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Manufacturing of hierarchically structured surfaces for decorative applications

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Abstract
We report on the development of a process flow for the manufacturing of polymer parts by injection molding with three levels of surface structuring. A stainless steel mold insert was first manufactured and treated with three different structuring methods. One of the key point was the ability to fabricate in a conformal way sub-microstructures on the flat and microstructured areas of the insert. These hierarchical structures were then replicated by injection molding. The replication process was optimized using a design of experiments. The replica produced showed different optically varying effects due to the microstructures. The sub-microstructures lead to a opaleascent effect on the surface.

Microstructuring; nanostructuring ; injection molding ; hierarchical structure

1. Introduction

The aesthetics of injection molded plastic parts is traditionally done by controlling the surface texture of the mold, combined with painting/stamping decals or by using in-mold labelling processes. To obtain specific colors and optical effects, pigments and dyes are generally used, which can be problematic for some applications. There is currently a trend in the manufacturing of surfaces with controlled aesthetics avoiding the use of such pigments/dyes, using instead so-called structural colors [1]. These bioinspired approaches involve submicrometer surface structures combined with metal and dielectric layers. One of the challenge for the manufacturing of structural colors is to develop processes to apply such solutions on non-planar and prestructured parts.

In this study, a process flow is reported to manufacture injection molded parts with three levels of surface structuring. At a micrometer scale, two types of structures have been manufactured, leading to optically variable effects based on geometrical optics. A third level of structuring has then been done at a submicrometer scale to obtain an opalescence on the microstructured surface (light scattering and interferences). A hierarchically structured mold was manufactured and an injection compression process was optimized using a design of experiments.

2. Manufacturing of hierarchically structured mold inserts

The first objective was to produce the three types of surface structures on a stainless steel mold insert. The process flow consisted in the following steps: the surface of a 40mm diameter mold insert was first mirror polished. A first microstructure was made by means of micromilling. This guilloche pattern was applied in the center of the part as a background. This resulted in a continuous wave like optical effect on the surface.
In a second step, a surface sub-microstructure was applied on the complete surface of the insert. These structures were made by nanosphere lithography [2]. This process involves two steps with first the manufacturing of an etch mask using particles as templates and second an electrochemical etching step to transfer the structures into the underlying substrate. The size of the particles is used to control the lateral dimensions of the structures while the etching step was used to adjust the depth of the structures. In this study, the particles had a diameter of 1µm and the etched structures had an aspect ratio of 0.5. As illustrated in figure 1, this structure lead to a opalescent color on the surface.

Figure 1. Photograph of a structured injection mold insert.

In a last step, a second microstructure was introduced using electrochemical micromachining [3]. A microtructured etch mask was made by protecting the surface of the mold insert with a resin followed by a laser ablation to locally expose the surface of the stainless steel. The structures were then etched by electrochemical dissolution. The resulting microstructures had a lateral size of 40µm, an aspect ratio of 0.4 and a mirror polished finishing on the etched areas. On a design point of view, a complex dithering process of the microstructures allowed the creation of optically variable effects leading to animations upon tilting and rotation.
Figure 2 presents SEM images of the resulting stainless steel insert with the three levels of structuring. On top image, the wave-shape of the guilloche pattern can be observed at the

bottom left. The higher magnification image shows the superposition of the sub-microstructures, which follow conformally the surface of the microstrucutres. On the second high magnification image, the electrochemically etched microstructure can be seen, with very smooth surfaces on the etched areas.

