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Zsiros L., Suplicz A., Romhany G., Tabi T., Kovacs J. G.

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Development of a novel color inhomogeneity test method for injection molded parts

L. Zsíros, A. Suplicz, G. Romhány, T. Tábi, J. G. Kovács*
Department of Polymer Engineering, Budapest University of Technology and Economics, H-1111 Budapest, Műegyetem rkp. 3., Hungary,
*Corresponding author J. G. Kovács, e-mail: kovacs@pt.bme.hu

Abstract

Nowadays most research and development concerning injection molded products are focused on their mechanical properties although visual appeal plays an even more important role on the market. There are several standards and recommendations for the testing of mechanical properties, but appearance cannot be quantified easily. The visual aspects are almost completely neglected, and there is not a commonly accepted method for measuring color inhomogeneity.

The appearance and color homogeneity of injection molded parts depends on the coloring method itself, the applied technology and several other conditions. The method used nowadays to evaluate color inhomogeneity is based on visual inspection by humans. This research focuses on developing a new and automated method that can replace visual inspection. The functionality and precision of the new method and software have been tested and compared with visual inspection to prove its applicability.

Keywords: color inhomogeneity; injection molding; color differences; aesthetics

1. Introduction

To investigate color inhomogeneity in injection molded parts objectively it has fundamental importance to have a measurement system which is fast enough, works with relatively small standard deviation and produces results which is in correlation with human inhomogeneity perception. Unfortunately at least two of these criteria cannot be fulfilled by human inspections, since human decision incorporates a huge uncertainty. The only way to reduce this uncertainty is to increase the number of inspectors, and average their results, which slows down the evaluation process. Due to these issues it seemed necessary to develop an automated method, which reassuringly fulfills the criteria of being fast, working with low standard deviation, and correlating well with human inhomogeneity perception.

According to ASTM the standard measurement methods need to be precise, repeatable and reproducible [1]. These requirements also cannot be fulfilled by human visual inspections. Therefore possibilities of an evaluation algorithm executed by a computer, which works on digitalized pictures have been investigated. Commercial equipments that can digitalize pictures normally has their outputs in the RGB color space. Since the original goal was to establish a measurement method which is in line with average human color difference sensation, these color coordinates needed to be transformed to a color space where Euclidean distances, described in Eq. (1) are proportional to human color perception.

$$\Delta E = \sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2}\ , \qquad (1)$$

where ΔE is the Euclidean distance between two points in a three-dimensional space, and Δx, Δy, Δz are the coordinate differences of the three dimensions. Quite a lot of color spaces developed in the recent decades fulfill this requirement, however in most of the industrial applications where color is in correlation with important attributes or process parameters CIELAB color space is used to evaluate them. Sometimes CIELAB is also preferred over RGB because of its device-independency [2-4]. Transformation formulas from the RGB to the CIELAB color space can be obtained from literatures dealing with color space transformations [5-11], computer graphics [12] or industrial applications [3] of color measurement systems.

The appearance of injection molded parts is very important and it does not only mean the color properties only, but in most cases the evenness of the color as well. It has been shown by many authors [13-14] that injection molding parameters have a significant effect on the color and gloss of the finished parts, and the effect is different in the case of smooth and rough surfaces. Pisciotti et al. [13] measured the effects of injection molding parameters on color and gloss in the case of polypropylene parts, and concluded that mold temperature and packing pressure have a significant effect on the measured color and gloss. They also concluded that lower melt viscosity and higher shear rates provided a better replication of the mold surface, which had a different effect if they tested a smooth or a rough surface. In the case of rough surfaces gloss decreased as the quality of surface replication improved, while the opposite was observed with a shiny surface. Dawkins et al. [14] measured very similar results to these. Although they did not measure color inhomogeneity, only the color coordinates themselves, it can be assumed that these parameters and the surface texture of the cavity could influence the level of visually perceived color inhomogeneity as well.

Color inhomogeneity is often caused by the insufficient dispersion of the fillers or colorants, and it is also influenced by injection molding parameters, as in the case of nanofiller dispersion in extrusion, which was influenced by screw rotation speed according to S. Sathyanarayana et al. [15]. Color differences and deviations are often signs of certain processes taking place, such as various degradation processes. This was studied by Santos et al. [16], who examined the effectiveness and the durability of different stabilizers against photo-oxidation processes in ABS. Martínez-Morlanes et al. [17] found that there is a correlation between the color shade of the polyethylene samples and their E vitamin content and absorbed gamma radiation.

