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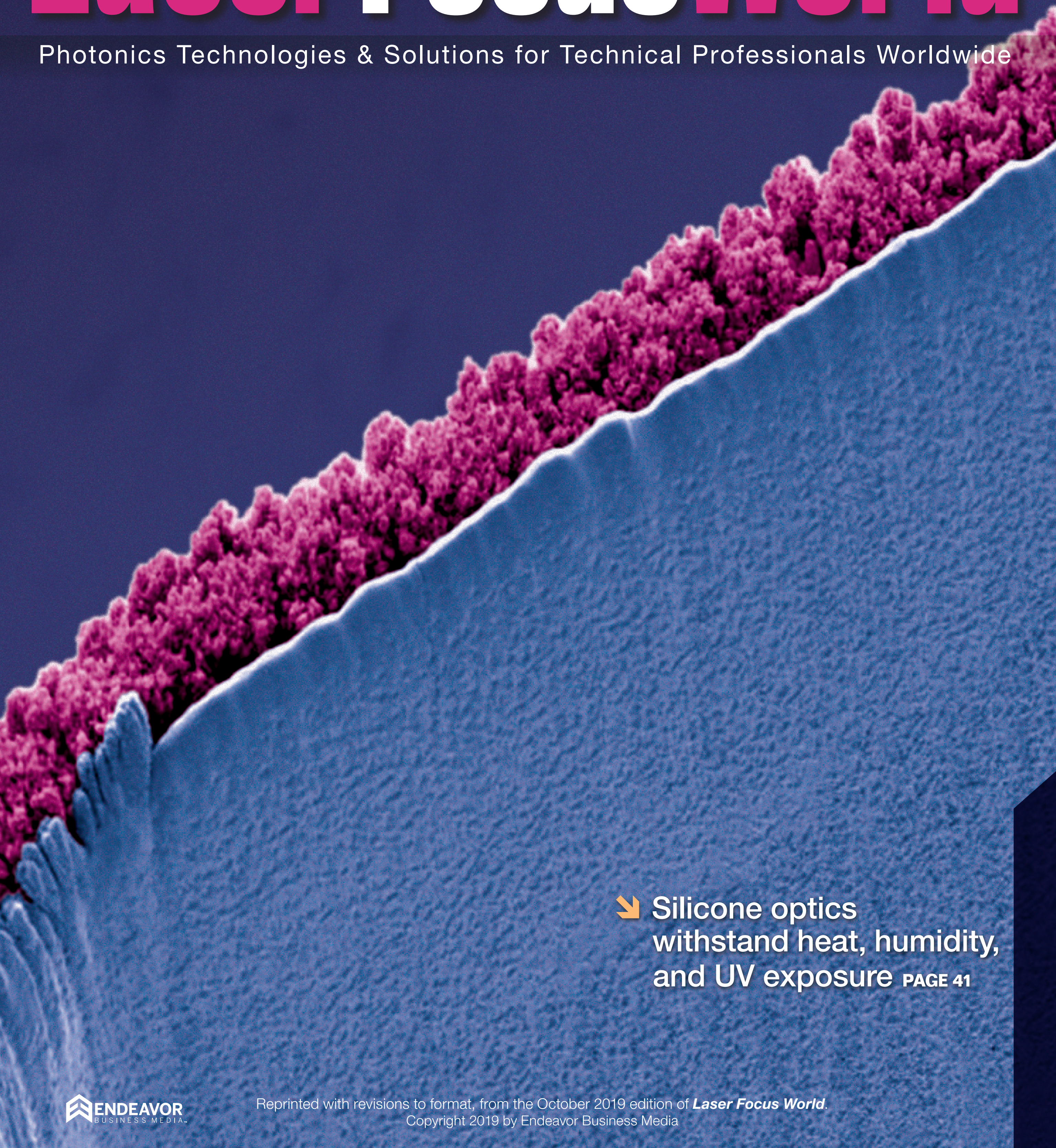

Silicone optics withstand heat, humidity, and UV exposure PAGE 41

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Moldable optical silicone elastomers spark creativity in LED lighting

MARTIJN BEUKEMA, MICHELLE CUMMINGS, FRANÇOIS DE BUYL, JAKE STEINBRECHER, BRAD TUFT, and **KEVIN VAN TIGGELEN**

Resistant to high heat, humidity, and UV exposure, optical-grade liquid silicone can be molded into complex shapes for LED lighting.

