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2001-01-0863

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Reprinted From: Lighting Technology Developments for Automobiles
(SP–1595)

The Engineering Society
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SAE 2001 World Congress
Detroit, Michigan
March 5-8, 2001

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ISSN 0148-7191
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Printed in USA

2001-01-0863

Evaluation of Fabrication Errors on the Performance of Injection Molded Light Pipes (Waveguides)

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ABSTRACT

This paper examines the consequences of fabrication effects on the performance of injection molded plastic light pipes for distributive automotive lighting. It discusses the magnitude of these effects on propagating and output light. Molding errors, such as sinks, voids, flow lines, knit lines, and warpage, will be examined through computer modeling and measurement of sample distributive lighting systems.

Two example light pipe systems will be presented, an instrument cluster pointer system and a regional distributive interior lighting system. For the pointer system, computer modeling results, such as total light output and output exitance distributions will be presented. Modeling results will be presented for both an error free system and system that include the aforementioned molding errors. These results will be compared to determine the output light loss and redistribution. For the regional interior lighting system, total output and exitance measurements of fabricated light pipe systems will be presented for comparison and to illustrate the effects of errors.

Since it is impossible or impractical to eliminate all injection molding fabrication errors from manufactured light pipe systems, this paper will conclude with a discussion of the circumstances under which individual errors should be diminished or eliminated.

INTRODUCTION

BACKGROUND

Plastic injection molded light pipes (or thick waveguides) offer an ideal nonimaging optical solution for automotive lighting and illumination. Figure 1 shows an example of a light pipe system for interior automotive display illumination such as radios and instrument clusters. Similar systems, typically of larger scale, are beginning to be used for general interior and exterior automotive lighting systems, including tail, puddle, and forward lighting applications.[1][2][3] Since image formation is not the goal in these applications, the refraction and total internal reflection (TIR) properties of light pipes can be efficiently used to collect, transport, and output light.[4] Light pipes can also be used to tailor the output light distribution to the needs of the illumation task.[5][6]

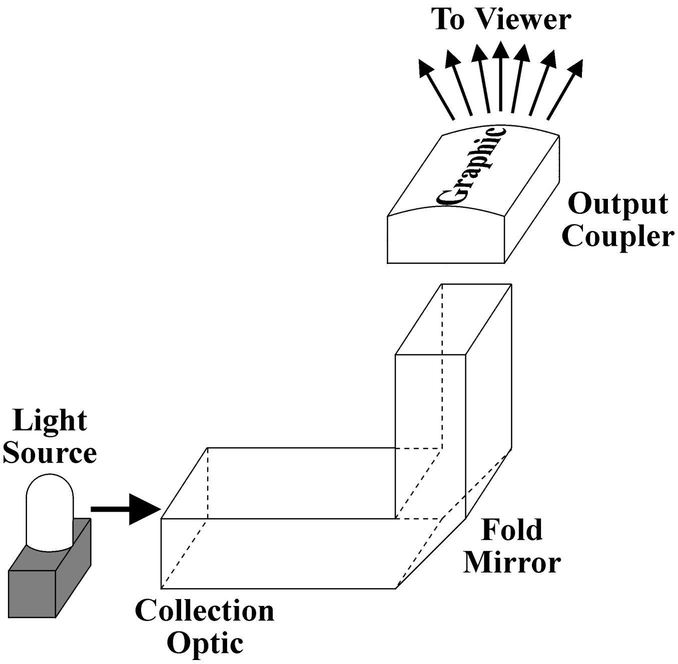

Figure 1. Example interior automotive light pipe illumination system.

Because they are injection molded, light pipes are well suited for automotive manufacturing. They are relatively inexpensive, easy to fabricate in large quantities (millions per year), and are versatile to design. However, the injection molding process can introduce some surface and volume properties that are detrimental to the optimal performance of these systems.

Surface and volume errors introduced by the injection molding manufacturing process include: sinks, voids, knit and flow lines, warpage, and blushing. Of these the most common and serious molding errors are sinks and voids. Sinks occur in the injection molding process when a large volume of liquid plastic is allowed to cool to rapidly. This results in a sinking or dimpling of the surface as the cooling plastic shrinks away from the tool cavity walls. Sinks can range from a very slight surface deformation to a severe deformation that extends through the part. Voids, or included areas of air, occur in injection molding when the melt temperature or cavity pressure is insufficient to fully fill the mold. Voids can range from very small bubbles to relatively large cavities.

