Setup and procedure of optical reflectometry to check the stage of finishing during the abrasive magneto-rheological polishing of glass surface

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A setup and a procedure of monitoring the stage of the magnetorheological abrasive finishing of glass surface by means of optical diffuse reflectometry is shortly described and a concrete application based on a transformed integral photometer in a reflectometer is proposed. Three mirrors of optical quality, two to re-direct the light beam and one as reflective reference surface are used. Specimens of two crown glasses, the indigene equivalent of BK 7 (Germany) and a Russian optical glass with TK 121 code were successively polished with an original installation of magnetorheological finishing (MRF), and their momentary reflective characteristics were photometrically checked in a transformed photometer after pre-established intervals of processing, 10 min and 15 min respectively. A special demountable support for the processed specimen was conceived. It permitted to make the measurement without detaching the processed optical piece blocked on it. The very good sensitiveness and reproducibility of the photometric measurements are graphically presented and interpreted.

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1. Introduction

Magnetorheological finishing of optical glasses and of other materials is a revolutionary method for subaperture processing of special components for civil and military applications [1-4]. Its very precise technology, by computer numerically controlled (CNC) with programmed logical controllers (PLCs) offers a nanometric level of surface roughness with no or negligible subsurface damage (SSD). This modern procedure of (super)finishning is based on an intelligent abrasive material, whose rheology is controlled by an external magnetic field applied in so-called processing zone, which change instantaneously its viscosity (typically, the order of increasing the magnitude is 10^4, from the initial value of the order of 0.5 poises) and transforms it into a polishing support. After the field is suppressed or when the magnetorheological material is transported out of the magnetic region, the viscosity falls in few milliseconds to its initial value. All modern installations of abrasive magnetorheological finishing have attached a lot of very precise optical devices to check up (preferably in situ) the momentary characteristics of the processed material. Corrective decisions are taken after each check by the used complex programs of manufacturing

An original laboratory setup was conceived, constructed, and tested to process glasses, ceramics, and semiconductors [5-9]. The adopted constructive variant is that with a horizontal processing vessel having the DC motor placed above it. A lot of practical variants of magnetic sources are recommended in literature. Finally, the option was for a complex combination of permanent magnets, which give good stability and an adequate intensity of field. It is placed underneath the vessel and, to vary the field intensity at the specimen level, it can be vertically displaced by acting its slide plate.

As abrasive material for glasses and ceramics [1, 2] can serve a proportioned combination of:

- a magnetisable powder consisting in calibrated carbonyl iron grit respectively, especially thermally and chemically treated in order to impose its very precise controlled mechanical properties and a good chemical stability;
- an abrasive, in the case of glasses the best efficiency having cerium oxide of about the same granulation as the former component;
- a transporting fluid, usually water;
- a stabilizer of the rheological properties, in our particular case the glycerine, which acts as an anti-agglomerant, too;
- as pH-conservator, very good results gives the sodium carbonate, it being at the same time an efficient anti-oxidant and a biocide;
- if necessary, a diamond nanopowder is added as processing accelerator.

Stationary and recirculated abrading fluid alternatives are used as technological variants. In our case, because only few specimens were processed in an experiment, the slurry stays al the time in the vessel.

The material removal mechanism on the glass surface is essentially based on the dragging force of abrasive material at the contact zone, the preponderant excavation actions being located in the converging gap between the specimen and the hardened surface of the abrasive slurry [10]. Depending of the processing programme, a MRF application could be conducted for surface form correction or roughness adjustment, or both.

Our experiments were mainly directed to the aim of testing the workability of different optical glasses while a photometric device was used to check the stage of finishing during optical glass finishing.

2. Experimental

In the image below (Fig. 1) the processing zone of our experimental setup is presented during the polishing action of a glass specimen [9]:

Fig. 1. Processing zone of used MRF setup.

Two DC motors are placed above the processing vessel made from transparent Plexiglas: on left side is the motor which put in pre-established uniform rotation the vessel and on the right the motor which uniformly rotates the specimen.

Refreshing of the material in the processing zone and the necessity to completely process the central region of the specimen (where the tangential speed is low and can not guarantee, by itself, a complete polishing of surface material) is assured by vessel rotation.