From the inhomogeneity problem described in many literature it is obvious that surface defects are often in a connection with chemical or physical changes during the plastic processing. Until now there are no standards and accepted measuring methods to characterize these color inhomogeneity problems, although it is a fundamental importance to establish a widely acknowledged method. Based on this demand from the injection molding industry the goal of this work was to establish a novel and automated measuring method for evaluating color inhomogeneity level. The new method should be fast and produce results as close as possible to the human evaluations, with better repeatability and reproducibility.

2. Materials and methods

In this study, the color inhomogeneity of specific specimens, injection molded from unfilled acrylonitrile-butadiene-styrene (ABS) with 4 wt% of masterbatch (MB) was examined. The matrix (Terluran GP-35, Styrolution Group GmbH) and the masterbatch (Renol-pink ABS143479Q, Clariant) were dry mixed, and samples were injection molded on an Arburg Allrounder Advance 370S 700-290 machine, with a screw diameter of 30 mm. The set of technological parameters were selected based on a DOE in which the most significant parameters have been identified. The range of parameters were set to have a wide enough range to show any differences in color inhomogeneity, but also to allow the execution of the injection molding cycle with these parameters. The injection molded samples were digitalized using flatbed scanner with 200 dpi resolution. These pictures have been evaluated by computer based method described in the *Mathematical method development* chapter. Human evaluations have been carried out on the physical samples in a conventional way, in which each sample has been evaluated by 6 trained technicians, under identical circumstances. They have been instructed to score the samples from 0 to 10 based on the inhomogeneity level, where 0 is the theoretically perfect sample, with no inhomogeneity problems at all and 10 is the worst case. These 6 scores have been averaged than correlated to the software scores.

3.1 Test mold development

For the color inhomogeneity evaluation tests a mold was built to produce 80x80 mm flat specimens. The mold (Figure 1) has exchangeable inserts to be able to produce sample parts with different gates (standard, film, and also multiple gates), with different mold surface finishes (polished, fine eroded, rough eroded) and different thicknesses (0.5-4 mm). Each parameter has a significant influence on surface quality, thus on the color homogeneity and appearance of the parts, as well. The mold contains a special ejector system, which works on the whole surface area of the product, thus eliminating the surface defects that ejector pins would cause. For the tests the 2 mm thick samples were injection molded using fine eroded surface finished inserts and film gates.

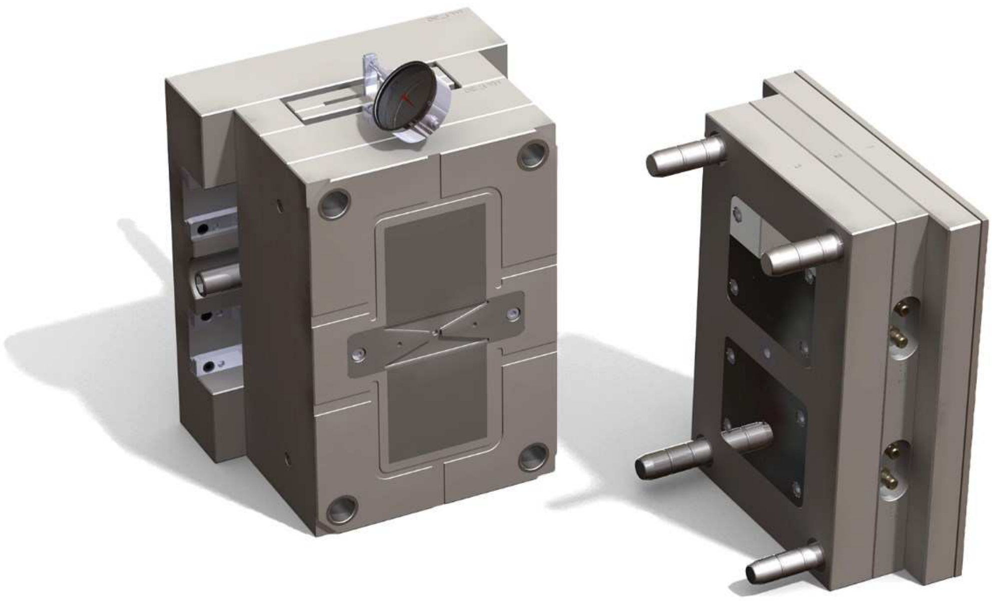

Figure 1. Test mold for color homogeneity evaluations

3.2 Mathematical method development

An image analyzer software was developed in order to objectively characterize the uneven color of injection molded products by using the image of the scanned samples. Because the Lab color system approximates human vision, the RGB color coordinates of the images of the scanned samples were converted into Lab color system (*P[L,a,b]*).

