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Probing 3M™ Trizact™ abrasive pads in the polishing and super-polishing phase of Fused Silica

M. M. Civitani[a1], J. Hołyszko[a2], G.Vecchi[a]

[a]INAF-OAB, Via E. Bianchi 46, 23807 Merate (LC), Italy

ABSTRACT

The use of 3M™ Trizact™ diamond tiled abrasive pads was proven as a cost-effective pre-polishing technique. Thanks to the low subsurface damages introduced it allows to speed up the polishing phases, reducing the amount of material to be removed. Nowadays, different kind of abrasive pads are available on the market and some of these are dedicated to the last phases of the surface finishing. In this paper, we present the results obtained with 3M™ Trizact™ Hookit™ Film Disc 268XA as last step of the polishing phases. The test activity has been carried out on fused silica samples prepared with initial R_q around 50 – 70 nm. In particular, we focused on the wear rate of the pads, the material removal rate and the micro-roughness evolution, in dependence of several parameters as the amount of water, pH, velocity and pressure. The removal rate depends on the status of the abrasive pad and on the polishing conditions, while the micro-roughness of the surface can be decreased well below 1nm rms on millimetre scale. Moreover, a combined process of bonnet pre-polishing followed by 3M™ Trizact™ polishing has been proven as a cost-effective solution to realize super-polished optical surfaces.

Keywords: Fused silica, polishing, Bonnet polishing, 3M^{TM} Trizact^{TM}

1. INTRODUCTION

In order to increase the speed and to reduce the costs of optical surface production, new methods of grinding and polishing have been explored in the last years. The usage of 3M™ Trizact™ diamond tiled abrasive pads has been proven as cost-effective pre-polishing technique. Thanks to the low subsurface damage it allows to speed up the polishing phases, reducing the amount of material to be removed [1, 2]. Different kind of abrasive pads are now available on the market and some of these are dedicated to the last phases of the surface finishing.

In this paper, we present the results we obtained with 3M™ Trizact™ Hookit™ Film Disc 568XA CeO damp as last steps of polishing phases of fused silica samples. Thanks to the smallness of its average grain size, the cerium oxide particle is one of the most effective abrasive in the final polishing steps of glass. Moreover, 3M™ Trizact™ Hookit™ Film Disc 568XA uses micro replication technology: tiny pyramids of abrasive mineral and then coated on a film backing. As these pyramids wear out, fresh and sharp mineral is continually exposed so that a consistent and predictable cut is expected. Nevertheless, as long as the pyramids wear out, other effects could impact on the abrasive performances in the opposite direction. The effective contact area of the pad increases, reducing the pressure applied. The amplitude of the gaps between pyramids reduces, hampering the fluid distribution. The microscope images of the cerium oxide pyramids in the abrasive pad at the beginning and after some polishing time are shown as example in figure 1-1.

An operative advantage of this kind of abrasive is that simple demineralized water can be used to lubricate the surface. Furthermore, in our experience, the usage of additional slurry did not improve the results. On the contrary it introduced all the cleanliness problems, which could significantly slow down the process. This is particularly true when complex supporting system are necessary for the surface under polishing, as it could be the case for very thin substrates.

[1] Corresponding author: marta.civitani@brera.inaf.it
[2] Moved to Officina Stellare S.r.l., Italy

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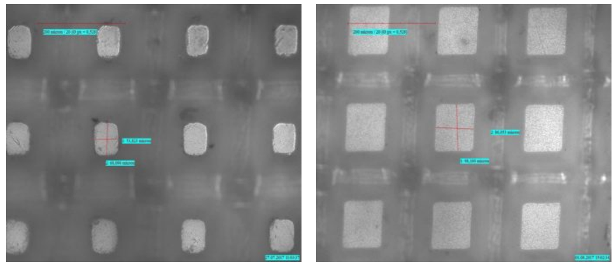

Figure 1-1: Status of the cerium oxide pyramids of 3M™ Trizact™ Hookit™ Film Disc 568XA CeO damp in different conditions: 'new' and 'used'

We focused on 3M™ Trizact™ Hookit™ Film Disc 568XA and we tested it on fused silica samples prepared with a starting micro-roughness of the order of 50 - 70 nm rms. We characterized the removal rate and the micro-roughness improvement rate in dependence of several parameters as amount of water, pH, velocity and pressure, taking care also of the wear rate of the pads. Moreover, we tested the 568XA in combination with 3M™ Trizact™ Hookit™ Film Disc 268XA (as suggested by the vendor, see figure 1-2), and on pre-polished samples with Bonnet tools. Paragraph 2 reports the test configuration while the results of the characterization activities are illustrated in paragraph 3. In paragraph 4, we show the results achieved on larger samples, while paragraph 5 reports the ones obtained on samples pre-treated with bonnet polishing. The conclusions are detailed in paragraph 6.