The specimen rotation is necessary for a good efficiency of the abrasive action by its multi-directionality.

Two rack mechanisms figured in the right side of the image permit an initial precise positioning in the processing zone of the specimen above the stiffened strap of abrasive magnetor-heological material.

The possibility to use the reflectance measurements in monitoring the finishing stage of abrasive MRF of glass surface was suggested by the proposed procedures for glass surface inspection during processing named total internal reflection microscopy (TIRM) and intensity-detecting total internal reflection microscopy (iTIRM) [11]. The only difference between these procedures and our procedure is that the formers are "internal" i.e. through the material and the last is an "external" one.

In the visible region of the radiation spectrum, a processed surface by an abrasive procedure can have three perceptible optical behaviours (Fig. 2) described by *Hunter* [12, 13]:

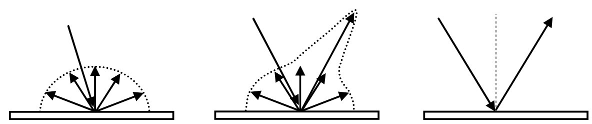

Fig. 2. Typical behaviours of a processed surface: Left: total diffusive/hazily Centre: gloss with milky haze Right: specular / glossy reflection.

Hazily, i.e. completely diffuse is an initial diffusing surface after harsh grinding used for e.g. shape forming. Specular or glossy is the behaviour of a completely finished/polished surface and a gloss with milky haze appearance has a surface in an intermediary stage of processing. The reciprocal proportions of specular and hazy components depend directly on the momentary roughness of the processed surface. They vary continuously if the polishing with the magneto-rheological procedure is in an uniform development.

Concerning the incidence and observation angles of the surface diffuse reflection, the literature recommends a quasi-tangential/grazing examination (incidence and viewing). As the surface in processing is in fact milky diffusive the standardized angles of incidence and observation of 85° was adopted.

An integral photometer for the assessment of diffuse transmission in glass [14], manufactured in a research institute on Măgurele Platform, was adapted for reflexion tests of glass processed surfaces. The 0% (lower limit) and 100% (upper limit) of the measuring range is potentiometrically adjusted with the butons for the reference values, placed in adjacent positions, in the right side of the apparatus. They have the same functions in the transformed device as reflectometer. As photometric sensor, an integrating cylinder internally covered with $BaSO_4$ which has a non-selective uniform reflection for visible wavelengths, is used. This subassembly functions similarly to an integrating sphere, its advantage being a more convenient manufacturing in a machine shop. A display of 3 ½ digits shows the measured value with a guaranteed precision of ± 0.2%. It was necessary a very good stability of DC power sources because the reflective measurements of processing stages are of necessity succesive (an accepted insufficency of this photometric procedure).

By convention, the adaptation was conceived in order to assure the measurements of diffuse reflection with no alteration of the placements of the pre-existing optical components, i.e. the modified apparatus can and must be whenever re-transformed in an integral (transmission) photometer. This means that the reflection attachement must be a dismountable subassembly.

Three optical mirrors deposed on the frontal face and having an excellent reflection in visible range were used as reflecting surfaces. They were placed in vertical position and their supports have the possibility to be rotated round a vertical axis and fastened in desired position.

A rather restrictive supplementary condition is to locate the measured surface (reference mirror or glass surface) in the same plane with reference to the incident light beam, i.e. to preserve the projected dimensions of the luminous beam on each of reflecting plane surfaces. In practice, it was preferable to not dismount the specimens in processing from its support because the blocking and de-blocking on the specimens traditionally fastened on metallic supports with wax-based glues is time consumable and is made manually at rather high temperature. Moreover, for good and objective conclusions referring to the processing details it is necessary to not modify the processing parameters one of them being the position of the specimen from the rotation centre of the processing support.

