Effects of dynamic mixers on color homogeneity and the process in injection molding

Dániel Török[1, a], László Zsíros[1,b] and József Gábor Kovács[1,c]

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

[a]torok@pt.bme.hu, [b]zsiros@pt.bme.hu, [c]kovacs@pt.bme.hu

Correspondence to: József Gábor Kovács (E-mail: kovacs@pt.bme.hu)

Keywords: injection molding, homogeneity, dynamic mixer, process parameters, melt mixing

Abstract. The quality of any injection molded part is related to the defects visible on the surface. Injection molded parts are usually colored with a masterbatch due to its cost-effectiveness. The most common surface defect is unevenness of color. This can result from an inadequate coloring process. The problem is the uneven dispersion of the coloring additives in the polymer. In this paper we examined the mixing efficiency of non-return screw tips of various flow cross sections using different technological parameters. The increase in melt temperature was examined as a function of flow cross section. The relationship between mixing efficiency and the warming of the melt was determined. We also proved that mixing efficiency depends on both shearing processes and the temperature increase.

Introduction

Injection molding is one of the most widely used processing technologies for plastic parts. The technology became popular because of the efficiency of production, and because it allows plastic parts with complex geometry to be produced with fine detail. The products vary greatly in size, geometry, application and visual appearance [1]. This appearance can be influenced by the coloring of the neat polymer. Three types of color preparations (liquid, powder and granulated form) can be used to color thermoplastics, but many customers prefer the granulated form, known as masterbatch, because of its easy handling and good metering properties. However, there are some disadvantages, such as difficult dispersion in the polymer melt during the injection molding process [2].

There are two types of mixers that can be used to improve the homogeneity of the distribution of the colorants: static and the dynamic mixers [3]. Thakur et. al. [4] and Meijer et al. [5] summarized the types and application of static mixers in their paper, where the different static mixer types are described and compared. Rauline et. al. [6] compared six different static mixers, employing finite element modeling. They also examined the pressure drop on static mixers, the shear rate in the mixers and mixing efficiency. Galaktionov et. al. [7] analyzed and optimized the commonly used Kenics-type static mixer. Li et. al. [8] examined the pressure drop when Newtonian and non-Newtonian fluids flow through the widely used SMX-type static mixer. Static mixers usually consist of a combination of identical elements (such as parallel beams) stacked in series and each element is turned 90° relative to the next element. Török et. al. [9] investigated the effects of these mixing elements on the homogeneity of injection molded parts and the molding process. As opposed to static mixers, dynamic mixers do not appear in the literature very often; there are only a few articles on dynamic mixers. Dynamic mixers used in injection molding can be fixed on the end of the screw or on the tip of the screw, working as a non-return valve. The screw tip dynamic mixer developed by Hindmarch [10] has cavities in its static and rotating part, which mix the polymer melt as the screw turns. On the other hand, Rauwendaal's [11] dynamic mixer does not contain such cavities; its mixing effect is based on the stretch flow in the mixer. These screw tips mix the polymer melt during the plastification phase, and therefore do not influence filling pressure. According to Manas-Zloczower [12], there is more dispersive mixing in these devices than distributive mixing. To compare the efficiency of the mixers, it is necessary to evaluate the color homogeneity of the samples, and the effect of dynamic mixers on the injection molding parameters. Domingues et. al. [12, 13] investigated flow and the dispersion of agglomerates of additive in the homogenization zone of single-screw extruders. The efficiency of mixing was rated by the size distribution and Shannon entropy of agglomerates of additive. Wang and Manas-Zloczower [14] investigated the flow in cavity transfer mixers, which are generally used in extruders. They validated their flow simulation results with measurement results.

L. Zsíros et al. [15] investigated methods to evaluate homogeneity and defined an algorithm capable of quantifying the inhomogeneity of injection molded samples. First, the color coordinates of the pixels of a scanned picture are converted into the Lab color space from RGB. After this, a moving window (Fig. 1.) with a side width of 35 pixels scans the picture and the mean color coordinates are calculated in every position. In each position, the Euclidian distances of the pixel color values and the mean color value were calculated according to Eq. 1.

$$\Delta E = \sqrt{\Delta L^2 + \Delta a^2 + \Delta b^2}, \tag{1}$$

where ΔE is the color difference, ΔL is the difference of the average lightness of the pixel and the image, Δa is the average "a" value of the pixel and the image, while Δb is the average "b" value of the pixel and the image.