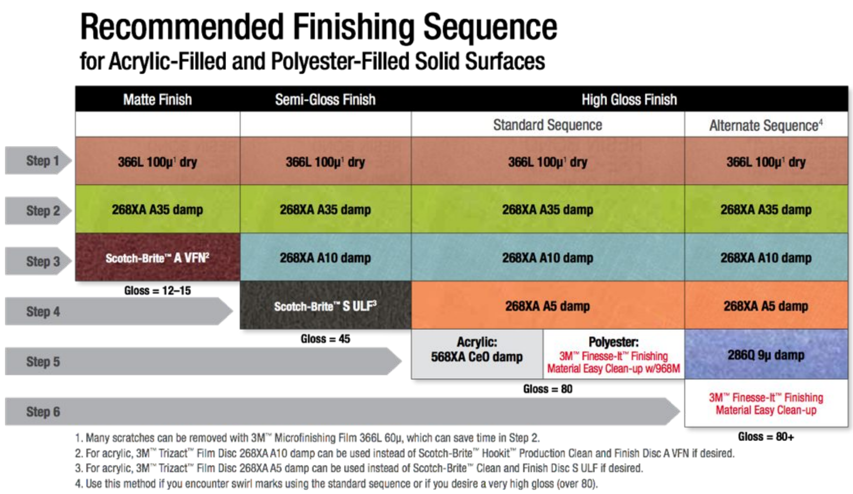

Figure 1-2: Recommended finishing sequence by the vendor (3M^{TM}).

2. TEST CONFIGURATION

As the characterization process was dedicated to a specific application [3], the test set-up was chosen to be as much as representative of the final set up, both in terms of sample initial status and in terms of sample-tool relative motion.
The polishing process has been tested on Fused Silica samples with an initial surface micro-roughness of around 50 -70 nm rms. The sample disks were 5 mm thick and 200 mm in diameter. They were fixed to a supporting plate moving in vertical direction with a velocity of 1000 mm/sec. In order to optimize the available space and performing different tests on each of the samples, two opposite area of 1 cm x 2 cm were polished for each of the test cases. The 3M™ Trizact™ Hookit™ Film Disc 568XA was fixed in two strips near the edges of a pitch tool. The abrasive was fixed with an additional bi-adhesive layer (1 mm thick). An example of the final configuration is reported in figure 2-1A, where the 3M™ Trizact™ Hookit™ Film Disc 268XA is shown together with the footprint of the expected central part of the polished area on the sample mask.

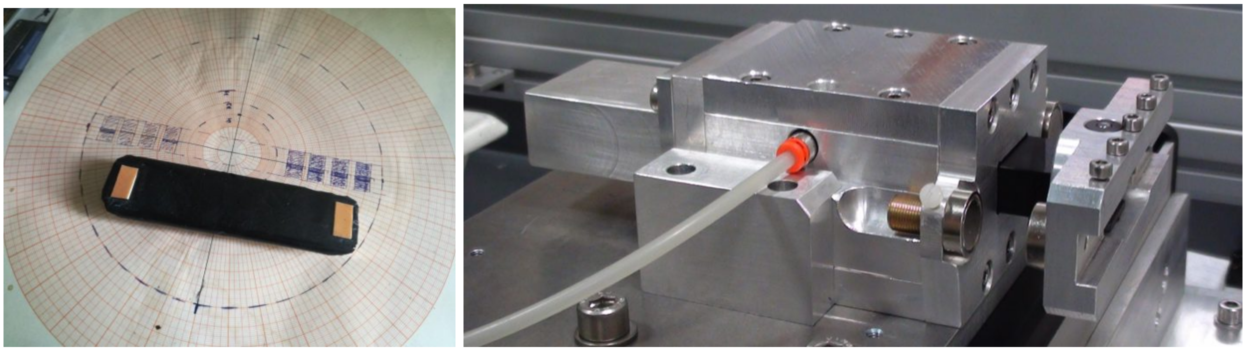

Figure 2-1: (A) The 3M™ Trizact™ Hookit™ Film Disc 268XA pad TO is fixed at the edge of a pitch tool with bi-adhesive layers. (B) The pitch tool is held by an air bearing carriage: the pressure is regulated changing the distance of magnets.

The pitch tool was moved in horizontal direction by a linear stage, which allowed an oscillatory movement (2 mm amplitude) with frequencies up to 15 Hz. The surface under polishing was in vertical configuration with the water flowing from the top of each of the two areas. The pressure was applied with a couple of two opposite magnets acting on an air bearing stage. The knowledge of the calibration curve between the magnets distance and the applied force allowed the proper setting of the system. In figure 2-1B the pitch tool supporting system is reported.
In order to characterize the polishing process, several polishing runs were repeated in different conditions. The test cases are listed in table 1. For each of them, the status of the surface and of the abrasive pads were checked at fixed temporal steps. At each step, several parameters were monitored:

- Surface micro-roughness. It was measured with Micro-Finish Topographer (MFT) 10x [4] on a scale of 1 mm. Three measurement points were acquired on each polished areas.
- Material removal rate. It was monitored with ZYGO measurements. A final measurement with a profilometer was acquired to determine the full depth of the removed material.
- Wear of the abrasive pad. An image of the surface of the 3M™ Trizact™ Hookit™ Film Disc 568XA pad was taken with Normasky microscope 10x. The lateral sizes of the pyramids were determined from these images.