Fig. 3 shows the optical diagram of the adapter and Fig. 4 the arrangement of used optical pieces:

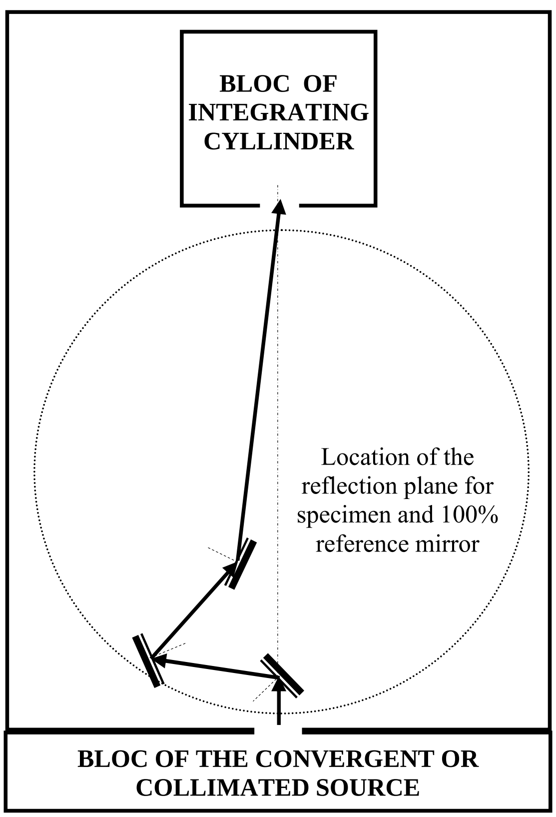

Fig. 3 Adaptation of the integral photometer to measure the reflectance of glass specimens in different intermediary stages of polishing with abrasive magnetorheological materials.

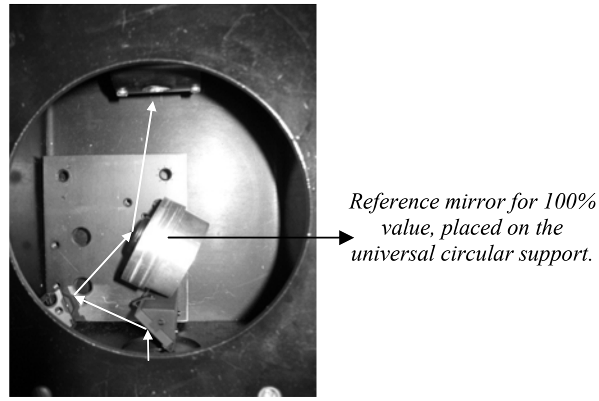

Fig. 4 Image of measuring enclosure, in which there are the two mirrors to redirect light and the reference mirror for 100% value.

In order to simplify the procedures of blocking and measurement, two special devices were conceived:

- a plastic-made support for the processed specimen which consists in two parts assembled by screwing, one of them serving as base to block the specimen by gluing with and organic glue and the other one being mounted on the axle of the DC motor (Fig. 5);
- a sliding metallic cylindrical adapter to guide the dismounted support of the specimen in the measuring support (Fig. 6).

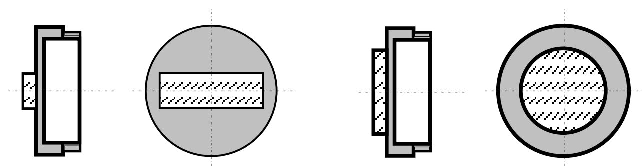

Fig. 5. Location of glued rectangular and disk glass specimens on the frontal part of dismountable support used in abrasive magnetorheological processing.

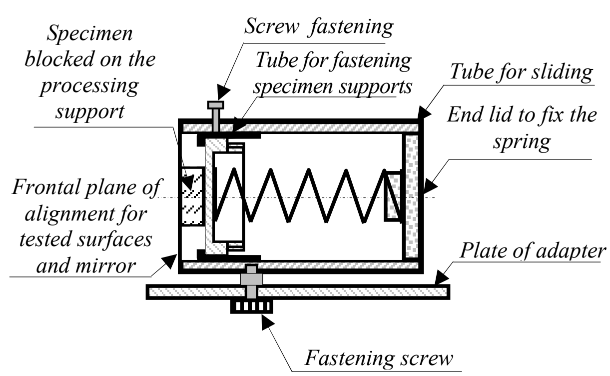

Fig. 6. Device to fix the specimen support for diffuse reflection measurements between intermediary processing stages.

