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From university to industry - challenges in upscaling optical microstructures for daylight redirection in buildings

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Abstract. In this paper we present some of the challenges faced when upscaling optical microstructures from a lab scale 1x1 cm sized proof of concept sample to a square meter sized object that can be installed in a building. The optical microstructure in question is obtained by a chain of fabrication steps, all linked with each other and with a certain level of complexity. Each of the total of 8 distinct steps presented difficulties that will be briefly introduced in this paper. On a less technical level, long term commitment of public funding and industrial partners was the base for the first upscaling of this complex technologies for pilot production. Taking the best from two worlds: industry and academia has proven effective in the development of such a novel technology.

1. Introduction

1.1. Context & Problematic

Increasingly glazed surfaces in the build environment raise new problems for occupants. Visual & thermal comfort must be maintained and require the adaptation of the glazed part of the envelope to favourably control a component simply blocked by opaque parts in the building: light and radiation. From nanometre thick coating to meter wide overhangs and façade elements, there is a large set of solutions to control the amount of daylight and radiation that is allowed into the building. Optical microstructures for advanced functionalization of windows were previously developed in a doctoral dissertation [1] with the ambitious goal to offer simultaneously and with a static device: light redirection, glare protection and a seasonal thermal comfort while conserving the view through the window. A proof of concept was made with a centimeter squared sample, identifying the required steps to obtain embedded mirrors for light redirection and seasonal thermal control.

1.2. Steps in the fabrication process

To scale-up the fabrication process, each of the following steps had to be reviewed and adapted. The novel limitations and requirements were imposed by the change of scale and the change from an academic research project to a real world, pragmatic need for a reliable process and product. These steps are:



- Simulation of a design, including daylight & thermal performances
- Fabrication of film
 - Origination of a master structure
 - Replication of the structure in a transparent, UV curable material
 - Coating of selected facets using a tilted deposition
 - Encapsulation of the resulting mirrors
- Measurement of the resulting sample's light redirecting properties
- Computation of corresponding performance
- Installation within an insulating glazing unit

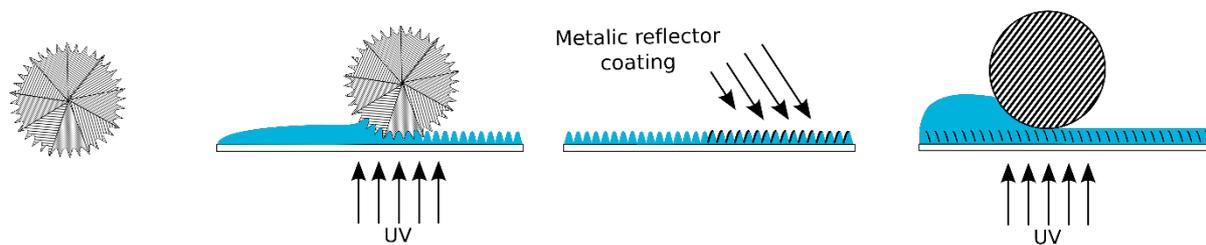


Figure 1 - Four key steps in the fabrication process of the film. Origination, Replication, Coating and Encapsulation

2. Simulation of a design, including daylight & thermal performances

During the doctoral dissertation, CFSpro, a software tool which covers all aspects for the simulation of complex fenestration systems was developed [2]. CFSpro is a raytracing tool for the modelling of parameterized geometrical designs to visualize the light distribution resulting from extruded 2D profiles. It includes modules for climate-based data, where the daylight calculation is based on Radiance simulations and the annual thermal performance calculation uses a nodal thermal model. This tool was the base for the development of a patented design achieving angular dependent transmittance, transparency, daylight redirection and glare protection [3]. In this paper we will refer to this design as the microstructured (MS) film. Because of the static nature of the MS design, the daylighting model did not include any dynamic element such as venetian blinds. The thermal model shows energetic savings of 20% for a sunny climate (Torino) using MS film on the full surface of the window, with a window covering 60% of the façade and without the usage of blinds [4]. Positive effects on daylight illuminance and reduced glare risk were shown in comparison with clear glazing [5] with MS placed only in the upper, daylighting section of the window situated above line of sight.

During the validation of the technology within BASF Schweiz AG, Bartenbach performed additional evaluations of the MS film. The focus was first set on the daylighting aspect, a core competence of Bartenbach [6,7]. The film was compared with two standard glazing products: an insulating glazing unit (Guardian ClimaGuard® Premium 80/63) and a solar protection glazing with minimized energetic transmittance (Guardian SunGuard® SN 40/23). The simulations were run in a large set of building environments and for a large set of climates. The film was placed both in the upper section only and on the full surface of the window, respectively. The glazing model was composed using Window7 [8]. A screen with visible transmittance of 10% was used and various glare protection strategies were applied (no screen, screens on full surface, only in the lower part on classical window surface, always open in summer, difference setpoint for window luminance, and combinations of these strategies).