The standard deviation of these distances can characterize the evenness of color inside the window. The image is characterized with the highest mean standard deviation (HMD). In order to correlate with human perception better, the HMD values are modified as follows (Eq. 2):

$$IH = 5 \cdot \left[\log(HMD - GMD) + 1\right], \tag{2}$$

where *IH* is the level of inhomogeneity, *HMD* is the highest mean standard deviation and *GMD* is the standard deviation of Euclidean distances that belong to the window size of 610 pixels (image size: 610x610 pixel).

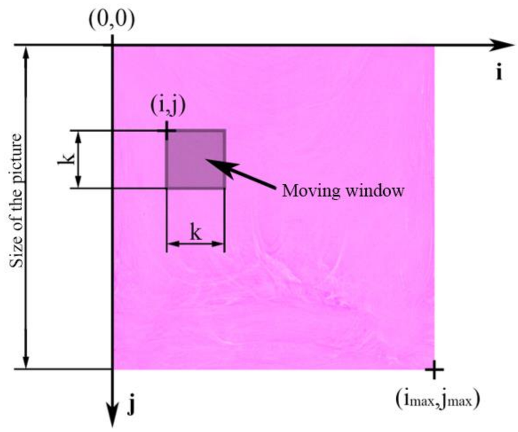

Fig. 1. Digitized image of a test specimen and the measuring method with the moving window

There are some other methods in the field of digital image processing to quantify homogeneity. There is not much literature on color homogeneity in the mixing of polymers, but there are some papers on the color homogeneity of injection molded products and on the mixing of powders. Akira et. al. [16] investigated the distribution of reinforcing fibers and fiber length distribution in injection molded parts. They compared various injection molding screws in their research. Cheng et. al. [17] worked on the contrast enhancement of images, which is based on the measurement of the homogeneity of the image. The authors take into account four parameters when determining the homogeneity of the images: the edge value of the images, which is related to the gradient of the color values of the pixels, the Shannon entropy and standard deviation of the pixels, and the impulsiveness of the distribution of the color values. As opposed to Zsíros et. al. [15], they use one-dimension grayscale instead of the 3-dimensional color space. Gosselin et. al. [18] investigated the mixing of polymer powders. In their paper, they used digital image analysis software to determine the time required for the mixing of multi-component powders. Gu and Chen [19] examined the entropy of the mixing of powders during mixing. Daumann and Nirschl [20] also investigated the mixing of powders, and determined the ideal mixing time of a single-shaft mixer with digital image analysis.

Machine, materials and methods

Five different dynamic mixers were investigated. Each of them was mounted onto the screw as a non-return valve (Fig. 2.). Dynamic mixers consist of two parts: the rotor, which is attached to the rotating screw, and the mixing ring, which does not turn with the screw and the rotor. For each mixer the smallest flow cross section was used to characterize its geometry. These gaps – the smallest flow cross section (Fig. 2.) – were 14, 38, 56, 91 and 211 mm^2. The dynamic mixers used were manufactured with conventional and with Direct Metal Laser Sintering technology.