The above figured spring press the specimen support toward the frontal plane of alignment, common for the reference mirror and the measured specimen. Accordingly, the image of the light source given by the specular component of the reflected beam is located in the same position on the entrance hallow of the cylindrical integrator.

In order to eliminate the possible diffusions of light by the lateral sides of specimens, it was necessary to paint them in a dark colour or to bind a black adhesive foil on its lateral wall.

The procedure of calibration was the same as in the case of (diffuse) transmission measurements i.e. the zero and 100% values were successively adjusted. The zero value was potentiometrically adjusted while the entrance gap of the integrating cylinder was completely covered. The 100% value was potentiometrically adjusted using the spot coming from the rigorously cleaned reference mirror surface disposed in the recommended position i.e. at incidence / emergence angles of 85º.

Tested specimens

Four disk shaped specimens made from crown optical glass were used in order to establish the sensitiveness of the proposed procedure and adapted equipment to measurements: TK 121 (heavy crown from Lytkariono factory, Russia, noted as 1, ... , 4) having 30 mm in diameter and 2 mm thickness and three from Romanian variant of BK 7 (Schott, Germany), 28 mm in diameter and 3 mm thickness, noted as A, B, C.

Specimen preparation

The specimens were successively manually grounded with #380, #600, #800 SiC (silicon carbide) and afterwards with #1000 and #1200 Al_2O_3 (alumina). This procedure was specially adopted in order to verify the sensitivity of the conceived procedure of reflectance measurement vs. little differences introduced by this manual non-uniform processing. Each stage of grounding consisted in 10-15 min of multidirectional movements of the optical piece on the abrasive layer placed on a flat humid surface, periodically making little rotations of the disk. A stage of grounding was considered finished when the frictional opposition to the translation movement was considerably diminished for respective grit. Finally, both types of optical glass specimens were glued on identical supports made of plastic (described and figured above) and successively MRF processed.

Main experimental parameters

The magnetic induction at the specimen-abrading material interface was ~ 0,75 T, the vessel rotation speed, 90 rot / min, and the specimen rotation speed, 380 rot/min.

For both DC motors, the effective value of the rotation speed was non-contact measured using a laser speedometer.

Reflectance measurements

The unscrewable support with the specimen was carefully washed and wiped after each pre-established period of abrasive magnetorheological finishing. The specimen support was stiffened in the measuring device. Minimum 5 measurements of reflectance, disposed on a circle concentric to the glass disk were made on different locations on the specimen surface. (For a suitable experimental arrangement, the centre of the specimen was situated upon the centre of the luminous beam and the specimen support was successively rotated by approximately equal angles).

3. Results

The values of reflectance measured on each of seven disks are given in *Table 1*:

Table 1. Reflectance values before polishing and mean values (accountable for the reference mirror).

Specimen symbol	***Initial value of reflectance, %***					***Mean initial value, %***
1	*20,3*	*18,4*	*16,1*	*16,4*	*17,3*	*17,70*
2	*21,9*	*24,8*	*20,6*	*20,1*	*20,9*	*21,66*
3	*21,5*	*21,6*	*19,9*	*20,0*	*19,7*	*20,54*
4	*21,9*	*22,4*	*23,2*	*22,7*	*24,6*	*22,96*
A	*16,2*	*15,8*	*16,0*	*15,6*	*15,7*	*15,86*
B	*16,6*	*21,1*	*17,8*	*16,4*	*16,9*	*17,76*
C	*20,6*	*18,5*	*19,8*	*15,8*	*20,7*	*19,08*

Even if the specimens were manually fine / smooth grounded the values given in Table 1 are located relatively around each mean value and between the specimens made from the same optical glass the differences are explainable by their different initial finishing before the operation of magnetorheological processing, the level of acceptance being appreciated predominantly physiologically (visually and tactually). Nevertheless, the adapted apparatus was able to distinguish small differences between specimens seeming identical after a visual examination.

Figs. 7 and 8 show diagrammatically the obtained results in different stages of AMRF processing [15], succeeded at equal interval of time considered from the beginning of polishing, referring to: *(i)* the relative reflectance of MRF processed crown optical glasses symbolized as *1* (TK 121) and *A* (BK 7) accountable to the standard mirror, considered as 100% reflective, *(ii)* the relative reflectance of these glasses, accountable to their own initial relative value.