Luminaire manufacturers have traditionally used glass or optical thermoplastics like polycarbonate (PC) and polymethyl methacrylate (PMMA) for producing optics. However, increases in LED power for high-lumen applications are placing new demands on traditional materials. As heat generated near the LED steadily increases, these materials can degrade. Yet high-power, high-heat luminaires must be pursued to maximize the energy-efficiency advantages of LEDs.

But there is a solution: Optical-grade liquid silicone rubber (LSR) is becoming the material of choice for optimizing the use of LEDs. Liquid silicone rubber is used in a growing number of indoor and outdoor lighting applications.

This article, illustrated by case studies, describes the performance and design benefits of moldable optical silicones for applications such as high-performance LED lamps and luminaires. These advantages include ultraviolet (UV) stability; resistance to high heat, scratching, and impact; and enhanced design capabilities for total internal reflection (TIR) optics and freeform lenses.

The article also discusses the need to account for the influence of the coefficient of thermal expansion (CTE) and thermo-optical coefficients (TOCs) when designing optics with silicone materials and presents strategies for ensuring optimal integration of optical silicones within LED lighting modules.

Unique benefits of silicone

Silicone materials display unique characteristics resulting from the unusual combination of an inorganic chain, similar to silicates or glass, which is often associated with high surface energy, and side methyl groups that are organic and associated with low surface energy.[1] Compared to many organic materials, the chemical backbone of silicones makes them particularly well suited to manage the increasingly high temperatures and light flux of LED lighting systems.

In addition, the higher difference in electronegativity of silicon (Si) vs. oxygen (O) atoms compared to carbon (C) vs. O atoms turns Si-O bonds to be very polarized and highly ionic

Typical bulk properties of optical materials: silicone, glass, polycarbonate (PC), and polymethylmethacrylate (PMMA)

Material/properties	SILASTIC MS-1002 moldable silicone	Glass	PC	PMMA
Physical form at ambient temperature	Liquid (solid after curing)	Solid	Solid	Solid
Processing T (°C)	15–25	1500	280–320	250
Molding T (°C)	125–180	600 (tin bath)	90–120	60 - 80
Refractive index (n)	1.42	1.52	1.58	1.49
Thermo-optical coefficient (dn/dT)	$-3.2\ 10^{-4}$	ca. $2\ 10^{-6}$	$-1.07\ 10^{-4}$	$-1.1\ 10^{-4}$
Total transmittance (%) Average 400–700 nm at ca. 1 cm white light path length	94	91	89	93
Abbe number	ca. 50	20 to 65 (a)	ca. 30	ca. 58
Max service T (°C)	150	>200	120	90
Vicat softening T (°C)	NA	NA	144	108
Glass transition temperature Tg (°C)	-127	ca. +600	+145	ca. +120
Density (g/cm^3)	1.07	2.5	1.2	1.2
Coefficient of thermal expansion (CTE; ppm/°C)	275	10	65	72

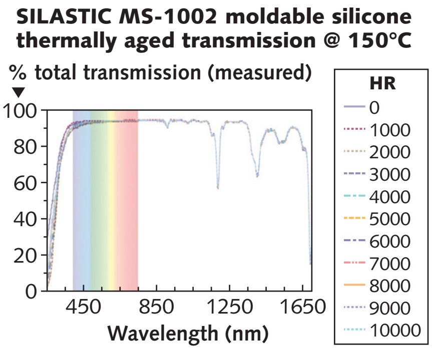


FIGURE 1. Light-transmittance spectra of SILASTIC MS-1002 are shown as a function of accelerated aging of plaques of ca. 4 mm thickness at 150°C up to 10,000 hours. Overtones of C-H of CH_3 groups along the siloxane backbone are causing absorption in the near-infrared (near-IR) region above 1050 nm. Absorption in the deep-UV region starts at wavelengths below 300 nm. These are typical properties, not to be construed as specifications.

