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RESEARCH ARTICLE

Surface Homogeneity of Injection Molded Parts

László Zsíros[1], József Gábor Kovács[1*]

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Abstract
In this paper we are presenting a novel method for color inhomogeneity evaluation. We proved that this method has a higher than 95 % linear correlation coefficient if results are correlated with human visual evaluations.
We applied this evaluation method to analyze the homogenization in the injection molding process, therefore we measured the homogenization properties of various solid phase masterbatches on injection molded parts. We tested the effects of the processing parameters of injection molding and analyzed various dynamic and static mixers as well. We have also measured the influence of the mold surface texture on the sensation of inhomogeneities on the part surface.
We have carried out our tests on an injection grade ABS material using various masterbatches. The method was based on the digitization of the molded flat specimens. The images of these specimens were evaluated with an own developed formula using the CIELAB color space resulting high correlation with human visual inspections.

Keywords
mold design, color inhomogeneity, injection molding

1 Introduction

The visual outlook and the surface properties of the mass-produced parts is an important property [1-2]; however, this is researched in much less articles compared to the mechanical properties [3-4]. Since nowadays most of the plastic parts are manufactured by injection molding, we focused our work on measuring and evaluating the influencing factors on injection molded elements.

The applied methods to calculate inhomogeneity of an image varies widely based on the purpose. Cheng et al. [5] put these calculation methods into the following categories: edge value-based methods (or edge detection) [6], standard deviation (or variance) based calculations [7-9] and entropy-based calculations [10, 11]. For evaluation of the concentration or color variance typically the standard deviation based methods are used.

In three dimensional color spaces the color difference can be calculated from the Euclidean distance, which can be calculated from the individual color coordinates according to Eq. (1).

$$\Delta E = \sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2}. \tag{1}$$

In Eq. (1), ΔE is the color difference, and Δx, Δy, Δz, are the individual color coordinates. Unfortunately, in certain color spaces, such as the RGB color space, this color difference is not proportional with human visual sensation. Therefore, in most of the industrial applications where it is important to have color differences which are mainly proportional to human sensation the CIELAB color system is used [12].

Pisciotti et al. [13] has measured the effects of injection molding parameters on color and gloss in case of PP parts, and has 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 and a rough surface. In case of a rough surface gloss has been decreased with the increase of the surface replication, and the opposite has been recognized with a smooth surface. Dawkins et al. [14] has measured very similar results to these. Although they did not measure color inhomogeneity, just the color coordinates itself, it can be assumed that these

[1] Department of Polymer Engineering,
Faculty of Mechanical Engineering,
Budapest University of Technology and Economics,
H-1111 Budapest, Muegyetem rkp. 3., Hungary

[*] Corresponding author, e-mail: kovacs@pt.bme.hu

parameters and the surface texture of the cavity could influence the level of visually obtained color inhomogeneity as well.

In plastic melt processing several different types of static and dynamic mixers are applied to improve melt homogeneity. In injection molding the main difference between these two types are that dynamic mixers are altering the dosing phase, while static mixers are altering the injection phase of the injection molding cycle. Fig. 1 illustrates a special screw tip, which has an additional purpose of improving melt homogeneity on top of its original non-return valve function.

Fig. 1 The TMR mixing screw tip [15]

There are several articles trying to evaluate the homogenization capabilities of different static mixers, but unfortunately most of them are using numerical studies, in which the authors do not consider any effects from the dispersion of the masterbatch components [16-19]. Furthermore, a quantitative comparison of different static and dynamic mixers considering their mixing efficiency is completely missing from the literature.

In masterbatch manufacturing it is also known, that certain components or the interaction of the components has a significant influence on the homogenization properties, but a scientific approach to evaluate these effects is also missing.