After a initial assessment on the results, the unitary temporal step was set to 3 min. Multiples of this time scale were considered in the latest part of the polishing procedure. The reference force was set to 2 kg and dedicated tests were performed to check for the linearity.
Examples of the ZYGO measurements are shown in figure 2-2. On the left side, the area under polishing is getting deeper along as the polishing runs proceed. On the right, the vertical and horizontal profiles are extracted from the map to infer the removal rate. We checked the constancy of the removal rate by fitting linearly the depth of the polished area.
In figures 2-3, 2-4 and 2-5 we display the maps on the surfaces acquired with the MFT 10x in one of the test cases. Each of the lines corresponds to the six measures taken at each of the polishing step (three measurement points for each of the two polished surfaces). On the right side of the figure, we show the PSD calculated along the horizontal direction.
Figure 2-3 refers to the surface during polishing with 3M™ Trizact™ Hookit™ Film Disc 268XA: as no major differences were observed between after 6 min and 9 min polishing time, both in terms of surface micro-roughness and surface quality, the duration of the pre-polishing with 3M™ Trizact™ Hookit™ Film Disc 268XA, when applicable, was set to 9 min.
Figure 2-4 and 2-5 refer to 3M™ Trizact™ Hookit™ Film Disc 568XA polishing steps. The surface micro-roughness was improving at each of the steps starting from around 50 nm rms down to below 1 nm rms. The traces of the pyramids are visible in some of the maps of the last line. Given the fast movement in the horizontal direction, the pyramids print-through can be avoided by removing the pitch tool from the surface abruptly while outside of the polished area.

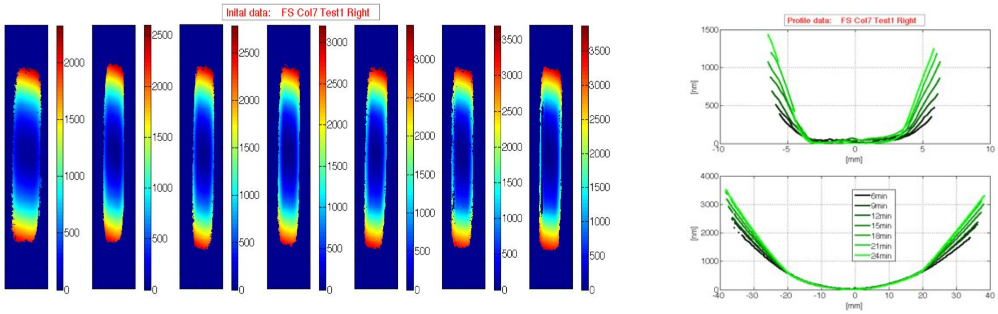

Figure 2-2: (A) ZYGO maps on one of the polished area at different polishing steps. (B) The horizontal and the vertical central profiles are extracted from the maps in order to check for the removal rate constancy. The colour scale is adjusted to show the latest data in light green.

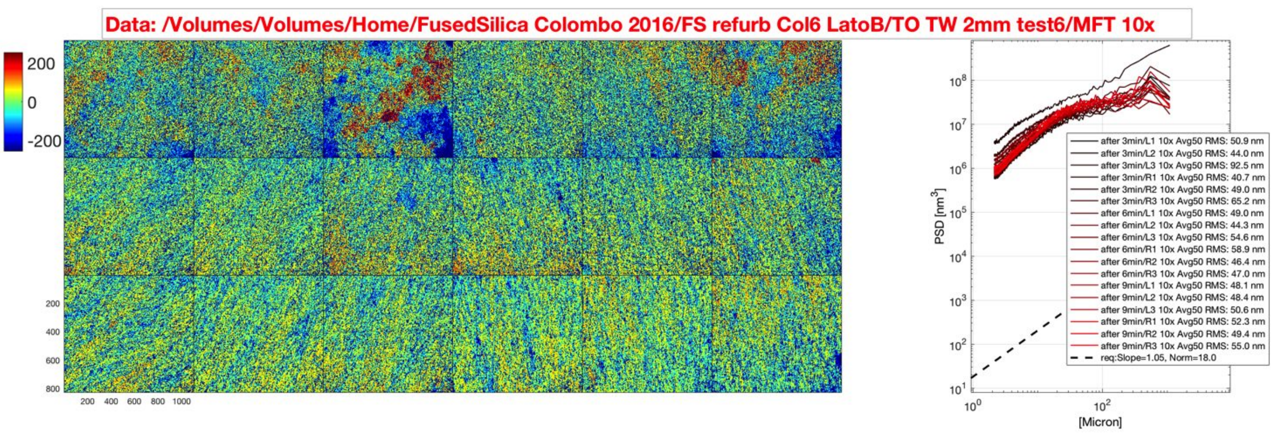

Figure 2-3: MFT 10x maps acquired during polishing with 3M™ Trizact™ Hookit™ Film Disc 268XA. Each row of six maps contains the data corresponding to a polishing step of 3 min. The average Power Spectral Density (PSD) for each of the map is reported on the right panel. The RMS of the different maps are reported in the legend.