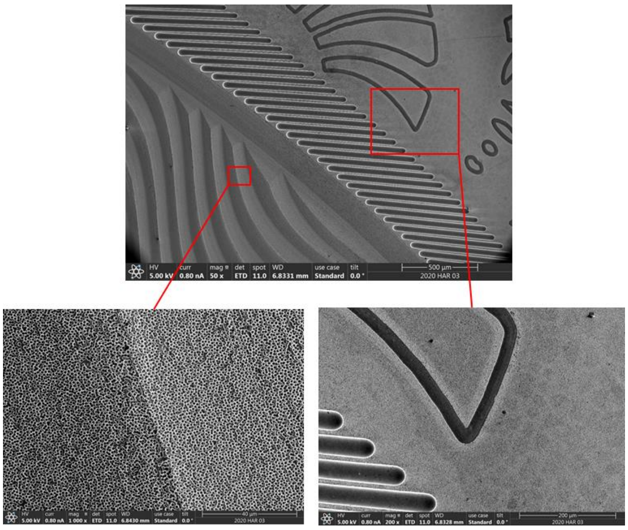

Figure 2. SEM images of a of a structured injection mold insert

3. Optimization of the injection molding process

An injection-compression molding process was then used to produce series of hierarchically structured plastic parts. The tests were made using polystyrene. A five parameter, two level design of experiment (DOE) was made for the optimization of the replication process. A fractional factorial design was used and a total of 16 runs with different combinations were performed. In table 1, the high and low levels of the DOE are presented for each parameter. The melt and mold temperature were the first parameters varied. As an injection-compression process was used, the other three parameters were the injection speed, the gap size before compression and the injected volume.

Table 1 : parameters used for the design of experiment

Level	T melt [°C]	Tmold [°C]	Injection speed[ccm/s]	Gap [mm]	Injected volume [ccm]
1	245	75	50	4	8.5
-1	225	50	10	2	6

For the output of the DOE, the mean height of the replicated submicrometer structures was measured from confocal images of the surface. The effect of each parameter on the height of the structures is presented in figure 3.

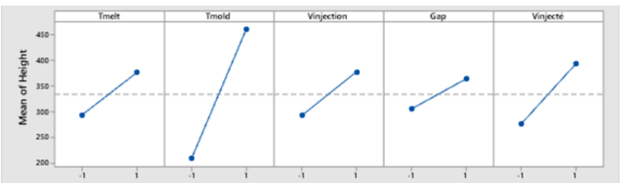

Figure 3. Main effect plot of the optimization of the injection-compression molding process.

In this injection molding campaign, we found that the most influencing parameter was the mold temperature, with a two fold increase in the structure-height when increasing the mold temperature from 50 to 75°C. This agrees well with previously reported results [4]. Increasing the mold temperature can indeed effectively delay the solidification of the polymer on the mold surface, giving more time for the melt to fill the submicrometer structures to replicate. The injected volume was the second most influencing parameter, a higher volume leading to a higher structure, probably due to an increased pressure during the compression phase. For the set of parameters selected, the melt temperature, injection speed and gap also had an influence on the replication but to a lesser extent.

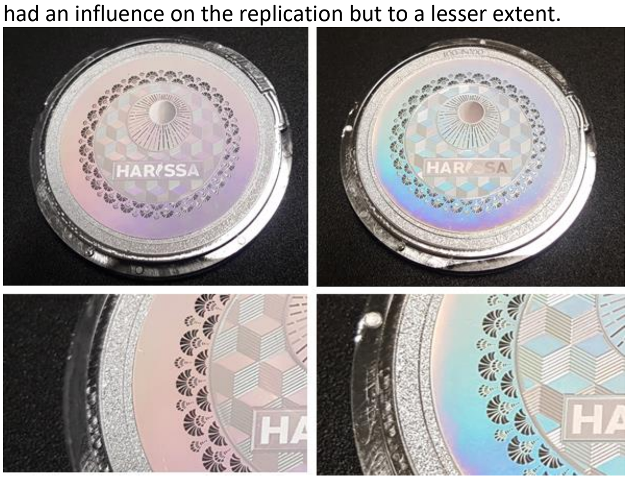

Figure 4. photograph of an aluminium coated replica. Left) made with optimized parameter right) made without injection compression.

The polystyrene replica produced had all the features of the mold insert, with the three levels of surface structuring. The optical effects of the microstructures were clearly observed but the opalescence was only obtained by applying a reflective aluminium coating on the parts. As shown on figure 4, the replication quality was strongly influenced by the compression phase. The final part exhibited all the optical features of the mold, with optically varying effects from the microstructures and a pale, opalescent color from the sub-microstructure.

4. Conclusions

A process flow was proposed and optimized for the manufacturing of hierarchically structured surfaces for decorative applications. Two main cahllenges have been addressed : (1) the conformal fabrication of sub-micrometer structures on the surface of a stainless steel insert prestructured at a micrometer scale ; (2) the optimization of the replication by injection molding. Adding a compression step to the injection process was necessary to obtain satisfactory results. The DOE performed for the optimization of the replication process showed that the most critical parameter to obtain a faithfull replication is the mold temperature, which has to be high enough to ensure a complete filling of the sub-micrometer features.

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