2 Investigation aims

The aim of this work is to apply an experimental method to quantitatively evaluate and compare different equipment, material properties and processing conditions to see an overall picture, how much these influence the homogeneity of injection molded parts. This experimental approach is also aimed to measure the combined effect of dispersive and distributive mixing capabilities of different mixer types and processing conditions. Based on these we aimed the followings in this paper:

- Evaluate the effects of various injection molding parameters on the surface color inhomogeneity.
- Quantitatively evaluate and compare static and dynamic mixers.
- Evaluate the effects of individual masterbatch components and their interactions.
- Evaluate the effect of multiple compounding of the masterbatch.
- Evaluate the effects of mould surface texture and wall thickness on the perceived color inhomogeneity.

3 Materials, methods and equipment

In this chapter we will give a detailed insight how the measurement was executed, and how the evaluation software calculated the inhomogeneity scores. We have used the method developed by Zsíros et al. [1], because they have created a measurement method which gives inhomogeneity scores correlating quite good (R = 0.95 %) with human visual inspections. Furthermore, we will give a detailed list about the applied equipment and materials.

3.1 Evaluation method

In this work we have injection molded 80 x 80 mm flat specimens, which had a 2 mm thickness, except in the last investigation, where we molded 1.2 mm and 1.6 mm thick flat specimens as well. The test specimens were digitized with a flatbed scanner, and the images were evaluated with an own developed algorithm. The algorithm scans the images with a *k* pixel window size (Fig. 2) and calculates the average color coordinates in every *i, j* position according to Eq. (2).

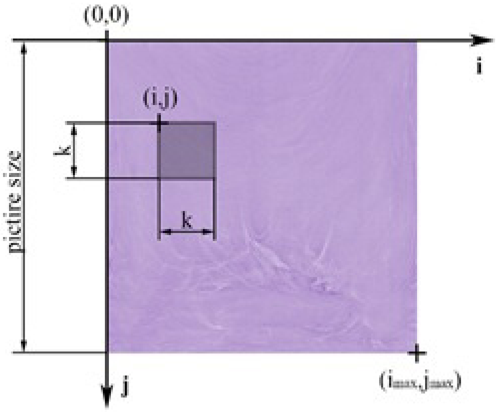

Fig. 2 Parameters for the software calculation

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

Then the average color difference is calculated within this window according to Eq. (3), and the highest MD (HMD) value is used to characterize the inhomogeneity level of the given image. The test specimens were tested by human visual inspectors as well.

$$MD_{i,j,k} = \frac{\sum_{x=i}^{i+k-1}\sum_{y=j}^{j+k-1}\sqrt{\sum_{\varepsilon=L,a,b}\left\{P[\varepsilon](x,y)-A[\varepsilon](x,y)\right\}^2}}{k^2}. \tag{3}$$

The human scores used in further calculations were the average scores given by a group of color technicians. This group consisted of six trained color technicians, from whom there were three males and three females. The samples were inspected under homogenous D65 illumination. The color technicians were instructed to score the samples based on the rules, that the perfectly homogenous sample should have a score of zero – which practically does not exist – and the worst sample from the inspected set should have a score of ten. When *HMD* values were compared to human visual inspection, high correlation were noticed between them, however this correlation was not linear. It was also noticed that in the case of different colors, the calculation method gave a small but consistent level of inhomogeneity even if the injection molded flat specimens did not show any visually perceivable color inhomogeneity. After the individual visual inspection of the scanned samples and its images it turned out that it is caused by the scanning process. Therefore, a color dependent correction was applied to the obtained *HMD* values according to Eq. (4).

$$CMD = HMD - GMD, \tag{4}$$

where *CMD* is the corrected value and *GMD* is obtained from Eq. (3), when *k* is the maximum pixel size of the image.

After calculating linear correlation coefficients with a window size from $k = 2$ pixels to $k = 250$ pixels in the case of various masterbatch colored injection molded samples, the highest correlation was reached after the logarithmic transformation of the *CMD* values at a *k* = 35-pixel window size. Fig. 3 shows the calculated inhomogeneity scores (*IHS*) at *k* = 35-pixel window size as a function of the human visual inspection scores in the case of nine large color difference masterbatches.

