Figuring sequences on a super-smooth sample using ion beam technique

Jean-Phillippe Tock[a], Jean-Paul Collette[a], Patrick Gailly[a], Dirk Kampf[b]

[a] Centre Spatial de Liège – Université de Liège Parc Scientifique du Sart-Tilman,
Avenue du Pré-Aily, B-4031 ANGLEUR, BELGIUM
Phone : +32 4 367 66 68 ; Fax : +32 4 367 56 13 ; Email : jptock@ulg.ac.be.

[b] Kayser-Threde GmbH, Wolfratshauser Str. 48, D-81379 MUNICH GERMANY
Phone : +49 89 724 95 171 ; Fax : +49 89 724 95291 ; Email : kd@kayser-threde.de.

ABSTRACT

An ion beam figuring facility is operational at the Centre Spatial de Liège since 1997. Its present capabilities are described. An extensive characterisation programme is running in order to determine the optimised parameters for various materials and operating conditions. In this frame, tests have been performed on a spherical gold-coated aluminium mirror plated in between with nickel. The nickel plating was used to be super-polished to a BRDF of 1 10^{-4} at 1 deg at 10 µm wavelength. Micro-roughness and etching rate measurements were realised and influence of ion bombardment on the coating has been established after removal of the gold coating. The gold coating removing was performed by using the ion beam flux.

Finally, the mirror has been figured from the original sphere to a parabola. Surface characteristics evolution is also described in terms of micro-roughness and surface error.

An overview of the research and development programmes related to this facility is given. Results of this technique and potential impact on optics fabrication are then briefly exposed.

Keywords : ion beam figuring, optical fabrication, super polishing.

1 INTRODUCTION

Ion figuring systems have been used for more than 10 years[1] to figure high quality optics of various materials and dimensions. The ion beam figuring process consists in removing matter by transfer of kinetic energy from the argon ions coming out of the ion source to the substrate atoms. It is comparable as having a material removing tool with a Gaussian shape. This profile is very stable and could be reproduced with a high accuracy. Thanks to these characteristics, a deterministic figuring process is made available. The removal function is strongly dependant on the source parameters (type of gas, dimension, current intensity,...), on the substrate type (size, shape, material, ...) and on the facility itself (vacuum chamber geometrical characteristics, pressure,....).

CSL (Centre Spatial de Liège) has developed a laboratory ion beam figuring facility in order to study this process in details. The facility and its main capabilities are given in the next chapter. A wide research and development programme aiming to characterise ion beam figuring process with various materials and in various operating conditions is currently running at the CSL.

In this frame, a figuring sequence was run on a super-smooth sample. This mirror is a spherical gold-coated aluminium mirror plated in between with Nickel. The nickel plating was used to be super-polished to a BRDF (Bi-directional Reflectance Distribution Function) of about $1\ 10^{-4}$ at 1 deg at a wavelength of 10 µm. This kind of mirror is typically used in infrared applications.

The full figuring sequence is given in details. At each step, surface characteristics in terms of micro-roughness and surface error are given. At the end, potential impact and results achieved with this technique on optics fabrication are exposed briefly. In collaboration with a local optics manufacturer, an industrial ion beam figuring facility is under development to accommodate larger optics of more than 1-meter diameter.

2. ION BEAM FIGURING FACILITY

The ion beam figuring facility has already been described[2] but its main characteristics are reminded hereafter. The vacuum chamber is 1.4 m high and has a diameter of 1.2 m, giving an internal volume of about 1.5 m_. A turbo-molecular pumping system is installed on the chamber. The overall facility is located in a class 10 000 cleanroom. Substrates up to 200 mm diameter could be accommodated in the facility on a translation stage. A hollow cathode ion source of 3 cm diameter is fixed on a 4-axis motion system. Argon is used but other neutral gas such as Krypton or Xenon could also be employed. The maximum current is 100 mA and the beam energy could be adjusted from 50 eV to 1200 eV. No cooling is required for this source.
Metrology instruments are also part of the facility : interferometers, interferometric microscope used as a profilometer, ... Examples of utilisation of this microscope are given in reference 3. Picture 2.1 gives an overview of the facility. The ion beam vacuum chamber is on the left with its control system in the middle; the interferometric microscope is on the right. Its computer system is not shown.