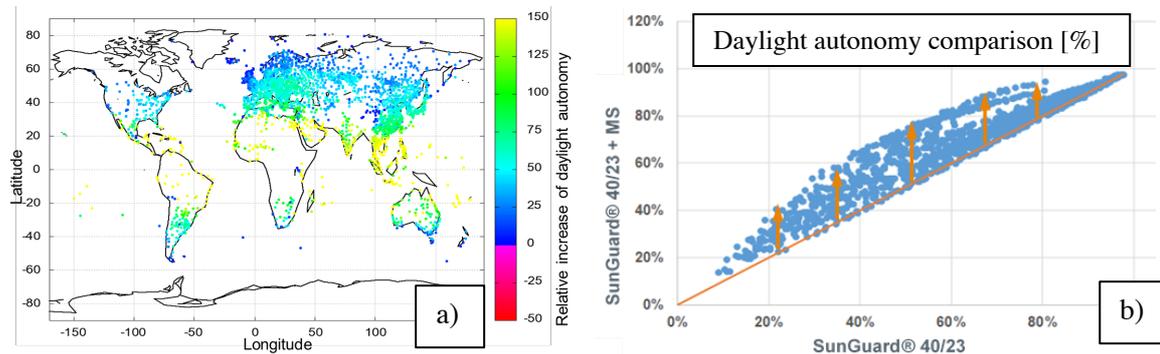


Figure 2 a) Relative increase of daylight autonomy worldwide for 60% glazed fraction and 8m deep offices b) Daylight Autonomy compared between SunGuard® 40/23 and a SunGuard® 40/23 equipped with MS film for a large set of different building configurations in Torino

The simulations were performed with an adapted version of the DALEC tool [9]. The thermal modelling is based on the hourly method according to ISO13790, where e.g. also night cooling was considered. In these simulations the improvement of daylight autonomy was dominating and showed to be positive regardless of the building type and the climate as shown in figure 2. Daylight autonomy in this case is the continuous daylight autonomy, i.e. the fraction of office hours where illuminance on the work plane by daylight only is exceeding 500 lux and a weighed contribution for times where illuminance is between 0 and 500 lux. The effect on thermal loads (both cooling and heating) however was negligible and varying depending on climates and building types. The different behaviour of daylight and thermal results can be explained by a number of points. Daylight performance is mainly influenced by a reduced set of parameters: the usage of shading systems, the depth of the considered space, the transmittance of the glazing and the radiative component of the climate. The thermal performance on the other hand is influenced by almost every parameter in the building performance simulation: that means all of the above, but also thermal inertia, temperatures, internal gains, night cooling, natural ventilation, building envelope (U values) and cooling & heating strategy. Only the latter was not considered in this study where a fixed COP was used.

The state of the art in modelling of CFS in building simulation has been continually evolving between 2008 and 2018. The appropriate tools have been used on a day to day basis by Bartenbach and such an expertise has been very valuable in this work to confirm the relevance of the developed technology.

3. Origination of a master structure

For the fabrication of the MS film, the first step is to generate a tool. Several state-of-the-art methods are used in this step in the industry. Two approaches can be distinguished: one using a small area template that is then extended by a step and repeat process and direct micromachining of a tool. Both approaches were taken, starting with the first one which has the potential to be more flexible for the experimentation of different geometries. Several methods exist for template origination, in this work we used direct laser ablation in polycarbonate [10]. The template can then be copied into a nickel master shim and this master shim used to extend the surface by step and repeat. The polycarbonate (PC) template had a satisfying aspect ratio of 1.8 but due to several misfunctions of the laser setup at the time of this work, it had a high roughness (figure 3a) which transferred into the master shim. This roughness was strongly detrimental to subsequent step and repeat trials which failed with the first step and repeat methode (figure 3b) and were only successful (figure 3c) at the price of a strong reduction of the aspect ratio: down from 1.8 to 1.3. Despite these limitations, the obtained shim could be used to experiment with the next steps (imprinting, coating and encapsulation).

Generating structures with an aspect ratio superior to 1.5 is very challenging for the micromachining approach. Ultra-precision diamond turning laths can be used for the direct engraving of a metallic roller

with a diamond tool. Material removal becomes very difficult from a certain depth on and the tool undergoes high stress. Structures with an aspect ratio of 1.7 were nevertheless successfully machined with only minor defects.