Until recently the detrimental ramifications to lighting quality caused by injection molding was not readily apparent. However, with the advent of powerful commercial optical modeling software packages and new nonimaging design tools, light pipe system design has become more precise and efficient.[7][8][9] In fact, design precision has increased to such a level that injection molding fabrication effects are now becoming a limiting factor in some cases.

SCOPE OF PAPER

In three main sections, this paper explores the effects of injection molding errors on the performance of distributive lighting systems by providing two examples. The first section of this paper presents an instrument cluster pointer light pipe system. It describes a computer modeling examination of the effects of sinks on the light collection of the system. The geometry and illumination properties of the system are first presented. Next, computer simulated output flux and distribution results of an ideal system and a system with simulated sinks are presented. Finally these results are compared.

The second section presents a regional distributive general automotive interior lighting system. It presents measurements of fabricated parts that characterize light output. Measurement results for parts with and without voids and sinks are given and compared. Two types of light pipes are explored in this manner, straight rectangular light pipes and rectangular cross-section Y branch light pipes. The geometry of the light pipes is given along with the measurement results. Comparison of the results with and without voids is also presented.

The final section reviews the results of these two examples to draw general conclusions. It discusses what injection molding errors present the biggest problems and in what situations the most concern should be given to reducing or eliminating these errors.

INTSRUMENT CLUSTER POINTER SYSTEM

Pointer indicators are used often in automotive instrument clusters to indicate vehicle speed, engine temp, oil pressure, etc. They are easy to read and infer information from at a glance. Since pointers are kinetic displays they can also provide further information, such as vehicle acceleration, by the rate at which they move. Because pointers provide critical information about the vehicles operation, it is critical for safety that they are brightly and uniformly illuminated over the range of motion.

The pointer light pipe system explored here is a part going into production for model year 01. It was computer modeled to examine design issues and to explore lamp toleranceing. Simulated manufacturing errors were introduced to the model to mimic production issues.

GEOMETRY

Figure 2 shows the right half of a cross-sectional view of the pointer light pipe system. This system is designed to illuminate two pointers from one lamp. However, since this system is symmetric about the lamp only one side is considered. It consists of: a T194 lamp source, a collection optic, a fold mirror, a slab subdial light pipe, pointer mirrors, and pointers.

Light is collected from the lamp and bent 90^o by the fold mirror into the subdial. The light propagates in two directions through the slab light pipe until it encounters a pointer mirror. It is then bent another 90^o out of the subdial and is incident on a pointer. The pointer output couples the light to the viewer. The detector plane shown in Figure 2 is not in the actual system but is used for modeling purposes.

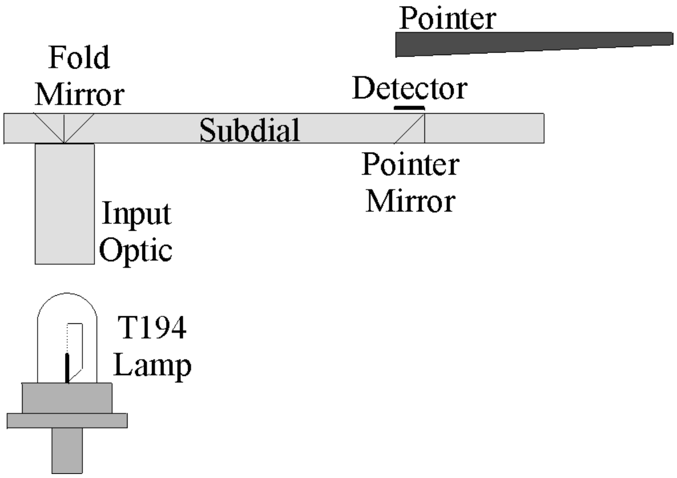

Figure 2. Instrument cluster pointer light pipe illumination system.