character, therefore larger bond energy.[2] This explains the high heat and UV stability of the Si-O-Si dimethylsiloxane backbone used in moldable optical silicone for LED lamps and luminaires, as well as their outstanding flame retardancy performances.

Optical materials comparison

The properties of moldable optical silicones, glass, polycarbonate (PC), and PMMA (acrylic), compared in the table, illustrate differences in key bulk materials characteristics. The unique properties of optical silicones based on polydimethylsiloxane (PDMS) polymer and siloxane resins give them mechanical strength and toughness for freeform lenses or light guides after crosslinking during the injection molding process.

The high heat stability of LSR is illustrated by SILASTIC MS-1002 moldable silicone, an optical-grade LSR (see Fig. 1). After 10,000 hours of accelerated aging exposure to 150°C, the optical silicone remains perfectly transparent in the 400–800 nm visible-light range.

Optics made with silicone materials are also extremely resistant to UV radiation. They show no signs of yellowing nor any degradation in mechanical properties after exposure to harsh outdoor environmental conditions.[3]

Their relatively low haze of 2% to 3% makes optical silicones appropriate for most LED lighting applications. An Abbe number on the order of 50 indicates that optical silicones do not cause significant dispersion of visible light wavelengths within the material. This low dispersion enables good control of white-light beam homogeneity from a TIR lens, collimator, or light guide, similar to PMMA. Compared to PMMA and other thermoplastics, however, optics molded from silicone elastomers will not soften or melt under high temperatures. Instead, under long-term, permanent, and intense heat, silicone optics can harden progressively.

Designing optics with moldable silicone elastomers

Designers using optical-grade silicone materials need to consider thermal effects, including the CTE and TOC. Given the CTE of 275 ppm for SILASTIC MS-1002 moldable silicone, the volume of a TIR lens for a 9° beam angle collimator increases by almost 11% as the temperature rises from 25° to 150°C, but only 4% from 25° to 75°C (see Fig. 2). Due to increasing temperature, both optical efficiency and center beam candela power increase (an effect of the negative TOC value) and beam angle decreases slightly (an effect of volume increase of the TIR lens).

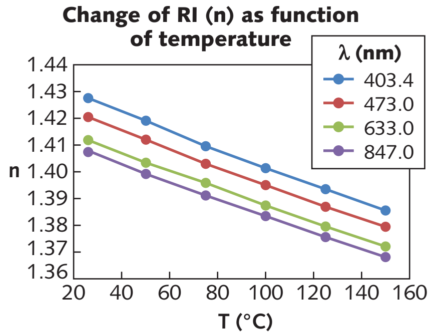


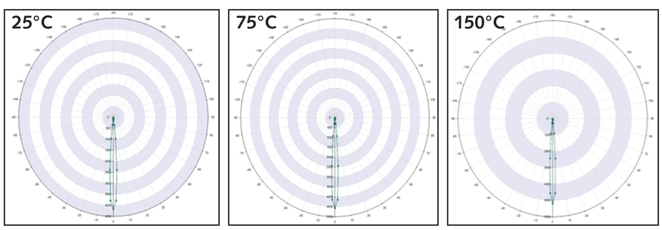
FIGURE 3. Refractive index was measured with a Metricon 2010/M prism coupler at four laser wavelengths, from room temperature up to 150°C, for SILASTIC MS-1002 moldable silicone.