Picture 2.1 : Ion Beam Figuring Facility : general view

3. SUPER-SMOOTH SAMPLE

The sample (see picture 3.1) was an aluminium mirror of 70 * 64 mm_ useful surface. It was figured to a sphere of 795 mm radius of curvature. The optical axis is tilted by 3.9° with respect to the mechanical interface plane. The aluminium substrate had been plated with Nickel then polished to the required microroughness. Finally, it was gold coated.

Picture 3.1 Sample in its mechanical interface

4. FIGURING SEQUENCE

4.1 Overview

The ideal figuring sequence is given in figure 4.1. It is necessary to know accurately the removal function. It is assumed that this function is measured on a witness sample. A reference interferometric surface measurement is done then the ion source is positioned for a pre-determined time (a few minutes) on this sample. After this, a second reference interferometric surface measurement is performed. The difference between the two measurements gives the removal function. Other techniques could be used to determine the erosion profile. If the substrate material and operating conditions are known, a beforehand stored profile could be used, if it is available. The availability of a library with various removal functions is leading to savings of time and a witness sample is not necessary any more. In parallel, the initial substrate shape is measured and, taking the goal shape into account, the removal material function is computed. Introducing the removal function parameter in the software, the dwell times and ion source trajectory are computed. This step demands dedicated software. After this, figuring sequence on the substrate is performed and a last interferometric surface measurement is done to check the figuring process. As this is a very deterministic and predictable process, no further iteration is expected.