MODELING AND RESULTS

The system was computer modeled in three-dimensions with the geometry shown in figure 2. The plastic material used was polycarbonate (index n=1.59). The dimensions of the physical system were reproduced as accurately as possible. The geometry and optical properties of the lamp were modeled to closely approximate the measured lamp output.[4] A detector plane was placed above the pointer mirror to collect the pointer mirror output flux.

Light rays were traced through the system and collected on the detector plane. One million rays were used to ensure statistical accuracy. The resulting error in this analysis was less than 5%. From the ray trace both the relative total amount of output flux and the exitance distributions were calculated.

The relative total output flux from the pointer mirror for this system is 0.88. Figure 3 shows the exitance distribution from the pointer mirror.

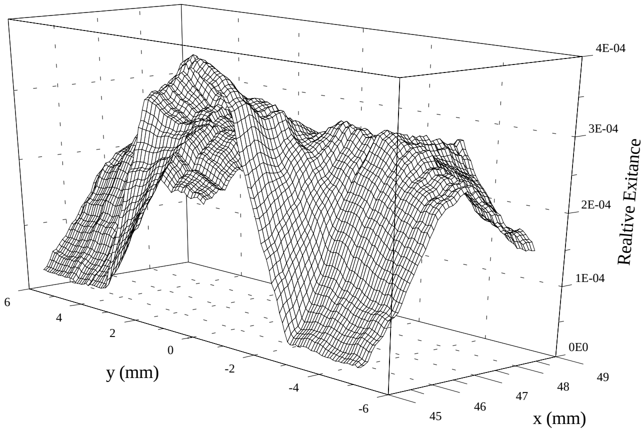

Figure 3. Relative exitance distribution of pointer mirror.

The plot in figure 3 shows a relatively uniform distribution. The corners of the distribution at x=45mm fall to zero because there is no mirror under the detector at this point. The pointer mirror is made up of three sections, a longer middle section and two shorter end sections. The shorter end sections do not extend completely across the detector.

Another model of this system was created identical to the first except with sinks on the wall surface of the input optic. The positions of the sinks are shown in figure 4. Two symmetrical sinks were added to the model to mimic what would be seen in manufacturing. The cross-section of the light pipe system at this point is very thick for the injection molding machines being used. This would all but ensure a sink at this location. The sinks were mimicked by a spherical indentation centered in the flat wall surface with a depth into the material of 0.5mm and a length of 11mm.

Again light rays were traced through the system and collected on the detector plane. One million rays were used to ensure statistical accuracy. The resulting error in this analysis was also less than 5%.

The relative total output flux from the pointer mirror for the system with sinks is 0.54. Figure 5 shows the pointer mirror exitance distribution for this system.

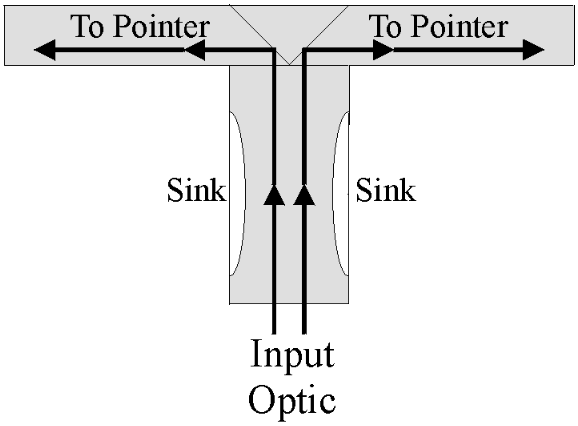

Figure 4. Location of sinks on input optic.

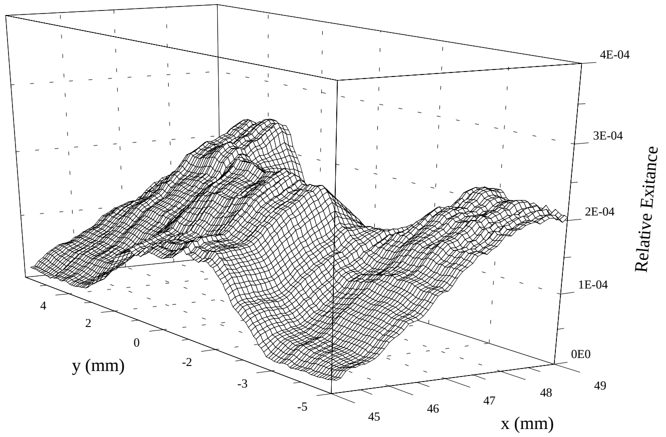

Figure 5. Relative exitance distribution of pointer mirror with simulated sinks.