A moving window scans the picture, and at every (*i,j*) position of this window the mean color coordinates are calculated ($\bar{a}_{i,j,k}$), where *k* is the size of the window. The window size (*k*) could be varied from 1 to the maximum size of the picture. A matrix can be generated from the mean color coordinates as follows (Eq. (2)-(4)):

$$\bar{\bar{A}}_{i,j,0} = \begin{bmatrix} \bar{a}_{0,0,0} & \bar{a}_{1,0,0} & \cdots & \bar{a}_{i,0,0} \\ \bar{a}_{0,1,0} & \bar{a}_{1,1,0} & & \bar{a}_{i,1,0} \\ \vdots & & \ddots & \vdots \\ \bar{a}_{0,j,0} & \bar{a}_{1,j,0} & \cdots & \bar{a}_{i,j,0} \end{bmatrix}, \quad (2)$$

$$\bar{\bar{A}}_{i,j,1} = \begin{bmatrix} \bar{a}_{0,0,1} & \bar{a}_{1,0,1} & \cdots & \bar{a}_{i-1,0,1} & n.a. \\ \bar{a}_{0,1,1} & \bar{a}_{1,1,1} & & \bar{a}_{i-1,1,1} & n.a. \\ \vdots & & \ddots & & \vdots \\ \bar{a}_{0,j-1,1} & \bar{a}_{1,j-1,1} & & \bar{a}_{i-1,j-1,1} & n.a. \\ n.a. & n.a. & \cdots & n.a. & n.a. \end{bmatrix}, \quad (3)$$

$$\bar{\bar{A}}_{i,j,k} = \begin{bmatrix} \bar{a}_{0,0,k} & n.a. & \cdots & n.a. \\ n.a. & n.a. & & n.a. \\ \vdots & & \ddots & \vdots \\ n.a. & n.a. & \cdots & n.a. \end{bmatrix}, \qquad (4)$$

where the elements of the matrix can be calculated as follows (Eq. 5):

$$\bar{a}_{i,j,k} = \frac{\sum_{x=i}^{i+k-1} \sum_{y=j}^{j+k-1} P[L,a,b](x,y)}{k^2}, \qquad (5)$$

where i and j are the position of the moving window within the whole picture, k is the width and height of the moving window, and x and y are the local coordinates within the moving window.

For all window sizes and positions the Euclidean distance of each pixel from the mean color coordinates ($\bar{a}_{i,j,k}$) in the given window were calculated. For each window the average Euclidean distance has been calculated Eq. (6).

$$MD_{i,j,k} = \frac{\sum_{x=i}^{i+k-1} \sum_{y=j}^{j+n-1} \sqrt{\sum_{\varepsilon=L,a,b} \{P[\varepsilon](x,y) - A[\varepsilon](x,y)\}^2}}{k^2} \qquad (6)$$

In the Lab color space the distance of two colors are independent from the reference white, therefore it was not necessary to measure that.

The lower the $MD_{i,j,k}$ value is, the more even the color of the sample in the area covered by the moving window is. Moving the window pixel by pixel the software can locate the area having the highest MD_k value (HMD_k). If the size of the moving window is equal to the image size in pixels, a global MD value (GMD) can be obtained. The software calculates the HMD_k values for different window sizes which can be compared to human evaluations.

4 Results and discussion

Samples have been injection molded with different parameters, and the samples were scanned. The default injection molding parameters were the following: 700 kN clamping force, 225°C melt temperature, 55 cm^3/s injection rate, 127.5 s residence time and 40°C mold temperature. Three tests were executed, and in each test only 1 parameter was changed to a low, a medium and a high value. In the first test the injection rate was set to 10 cm^3/s and 100 cm^3/s next to its base value, and the measured inhomogeneity values were compared to human evaluations (Figure 2). The samples were evaluated by the software with 3 different window sizes – respectively 1.2 mm, 2.6 mm and 4.0 mm – that previously have been considered as a typical defect size. It can be seen that an increase in the injection speed resulted not only in decreased inhomogeneity, but a decrease in the standard deviation of the measured values as well. It also shows that measurements correlated quite well with human scores.