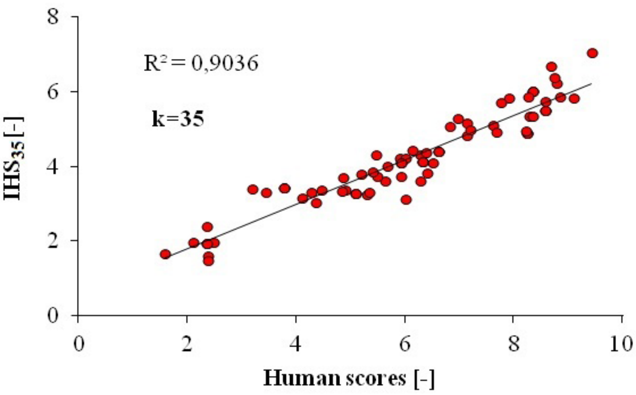

Fig. 3 Inhomogeneity scores as a function of human scores

3.2 Materials and equipment

The measurements have been carried out with a base material ABS, Styrolution Terluran GP 35. This base material was colored by various commercially available masterbatches, and special masterbatch compositions which were produced only for testing purposes. The test specimens were injection molded on an Arburg Allrounder 370S 700-290 injection molding machine. An Arburg general purpose screw and non-return valve was used except for the cases where it is stated otherwise. For the digitization a HP Scanjet G4010 flatbed scanner was used. With the help of this scanner digitized images of the test samples were generated in 200 DPI resolution. This resolution was chosen because it was measured and tested that higher resolution images did not improve the quality and the repeatability of the measurement, but with higher resolution images the calculation time of Eq. (2) and Eq. (3) increased exponentially with the increase of the image DPI. The 80x80 mm samples were injection molded in a special mould with exchangeable cavity surfaces and gate inserts (Fig. 4). The thickness of the samples was variable from 0.5 mm to 4.0 mm.

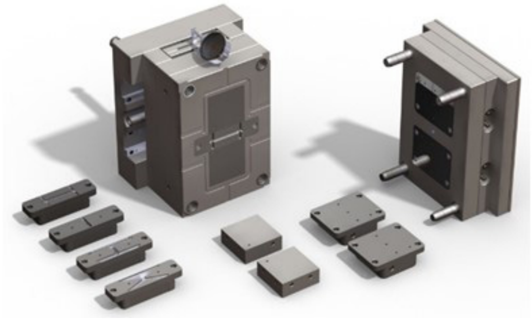

Fig. 4 The injection mold used to produce the test specimens

Compounded materials were produced on a Labtech Scientific co-rotating twin-screw extruder (L/D = 44, Ø = 26 mm), where needed according to the investigation. The default injection molding parameters were used to produce the samples shown in Table 1, except if indicated otherwise in the text.

Table 1 The default injection molding parameters

Injection molding parameter	Value
Volume [cm^3]	50
Injection rate [cm^3/s]	55
Holding pressure [bar]	600
Holding time [s]	6
Residual cooling time [s]	11
Screw rotational speed [m/min]	25
Backpressure [bar]	60
Decompression volume [cm^3]	6
Decompression rate [cm^3/s]	20
Barrel temperature [°C]	225
Mold temperature [°C]	40

4 Results and discussion

In the first subchapter test samples were injection molded with different parameters to analyse the effect of various injection rates, barrel temperatures, and residence time of the polymer melt in the injection barrel. The second subchapter shows the results of three different dynamic mixers and a static mixer compared to the homogeneity level of test samples injection molded from a compounded material. In the third subchapter the effects from the masterbatch composition were analysed, while in the fourth subchapter we have concluded that the multiple compounding had not improved the homogeneity of the samples. The last subchapter illustrates the results from testing two important mold design parameters such as the influence of the wall thickness and the surface roughness. However, the results of the test samples with various surface roughness seem to be impressive, it must be noted that after analysing of these samples it turned out that the same inhomogeneity marks could be noticed on all samples, however, on the rougher samples it was more difficult to notice, and this was represented also in the measurement results based on the evaluation of the digitized images of the samples.