The plot in figure 5 shows a distribution similar to that in figure 3. The three segments of the pointer mirror can be seen with a fall off at the corners at x=45mm. However, the exitance distribution from the model with the sinks is not as uniform as the distribution from the ideal system. More variation in exitance level is seen along the x-axis. The total level has also dropped significantly.

ANALYSIS

It is evident from comparing the above results that the simulated sink greatly affected the performance of the system. The total output flux dropped ~39% when the sinks are included. Further modeling was performed for this system in which the position of the lamp filament was moved to examine tolerance. At the extreme position, with the filament moved 2mm, the total pointer mirror output flux was 0.80 for the ideal system and 0.32 for the system with sinks. This is a decrease in output of 60%. So, not only do the sinks significantly decrease the output of this system, but also they greatly reduce this systems tolerance to shift in filament position.

The addition of the sinks in this system also adversely effects the output distribution. Not only is the overall level of the exitance distribution reduced but also the uniformity of the distribution suffers. The exitance distribution of the system with sinks is less uniform than the ideal system.

REGIONAL INTERIOR LIGHT PIPE SYSTEM

Light pipes are gaining acceptance for general lighting applications in automotive interior applications. These regional systems, in a door panel for example, can light several switches, cup holders, map lights, door handles, assist grips, locks, and bins from one lamp. The use of these systems can greatly reduce the overall lighting cost by eliminating lamps, wiring, harnesses, and connectors.[1]

The light pipes examined here are prototypes of a regional interior lighting system. They were fabricated through injection molding. Two types of light pipes were examined, straight and Y branch. Due to the thickness of these light pipes numerous parts were fabricated with voids and sinks. Parts were chosen for this study that contained manufacturing errors of interest. Other parts, with no errors, were chosen as control samples for comparison. Note that no post processing was done on these parts other than to disconnect them from the runner.

STRAIGHT LIGHT PIPE

Figure 6 shows the geometry of the straight rectangular light pipe. These polycarbonate light pipes are 5mm x 5mm in cross section and have a length of 100mm. A sample part was chosen with a substantial elliptical void (4mm long by 1.5mm wide) included. This void is ~20mm from the end of the waveguide.

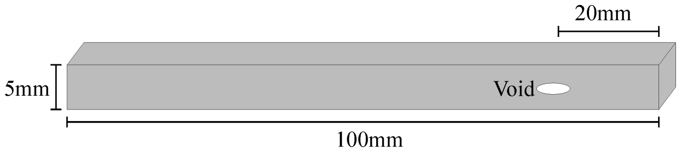

Figure 6. Straight light pipe geometry.

Both the control and void included light pipes were illuminated and measured. The void included light pipe is measured with the void nearest to the output surface. The light pipes were illuminated on the small surface with an integrating sphere uniform illuminator. This ensures a uniform input distribution. The output surface was measured with a scanning fiber photometer to determine the exitance distribution. This instrument scans a fiber optic probe in a raster pattern a distance from the output surface. The fiber is scanned in discreet overlapping steps to cover the entire surface. For these measurements the fiber was scanned a distance of 0.5mm from the output surface

Figure 7 shows the measured exitance distribution for the clear control light pipe and figure 8 shows the exitance distribution for the light pipe with the void.

