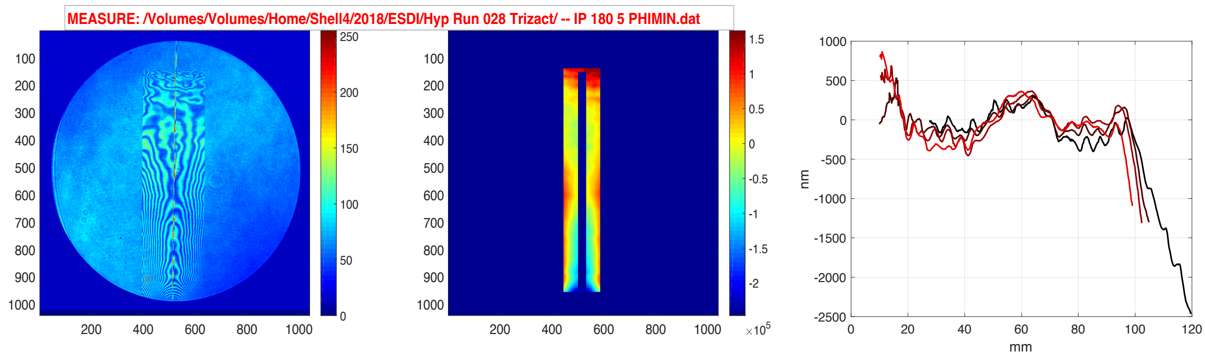

Figure 11: (left) The fringes pattern during the measurement with the interferometer. (center) The reconstructed error map. (right) The evolution of one profile extracted from the maps corresponding to the last four polishing runs.

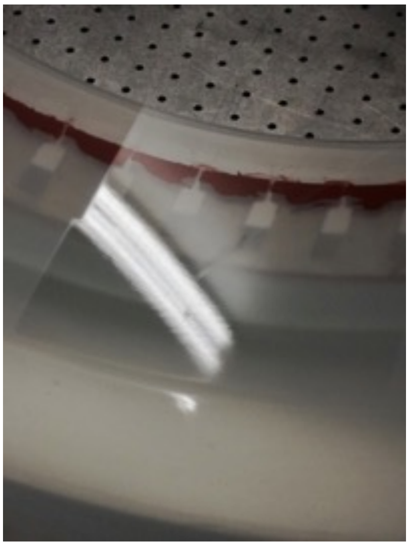

Figure 12: The azimuthal section of the shell before the IBF test.

4 Conclusions

Due to a breakage on one section of the shell, the polishing configuration is not straightforward as the azimuthal symmetry guarantees for full shells. Nevertheless, in order to have a clear process overview, the figuring of a section started from an area of the hyperbolic section, which experienced only the grinding phase. After some preliminary test on the parabolic side, we proven the Bonnet pre-polishing step with the Zeeko IRP1200 machine, available at INAF/OAB, realizing an ad-hoc tool path for an azimuthal raster scan. The mid-frequency smoothing, implemented directly on the machine robotic arm, is in progress but runs quite slowly due to the equipment constrains. As the up-grade of the IBF facility was completed, with the introduction of a rotary table and of a new ion gun compatible with the size of the shell, the IBF will be tested on this azimuthal sector.