# Analysis of dimensional stability of recycled plastic material obtained by grinding

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**Abstract**: A study to identify the products of grinding process for the purposes of the recycling of elements, installations and materials made from polymers was proposed. The ground material was analyzed, evaluated and then described using the latest granulometric models. Based on the stability models, a mathematical description of granulometric distribution of particle size of the recycled polymer products obtained in the grinding process was found.

**Keywords**: grinding process, recycling of polymer materials.

## Analiza stabilności wymiarowej produktu rozdrabniania w recyklingu tworzyw

**Streszczenie**: Dla potrzeb recyrkulacji elementów, instalacji i materiałów z tworzyw polimerowych zaproponowano badania identyfikujące produkty rozdrabniania. Analizowano, oceniano, a następnie opisano je na bazie najnowszych modeli granulometrycznych. Modele stabilności pozwoliły na znalezienie matematycznych opisów rozkładów granulometrycznych uzyskanych produktów rozdrabniania w procesie recyklingu tworzyw polimerowych.

**Słowa kluczowe**: proces rozdrabniania, recykling tworzyw polimerowych.

In most approaches, the dimensionally stable precision grinding design should include the following aspects:

– kind of polymer material and its properties,

– technical preparation of granulated product from various elements,

– conditions of forming of granulated product,

– the parameters of processes that are combined,

– variation of tools, installation, use of instrumentation,

– requirements of mixing, shearing and other processes.

Accuracy of grinding represents a separate issue. When studying multi-disc grinding machines, and others that contain several rings (Table 1, item 1), to achieve the precision grinding of PVC [poly(vinyl chloride)] pieces, the most important were accuracy of setting the speed of the rotor and maintaining constant velocity in the range of 10–100 m/s (Table 1, item 1, col. 3).

Similar requirements ensuring the precision operating process were found in the case of multi-disc grinding of PE (polyethylene) materials (Table 1, item 2).

The precision grinding by quasi-shearing equaled $P_{R\text{-}q} = 1$ in this case, for 100 % load of each piece.

The aim of this work was to analyze and evaluate the stability of particle sizes and geometric forms of the grinding products in recycling of polymers.

For achievement of the objective, it was decided to solve the problem given in the form of questions: which technical conditions (construction, tools and machines, parameters of process) are essential for the existence of the highest geometric quality of the grinding product in the recycling of selected polymers, while maintaining reasonable parameters of efficiency and safety of the process [1–4].

## GRANULOMETRIC MODELS OF GRANULATED POLYMER PRODUCTS

Polymers are a group of materials for which, in recent years, an expansion in volume of about 9 % by weight per year has been observed. They represent one of the most dynamically developing industries. According to UNIDO (The United Nations Industrial Development Organization), production and processing of macromolecular materials have been recognized as the most expansively growing field of materials in the world.

In polymer processing technology, the materials, methods, equipment and organizational aspects are very closely related, and one of the important issues linking this fields is the transfer of knowledge [5–7]. The question of dimensional stability of polymer material subjected to

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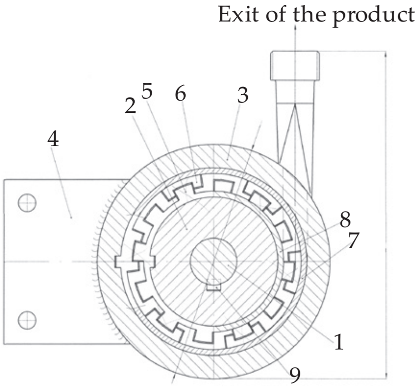
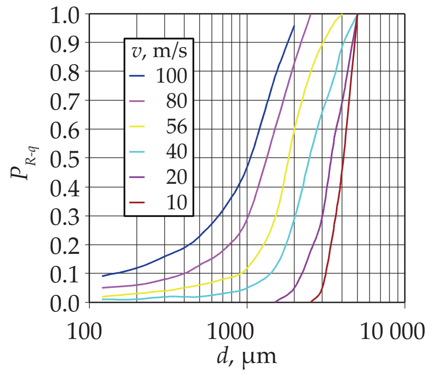
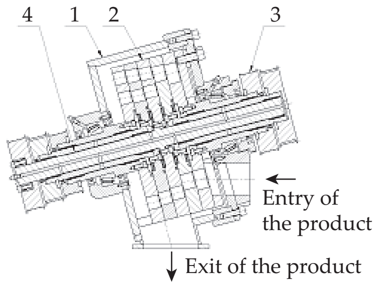
**T a b l e 1. Selected technological solutions and product stability**