The refractive index (RI) as a function of wavelengths in the visible spectrum is available for SILASTIC MS-1002 moldable silicone and a few other optical silicones in the same family from software databases such as LightTools, Photopia, and Speos. Measurements of RI as a function of temperature result in a value of -3.2×10^{-4} for the TOC (see Fig. 3).

Injection molding of optical silicones

Moldable optical silicones are two-component, viscous liquids that must be mixed in a 1:1 ratio by weight to produce a solid part after heat curing. The underlying chemical reaction, known as crosslinking, occurs when a vinyl-terminated polysiloxane is added to a Si-H functional polysiloxane oligomer in the presence of a platinum catalyst.[4]

Temperature of lens	Optical efficiency	Δ	CBCP (cd)	Δ	Beam angle / FWHM	Δ
25°C	90.70%	–	4179	–	8.9°	–
75°C	91.07%	↑0.4%	4336	↑3.8%	8.6°	↓0.3°
150°C	91.54%	↑0.9%	4540	↑8.6%	8.3°	↓0.6°



Temperature	Volume (cm^3) narrow collimator
25°C	5.58
75°C	5.81
150°C	6.18

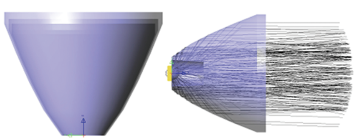


FIGURE 2. An optical simulation is done for a 9° beam angle collimator made of SILASTIC MS-1002 moldable silicone. The spiral graphs illustrate the intensity of light flux as a function of the beam angle (ca. 9°) and the increase of center beam candela power (CBCP) with increasing temperature.

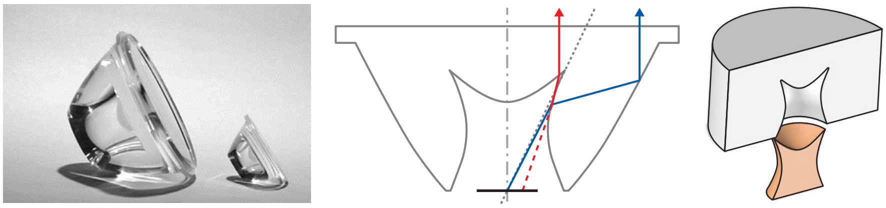


FIGURE 4. The Gaggione LLC66 and LLC32 collimator series is designed for use with light emitting sources of various diameters.

The liquid form of moldable optical silicones allows injection at room temperature and at relatively low pressure through small gates, showing good flow lengths in thin-wall sections. Compared to thermoplastics, a liquid-silicone injection-molding press can run effectively at relatively low pressures and moderate clamping forces. A relatively low viscosity at room temperature (15° to 25°C) combined with the drop-in viscosity during mold filling enables perfect replication of microsized features with small radii of curvature, such as Fresnel lens patterns.

The material is released from the mold in a solid form after being cured at high temperature (approximately 125° to 180°C). Cold runners allow direct gating on the part so silicone optics can be produced with an optimized mold design that minimizes waste and reduces gate sizes. Gate sizes are typically around 0.2 mm for small optics and up to 1–2 mm for large and thick optics, and therefore have a minimal influence on optical performance. These small gates do not require labor-intensive post-finishing steps.

Case studies of moldable optical silicones

Recently, there has been growing interest from designers in optical silicones for enhancing the performance of lamps or luminaires.[5] For instance, collimator designs with negative draft angles can be produced using industrial-scale injection molding of optical LSR (see Fig. 4).[6]

Another application is a molded silicone optic for controlling light flux and correlated color temperature (CCT) of a 4000 K CCT LED lighting fixture (see Fig. 5). In such linear luminaires, there are several options for protecting the LED boards against harsh environmental exposures. However, each carries benefits and compromises regarding light flux intensity and CCT controls.[7] In Figure