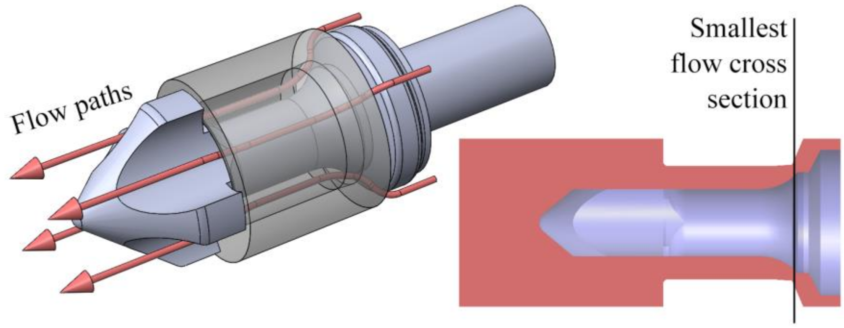

Fig. 2. Gap sizes of different dynamic mixer geometries

The test specimens were injection molded on an Arburg Allrounder Advance 270S 400-170 machine. The injection unit of the injection molding machine has a universal single flight, three-zone nitrided screw of a diameter of 30 mm and an L/D ratio of 20. Its axial displacement is a maximum of 120 mm, therefore the maximum shot volume is 85 cm^3. The highest value of the injection pressure and holding pressure is 2000 bar. The screw is position-regulated, therefore the shot volume set in the injection molding parameters can be maintained more accurately during manufacturing.

The specimens were made in a two-cavity mold, which produces 80x80 mm flat specimens with a thickness of 1.2 mm. The cavity of the mold is polished in order to minimize the surface roughness of the specimens as the smooth surface increases the accuracy of color inhomogeneity measurement. The injection molding parameters are summarized in Table 1. The specimens were produced from unfilled acrylonitrile-butadiene-styrene (ABS, Terluran GP-35 from Styrolution Group GmbH) with 4 wt% of masterbatch (MB, Renol-pink ABS143479Q from Clariant.).

Table 1. The injection molding parameters

Injection molding parameter	Value
Volume [cm^3]	26
Injection rate [cm^3/s]	55
Switchover volume [cm^3]	5
Holding pressure [bar]	600
Holding time [s]	6
Residual cooling time [s]	11
Screw rotational speed [m/min]	10, 25 and 50
Backpressure [bar]	60
Decompression volume [cm^3]	6
Decompression rate [cm^3/s]	20
Barrel temperature at nozzle [°C]	225
Mold temperature [°C]	40

The injection molded parts were digitized with a flatbed scanner (Epson Perfection V600 Photo). The plastication rate was measured according to the EUROMAP 5 standards on the Arburg Allrounder Advance 270S 700-290 machine. The melt temperature was measured with a Fluke 51 II type single input digital thermometer. The accuracy of the equipment is 0.05% + 0.4°C.

500 specimens were injection molded with each dynamic mixer. All relevant process parameters (machine cycle number, cycle time, maximum injection pressure, switchover pressure, switchover volume, cushion and screw rotation time) were recorded on the injection molding machine for each cycle.

The ***plastification rate*** was determined for three different screw rotation speeds (10, 25 and 50 m/min) using 5 independent measurements for each. The ***melt temperature*** was measured five times during purging. The melt temperature was measured for 20-30 seconds in the purged material for each measurement, then the highest temperature values were averaged and used as the melt temperature for the given process parameter set.

We used an algorithm based on the standard deviation method to evaluate the images because the flow lines and color inhomogeneity can be detected quite precisely. Finally, the test specimens were digitized with a flatbed scanner for the ***homogeneity measurements*** and the digital images were evaluated with our own algorithm described earlier in the introduction [15]. The image analyzer software characterizes the unevenness of color in the picture (Fig. 2.).

Results and discussion

In injection molding one of the most important process parameters is melt temperature. The lower the viscosity is, the better the flow properties are, and therefore the better the mold cavity is filled. On the other hand, too high a melt temperature can cause the degradation of the polymer molecules. Dynamic mixers can raise the melt temperature during plasticization because of their small flow cross section. The laminar flow of the polymer melt through the screw tip increases inner friction in the melt and this produces extra heat. As a result, the temperature of the melt increases to a greater extent than in the case of screw tips with a large cross section. The melt temperature rise was examined as a function of the flow cross section of dynamic mixers (Fig. 3). Temperature rise follows a power function of the smallest flow cross section, at the screw rotation speed of 25 m/min, used in the experiments. As is known, the ABS melt cannot flow through a smaller gap than 0.05 mm, therefore this is the smallest theoretical gap size. The smallest flow cross section calculated from this gap size is about 4.7 mm^2, which gives a maximum temperature rise of about 82°C. Melt temperature cannot exceed the maximum processing temperature allowed for the material, and processing must fulfil several other criteria, too.