| Item | Technological and design solutions | Estimation of the grinding product stability |
|---|---|---|
| 1 | Multi-blade grinding machine, rings, PVC, variable linear velocity: 10–100 m/s<br><br><br>1 – drive shaft, 2 – impeller, 3 – stator, 4 – body fastening, 5 – moving knife, 6 – fixed knives, 7 – outer distance bushing, 8 – inner distance bushing, 9 – wedge | Size distribution of the pieces produced by grinding in PVC recycling with variable linear velocity of the blade (rotor ring) of multi-blade grinding machine<br><br> |
| 2 | Multi-disc grinding machine, multi-holes, PE, variable linear velocity: 0.2, 4.8 m/s<br><br><br>1 – grinder body, 2 – discs with holes, 3 – tooth wheel, 4 – disc drive bushing | Size distribution of grinding product for PE with variable linear velocity ($u$) and edge holes:<br>– productive pieces PE (mean speed $w_{50}$ = 1.545 m/s, standard deviation $s$ = 0.19):<br>$P_{R-q} = \begin{cases} 0 \text{ for } w < 0.93 \text{ m/s} \\ \frac{1}{s\sqrt{2\pi}} \int_{-\infty}^{w} \exp\left[-\frac{(\ln w - \ln w_{50})^2}{2s^2}\right] \\ 1 \text{ for } w > 2.45 \text{ m/s} \end{cases}$<br>$d \ln w$ for 0.94 m/s < $w$ < 2.44 m/s<br>– pipes PE, recycling ($w_{50}$ = 2.09 m/s, $s$ = 0.20):<br>$P_{R-q} = \begin{cases} 0 \text{ for } w < 1.19 \text{ m/s} \\ \frac{1}{s\sqrt{2\pi}} \int_{-\infty}^{w} \exp\left[-\frac{(\ln w - \ln w_{50})^2}{2s^2}\right] \\ 1 \text{ for } w > 3.78 \text{ m/s} \end{cases}$<br>$d \ln w$ for 1.20 m/s < $w$ < 3.77 m/s |

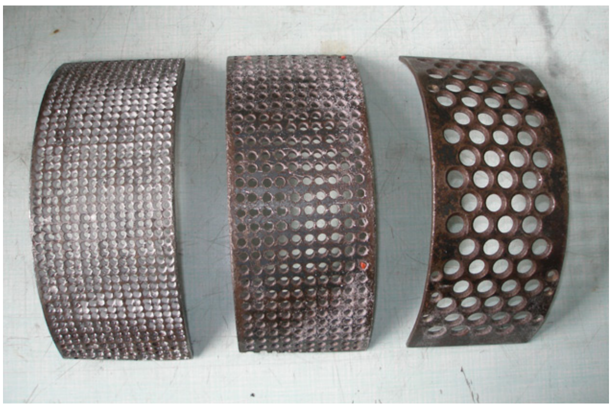
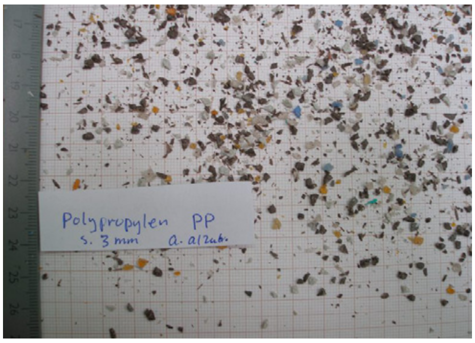
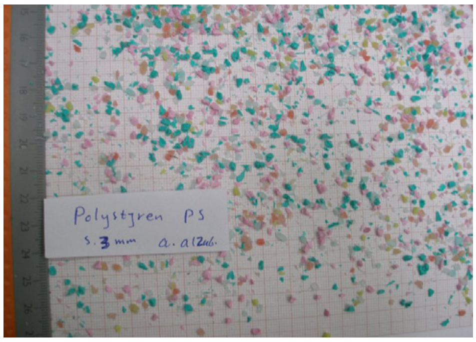
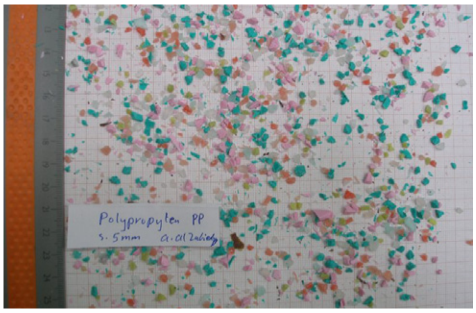
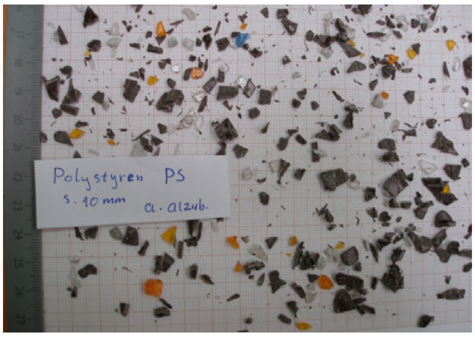
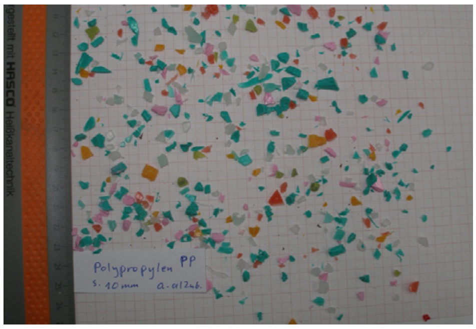