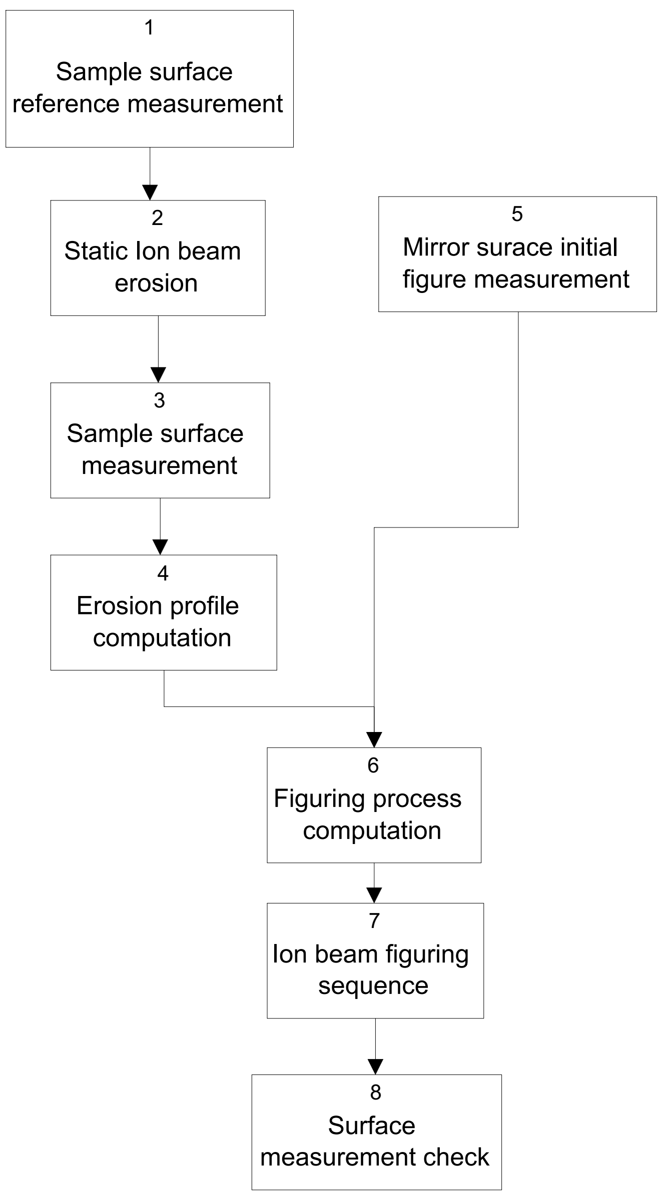

Figure 4.1 : Nominal ion beam figuring sequence

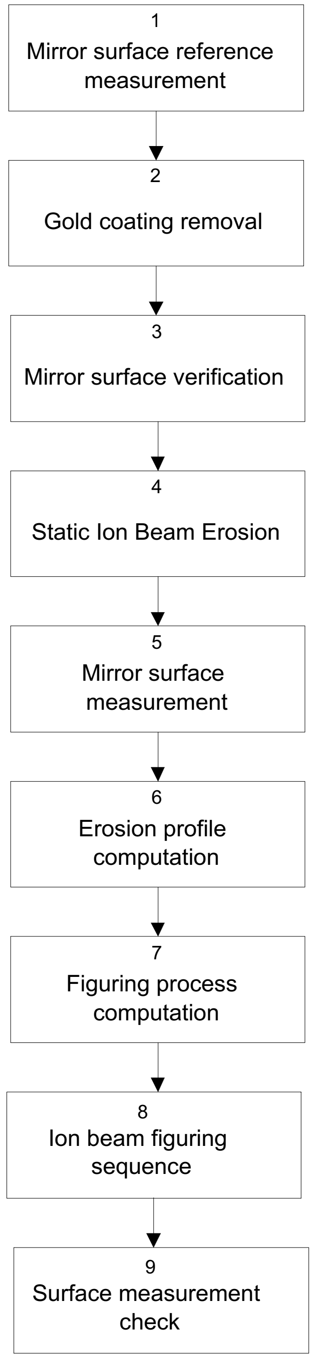

Figure 4.2 : Actual specific ion beam figuring sequence

In the case of this specific sample, no removal function was available because most of the tests previously performed by CSL were performed on glass materials : BK7, Zerodur, ... as developed in the paper reference[1]. Data on metallic substrates were available but not for this one. It is always better to check the BRF on the actual material. This mirror was a unique piece ; so no witness sample to measure the erosion profile was available. As it is mandatory to characterise the erosion profile, the substrate was usedfor this purpose. By bombarding the substrate, a small crater was created in the mirror. This crater was considered as default to be corrected during the subsequent figuring process. The erosion profile extends up to 100 (TBC) mm in diameter. The mirror being small compared to this (diagonal of 95 mm); the static ion bombardment was not performed on the centre of the mirror but slightly shifted. Moreover, gold coating of about 100 nm was present on the substrate. The material thickness to remove was more than the gold coating thickness so it was decided to remove it completely. This was done with the ion gun. Finally, the mirror was figured to a parabola close to the initial sphere. The actual figuring sequence is presented in the flowchart in figure 4.2.

4.2 Mirror surface reference measurement

As explained in paragraph 4.1, it is necessary to measure the surface figure with a high accuracy. It must be noticed that the measurement accuracy is presently the limiting factor in the overall process achievable performance. A ZYGO Mark IV interferometer was used. To match the radius of curvature, a spherical lens was used with the following characteristics : 100 mm diameter, f-number 1,5. The measured sphere radius was 795 mm. It was decided to figure a parabola close to this sphere. The chosen parabola focal length is 396.8 mm. This is illustrated in figure 4.2 where the amount of material to remove is shown. The parabola equation is corrected by a constant factor to have an erosion depth of 0 mm on the border. This function assumes that the initial sphere is perfect.

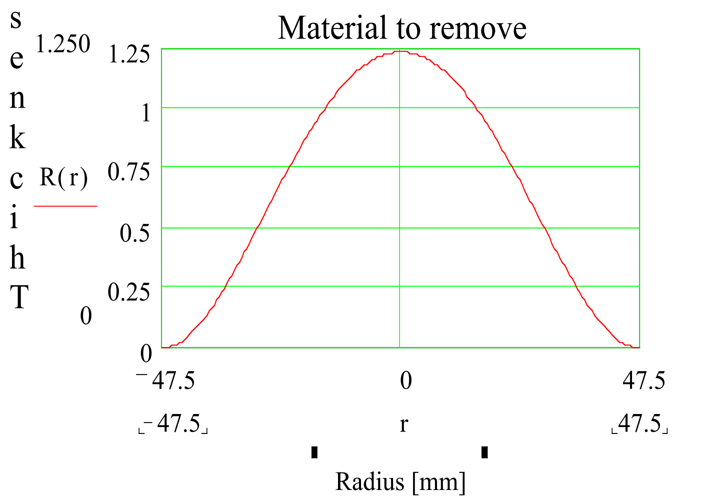

Figure 4.3 : Material thickness to remove

The initial surface micro-roughness was measured with the WYKO interferometric microscope. Several measurements were performed. The average RMS value is 13.40 ± 0.55 Å. A typical result is given in figure 4.4. The objective used is a 10 X, corresponding to a field of view of 612.3 * 462.3 µm_. The lateral sampling is about 0.8 µm. though the microscope is installed on an air-isolating table, low residual vibrations are still present. To increase the measurement quality, each result is the average of 8 consecutive measurements, giving a reproducibility of about 0.2 Å on the RMS value.