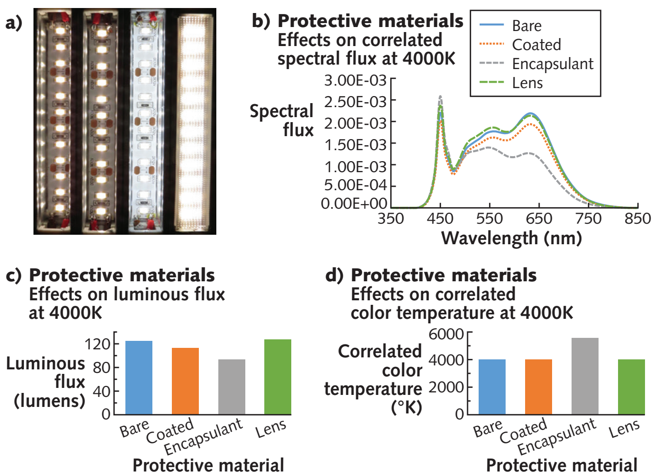


FIGURE 5. An LED board with a CCT of 4000 K is shown in four variants: a bare board, with a conformal coating, with an optical encapsulant, and with a molded optical silicone lens (a). The effects of a molded silicone lens vs. the other variants on spectral flux (b), luminous flux (c), and CCT at 4000 K (d) can be seen. These are typical properties, not to be construed as specifications.

5a, the LED boards from left to right show the light emitted by the linear fixture protected with, respectively, nothing, a conformal coating, an optical encapsulant, and a molded optical silicone lens. The corresponding LED light spectral power distributions are shown in the line graph (see Fig. 5b).

As shown in the bar graphs in Figures 5c and 5d, the silicone lens is the only solution that maintains a CCT close to the initial CCT of 4000 K for the bare LED board and enables the maximum and most homogeneously distributed light flux. These performance properties were achieved using a unique design for the light-extracting surface of the silicone lens (see Fig. 6). The linear lens design by LumenFlow (Grand Rapids, MI)[8] demonstrates how optical silicone elastomer can deliver multiple functions, homogeneous light extraction and distribution, undercuts, and sealing for ease of construction and assembly.

Advanced silicone optics have demonstrated their value in high-power LED lighting fixtures and, therefore, high-photothermal-load applications (up to 35,000 lumens).

In the area of LED lighting for streets and roadways, VS Lighting (Vossloh-Schwabe Baden-Wuerttemberg, Germany) designed a cost-effective module with high ingress and impact protection ratings (IP67, IP69K, IK08).[9] The optical silicone and silicone adhesive used in the LED module provide strong resistance to outdoor UV light and impact. Importantly, PDMS-based materials are permeable to volatile organic compounds (VOCs), helping prevent contamination of the LED die or its light-converting phosphor layer.[10]

In exterior automotive applications, SoundOff Signal (Hudsonville, MI) designed an LED lighting module for emergency vehicles using two optical LSRs. Here, the specially designed clear lens is molded from SILASTIC MS-1002 moldable silicone. This lens is then co-molded with SILASTIC MS-0002 moldable silicone to form the housing. The LED module has a small footprint with maximized candela output, outstanding resistance to damage such as gravel pitting, improved sealing performance to prevent water entry, and high UV and photothermal stability to prevent lens yellowing.[11]

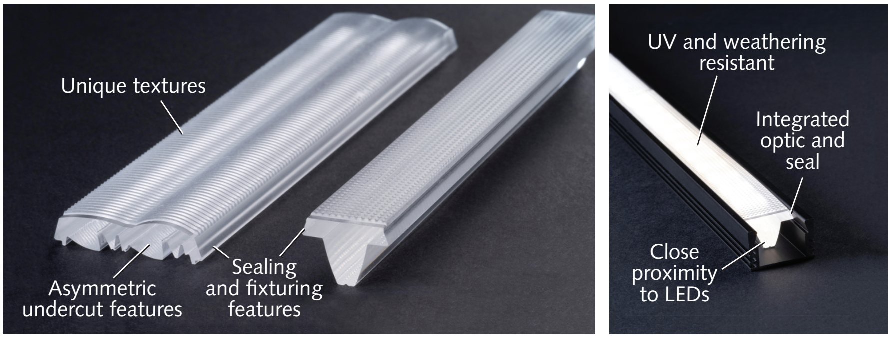


FIGURE 6. This example optic design by LumenFlow, including unique surface texturing, undercuts and sealing features for optimal light output effects, is made possible using optical-grade silicone. *(Courtesy of LumenFlow)*