**Fig. 1. Set of sieves in grinding machine with different hole sizes**


**Fig. 2. Image recording and analysis: a) stereo microscope, b) digital camera, c) computer software**

**T a b l e 2. Characteristics of the grinding product in the stabilization process**

| Type of product | Polystyrene (PS) | Polypropylene (PP) |
|---|---|---|
| Starting materials PS, PP |  |  |
| Sieve ϕ 3 mm |   |   |
| Sieve ϕ 5 mm |   |   |
| Sieve ϕ 10 mm |   |   |

grinding in the recycling process should consider a number of areas of interest: technical, material and process control. First of all: the properties of polymer materials to be grinded, motor control and feedback tools to change inertia uniformity, provide basic solutions.

The results of grinding using multi-blades with sieves of different diameters ϕ (3, 5, 10 mm) can be analyzed based on RRSB (Rosin-Rammler-Sperling-Bennett) Equation (1), which with a fairly good precision approximates the actual distribution of particle size.

$$R = \exp\left[-\left(\frac{d}{d^*}\right)^n\right] \tag{1}$$

where: $R$ – the total residue on the sieve, $d$ – substitute particle diameter in mm, $d^*$ – average static linear dimensions of all the particles contained in the mixture flowing (loose) in mm, $n$ – coefficient of grain size uniformity.

**T a b l e 3. Analysis of sieving process of polypropylene – ϕ 3 mm**

| No. | Hole size in the sieve *a*, mm | Mass of material on the sieve *m*, g | Substitute dimension of the particle *d*, mm | Mass fraction of the particle on the sieve *x*, % | Total remain *R*, % |
|---|---|---|---|---|---|
| 1 | 3.15 | 0.000 | 0.000 | 0.00 | 0.00 |
| 2 | 2.50 | 0.940 | 2.806 | 0.95 | 0.95 |
| 3 | 2.00 | 25.775 | 2.236 | 26.17 | 27.12 |
| 4 | 1.60 | 33.190 | 1.789 | 33.70 | 60.82 |
| 5 | 1.00 | 26.700 | 1.265 | 27.11 | 87.93 |
| 6 | 0.80 | 5.295 | 0.894 | 5.38 | 93.31 |
| 7 | 0.63 | 1.740 | 0.710 | 1.77 | 95.08 |
| 8 | 0.40 | 2.800 | 0.502 | 2.84 | 97.92 |
| 9 | 0.25 | 1.250 | 0.316 | 1.27 | 99.19 |
| 10 | 0.20 | 0.270 | 0.224 | 0.27 | 99.46 |
| 11 | < 0.20 | 0.530 | – | 0.54 | 100.00 |
| | | **98.490** | | **100.00** | |