4.1 Effects of the injection moulding process parameters

The effect of injection rate was analysed on three different levels of injection rate, which was 10 cm^3/s, 55 cm^3/s, and 100 cm^3/s, while all other processing parameters were set to the default value (Table 1). 50 samples were injection molded with every single parameter combination, and their results were averaged. It can be seen that homogeneity improves as the injection rate increases (Fig. 5).

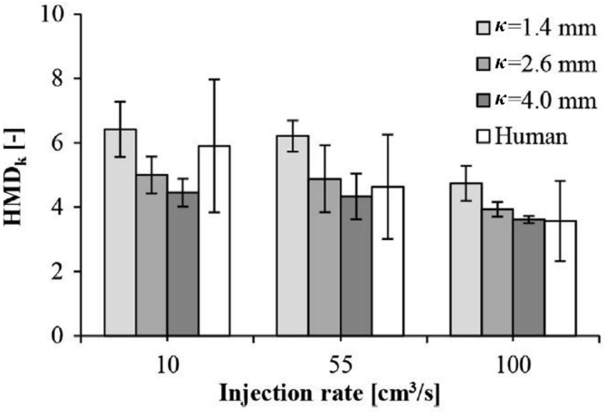

Fig. 5 Inhomogeneity as a function of injection rate

It can be seen on Fig. 6 that residence time of the polymer melt did not have any significant effect on the color homogeneity of the test specimens.

From the analysed processing parameters, the barrel temperature had a significant effect as well. Fig. 7 shows that the increase of the barrel temperature has increased the calculated inhomogeneity scores of the samples as well.

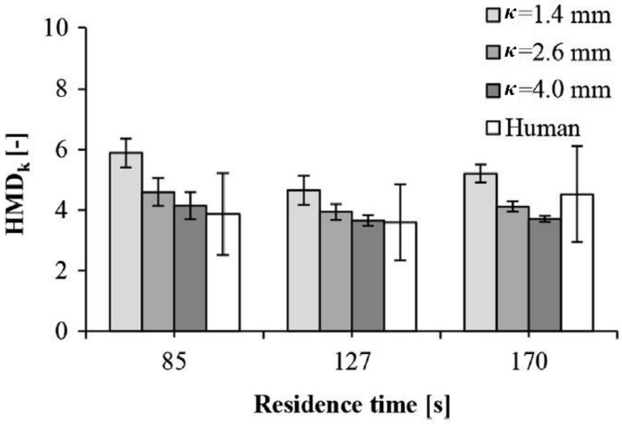

Fig. 6 Inhomogeneity as a function of residence time

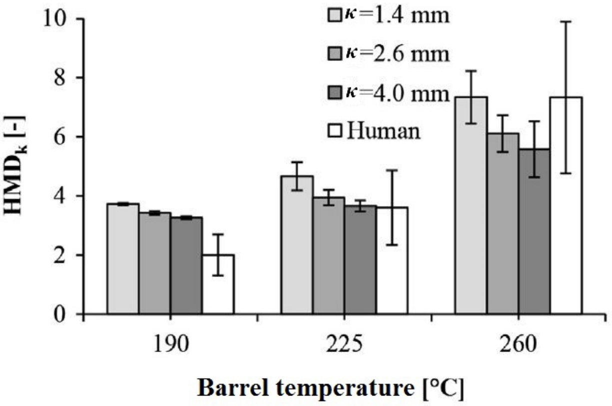

Fig. 7 Inhomogeneity as a function of barrel temperature

Generally, it can be stated that the human evaluations followed the same trends as the software evaluations, however with much bigger standard deviations.

4.2 Quantitative analysis of different static and dynamic mixers

In the first test setup of the analysis three different dynamic mixers, such as a simple non-return valve (Fig. 8), an Arburg non-return valve (Fig. 9), a special mixing non-return valve (Fig. 10) and a StaMixCo static mixer (Fig. 11) was tested and compared to the results of the test specimens injection molded from a previously compounded material. In the case of the compounding the same masterbatch was used to color the base material as the one used in the cases of the static and dynamic mixer measurements.