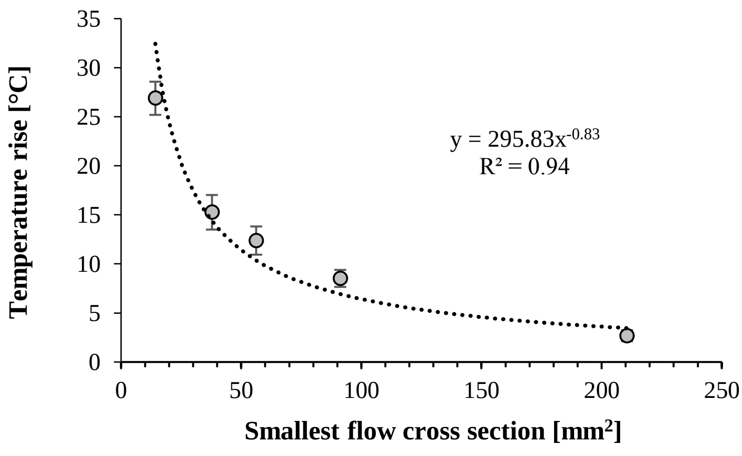

Fig. 3. Temperature rise in the melt as a function of the gap size in the mixers, with a screw rotation speed of 25 m/min.

For the measurements of plastification rate, screw rotation speed was fixed at 10, 25 and 50 m/min (Fig. 4). It can be stated that dynamic mixers act as flow resistance, which highly depends on screw rotation speed. For each screw rotation speed the plastification rate has a limit, which is the maximum throughput of the injection screw without the screw tip. Plastification rate increases as the smallest flow cross section decreases.

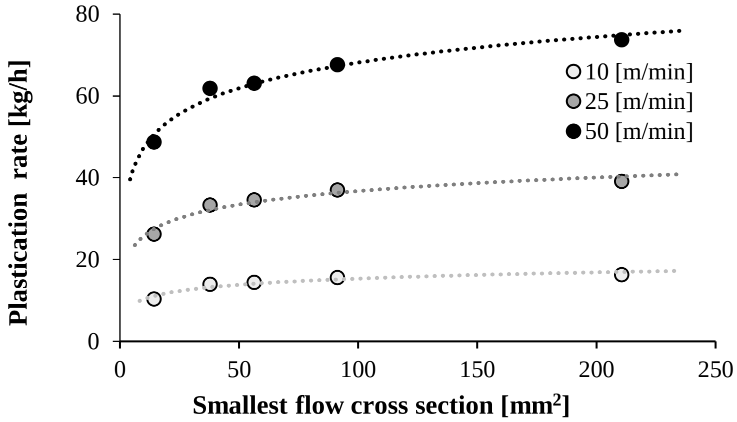

Fig. 4. Plastification rate as a function of the geometry and screw rotation speed of the dynamic mixer.

The maximum injection pressures decreased as the smallest flow cross section decreased (Fig. 5). This phenomenon is related to the shear that develops in dynamic mixers, thus the temperature change of the polymer melt. As melt temperature increases, the viscosity of the melt drops, thus filling pressure decreases as well. This allows longer flow paths, and the shrinkage and warpage of the products can be controlled better. Thanks to the better fluidity of the melt, the compensation of the decrease of specific volume can also be more effective. The effect of the screw tip on the polymer has to be taken into account because small cross-section screw tips strain the plastic more and can lead to degradation.

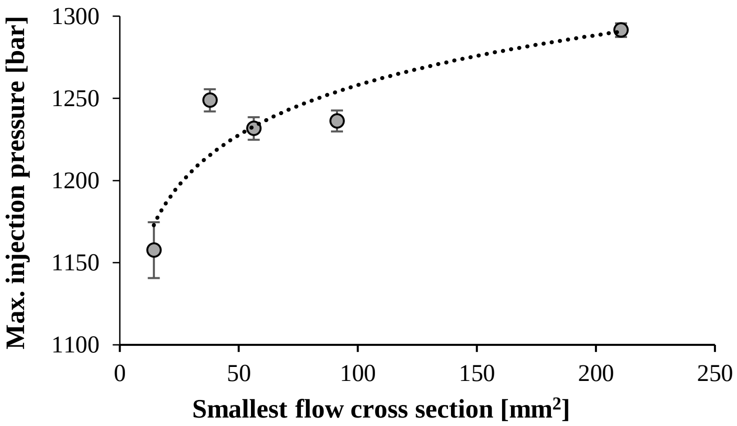

Fig. 5. Injection pressure as a function of the smallest flow cross section.