**T a b l e 4. Analysis of sieving process of polystyrene – ϕ 3 mm**

| No. | Hole size in the sieve *a*, mm | Mass of material on the sieve *m*, g | Substitute dimension of the particle *d*, mm | Mass fraction of the particle on the sieve *x*, % | Total remain *R*, % |
|---|---|---|---|---|---|
| 1 | 2.50 | 0.000 | 0.000 | 0.00 | 0.00 |
| 2 | 2.00 | 13.620 | 2.236 | 14.94 | 14.94 |
| 3 | 1.60 | 31.430 | 1.789 | 34.47 | 49.40 |
| 4 | 1.00 | 36.410 | 1.265 | 39.93 | 89.33 |
| 5 | 0.80 | 6.340 | 0.894 | 6.95 | 96.28 |
| 6 | 0.63 | 1.950 | 0.710 | 2.14 | 98.42 |
| 7 | 0.40 | 0.940 | 0.502 | 1.03 | 99.45 |
| 8 | 0.25 | 0.290 | 0.316 | 0.32 | 99.77 |
| 9 | 0.20 | 0.210 | 0.224 | 0.23 | 100.00 |
| 10 | < 0.20 | 0.000 | – | 0.00 | 100.00 |
| | | **91.190** | | **100.00** | |

**T a b l e 5. Analysis of sieving process of polypropylene – ϕ 5 mm**

| No. | Hole size in the sieve *a*, mm | Mass of material on the sieve *m*, g | Substitute dimension of the particle *d*, mm | Mass fraction of the particle on the sieve *x*, % | Total remain *R*, % |
|---|---|---|---|---|---|
| 1 | 5.00 | 0.000 | 4.472 | 0.00 | 0.00 |
| 2 | 4.00 | 11.480 | 3.464 | 11.47 | 11.47 |
| 3 | 3.00 | 45.440 | 2.739 | 45.39 | 56.85 |
| 4 | 2.50 | 24.350 | 1.936 | 24.32 | 81.17 |
| 5 | 1.50 | 10.750 | 0.803 | 10.74 | 91.91 |
| 6 | 0.43 | 7.850 | 0.254 | 7.84 | 99.75 |
| 7 | 0.15 | 0.250 | – | 0.25 | 100.00 |
| | | **100.120** | | **100.00** | |

Substitute particle diameter on the sieve was calculated as the average of the geometric dimensions of the holes of two adjacent sieves ($a_i$, $a_{i+1}$) [Eq. (2)]:

$$d_i = \sqrt{a_i \cdot a_{i+1}} \tag{2}$$

Total sieve residue *R* (ex. sifting) was determined as a sum of mass fractions *x* of material on each sieve starting from the sieves having initial mesh size [4, 6, 8].

**The plan and realization tests**

The multi disc-grinding device was equipped with a set of interchangeable sieves with different values of hole diameters, that were in a range from ϕ 3 mm to ϕ 10 mm (Fig. 1). The project used three pairs of sieve of different hole sizes: 3, 5, 10 mm.

Recording of images was carried out by a stereo-microscope (Fig. 2). Images from the microscope were automatically handed over to the camera Opta-Tech created based on CMOS sensors with a resolution of 3 mega pixels (2048 × 1536). A special program for image recording and analysis was included with the camera.

Opta-Tech microscope SN Series, additionally equipped with a diode and ring lighting system that provided illumination of the sample, was used in the study. Controlling illumination intensity zones eliminated shadows, that played a major role in the image analysis.

In the study of optical geometric features (form and dimensions) of recyclate grains, OptaView software from Opta-Tech company was used. The geometrical characteristics of recyclate was investigated using MultiScan software, version 18.03 from Computer Scanning Systems II. This program enabled manual and automated analysis of recorded images. This allowed, among others, the automatical estimation of the geometric characteristics of a set of grains on the basis of digital recording.

## RESULTS AND DISCUSSION

Examples of the forms of recycled products before and after grinding are shown in Table 2. The left-hand column of the table refers to polystyrene (PS) elements, while the right column shows polypropylene (PP) elements subjected to recycling. The elements were passed through sieves with diameter ϕ = 3, 5 and 10 mm.

In the Figs. 3–8 performance characteristics, statistical analysis and evaluation of the grain size and dimensions of the products obtained by grinding recycled polymeric materials (PP, PS) are shown. The results of sieve analysis enable to determine the contribution of individual fractions *Xi*, according to the Equation (3):

$$Xi = \frac{\Delta m_i}{m} \qquad (3)$$

where: $\Delta m_i$ – mass remaining on the sieve, (g), $m$ – total sample mass, (g).

### Polypropylene, sieve ϕ 3 mm

The results of sieve analysis are shown in Table 3, including calculated values of the variables of RRSB equation. Compliance with the experimental point distribution curve RRSB is shown in Fig. 3.