4.3 Gold coating removal

The initial mirror gold coating was about 0.1 µm thick but the material thickness to remove is at least 1.2 µm. To avoid to work on two different materials, it was decided to remove the gold coating by performing a uniform bombardment of the mirror. Micro-roughness remained stable after this short exposure to ion flux. An RMS value of 13.40 ± 0.20 Å was obtained. The mirror surface was measured again interferometrically to get a reference for the determination of the erosion profile.

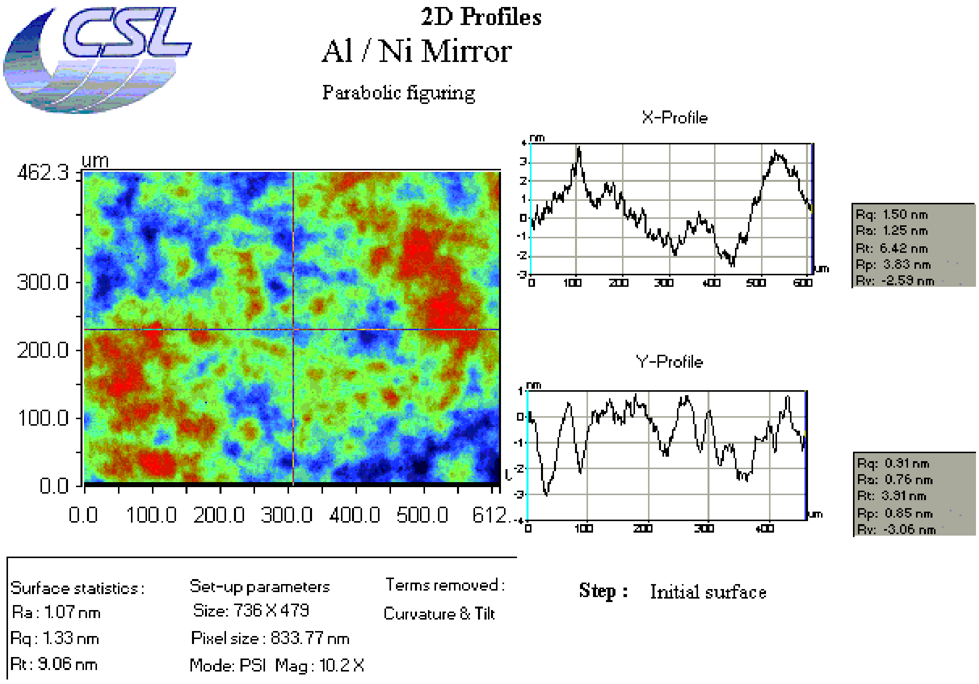

Figure 4.4 : Initial surface analysis

4.4 Static ion beam erosion

As no witness sample is available to perform a test to determine the Beam Removal Function (BRF), the mirror itself is used for this purpose. In view of the shape to figure where a maximum of material must be removed at the centre of the mirror, it is decided to perform a static shooting close to the middle of the mirror. A few minutes bombardment was performed. The mirror was measured again after this erosion. The BRF was computed by analysing the difference between the two surface measurements. The BRF is approximated by a Gaussian shape of this type :

$$BRF(x) = A_{MAX} * e^{-\frac{1}{2}\left(\frac{x}{\Delta}\right)^2}$$

where the two parameters A_{MAX} and Δ are determined by a least mean square fitting algorithm.

Microroughness is again measured and was still the same : RMS value of 13.17 ± 1.25 Å. The higher dispersion is probably due to the fact that the eroded thickness is varying along the mirror surface.

4.5 Ion beam figuring sequence

Using the mirror surface measurement performed after static erosion to take into account the actual mirror surface and introducing the target shape as defined in §4.2 and the BRF determined in §4.4, the amount of material to remove is computed. A 3D view is given in figure 4.5.