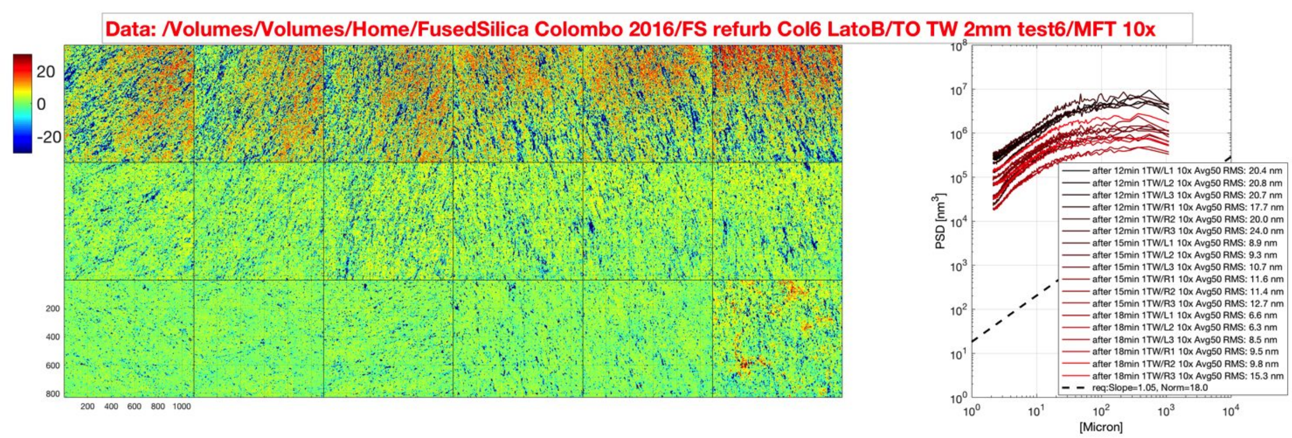

Figure 2-4: MFT 10x maps acquired during polishing with 3M™ Trizact™ Hookit™ Film Disc 568XA. Each line contains the data corresponding to a polishing step of 3 min. The average PSD for each of the map is reported on the right panel. The RMS of the different maps is reported in the legend.

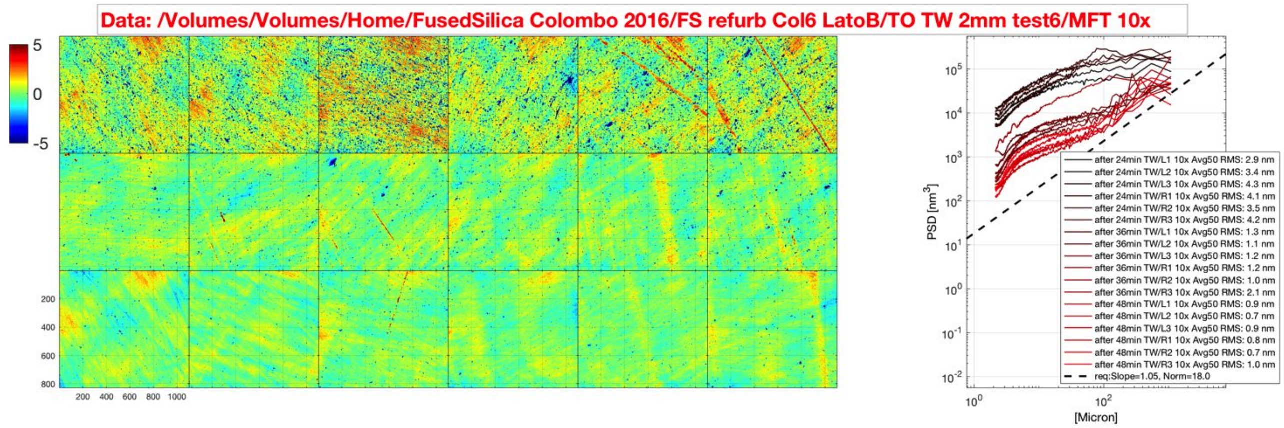

Figure 2-5: MFT 10x maps acquired during polishing with 3M™ Trizact™ Hookit™ Film Disc 568XA. Each line contains the data corresponding to a polishing step respectively of 6 min, 12 min and 12 min. The average PSD for each of the map is reported on the right panel. The RMS of the different maps is reported in the legend.

Some defects were still remaining on the surface. They are visible in blue as holes, even if the overall micro-roughness is below 1 nm rms. The presence of this kind of defects is traced by the residual Peak to Valley (PtV) error of the micro-roughness values. The PtV values are in the range of 100 - 200 nm.

3. TEST RESULTS

The complete list of the polishing tests is reported in table 1. For each of the twelve test cases, the table reports the setting of different parameters: the force applied, the frequency of the horizontal oscillation, the temporal steps at which the process was monitored, the total polishing time, the status/sequence of the abrasive, the water amount and pH. The removal rate in terms of nm/min was calculated from the maximum depth of each polished area (12 mm x 60 mm) divided for the total polishing time. When applicable, we took into account also the amount of material removed with 3M™ Trizact™ Hookit™ Film Disc 268XA. In the column reporting the temporal steps for the process monitoring the characters in bold refers to this preliminary phase.

In the first three test cases, the polishing started directly with 3M™ Trizact™ Hookit™ Film Disc 268XA. The first two test cases were dedicated to verify if the polishing time scales inversely with the force: in test#1 the force was set to 2kg, while in test#2 it was reduced to 1 kg and the polishing time doubled. The removal rate doubles when the force is doubled. Moreover, the results in terms of micro-roughness are not equivalent as the process with 1 kg converges to around 3 nm RMS while it appears still improving, in the equivalent time, applying 2 kg force.