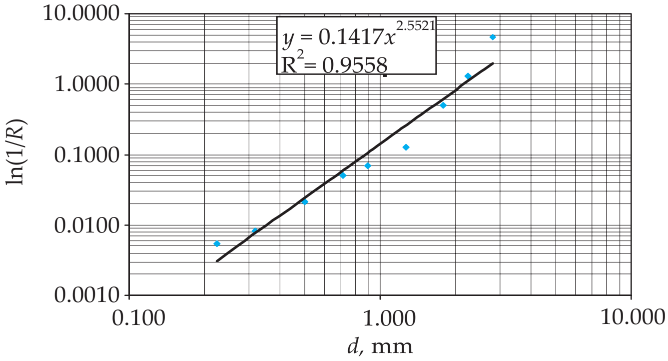



**Fig. 3. Compliance of experimental points of particle size distribution for PP – ϕ 3 mm with RRSB equation**

The coefficients of RRSB equation were calculated using rectilinear regression and the least squares method and equal: $n$ = 2.55211, $d^*$ = 2.150507.

### Polystyrene, sieve ϕ 3 mm

The results of sieve analysis are shown in Table 4, including calculated values of the variables of RRSB equation. Compliance with the experimental point distribution curve RRSB is shown in Fig. 4.

The coefficients of RRSB equation were calculated using rectilinear regression and the least squares method and equal: $n$ = 3.503392, $d^*$ = 2.102052.

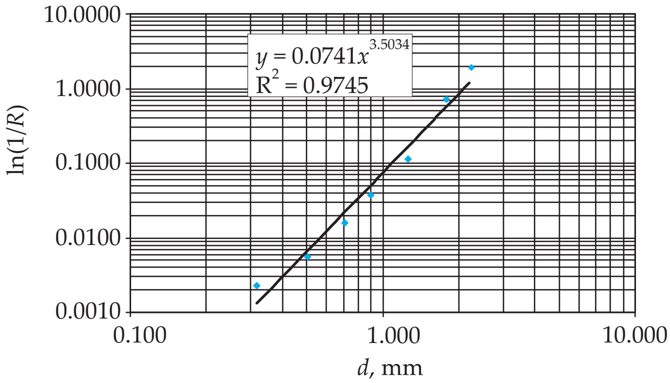



**Fig. 4. Compliance of experimental points of particle size distribution for PS – ϕ 3 mm with RRSB equation**

### Polypropylene, sieve ϕ 5 mm

The results of sieve analysis are shown in Table 5, including calculated values of the variables of RRSB equation. Compliance with the experimental point distribution curve RRSB is shown in Fig. 5.

The coefficients of RRSB equation were calculated using of rectilinear regression and the least squares method and equal: $n$ = 3.81818, $d^*$ = 3.868192.

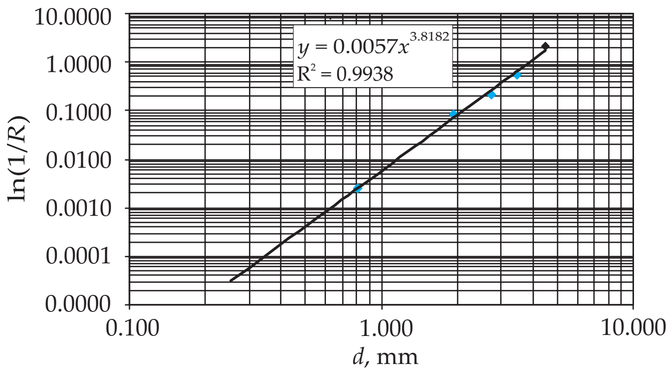



**Fig. 5. Compliance of experimental points of particle size distribution for PP – ϕ 5 mm with RRSB equation**

**T a b l e 6. Analysis of sieving process of polystyrene – ϕ 5 mm**

| No. | Hole size in the sieve *a*, mm | Mass of material on the sieve *m*, g | Substitute dimension of the particle *d*, mm | Mass fraction of the particle on the sieve *x*, % | Total remain *R*, % |
|---|---|---|---|---|---|
| 1 | 5.00 | 0.000 | 4.472 | 0.00 | 0.00 |
| 2 | 4.00 | 5.290 | 3.464 | 5.28 | 5.28 |
| 3 | 3.00 | 26.750 | 2.739 | 26.70 | 31.98 |
| 4 | 2.50 | 24.920 | 1.936 | 24.87 | 56.85 |
| 5 | 1.50 | 20.620 | 0.803 | 20.58 | 77.43 |
| 6 | 0.43 | 21.350 | 0.254 | 21.31 | 98.74 |
| 7 | 0.15 | 1.260 | – | 1.26 | 100.00 |
| | | **100.190** | | **100.00** | |