Homogeneity is directly proportional to the shear rate and melt temperature. The effect of melt temperature on homogeneity was measured and the results show that inhomogeneity increases as melt temperature increases (Fig. 6.). As the viscosity of the polymer melt decreases, homogeneity is reduced because less shear is produced and this results in worse mixing.

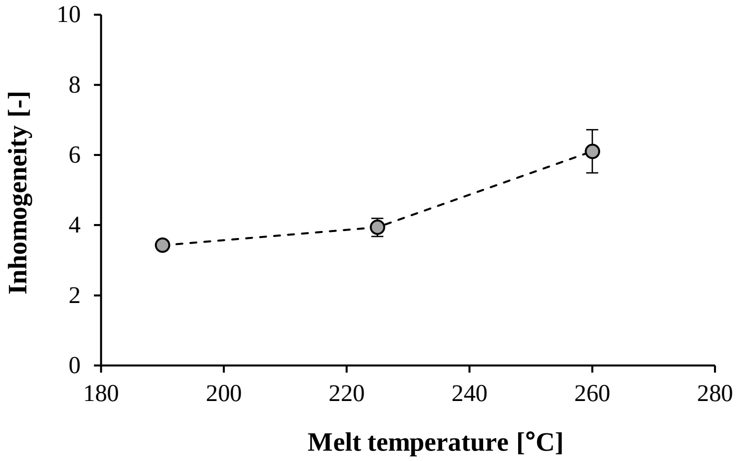

Fig. 6. The homogeneity of the samples molded with different melt temperatures

An increase in the shear rate has the opposite effect. The higher the shear rate, the better homogeneity is. The effect of shear rate on mixing was investigated by Kasaliwal et. al. [21]. They used polycarbonate filled with multi-walled carbon nanotubes (MWCNT). They also showed that as mixing performance (shear rate) increases, the MWCNT agglomerates get smaller, therefore mixing gets better. The resultant of the effects of shear rate and melt temperature probably determines inhomogeneity, as shown by Fig. 7.

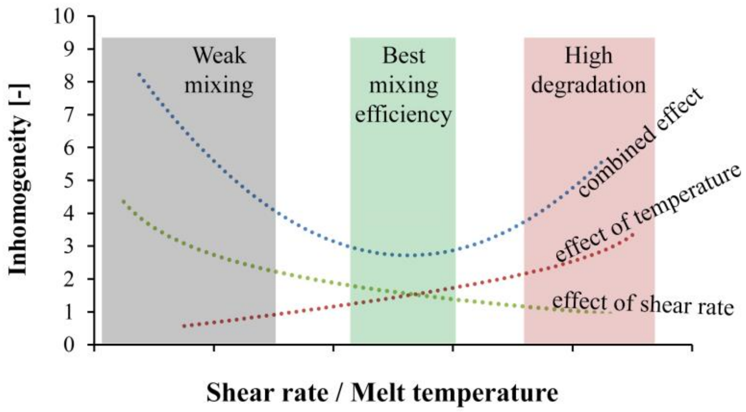

Fig. 7. The effects of the shearing action and melt temperature on color homogeneity.

The homogenization ability of dynamic mixers was evaluated. Fig. 8 shows the homogeneity of the samples as a function of gap size. Gap size has a direct relationship with shear rate and the increase in temperature. Similarly to Fig. 7, as gap size decreases, homogeneity first improves up to a certain limit, then it gets worse. Therefore homogeneity has an optimum, where the quality of the samples is the best.

Decreasing gap size in the higher ranges results in better quality. The reason for this is increasing shear rate, which leads to better mixing. In this range shearing does not increase melt temperature considerably. In the range of significantly smaller gap sizes increasing shear rate results in a considerable increase in temperature, which causes worse homogeneity as a result of a change in viscosity.