As anticipated in the previous paragraph, the abrasive changes its status in time. The third test case was dedicated to verify the performance of 'used' abrasive pad. In this case, the removal rate is 30% lower with respect to the reference test case (#1) and the polishing was interrupted after three steps, as the overall convergence was low.

In order to verify if the initial quality of the surface had an impact on the results, a pre-polishing with 3M™ Trizact™ Hookit™ Film Disc 268XA was introduced. From a general point of view, this step is part of the suggested polishing sequence by the vendor. This pre-polishing was carried out for test cases between #4 and #10. As reported in the previous paragraph, a total of 9 min with 3M™ Trizact™ Hookit™ Film Disc 268XA was carried out in order to converge on the surface micro-roughness of around 50 nm rms.

The introduction of this additional pre-polishing step decreased the removal rate of the 3M™ Trizact™ Hookit™ Film Disc 568XA of around the 25% (Test#4 results). In this configuration, the results achieved scaling the time with the force became equivalent in terms of micro-roughness (Test#4 and Test#5). As this pre-polishing step turned out to be effective, it was carried out in all the remaining test cases.

Table 1: Test cases considered and parameters. In the table TO indicates 3M™ Trizact™ Hookit™ Film Disc 268XA, while TW refers to 3M™ Trizact™ Hookit™ Film Disc 568XA.

Test	Force (kg)	Tool Horiz. Freq. (Hz)	Temporal steps for measurements	Total Time (min)	Description	nm/min	nm/min
1	2	15	3,6,9,12,15,18,21,24	24	TW	81.3	
2	1	15	6,12,18,24,30,36,42,48	48	TW	39.3	
3	2	15	6,12,18	18	TW old		57.5
4	2	15	**3,6,9**,12,15,18,24,36,48	48	**TO** + TW (ref)		52.2
5	1	15	**6,12,18**,24,30,36,48,60,72	72	**TO** + TW (1kg)		10.0 (tot)
6	2	15	**3,6,9**,12,15,18,24,36,48	48	**TO** + TW (water 2x)		30.9
7	2	15	**3,--,9**,12,15,18,24,36,48 up to 120	48	**TO** + TW (Ph 4)		20.9 (tot)
8	2	5	**--,27**,36,45,54,72	72	**TO** + TW (1/3 freq)		33.6
9	2	15	**--,9**,12,15,18,24,36,48	18	**TO** + TW (Ph 10)		48.9
10	2	15	**--,9**,12,15,18,24,36	36	**TO** + TW new		60.7
11	2	15	**--, 30**	30	**TO** (up to end)	145.3	
12	2	15	**--, 9**	9	**TO**	147.3	

As explained in the previous paragraph, an automatic system, based on a peristaltic pump, irrigated the polished region with drops of demineralized water. In order to verify if the amount of water had an impact on the results, the input of water was doubled in test#6. In this configuration we achieved the best results in terms of micro-roughness, with final values below 0.8 nm RMS, but the removal rate was observed 40% lower.

The effect of the water pH was checked with test#7 and test#9. The water pH was turned respectively to acid (pH4) and to basic (pH10). In both cases the improvement rate of the micro-roughness was worsen, with a final rms of 2-6 nm and PtVerrors of the order of 200-300 nm.

As the removal rate of the 3M™ Trizact™ Hookit™ Film Disc 568XA decreases with its usage, the test#10 was dedicated to check its performance when used in its original condition. In this case, the removal rate was about 20% higher with respect to the value determined without the pre-polishing phase.

The removal rate of 3M™ Trizact™ Hookit™ Film Disc 268XA has been measured almost 2.5 times greater than the value of the 3M™ Trizact™ Hookit™ Film Disc 568XA on the same surface condition and remained independent from the abrasive status.

In figure 3-1 the average values for the PtVerror and the RMS are shown as derived from the MFT 10x maps at each of the temporal steps. Several measurements were carried out for each of the step, therefore, the error bars were derived from it. When pre-polishing phases with 3M™ Trizact™ Hookit™ Film Disc 268XA have been carried out, the temporal scale of the data has been shifted on the left, so that all the curves with 3M™ Trizact™ Hookit™ Film Disc 568XA begin at the same temporal step. Moreover, the time scale of test cases with 1 kg force or smaller oscillation frequency has been scaled as a simple linear relationship was expected. The values of temporal steps are divided by two for Test#2 and Test#5 (they corresponds to 1 kg force), while they are divided by three for Test#8 (the oscillation frequency is one third of the reference one). Square bullets are reporting data of polishing tests carried out without pre-polishing.

