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Injection moulding of plastic parts with laser textured surfaces with optical applications

J. Pina-Estany[a,b,*], A.A. García-Granada[b], E. Corull-Massana[a]

[a] SEAT S.A, Autovía A-2 KM 585, 08760, Martorell, Barcelona, Spain
[b] IQS-Universitat Ramon Llull, Via Augusta 390, 08017, Barcelona, Spain

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ABSTRACT

The purpose of this work is to manufacture micro and nanotextured surfaces on plastic injection moulds with the aim of replicating them and obtaining plastic parts with optical applications. Different patterns are manufactured with nanosecond and femtosecond lasers in order to obtain three different optical applications: (i) homogeneous light diffusion (ii) 1D light directionality and (iii) 2D light directionality. Induction heating is used in the injections in order to improve the textures degree of replication. The steel mould and the plastic parts are analyzed with a confocal/focus variation microscope and with a surface roughness tester. A mock-up and a luminance camera are used to evaluate the homogeneity and luminance of the homogeneous light diffusion application in comparison with the current industrial solutions.

1. Introduction

Microtextured and nanotextured surfaces (MTS and NTS, respectively) are surfaces covered with micro and nano-sized structures that can be random or have specific shapes like cones, columns or fibres. Such surfaces are gaining popularity due to their unique physical properties. Several applications have been reported in the literature such as surfaces with self-cleaning capabilities (Yoo [1]), antimicrobial surfaces (Kim [2]), water purification (Baruah [3]), optical applications to achieve antireflection (Christiansen [4]) or light transmission enhancements (Kim [5]), etc.

In order to manufacture large series of plastic parts, injection moulding is a well-established manufacturing method due to its low costs. However, the large surface-area-to-volume ratio characteristic from the nanoscale tends to solidify the polymer before it has replicated all the nanotexture cavities, reducing the efficiency of the nanotexture. Several authors like Kuhn [6], Pakkanen [7], Rytka [8] or Tofteberg and Andreassen [9] have studied how the process and geometrical parameters can be tuned in order to improve the replication.

The purpose of this paper is to manufacture in the mould and replicate in the plastic textures that enable three optical functionalities: homogeneous light diffusion, 1D light directionality and 2D light directionality.

Concerning the **homogeneous light diffusion**, obtaining a homogeneously illuminated surface is a target in different sectors such as interior and exterior lighting, automotive headlamps and rear lamps, backlight units in electronics, etc. In order to obtain such homogeneity, it is a common practice to scatter the light by placing a diffuse material in front of the light source (Evonik PLEXIGLAS® df23 8 N, PLEXIGLAS® Satinice df23 8 N, etc.), thus, the homogeneity is obtained due to the presence of disperse spheres of PMMA inside the PMMA bulk (see Fig. 1 left). Such materials are commercially sold but, from the point of view of the cost, they are expensive. Furthermore, they are not included in the List of Acceptable Plastics of the Automotive Manufacturers Equipment Compliance Agency, Inc (AMECA) and, therefore, they cannot be used in the countries regulated by the SAE regulation. Besides, they are technically limited since the spread beam output cannot be controlled and the efficiency is of approximately a 10% for 2 mm depth. Replacing the diffuse material with a nanotextured plastic part (see Fig. 1 right) that provides a good compromise between homogeneity and luminance is one of the purposes of this work.

Concerning the **1D and 2D light directionality**, refractive optical elements (ROEs) are manufactured in the mould with a femtosecond laser and replicated in the plastic part. Such ROEs enable the shaping of the light beam via light refraction and generate the prescribed irradiance distribution. See Wittig [10], Laskin [11], Moiseev [12] or

Abbreviations: ICM, Injection Compression Moulding; Lc, Cut off; Lt, Traverse length; MTS, Microtextured surface; NTS, Nanotextured surface; PTL, Power Top LED; Ra, Arithmetical mean deviation of the roughness profile; ROE, Refractive Optical Element; SMD, Surface-mount Device; SMT, Surface-mount Technology; VIM, Vacuum Injection Moulding; Wa, Arithmetical mean deviation of the waviness profile

* Corresponding author. IQS-Universitat Ramon Llull, Via Augusta 390, 08017, Barcelona, Spain.
E-mail addresses: jordi.pina@seat.es, jordipinae@iqs.url.edu (J. Pina-Estany).

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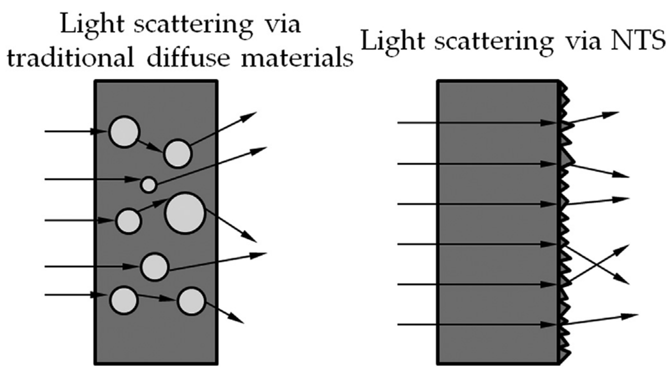

Fig. 1. Traditional light scattering and NTS light scattering approach.