Fig. 8 Simple non-return valve

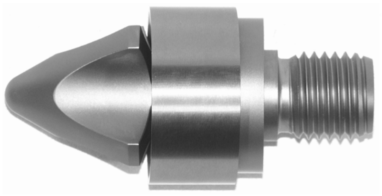

Fig. 9 Arburg non-return valve

Fig. 10 Special mixing non-return valve

Fig. 11 StaMixCo static mixer

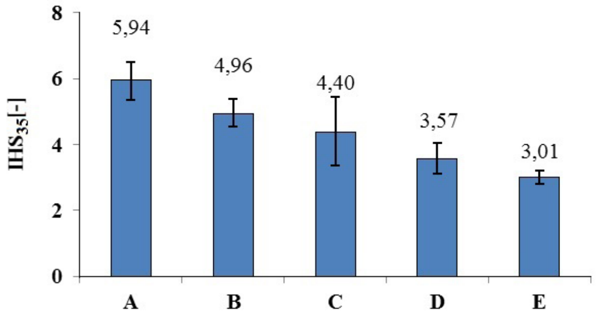

Fig. 12 Inhomogeneity levels reached by various dynamic and static mixers (A: Simple non-return valve, B: Arburg non-return valve, C: StaMixCo static mixer, D: Special mixing non-return valve, E: Compounded material)

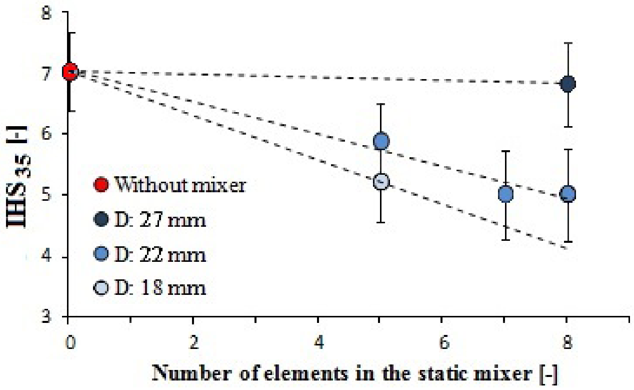

Fig. 13 Inhomogeneity as a function of static mixer diameter and element number

With each mixer type 50 samples were injection molded and the scores of the samples were averaged. In the case of the measurement of the static mixer, the injection screw was equipped with the Arburg non-return valve.

However, we focused on the evaluation of the mixing properties of the different static and dynamic mixers, it must be noted, that the functioning of the static and dynamic mixers is quite different. While the dynamic mixers are built on the screw or the non-return valve, and rotating together with the screw, the static mixers have various complex stationery mixing elements, which force the melt flow to separate and recombine several times. This means that the dynamic mixers will alter the dosing part of the injection molding cycle, but the static mixer will affect the injection phase.

Fig. 12 shows the results of the different mixers compared to the compounded material. The worst results have been produced by the simple non-return valve. The Arburg non-return valve produced more homogenic samples compared to the simple non-return valve, while the special mixing non-return valve produced samples were almost as good as the samples which were injection molded from a previously compounded material. The results from the static mixer were unexpected. However, on average it has produced better homogeneity samples compared to the setup, where only the Arburg non-return valve was mounted on the injection screw, but it has increased the standard deviance of the samples as well. This can be explained by the changing of the injection speed during the cavity filling. This phenomenon influences the generated shear rates in the static mixer which ultimately influences its mixing capability.

In the second test setup the mixing capability of various static mixers was further investigated. Static mixers with inner diameter of D = 18 mm, 22 mm, and 27 mm with different element numbers were tested. Fig. 13 shows that the *IHS* scores are a linear function of the element numbers built into the mixer, and the slope of the line is dependent on the inner diameter of the static mixer, if all other conditions and parameters are fixed.