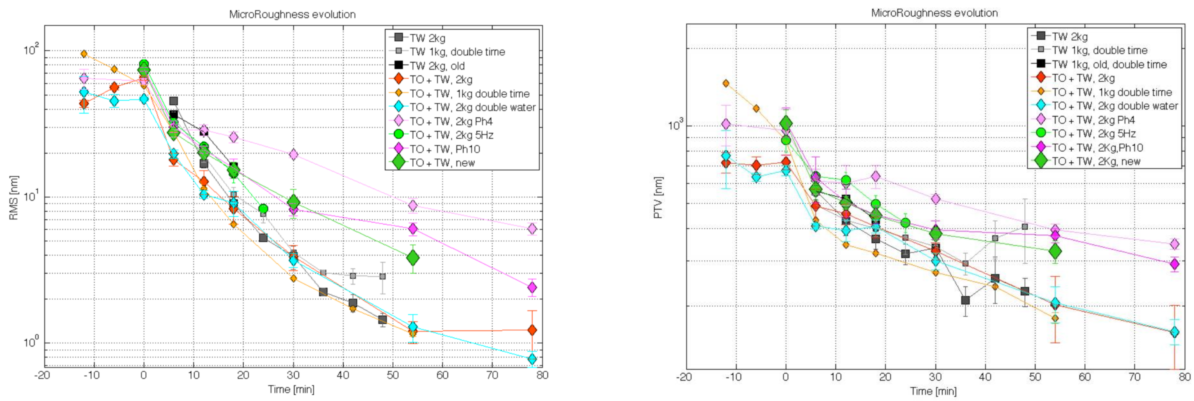

Figure 3-1: Micro-roughness as measured with MFT 10x on 1 mm scale. For each of the temporal steps used in the process characterization, the temporal scale has been scaled assuming simple inverse relation with force and oscillation frequency. (A) RMS and corresponding error bars (B) Peak to Valley and corresponding error bars.

There are some differences in the overall trends in micro-roughness improvement:

- When the polishing sequence starts directly with 3M™ Trizact™ Hookit™ Film Disc 5XA (light grey data), the micro-roughness converges to higher values (around 3nm Rq), unless higher pressure is used (dark grey).
- The usage of old 3M™ Trizact™ Hookit™ Film Disc 568XA in the first part of the process decreases the improvement rate (data in black).
- The achieved results are almost equivalent in terms of force/time relation if a pre-polishing with 3M™ Trizact™ Hookit™ Film Disc 268XA was performed.
- pH4 and pH10 worsen significantly the final expected micro-roughness with respect to standard de-mineralized water (pH7) (pink and violet data).
- The usage of new 3M™ Trizact™ Hookit™ Film Disc 568XA at each step does not increase the improvement rate in the first part of the polishing neither the expected final results (green data). Best micro-roughness results are achieved when the pyramids are worn out.
- Reducing the force or the oscillation frequency and scaling accordingly the time is equivalent.
- Best results are achieved with a pre-polishing with 3M™ Trizact™ Hookit™ Film Disc 268XA, with higher pressure setting and doubling the amount of demineralized water.

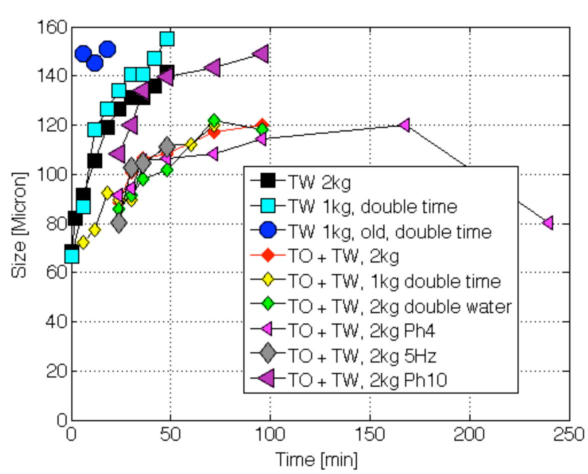

Figure 3-2: 3M™ Trizact™ Hookit™ Film Disc 568XA wear out: evolution of the pyramids size in the test cases.

As explained in paragraph 2, the wear out of the abrasive was monitored at each of the polishing steps. In figure 3-2 we show the evolution curves for each of the test cases relevant to 3M™ Trizact™ Hookit™ Film Disc 568XA (Test#1 to Test#10). Also in this case the time has been scaled out in an overall equivalent time. The initial lateral size of the pyramids is around 70 microns. When the pre-polishing with 3M™ Trizact™ Hookit™ Film Disc 268XA is not performed, the wear out of the pyramids is faster and converge to around 150 micron. In all the other cases, the size of the pyramids converges to around 120 microns apart for the case of pH10, when the observed behaviour is pretty similar to the first cases. This is in accordance with the data acquired on the removal rate, which was lower in this particular case. Form a general point of view, it follows that the size of the pyramids does not have an impact on the removal rate. Instead it has an impact on the micro-roughness. Used abrasive pads bring the better results.

4. RESULTS ON EXTENDED POLISHED AREA

The effectiveness of the polishing process was tested on larger samples. As in the previous tests, the polishing tool is an aluminium pad (130 mm x 30 mm), with a pitch layer previously conformed to the glass surface. Instead of localizing the abrasive pad in small areas, the pitch tool was completely covered with a layer of abrasive. As the length of the tool area was larger than the maximum size of the available abrasive pad, the abrasive layer has been divided in two parts with a diagonal cut to smash out the features, which could be introduced on the surface by the tool movements.
The process was started directly with 3M™ Trizact™ Hookit™ Film Disc 268XA, but the abrasive was changed twice during the process in such a way that the improvement rate remained constant for all the runs. As in the previous test cases, the tool movement choices were limited. The sample is forced to go up and down in vertical direction with a velocity of 1 m/s, while the polishing tool is moving in the horizontal direction.
The polishing process was repeated on different samples changing the setting of this horizontal movement and the abrasive disposition with almost equivalent results [3] in terms of micro-roughness improvement rate. On the other hand, differences are visible in the final micro-roughness results, as we decided to interrupt the process at different stages.
In figure 4-1 some examples of the micro-roughness are reported as measured in the last run (Run 12) on the sample polished for the largest time (80 hours). The three images refer to different scales, respectively 200 micron, 1 mm and 4 mm, with measured R_q values of the order of 0.3 nm, 0.6 nm and 1.2 nm. The wave pattern on the 200 microns scale is re-conducible to the print-through of the pyramids pattern, while the residual waviness on the 4 mm map is due to the oscillation at high frequency of the polishing tool. These results are well in line with the improvement rate as expected from the results presented in the paragraph 3, if scaled for a factor 10.5 to take into account the larger contact area.