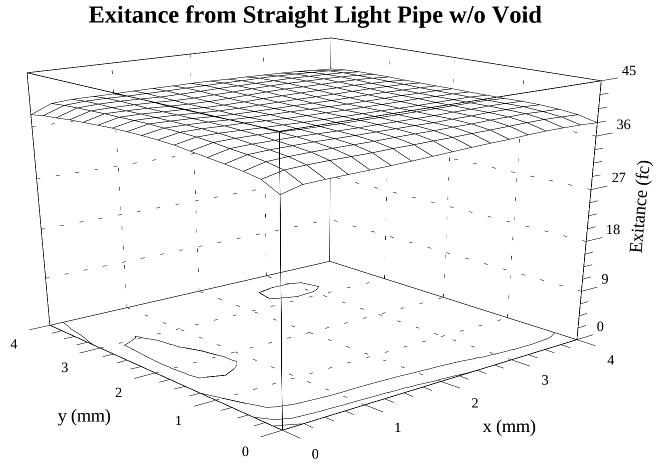

Figure 7. Straight light pipe exitance distribution.

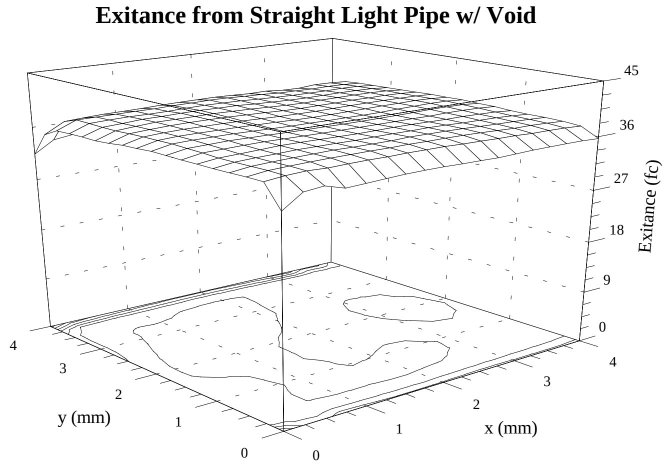

Figure 8. Straight light pipe with void exitance distribution.

As seen in figures 7 and 8 the two distributions are very similar. Both have a uniform output distribution with only a slight roll off at the edges due to fiber sampling. The only major difference between the two distributions is the overall output level. The control light pipe has an average exitance of 39.5fc and the void include light pipe has an average exitance of 37.6fc. This is a decrease in output of ~5%.

The light pipe with the void was turned around so the void was closest to the input surface. The measurements were repeated and found to be very similar, with the average exitance being 37.5fc.

These exitance results are not unexpected. Rectangular cross-section rods are often used to mix input distributions and obtain uniform output. Even with the void relatively close to the output end the distribution in the rod has enough time to become uniform again.

Y LIGHT PIPE

Figure 9 shows the geometry of the Y branch light pipe. These polycarbonate light pipes are 5mm x 5mm in cross section and have segment lengths indicated. The

Y branches are separated by 45°. A sample part was chosen with a substantial sink included at the point where the light pipe branches. This is the section of the piece with the most material, and therefore, the place most likely to get a sink. This sink is so severe that the opposite walls almost connect to create a void or hole.

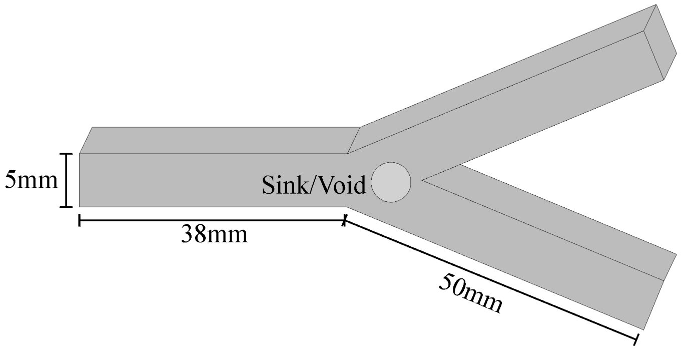

Figure 9. Y branch light pipe geometry.

Both the control and sink included Y branch light pipes were illuminated and measured. The light pipes were illuminated on the small surface with an integrating sphere uniform illuminator. One output surface was measured with a scanning fiber photometer to determine its exitance distribution. For these measurements the fiber was scanned a distance of 0.5mm from the output surface

Figure 10 shows the measured exitance distribution for the clear control Y branch light pipe and figure 11 shows the exitance distribution for the Y branch light pipe with the sink.