Based on this shape, the dwell times and ion gun trajectory are computed. An additional uniform thickness removal is allowed. The effects are that the achieved figure is better but the amount of material removed is higher and so the figuring time also. The optimum uniform thickness quantity is given by the software.
The software is also able to estimate the figuring time and to make a simulation of the optical quality of the results. Figure 4.6 shows the material actually removed during the ion beam bombardment. The difference between the foreseen removed material

and the actually eroded material is given in figure 4.7. In the middle, the error is much smaller than on the borders. This is probably due to a kind of edge effect. This is not a mechanical edge effect because this figuring method is a non-contact one.

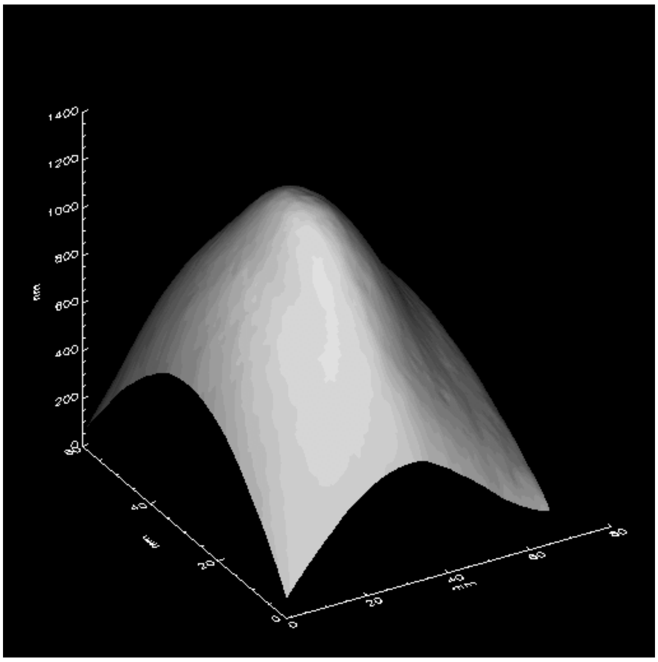

Figure 4.5 : computed material thickness to remove [nm]

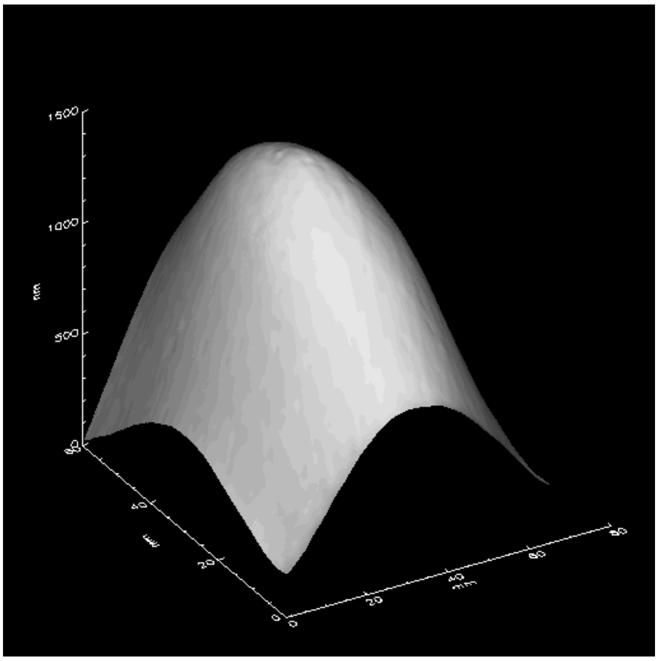

Figure 4.6 : material actually removed [nm]