4.3 Effects of the masterbatch composition

The effects from the masterbatch composition were tested in two separated setups. In the first test setup individual coloring agents were compounded with ABS, as the carrier of each formulated masterbatch. These types of masterbatches are usually called as monobatches, since they contain only one coloring agent besides the carrier itself. The purpose of this setup was to identify if there are any significant differences in the mixing properties of the tested coloring agents. Fig. 14 shows the results of the selected nine monobatches formulated from different individual pigments or dyes. From these nine monobatches there were five different red and four blue. As a general conclusion it can be seen, that there are no large differences between the individual coloring agents. Even though, monobatch 6 and 9 had significantly higher inhomogeneity scores than the others, these differences cannot explain the variations experienced in the homogenization properties of the masterbatches presented in Fig. 3. This means that most of the differences in the homogenization properties of the masterbatches are not coming from the different homogenization

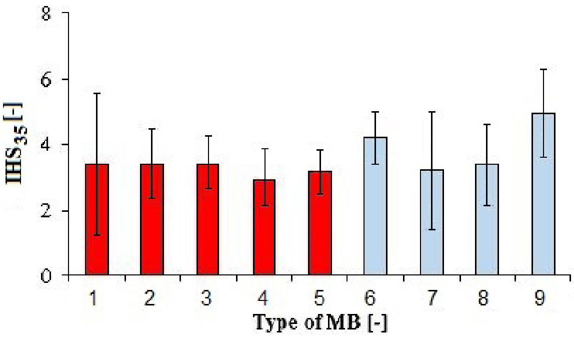

Fig. 14 Inhomogeneity of various monobatches

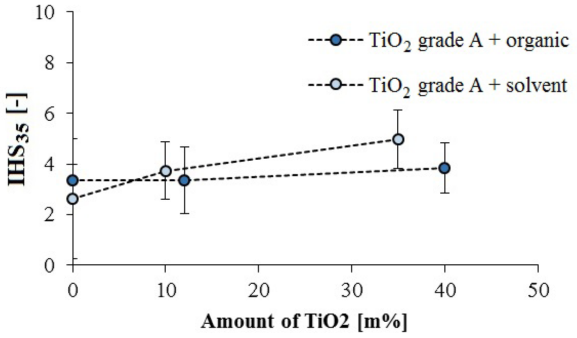

Fig. 15 The effect of TiO$_2$ amount on the homogenization

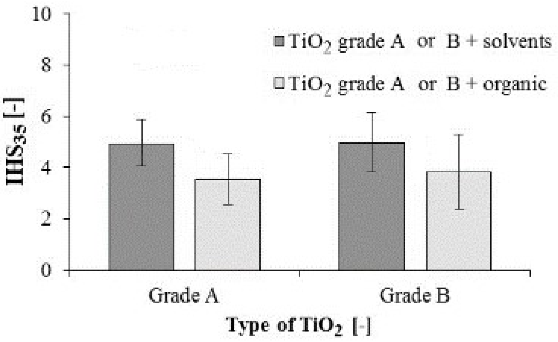

Fig. 16 The effect of the TiO$_2$ on the homogenization

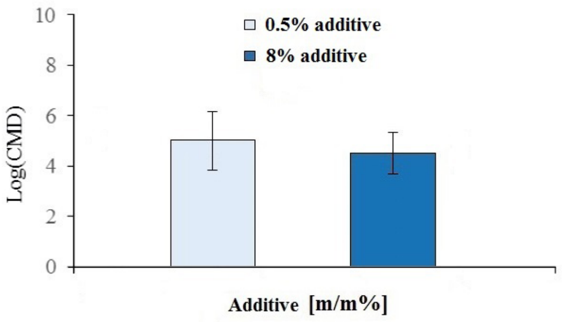

Fig. 17 The effect of the amount of additive on the homogenization

properties of the individual coloring agents, but from the composition of the given masterbatch recipes.

In the second test setup a commercially available masterbatch recipe was altered in different steps. In each step only one component or its concentration was modified compared to the original recipe. The modification was carried out in a way that the samples produced from the original and the altered recipe should have reached color matching. First the amount of TiO$_2$ was changed and evaluated its effect on the homogenization properties in the case of an organic pigment based and a solvent based recipe. Fig. 15 shows that in the case of the organic pigment based recipe the amount of the TiO$_2$ in the masterbatch did not influence the homogenization properties of the composition, while in the case of the solvent based homogeneity worsened somewhat with the increase of the TiO$_2$.