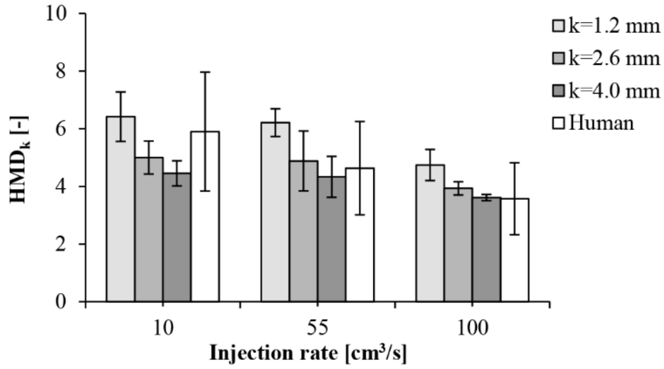

Figure 2. Inhomogeneity as a function of the injection molding rate and window size (k)

Figure 3. shows the effect of residence time on the measured inhomogeneity values. It can be seen that neither human evaluations nor the automated method showed any significant change. The software scores and the human scores correlates well, except in case of the 1.2 mm window, meaning that the software is more sensitive to the small scale defects than the humans.

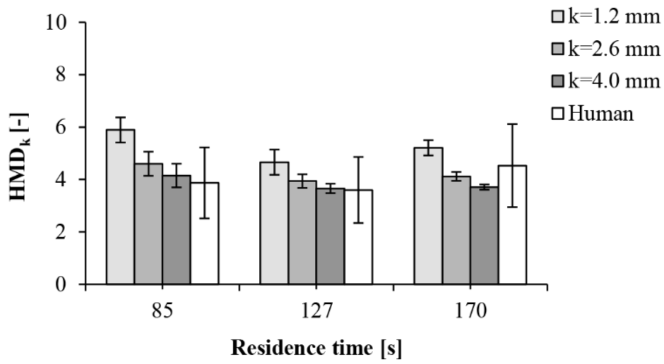

Figure 3. Inhomogeneity as a function of the residence time and window size (k)

Among the tested parameters, the melt temperature change had the biggest influence on visually observed and measured inhomogeneity (Figure 4). Although this, the software is less sensitive to melt temperature change than humans.

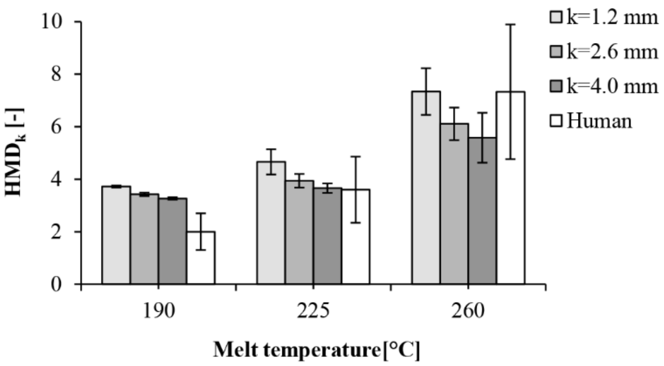

Figure 4. Inhomogeneity as a function of the melt temperature and window size (k)

Due to the high standard deviation of the color inhomogeneity it was necessary to evaluate the error sources. These errors may be originated from human factors in case of the human evaluations and the digitalization process in case of the software evaluation on the top of the injection molding process.

The measurement uncertainties of the injection molding process, digitalization process and the evaluation are independent thus the uncertainty of the whole process can be calculated according to Eq. (7).

$$\sigma^2_{total} = \sigma^2_{injection} + \sigma^2_{scanning} + \sigma^2_{evaluation} \qquad (7)$$

where σ^2_{total} means the squared standard deviation of the whole process, $\sigma^2_{injection}$, $\sigma^2_{scanning}$ and $\sigma^2_{evaluation}$ are the square of the standard deviations originated from the injection molding, scanning and evaluation. Since in the automated measurement system the evaluation is done by a computer algorithm, its standard deviation is zero. σ^2_{total} and $\sigma^2_{scanning}$ were measured directly, while $\sigma^2_{injection}$ has been calculated. For measuring σ^2_{total} 100 samples have been injection molded under identical circumstances, than scanned and evaluated. For measuring $\sigma^2_{scanning}$ one injection molded sample has been chosen (which inhomogeneity level was close to the average of the 100 previously evaluated samples), scanned and evaluated by the software 100 times (Figure 5.). The number of sampling was chosen to 100 to secure a less than 10% uncertainty of each calculated standard deviation.