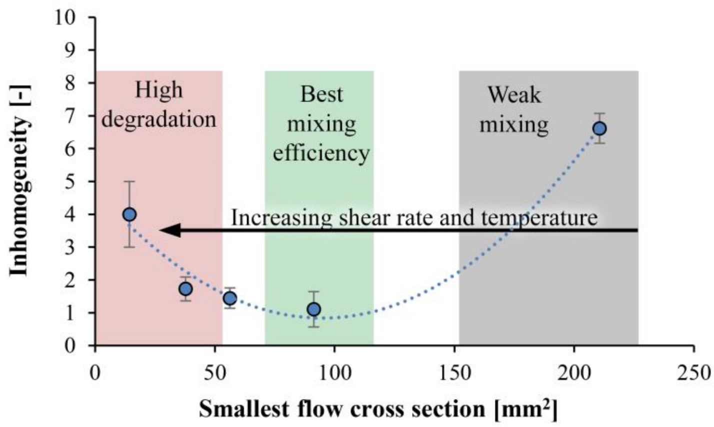

Fig. 8. The homogeneity of the samples as a function of the smallest flow cross section.

Conclusions

The objective of this work was to characterize different dynamic mixers based on their smallest flow cross section. We investigated the effects of the gap size of dynamic mixers on the process parameters of injection molding, the temperature of the polymer melt, and the homogeneity of the samples. We measured the actual temperature of the melt and proved that melt temperature increases more at small cross-section screw tips due to higher shear rates. In the case of the smallest cross section this increase reached 27°C. This increase in temperature affects injection pressure. Hotter, more fluid melt fills the cavity better, therefore injection pressure can decrease by up to 150 bar. Measurements showed that the efficiency of mixing depends on the shear rate during plastification and on the actual temperature of the melt. It was also proved that higher melt temperatures decrease color homogeneity, whereas a higher shear rate increases color homogeneity. Small cross-section screw tips cause a greater increase in temperature and higher shear rates, whereas in the case of higher cross-section screw tips both the increase in temperature and the shear rate are lower. The efficiency of mixing is determined by the resultant of the two opposite effects. We showed that the efficiency of mixing as a function of flow cross section has an optimum in the investigated parameter range.

Acknowledgments: The authors wish to thank Arburg Hungária Kft. for the Arburg Allrounder 370S 700-290 injection molding machine, Lenzkes GmbH for the clamping tool system, and Tool-Temp Hungary Kft. and Piovan Hungary Kft. for their support.

Conflicts of Interest: The authors declare no conflict of interest.

References

[1] Osswald T. A., Turng L-S., Gramann P. J.: Injection molding handbook, 2nd ed., Carl Hanser Verlag, München, Germany (2002)
[2] Müller A.: Coloring of Plastics, 1st ed., Carl Hanser Verlag, München, Germany (2003),
[3] C. Rauwendaal: Polymer mixing: Self-study guide, 1st ed., Carl Hanser Verlag, München (1998)
[4] Thakur R. K., Vial C., Nigam K. D. P., Nauman E. B., Djelveh G.: Static mixers in the process industries - a review, IChemE (2003), Vol. 81, No. 7, pp. 787-826, doi: http://dx.doi.org/10.1205/026387603322302968
[5] Meijer H. E. H., Singh M. K., Anderson P. D.: On the performance of static mixers: A quantitative comparison, Progress in Polymer Science (2012), Vol. 37, No. 10, pp. 1333-1349, doi: http://dx.doi.org/10.1016/j.progpolymsci.2011.12.004
[6] Rauline D., Tanguy P. A., le Blevec J. M. L., Bousquet J.: Numerical investigation of the performance of several static mixers, Can J Chem Eng (1998); Vol. 76, No. 3, pp. 527-535, doi: 10.1002/cjce.5450760325