Shultz [13] for the mathematical approaches used to calculate the refractive surface shape that provides the defined irradiance distribution in a certain plain. In the current work, for 1D light directionality a sinusoidal shape is manufactured, this allows a reduction of the number of LEDs necessary to light up a given area. For 2D light directionality an array of hexagonal microlenses is manufactured in order to project these hexagons, the projection of nanotextured geometries leads to interesting design applications.

Two technologies are combined in order to manufacture the above mentioned MTS and NTS. Indeed, **laser ablation technology** is used to texturize the mould surface and **mould induction heating** technology is used to improve the textures replication. Next, a brief of exposition of each technology is shown:

- Laser ablation technology

All the textures are manufactured on a mould insert with pulsed laser ablation. The laser light excites the metal electrons which rapidly relax to lower energy states by transferring the energy to the lattice of the material. Thereby, the material can be melted and evaporated. This technology can be used to remove material in a relatively controlled way. With ultrashort laser pulses the energy is transferred in a time that is shorter than the relaxation time between the electrons and the lattice. This creates very high energy densities and allows ablation to take place before heat conduction to the bulk material becomes important. As a result, ultrashort laser pulses (nanosecond, picosecond or even femtosecond laser sources) can be used to process materials without thermally affecting the surrounding bulk material (Lightmotif Website [14], Noh [15]).

- Induction heating of the mould technology

Injection plastic manufacturing technique commonly warms the mould either with flow processes (steam or pressurized water) or with electric heaters. Even though several studies show the replication of nanostructures with such warming systems (Oh [16], Kim [17], Rytka [8], Kuhn [6], etc.), incomplete replication is a common issue well known by both researchers and the industry. A good knowledge of the process and geometric parameters are necessary in order to avoid a premature solidification of the polymer due to the large surface-area-to-volume ratio that characterizes the nanoscale, especially for textures with large aspect ratios (Stormonth [18], Matschuk [19], Hattori [20], Su [21], etc.). Therefore, when common warming systems are incapable of successfully replicating the textures, alternative injection methods should be considered. Marco Sortino studied how Injection Compression Moulding (ICM) increases the replication of nanostructures, whereas Vacuum Injection Moulding (VIM) leads to a minor improvement [22]. Rytka [8] proved how a variothermal injection consisting in two chamber water systems increases the replication of nanocavities only in combination with a polymer of sufficiently low melt viscosity. In this work, induction heating is studied as a way to improve the replication in the base that the mould temperature is one of the factors with a large effect in the replication (Chen [23], Pina-Estany [24]). Induction heating is achieved by applying a high-frequency current to a copper induction coil that goes through the mould; this creates a magnetic field around the coil, inducing eddy currents that generate Joule heating on the mould. See Table 1 for a comparison of maximum temperature, heating speed and energy cost of different warming methods.

Table 1
Comparison of mould warming methods (Roctool Website [25]).

	Heating speed	Temperature	Energy cost
Induction heating	Up to 25 °C/s	Up to 400 °C	Low to medium
Flow processes (steam, pressurized water)	Up to 10 °C/s	Up to 140 °C	Medium to high
Electric heater	Up to 5 °C/s	Up to 300 °C	Very high

2. Materials and methods

This section is divided into the different materials and processes used in this publication: specifically, the mould manufacture, the textures engraving, the injections, the luminance evaluation with the mock-up and the topographic measurements.

2.1. Mould manufacture

Concerning the mould manufacture, the mould assembly depicted in Fig. 2 consisting in a typical combination of moving and fixed half is used. The induction coils necessary to warm the fixed half when using induction heating are depicted. The interchangeable insert that is first optically polished (Ra = 0.054 μm) and finally texturized is pointed. Even though the images show two interchangeable inserts, only the upper one is used in this publication to manufacture plastic parts of 3 mm depth.

The texturized interchangeable insert is depicted in Fig. 3. In the frontal picture different areas are visible, corresponding to the different textures. In total, 21 different textures were manufactured with different laser parameters. The publication gathers the results obtained for three of them, which leaded to successful results. In detail, the letter A indicates the position of the homogeneous light diffusion application, letter B indicates the position of the 1D light directionality application and letter C indicates the position of the 2D light directionality. Each texture is a rectangle of 5 mm·38 mm, these dimensions were chosen to make the texture fit the mock-up specifically manufactured to evaluate the optical efficiency. The position of the sprue is pointed as well as the insert dimensions.

2.2. Textures manufacture

Concerning the textures manufacture, nanosecond and femtosecond lasers are used in this work (GF AgieCharmilles Laser P 1000U with nanosecond laser and GF AgieCharmilles Laser P400 with femtosecond laser).

The three manufactured optical applications are described hereunder:

- Surfaces with homogeneous light diffusion

The texture for homogeneous light diffusion is manufactured with a nanosecond laser. Even though nanosecond lasers generate more burr and affect more the surrounding material than femtosecond lasers, they are technically enough for this application and more cost-effective than