The represented values in the graphics are mean values of minimum 5 readers, made by stepwise rotating the specimen in the measuring reflectometric device.

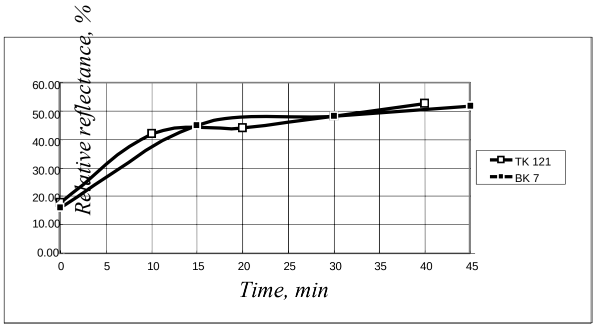

Fig. 7. Relative reflectance of two crown optical glasses accountable to standard mirror.

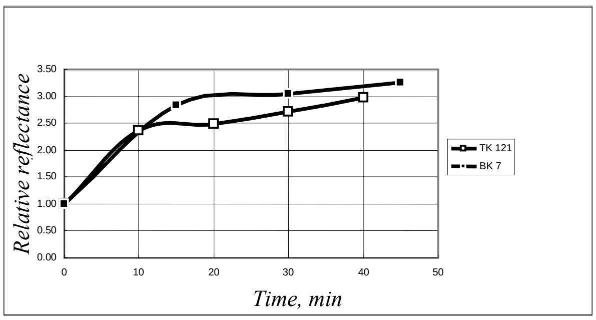

Fig. 8. Relative reflectance of two crown optical glasses accountable for their own initial relative values.

4. Discussion

Comparing the increasing rates of reflectance, it is clear distinguishable that BK 7 optical glass is faster workable by abrasive MRF than TK 112 optical glass, which is considered a "softer" one by opticians and, consequently, more difficult to polish even by classical procedures of felt or pitch.

In Fig. 8, the curve slopes for first ten minutes of processing corresponding to BK7 and TK 112 is approximately equal but after this period the difference in processing become distinguishable, the necessary time to reach the region of saturation tendency being shorter for BK 7.

The end of processing was considered when the differences between the last readings and the previous values were of the order of magnitude of experimental precision and when little differences were read between adjacent locations of measurement.

Can be seen on the graphics the presence of small "depressions" in the saturation regions. They can be interpreted as a diffusive effect persistent in the central region of the specimens, revealing an insufficient rotation speed of the vessel, which is mainly responsible for polishing of the centre of specimen (In the region including the centre of the specimen, the tangential speed is very little and can not assure the sufficient friction to completely polish it).

The graphics in Fig. 8 denote the fact that if the initial reflection value is considered as reference value it is possible to appreciate the stage of finishing using only a calibrated curve based on the values obtained after equal distributed intervals of time.

Two new fields of application were given to the adapted photometer for reflectance measurements: reflectance assessment of opaque surface of composite materials with aventurine optical effect, obtained by surface controlled crystallization processes [16] and evaluation of abrasion resistance of glasses and plastics by free falling particles (trickling procedure, abrasive surface effect measurement by photometric means) [17].

5. Conclusions

An attachment to an integral photometer for transmission measurements making it adequate to measure reflected light was conceived and tested in order to estimate quantitatively the stage of abrasive MRF processing of optical glass specimens.

Its main optical-technical features are:

- preserve the initial disposal of optical pieces of the photometer;
- it is a fast dismountable device, the basic function of photometer being immediately recovered;
- can make measurements without unblocking the specimen from its processing support;
- can distinguish small differences in momentary stage of surface finishing between neighbour locations on the sample;
- can distinguish significant differences in reflectance between two sorts of crown or flint optical glasses giving the possibility to compare their workability in different experimental conditions;
- a mirror surface or even own initial diffusive surface can be considered as reflective reference surface.

The proposed procedure of measurements gives fast, precise and repeatable results.

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