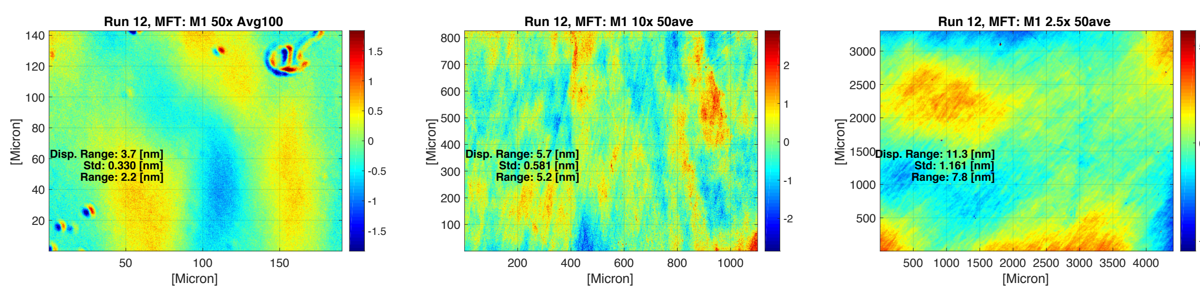

Figure 4-1: MFT 50x, 10x and 2.5x maps on the fused silica sample under test.

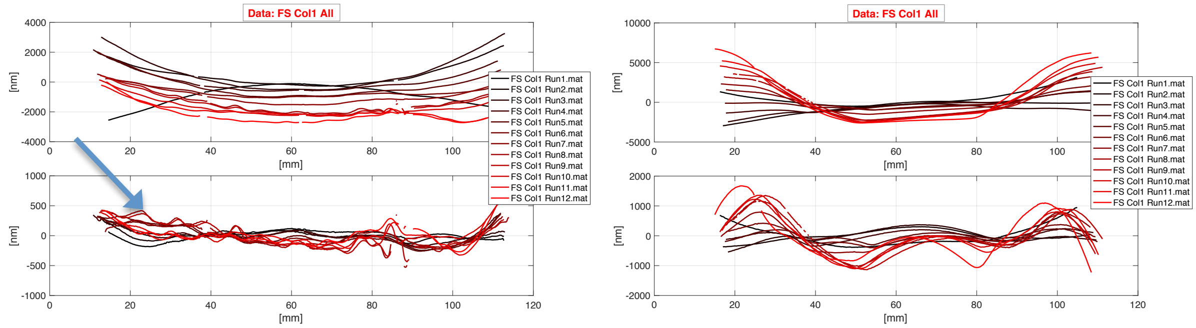

Figure 4-2: Residual profiles as extracted from interferometric map on the surface under test at the different polishing runs. (A) Horizontal central residual profiles as extracted after subtraction of piston and tilts (top) and after the subtraction of power and astigmatism (bottom). (B) Vertical central residual profiles as extracted after subtraction of piston and tilts (top) and after the subtraction of power and astigmatism (bottom).

In principle, the higher frequency pattern is controllable reducing the pressure in the last polishing run. Instead, higher degree of freedom in the horizontal movement randomization and de-phasing can decrease the features on larger scale. This kind of effects are visible in figure 4-2 where profiles extracted from interferometric maps of the surfaces in the same positions at each of the polishing runs, so that the changes in the surface shape can be highlighted. The colour scale is ranging from black (initial) to red (last). The profiles extracted in horizontal direction (corresponding to the polishing tool high frequency movement) are reported on the left while the profiles extracted in vertical direction (corresponding to the sample movement in vertical direction) are shown on the right. On the top panel of each of the figures we show the residual profiles after the subtraction from the original map of piston and tilt, while in the bottom panel we show the residual profiles after the subtraction of power and astigmatism. The change in the high frequency content is clearly visible at run 8, when the setting in the movement was intentionally changed. The random shift in horizontal direction of few mm, which was over imposed to the high frequency oscillation of 2 mm, was removed in run8. This caused an abrupt increase of the mid-frequency of the surface error. The features generated are due to the imperfect shaping of the tool, which is not simply due to the wearing of the pitch. As expected no features are highlighted in vertical direction. The observed mid-frequencies started to be smoothed out with the re-introduction of the random shift of the tool, starting from run 9. From a general point of view, the mid frequency error introduced in the polishing can be easily limited with a proper randomization of the tool path.