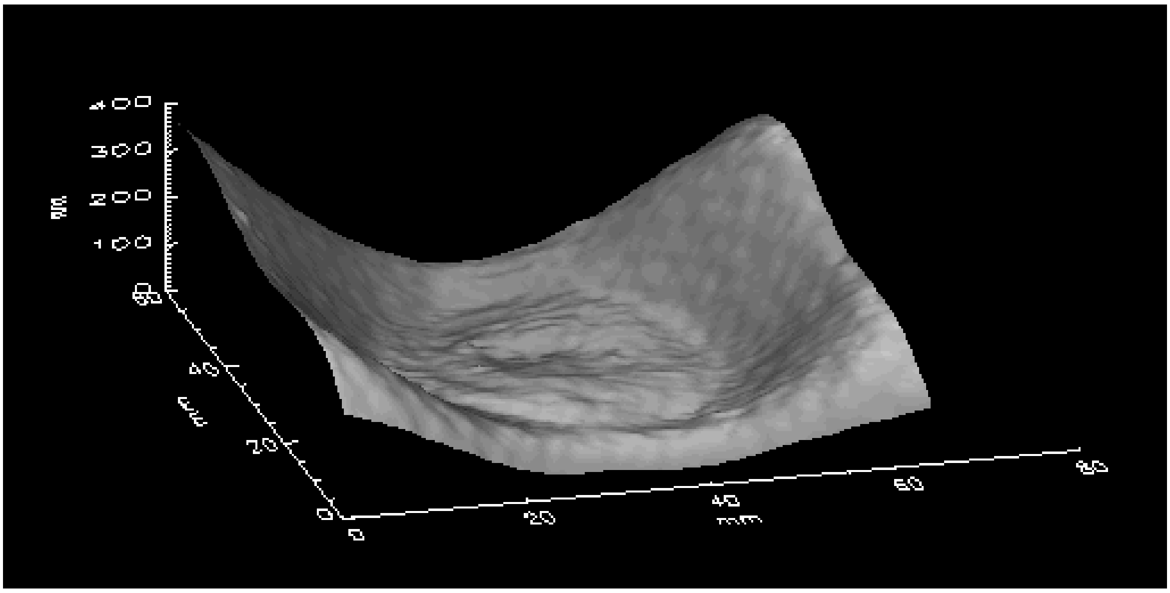

Figure 4.7 :
difference between material to remove ideally and material actually removed during the ion beam figuring process [nm]

Table 4.8 presents a summary of the results of the final figuring sequence. The values given are the surface “errors” with respect to the defined ideal parabola.

Surface error (λ=633 nm.)	Before figuring	After figuring : Simulated	After figuring : Measured
PV [λ]	2.54 λ	0.49 λ	0.61 λ
RMS [λ]	0,54 λ	0.08 λ	0.13 λ

Table 4.8 : Surface error evolution

The convergence factor is defined as the ratio between the error before and after figuring and the efficiency is the ratio between the actually achieved conversion factor and the theoretical one coming out of the simulation. They are given in table 4.9.

Convergence factor	Theoretical	Achieved	Efficiency [%]
PV	5.0	4.2	83
RMS	11.3	7.8	70

Table 4.9 : convergence factor

This efficiency is not as high as previously achieved results on other samples. This is due to the bad erosion on the edge of the mirror. One probable cause is that the sample size (width of 64 mm) is of the same order of magnitude as the beam size (grids of 30 mm diameter). This "edge effect" is known and solutions exist and are studied to avoid it to ensure a perfectly constant BRF on the entire mirror surface. To improve this, it would be interesting to work with a smaller beam. If only the central part is considered, the efficiency is reaching more than 90 %.

Microroughness was measured at the end of the figuring sequence to 15.63 ± 0.30 Å, resulting in an increase of about 2 Å. This slight degradation was not observed on previous samples. Careful analysis of the interferometric microscope images revealed parallel scratches as present on figure 4.10. Theoretical and experimental verifications demonstrated that their origin is not the ion beam figuring process. The probable origin is the diamond turning performed on the nickel in an earlier step (see Y profile on figure 4.10).