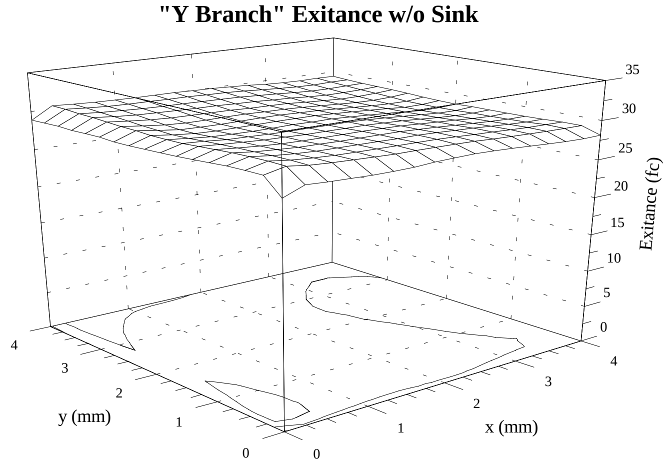

Figure 10. Y branch light pipe exitance distribution.

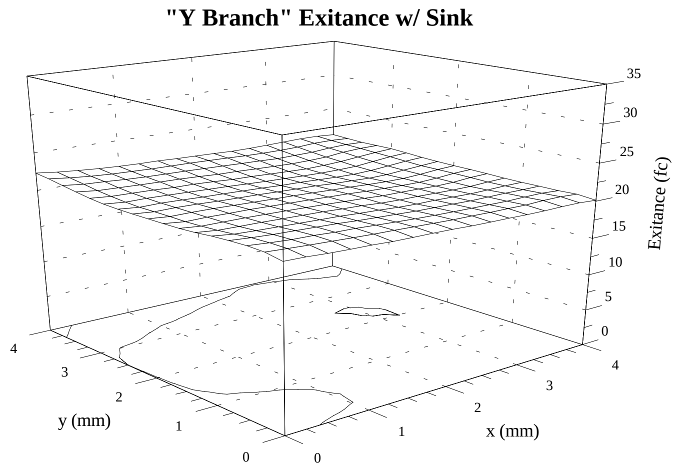

Figure 11. Y branch light pipe with sink exitance distribution.

As seen in the straight waveguide case the two distributions are very similar. Both have a uniform output distribution with only a slight roll off at the edges due to fiber sampling. The only major difference between the two distributions is the overall output level. The control light pipe has an average exitance of 28.7fc and the void include light pipe has an average exitance of 19.5fc. This is a decrease in output of ~32%.

Again these exitance results are not unexpected. The mixing of the light distribution as it travels down the rectangular cross-sectional rod is occurring. However, in this case there is a substantial decrease in total light output.

DISCUSSION

The examples presented above illustrate how the two most common injection molding errors, sinks and voids, can affect light pipe systems. The instrument cluster pointer example shows how sinks can significantly reduce the system performance. Both the total light output and the light output distribution was adversely affected. Sinks deform the surface shapes. Depending on the location and severity of the sink the effects will vary. In this case the sinks are on a portion of the optic that shapes the light so it can travel efficiently through the system. When these surfaces are deformed the light reflects in directions away from the intended output. This is also apparent when considering the resulting increased intolerance to filament position cased by the sinks. Sinks on any light shaping\steering surfaces, such as input surfaces or mirrors, can be severely detrimental and should be avoided.

The regional interior system example shows how voids can range in negative effect from minor, in the straight light pipe example, to severe, in the Y branch example. The void in the straight light pipe was small in cross section and sufficiently far away from the output surface. It caused to degradation of the exitance distribution and only resulted in a 5% loss in total output. If system efficiency is not critical, as is the case with some light pipe systems, than this void is not a factor. In the Y branch case the sink/void is at a critical location, where the light is redirected to the two branches. In this case the void reduces the total output significantly, by ~32%. Here the location of the error makes it a factor.

ACKNOWLEDGMENTS

The instrument cluster pointer work was funded and supported by DaimlerChrysler, Huntsville Electronics and performed in cooperation with Michael Pryor from DaimlerChrysler. The distributive tail light work was performed in cooperation with Federal-Mogul Corporation and performed in cooperation with George Hulse, formally of Federal-Mogul Corporation.

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