5. RESULTS ON BONNET POLISHED AREA

As evidenced in the previous paragraphs, the convergence of the process is quite repeatable starting from similar surface quality. The dependence on the initial condition of the surface was evaluated starting from a fused silica surface, which had been pre-treated with Bonnet polishing [5]. The starting quality of the sample was equivalent to the one used for the other tests (R_q = 70nm) but in this cases around 5 microns of material were removed. Two different areas of a sample where polished, with Bonnet R20 (down to $R_q = 6.1 \pm 1.8$ nm and PtV 34.9 $\pm$8.9) and Bonnet R40 (down to $R_q = 6.2 \pm 0.3$ and PtV = 52.6 $\pm$26.4) respectively.

Parts of these areas were polished with 3M™ Trizact™ Hookit™ Film Disc 568XA for 3 min a similar configuration used for previous tests. The results are reported in figure 5-1. On the left side, two maps acquired on the surfaces are reported for the area polished with R20 and R40. On the right side two maps show the surface status after 3 min polishing with 3M™ Trizact™ Hookit™ Film Disc 568XA. The acquired maps are reported in the same colour scale to evidence the improvement. On the right part of the figure, the PSD of the data are shown. The Bonnet residual pattern is much more evident in R20 results while it is smoothed out R40. The final surface quality reflects this intermediate status: the area pre-polished with R40 is characterized by lower amount of low frequency errors and lower final rms values. The changes in PSD are faster in the region between 10 and 100 microns, while the residual features left from the Bonnet tool need slightly longer polishing time. When Bonnet pre-polishing is not operated, the PSD decrease homogeneously on all the scales in a first phase (figure 5-2), while it decreases faster on scale greater than 100 microns.

Therefore, depending on the desired final results and on the finishing strategies applicable on the sample, different process sequences can be envisaged in order to reduce the overall time. The Bonnet polishing is one of these. An example is reported in [4] where a pre-polishing with Bonnet tool was considered advantageous with respect to the overall expected polishing time if compared with a typical grinding sequence. In fact, the grinding of thin substrates can be much more difficult due to the constraints that arise in the sample supporting system. In these cases, the Bonnet polishing, working on the dwell time base, can give a greater advantage as the offset applied for the figuring can be adjusted to be compliant with the substrate strength.

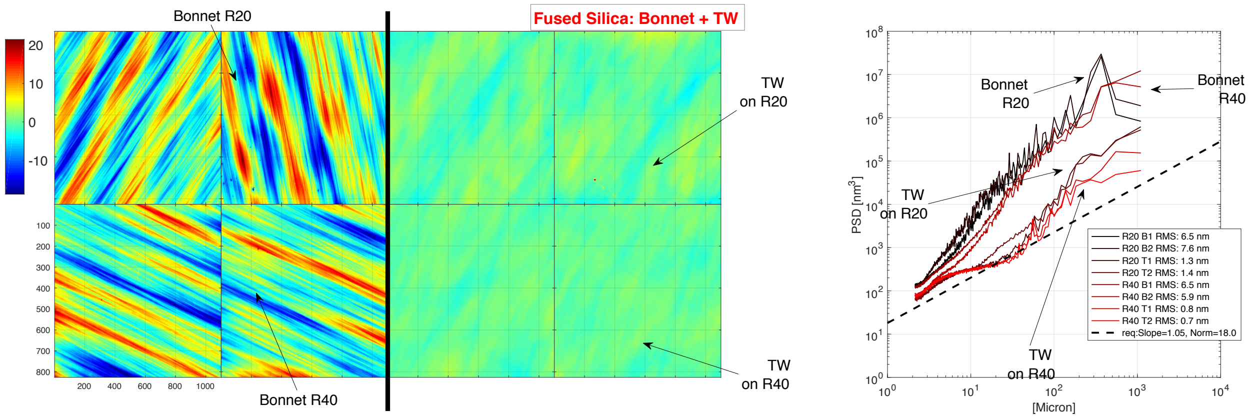

Figure 5-1: (A) Micro-roughness maps acquired with MFT 10x: Top, on area polished with Bonnet R20 and with Bonnet R20 + 3M™ Trizact™ Hookit™ Film Disc 568XA. Bottom, on area polished with Bonnet R40 and with Bonnet R40 + 3M™ Trizact™ Hookit™ Film Disc 568XA e. (B) PSD of the displayed maps.

6. CONCLUSIONS

Nowadays, different kind of abrasive pads are dedicated to the last phases of the surface finishing. In this paper we presented the results obtained with 3M™ Trizact™ Hookit™ Film Disc 568XA and 3M™ Trizact™ Hookit™ Film Disc 268XA as last steps of polishing phases of fused silica samples. In particular, we determined the wear rate of the pads and the removal rate on the surface. Moreover, we characterized the micro-roughness improvement rate in dependence of several parameters as amount of water, pH, velocity and pressure. The results achieved on small samples were verified extendible on larger surface area demonstrating that the process is deterministic. In particular, it was found that 3M™ Trizact™ Hookit™ Film Disc 568XA is able to bring the surface micro-roughness well below 1nm RMS on millimetre scale and around 0.3 nm on 200 microns scale. The convergence of the process is quite repeatable starting from similar status of the surface, but it is strongly dependent from the initial condition. Moreover, a combined process of bonnet pre-polishing and 3M™ Trizact™ Hookit™ Film Disc 568XA polishing was proven as a cost-effective solution to realize super-polished optical surfaces.

7. ACKNOWLEDGMENTS

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