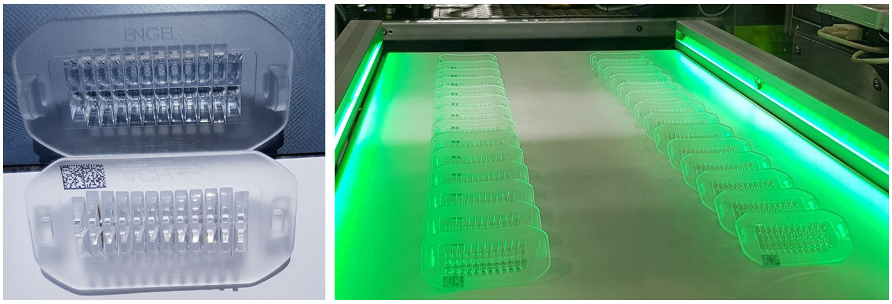


FIGURE 7. This demonstration part by Engel-ACH Hefner (Fischlham, Austria) is a silicone optic with 2 × 12 light guides molded from SILASTIC MS-1002 moldable silicone. *(Courtesy of Engel-ACH Hefner)*

FIGURE 8. A SILASTIC MS-1002 moldable silicone was overmolded onto 30% glass-reinforced polybutylene terephthalate (PBT) thermoplastic; the demonstration part design is by DOW–Gaggione. *(Courtesy of Dow)*

In another example,[12] optical silicones are being used to fabricate primary lenses with multisegmented LED light sources for adaptive driving beam (ADB) headlamps to improve the safety of drivers and roadways.[13] Adaptive driving beam technology allows drivers to keep their high beams on permanently because the system automatically adjusts intensity in response to varying traffic and road conditions.

From a manufacturing standpoint, injection-molding press suppliers and mold tooling companies have collaborated to improve automation of the liquid injection-molding process and associated quality control. The result is cost-effective production of silicone optics with multiple light guides (see Fig. 7).[14]

Recent developments aim to improve integration of silicone optics into the LED fixture, for instance, by overmolding optical LSR onto thermoplastic substrates.[15] In Figure 8, the optical silicone is overmolded onto 30% glass fiber polybutylene terephthalate (PBT). The two- or three-material injection-molding process can enable multiple-function LED light engines by combining rigid but brittle thermoplastics and flexible but tough silicone elastomers.

Optical moldable silicones deliver outstanding performance in demanding environments, including high heat, high humidity, and UV exposure. They combine excellent optical properties with resistance to yellowing, scratches, cracks, vibrations, gravel pitting, and other damage that may limit glass and thermoplastics.

From a design standpoint, the flexibility and consistent mold replication of silicones enable complex optical shapes, fine surface features, and integrated mechanical features more difficult with traditional plastics. Injection molding allows high throughput and lowers stress on molding tools.

Dow offers LED lighting designers and manufacturers of optics components a team with expertise in materials science, optics, and injection-molding tools and processing technology for LSR.

REFERENCES

For the complete list of references, please see https://bit.ly/Oct19References.

Martijn Beukema is Technical Service & Development Optical Engineer, **Michelle Cummings** is Research & Development Chemist, **François de Buyl** is Technical Service & Development Scientist, **Jake Steinbrecher** is Technical Service & Development Engineer, **Brad Tuft** is Research & Development Chemist, and **Kevin Van Tiggelen** is Technical Service & Development Injection Molding Engineer, all at Dow, Brussels, Belgium and Midland, MI; e-mails: francois.debuyl@dow.com and jacob.steinbrecher@dow.com; www.dow.com.