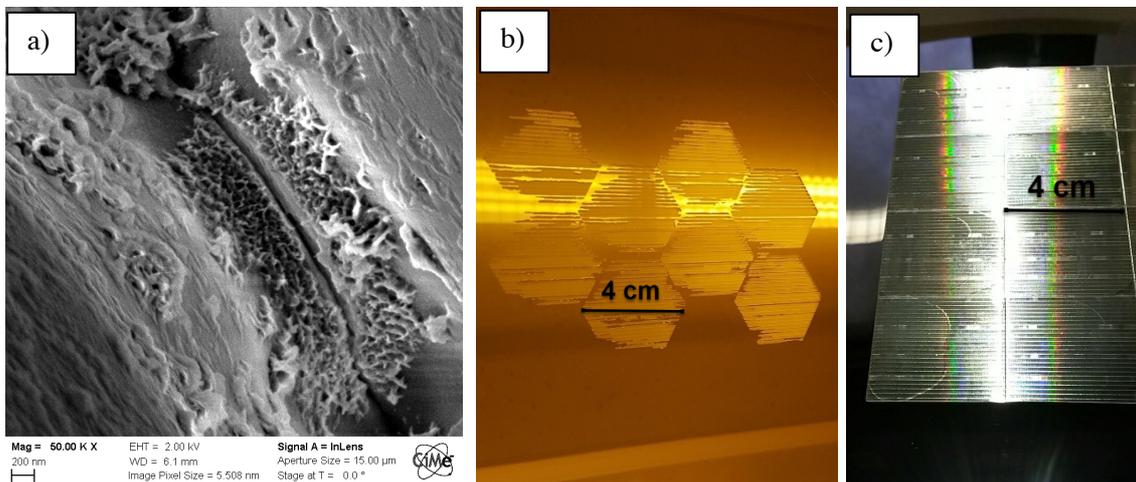


Figure 3 a) Roughness at the bottom of PC template as observed by scanning electron microscopy
 b) Failed honeycombed step and repeat using imprinting c) Hot embossing step and repeat with reduction of aspect ratio

4. Replication of the structure in a transparent, UV curable material

Roll to roll nano imprint lithography is an industrial process in which the geometry of a tool is transferred onto a flexible substrate using a liquid varnish that is cured by UV illumination [11]. Once a satisfying tool was available, the imprinting onto a polyethylene terephthalate film was rather straight forward and 100 m could be produced as a trial (figure 4a). In production, typical film coils are 1500 m long. The structure transferred successfully including the defects from the tool that can be seen in figure 4b.

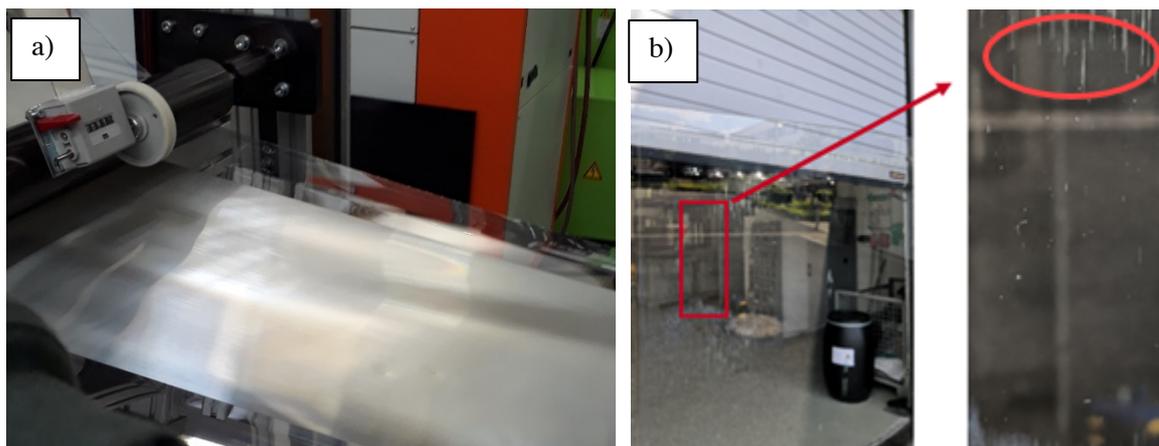


Figure 4 a) Structure film in the roll to roll imprinting process. Sides of the film are unstructured and remain transparent. Total width is 500 mm b) film after encapsulation without coating, close up shows defects at encapsulation (circled).