[7] Galaktionov O. S., Anderson P. D., Peters G. W. M., Meijer H. E. H.: Analysis and optimization of Kenics mixers, Int Polym Process (2003), Vol. 18, No. 2, pp. 138-150, doi: 10.3139/217.1732
[8] Li H. Z., Fasol C., Choplin L.: Pressure drop of a newtonian and non-newtonian fluids across a Sulzer SMX static mixer; Chem. Eng. Res. and Des. (1997), Vol. 75, No. 8, pp. 792-796, doi: 10.1205/026387697524461
[9] D. Török; L. Zsíros; J. G. Kovács. Investigation of StaMixCo static mixers with different number of mixing elements and diameter. Rubber and Plastic. (2014), Vol. 51, No. 9, pp. 346-351.
[10] Hindmarch R. S.: The cavity transfer mixer: A blender for all seasonings, Materials and Designs (1987), Vol. 8, No. 6, pp. 331-339, doi: doi:10.1016/0261-3069(87)90083-5
[10] Rauwendaal C.: New dispersive mixers based on elongational flow, Plastics, Additives and Compounding (1999), Vol. 1, No. 4, pp. 21-23, doi:10.1016/S1464-391X(99)80106-8
[11] Manas-Zloczower I. Cheng H.: Analysis of mixing in polymer processing equipment, Macromolecular Symposia (1996), Vol. 112, No. 1, pp. 77-84, doi: 10.1002/masy.19961120112
[12] Domingues N., Camesasca M., Kaufman M., Manas-Zloczower I., Gaspar-Cunha A., Covas J. A.: Modeling of Agglomerate Dispersion in Single Screw Extruders, Int Polym Proc (2010), Vol. 25, No. 3, pp. 251-257, doi: 10.3139/217.2350
[13] Domingues N., Gaspar-Cunha A., Covas J. A., Camesasca M., Kaufman M., Manas-Zloczower I.:. Dynamics of Filler Size and Spatial Distribution in a Plasticating Single Screw Extruder – Modeling and Experimental Observations, Int Polym Proc (2010), Vol. 25, No. 3, pp. 188-198, doi: 10.3139/217.2319
[14] Wang C., Manas-Zloczower I.: Flow field analysis of a cavity transfer mixer, Polym Eng Sci (1994), Vol. 34, No. 15, pp. 1224-1230, doi: 10.1002/pen.760341509
[15] Zsíros L., Suplicz A., Romhány G., Tábi T., Kovács J. G.: Development of a novel color inhomogeneity test method for injection molded parts. Polymer Testing (2014). Vol. 37, pp. 112-116, doi: http://dx.doi.org/10.1016/j.polymertesting.2014.05.009
[16] Inoue A., Morita K., Tanaka T., Arao Y., Sawadal Y.: Effect of screw design on fiber breakage and dispersion in injection-molded long glass-fiber-reinforced polypropylene, Journal of Composite Materials (2015), Vol. 49, No. 1, pp. 75-84 doi: 10.1177/0021998313514872
[17] Cheng H. D., Xue M., Shi X. J.: Contrast enhancement based on a novel homogeneity measurement, Pattern Recognition (2003), Vol. 36, No. 11, pp. 2687-2697, doi: 10.1016/S0031-3203(03)00054-2
[18] Gosselin R., Duchesne C., Rodrigue D.: On the characterization of polymer powders mixing dynamics by texture analysis, Powder Technology (2008), Vol. 183, No. 2, pp. 177-188, doi: 10.1016/j.powtec.2007.07.021
[19] Gu Z., Chen J.J.J.: An analysis of the entropy of mixing for granular materials, Powder Technol (2014), Vol. 266, pp. 90-95, doi: http://dx.doi.org/10.1016/j.powtec.2014.06.029
[20] Daumann B., Nirschl H.: Assessment of the mixing efficiency of solid mixtures by means of image analysis, Powder Technol (2008), Vol. 182, pp. 415-423, doi: 10.1016/j.powtec.2007.07.006
[21] G. R. Kasaliwal, S. Pegel, A. Göldel, P. Pötschke, G. Heinrich: Analysis of agglomerate dispersion mechanisms of multiwalled carbon nanotubes during melt mixing in polycarbonate, Polymer (2010), Vol. 51, pp. 2708-2720.