Next 50-50 samples were injection molded which were colored by masterbatches formulated from two different grades of TiO$_2$ was used with both organic pigments and solvents as coloring agents. The results are shown in Fig. 16. It can be seen that the different TiO$_2$ grades did not influenced the color homogeneity of the injection molded samples. However, it can also be concluded that the organic pigment based recipes had better results with both TiO$_2$ grades.

Next in the original solvent based masterbatch the amount of additive (which was a special dispersion aid) was modified from the usually applies 0.5 % to 8 %. Fig. 17 shows that in the concentration range the additive did not have any influence on the homogenization properties of the composition. This result suggests that the original masterbatch recipe could be simplified by leaving out this component from the formulation.

4.4 Effects of multiple compounding of the masterbatch

The aim of this test was to investigate if multiple compounding of the masterbatch would influence the homogeneity of the injection molded samples. The test was started with a relatively large amount of masterbatch from which approximately one sixth of the original amount was taken out and used to color a certain amount of ABS base material. This was enough to injection mold 50 test samples and evaluate them. Then the rest of the masterbatch was put through a twin-screw extruder, and regranulated in the same size as the original masterbatch. Then another one sixth of the original amount was taken out, and another 50 samples were molded and evaluated. The last amount was compounded and regranulated five times altogether. The results of this 50 samples in each step from zero to five extrusions are illustrated in Fig. 18. The ANOVA test showed no significant influence on the homogeneity of the test specimens from the multiple compounding of the used masterbatch.

4.5 Effects of mould surface texture on the homogeneity sensation

In this test setup the effects from the mold surface roughness was tested. 50-50 samples were injection molded with three different surface roughness. However, it needs to be noted, that changing the mould surface roughness caused significant

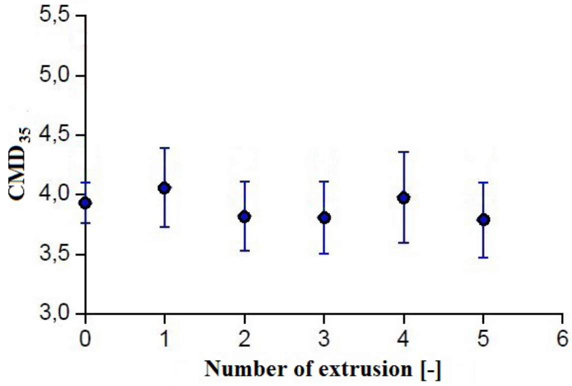

Fig. 18 The effect of multiple compounding on the homogenization

differences in the human visual inhomogeneity perception and in the measured inhomogeneity scores as well, the real inhomogeneity stripes did not disappear from the surface, but it was much more difficult to perceive or to measure them because of the rougher surface. From Fig. 19 it can be concluded that the perceived color inhomogeneity score is linearly decreasing with the increase of the logarithm of surface roughness (*Ra*).

Another 50-50 samples were injection molded with 1.2 mm and 1.6 mm wall thicknesses and their results were compared to the 2.0 mm samples which were produced in all other cases in this paper. Fig. 20 shows that injection molded parts with thicker walls are more likely to have surface color inhomogeneities. This is in correlation with the smaller developing shear rates at filling thicker parts under the same processing conditions.