5. Coating of selected facets using a tilted deposition

Selected facets of the structured film are then coated with an aluminium coating. The substrate is tilted and placed under vacuum, in a physical vapour deposition (PVD) chamber. The self-shadowing of the

peaks is generating a border between coated and uncoated surface. The effectiveness of the self-shadowing is however sensitive to process parameters such as distance, chamber pressure & type of deposition (by joule effect or e-beam). Evaporation and e-beam processes were used at different distances and process pressures. SEM images were made on a cross section of the finished film (figure 5). Backscattered electrons were used to identify the coating. The shadowing was successful and located where it was expected with an e-beam deposition but was less accurate when using evaporation. Possible explanations for the success with e-beam are the lower process pressure ($5 \cdot 10^{-6}$ mbar for e-beam and $5 \cdot 10^{-5}$ mbar for evaporation) resulting in longer mean free path and the lower temperature when using an e-beam source.

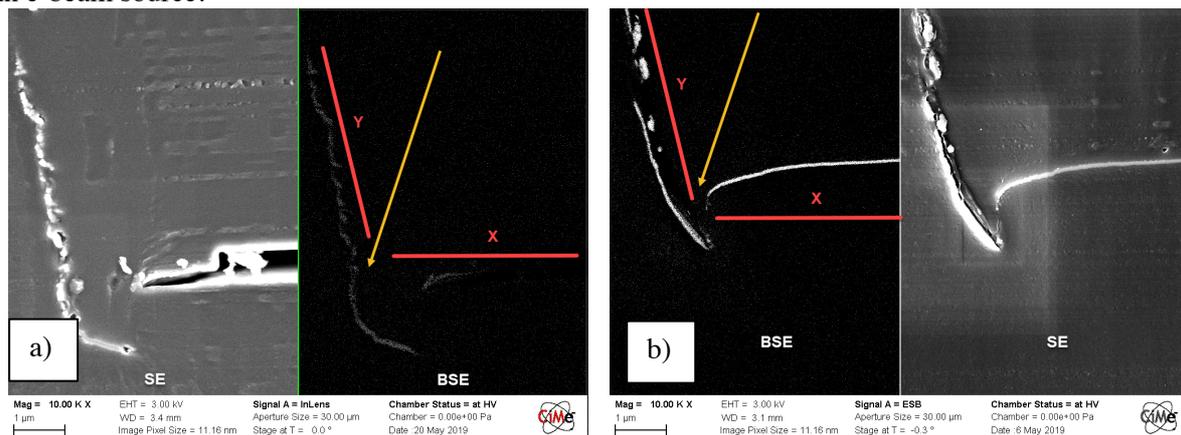


Figure 5: Scanning electron microscopy of the bottom of the structure in film cross section. Both images from secondary electrons (SE) and backscattered electrons (BSE) are shown side to side. Arrow shows the theoretical coating direction and point to the geometrical shadow line. The desired coated area should be next to the line marked Y and the undesired area next to the line marked X. The white / clear lines in the BSE images show the actual coating a) Coating by e-beam b) Coating by thermal evaporation

6. Encapsulation

The final step in the fabrication of the MS film is the encapsulation of the mirrors. An encapsulation test is performed without coating as quality is easily assessed looking at the transparency. Successful uncoated, encapsulated samples should be clear as glass when looking through them. When relying on industrial, standard processed for encapsulation, two defects persist: an orange peel surface due to some irregularities in the application and trapped air lines (figure 4b). In a manual process these defects were controlled and yielded a transparent, defect free result on an intermediate scale (10x10 cm).

7. Measurement of the resulting sample's light redirecting properties

Due to difficulties mentioned above there was some delay in the fabrication and no full bidirectional transmission distribution function (BTDF) measurement was done at the time of submission. Partial measurements were done at LESO on a miniature goniophotometer [1]. The measurement of direct transmission enabled to qualitatively compare the transparency by comparing the peak values and peak full width at half maximum. The integration of direct and main redirected peaks enabled the qualitative estimation of redirection efficiency. Those measurement enabled an optimisation of parameters for production.

8. Conclusions

In conclusion coordination of all research and tolling partners involved was crucial to adapt each step to the feedback from other steps. In total four full iteration from structure design to final sample

realisation were made before achieving a satisfactory result for a prototype and basis for a pilot production with each iteration taking between 6 to 12 months, the long-term support of the involved partners was crucial. About 100m of structured film could be produced and individual structured sheets were coated under a controlled angle. The coating was optimised to yield a satisfactory optical function and the challenges for a clean encapsulation were solved on an intermediate size (10 x 10cm). The path has been set to produce large scale windows (0.6 m x 1m) that should be installed in the NEST unit SOLACE in the end of summer 2019.

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