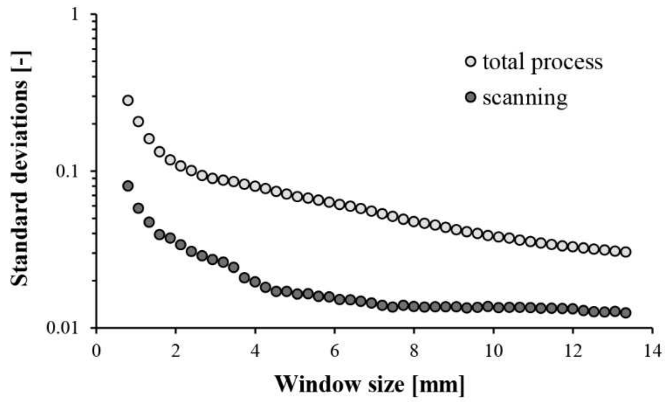

Figure 5. Normalized standard deviations of the scanning and the total process as a function of window sizes

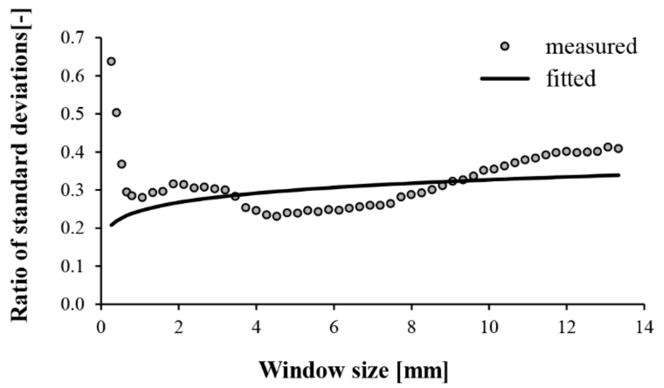

Figure 6. Ratio of $\sigma_{total}/\sigma_{scanning}$ as a function of window sizes

The standard deviation derived from the injection molding process is about three times bigger than the standard deviation of the scanning (Figure 6.). Under a certain window size (~0.65 mm, 5 pixel) the standard deviation derived from the scanning is increasing drastically, thus the calculations should exclude these values. The scanning process was further investigated by involving two different types of commercially available high end scanners measuring 65 samples on each. It was found that the difference between the standard deviations of those scanners are as high as 15%, thus an optimized digitalization method – such as professional scanners or photo camera based systems – could further improve the measurement repeatability. Comparing the standard deviation results it was proved that the human inspection resulted in one order of magnitude higher standard deviation than the new method.

Conclusions

A novel evaluation algorithm has been developed, which is able to quantify the level of color inhomogeneity of images. This algorithm was utilized in a full measurement method, which was used to evaluate the inhomogeneity of injection molded parts. The measurement results were compared to human evaluations where the correlation was 0.95 and the standard deviation was decreased with one order of magnitude.

The standard deviation of the injection molding process and the human visual inspections are in the same range thus the variations from the process cannot be captured with the human inspections. In contrast to this the new method has significantly lower standard deviation than the injection molding process itself, therefore it is capable of highlighting the differences caused by the technology. For testing the color inhomogeneity, among the injection molding parameters, injection time, residence time and melt temperature were chosen. It was proved that the melt temperature has the most significant effect on color inhomogeneity, as it was found that decreasing of the melt temperature from 260°C to 190°C reduced the inhomogeneity by 50%. While the residence time does not have any effect, the injection rate has a minor effect in the investigated range on the inhomogeneity level.

It was proved that the measurement uncertainties has been decreased significantly compared to human inspections and the measurement uncertainties in the new method is caused by the digitalization process itself. It was found that the difference between the standard deviations of the commercially available high end scanners could be as high as 15%, thus a professional scanner could further improve the measurement repeatability.

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