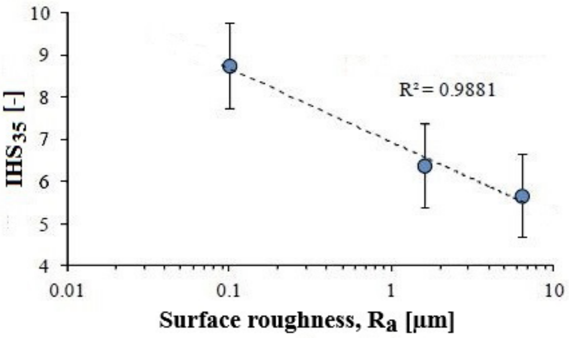

Fig. 19 The effect of surface roughness on the homogeneity sensation

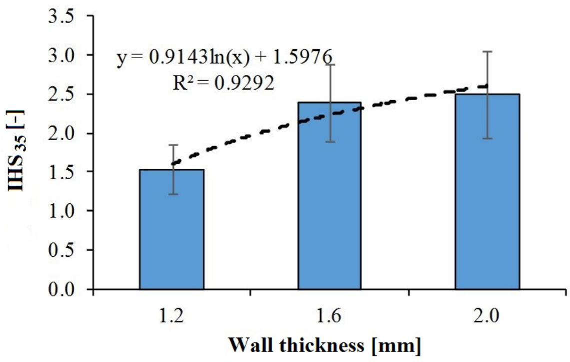

Fig. 20 The effect of wall thickness on the homogenization

5 Conclusions

We have developed a novel measurement method to objectively evaluate the color inhomogeneities which is performed according to the followings: 80 x 80 mm injection molded test specimens were produced from ABS GP 35 mixed with various solid phase masterbatches. The test specimens were digitized by a flatbed scanner, and the images have been evaluated by a software. The software is using a special, own developed algorithm to evaluate the images. It scans the image pixel by pixel with a defined window size and calculates the average Euclidean color difference of the pixels within the window. When the whole image is scanned the inhomogeneity level of the sample is calculated from the highest average Euclidean color difference calculated during the scanning. Furthermore, the average Euclidean color difference is calculated for the whole image as well. While the result from the defined window size is relevant from inhomogeneity point of view, the result of the whole image is typical to the evaluated color and is needed for the correction of the inhomogeneity level to be able to compare the inhomogeneity levels derived from different color shaded masterbatches. We have measured test specimen series with different window sizes, and inhomogeneity scores have been calculated. The results have been correlated to human visual inspections, and it has been found that the correlation maximum was more than 95 %.

This measurement method has been applied to evaluate differences in homogeneity level caused by various injection molding parameters such as the injection speed, the barrel temperature and the residence time of the plastic material in the barrel. It has been shown that increasing of injection speed decreases, while increasing of barrel temperature increases the measured color inhomogeneity. It was also proved that the residence time of the material in the barrel had no significant effect on the color inhomogeneity.

We have measured the mixing efficiency of different static and dynamic mixers, and we have shown that there are significant differences in their homogenization capabilities. We have measured several different diameter and element number StaMixCo static mixers, and concluded that the mixing efficiency of the static mixer is dependent on its diameter, which is in opposition with the numerical studies from the literature. We have objectively measured and compared the mixing efficiency of dynamic mixers to static mixers which was not possible by numerical studies due to their extreme complexity.

We have shown that the different masterbatch compositions had a significant effect on the inhomogeneity of the injection molded products. We have measured the homogenization properties of nine different masterbatches, and showed that the qualification of these masterbatches is possible with this measurement system, which significantly improve the possibilities of the development of masterbatch receipts for better homogenization. From the measurements of the different masterbatch receipts it had to be concluded that the primary driver of the inhomogeneity is the interactions between the different components and not the individual properties of the components. We have experienced consequently better results in masterbatch formulations based on organic pigments.

The effect of multiple compounding of the coloring masterbatch was evaluated as well. The coloring masterbatch was compounded and regranulated again and again in five steps altogether, and masterbatch samples were taken out in each step enough to color base material for injection molding 50 samples. The results showed that the multiple compounding of the masterbatch had no significant effect on the color homogeneity of the injection molded test specimens.

We have measured that the wall thickness of the injection molded elements and surface structure of the product had significant effect on the perceived color inhomogeneity. We have measured these effects in a special injection mold in which the gate inserts and the surface inserts were exchangeable and the wall thickness was variable. The measurements with inserts of different surface roughness showed that the perceived color inhomogeneity is inversely proportional to the logarithm of the surface roughness, and generally samples with thinner walls had better color homogeneity under the same conditions.

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