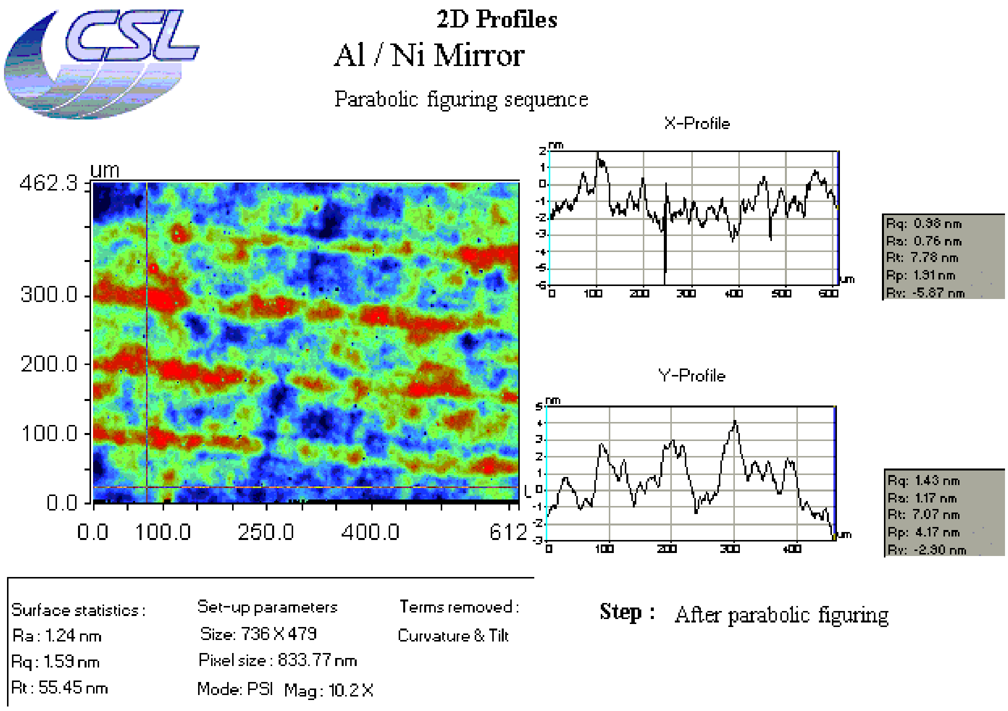

Figure 4.10 : Surface after ion beam parabolic figuring

Microroughness evolution is summarised in the table 4.11. The same procedure was applied for each of these measurements.

Microroughness	Ra[1] [Å]	Rq[2] [Å]	PTV [Å]
Initial	10.67 ±0.50	13.40 ±0.55	106.8
After gold removal	10.65 ±0.15	13.40 ±0.20	153.1
After erosion profile	10.13 ±0.70	13.17 ±1.25	203.4
After figuring	12.20 ±0.15	15.63 ±0.30	467.0

$$^{1}\ Ra = \frac{\sum |Z_i|}{N} \quad \& \quad ^{2}\ Rq = \sqrt{\frac{\sum Z_i^2}{N}}$$

where Z_i is the profile height deviation with respect to the mean surface and N is the number of pixels.

Table 4.11 : Microroughness evolution

5. SCHEDULE

For external reasons, a tight schedule had to be followed though several aspects were new for the CSL team. It was the first time that, in this facility, :

1. A non-circular mirror was used. Software modifications were necessary to consider this aspect. A dedicated basic mechanical interface was designed and built for this purpose. It was realised in advance and a fitcheck was done at the mirror delivery at CSL.
2. Such a low F-number mirror has never been figured in the facility.
3. A parabola was figured out of a sphere

Despite all these new aspects, the complete sequence including gold removing, BRF determination, microroughness and surface measurement was performed in less than 3 working days.

6. CONCLUSION

The ion beam figuring facility available at Centre Spatial de Liège (CSL) has been briefly presented. A real figuring sequence on a super-smooth mirror was described. By figuring a parabola out of a spherical mirror, undeniable potential of this technique in general and of this facility in particular has been demonstrated. The hardware and software versatility and the staff competence are illustrated by this real size shaping. Measurements of micro-roughness and optical surfaces were extensively realised during this sequence.

The present facility has shown that, although its fisrt objective was research and development activities, it was perfectly usable as an industrial tool for small size optics. This equipment is a solid basis for deeper research activities and also for figuring of specific small optics. For what concerns large optics, a fully industrial ion beam figuring facility is under development at AMOS and will be available by the end of 1999.

7. ACKNOWLEDGEMENTS

The authors wish to thank the CSL team involved in the development, tuning and operation of this facility that was used to get these valuable results.

This work was supported by “Direction Générale des Technologies, de la Recherche et de l’Energie” of the “Région Wallonne”, in Belgium. Development of the ion beam figuring facility is realised in collaboration with AMOS company.

8. REFERENCES

1. Allen L.N. and H. W. Romig, “Demonstration of an ion figuring process”, in Advances in Fabrication and Metrology for Optics and Large Optics, Proc. SPIE 1333, 22-33 (1990).
2. P. Gailly, J.P. Collette, L. Renson, J.Ph. Tock, “Ion beam figuring of small BK7 and Zerodur optics : thermal effects”, paper 3739-17, Europto Conference, Berlin May 1999
3. J Ph Tock, “Characterisation of various optical surfaces using a WYKO interference microscope”, European Metrology Users Meeting, Solvay, Brussels 1999