**T a b l e 7. Analysis of sieving process of polypropylene – ϕ 10 mm**

| No. | Hole size in the sieve *a*, mm | Mass of material on the sieve *m*, g | Substitute dimension of the particle *d*, mm | Mass fraction of the particle on the sieve *x*, % | Total remain *R*, % |
|---|---|---|---|---|---|
| 1 | 8.00 | 0.000 | 0.000 | 0.00 | 0.00 |
| 2 | 7.00 | 20.230 | 7.483 | 20.17 | 20.17 |
| 3 | 5.00 | 54.350 | 5.916 | 54.20 | 74.37 |
| 4 | 4.00 | 11.650 | 4.472 | 11.62 | 85.99 |
| 5 | 3.00 | 8.150 | 3.464 | 8.13 | 94.12 |
| 6 | 2.50 | 3.300 | 2.739 | 3.29 | 97.41 |
| 7 | 1.50 | 1.250 | 1.936 | 1.25 | 98.65 |
| 8 | 0.43 | 1.300 | 0.803 | 1.30 | 99.95 |
| 9 | < 0.43 | 0.050 | – | 0.05 | 100.00 |
| | | **100.280** | | **100.00** | |

**T a b l e 8. Analysis of sieving process of polystyrene – ϕ 10 mm**

| No. | Hole size in the sieve *a*, mm | Mass of material on the sieve *m*, g | Substitute dimension of the particle *d*, mm | Mass fraction of the particle on the sieve *x*, % | Total remain *R*, % |
|---|---|---|---|---|---|
| 1 | 8.00 | 0.000 | 0.000 | 0.00 | 0.00 |
| 2 | 7.00 | 2.850 | 7.483 | 2.85 | 2.85 |
| 3 | 5.00 | 40.580 | 5.916 | 40.58 | 43.43 |
| 4 | 4.00 | 20.830 | 4.472 | 20.83 | 64.26 |
| 5 | 3.00 | 19.950 | 3.464 | 19.95 | 84.21 |
| 6 | 2.50 | 8.450 | 2.739 | 8.45 | 92.66 |
| 7 | 1.50 | 4.090 | 1.936 | 4.09 | 96.75 |
| 8 | 0.43 | 3.100 | 0.803 | 3.10 | 99.85 |
| 9 | < 0.43 | 0.150 | – | 0.15 | 100.00 |
| | | **100.000** | | **100.00** | |

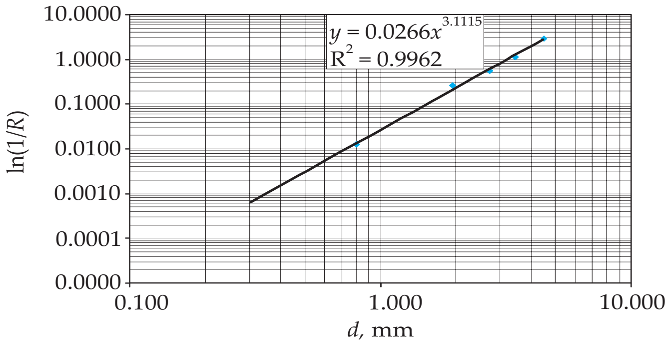



**Fig. 6. Compliance of experimental points of particle size distribution for PS – ϕ 5 mm with RRSB equation**

## Polystyrene, sieve ϕ 5 mm

The results of sieve analysis are shown in Table 6, including calculated values of the variables of RRSB equation. Compliance with the experimental point distribution curve RRSB is shown in Fig. 6.

The coefficients of RRSB equation were calculated using rectilinear regression and the least squares method and equal: $n = 3.111522$, $d^* = 3.207042$.

### Polypropylene, sieve ϕ 10 mm

The results of sieve analysis are shown in Table 7, including calculated values of the variables of RRSB equation. Compliance with the experimental point distribution curve RRSB is shown in Fig. 7.

The coefficients of RRSB equation were calculated using rectilinear regression and the least squares method and equal: $n$ = 3.39504, $d^*$ = 7.560506.

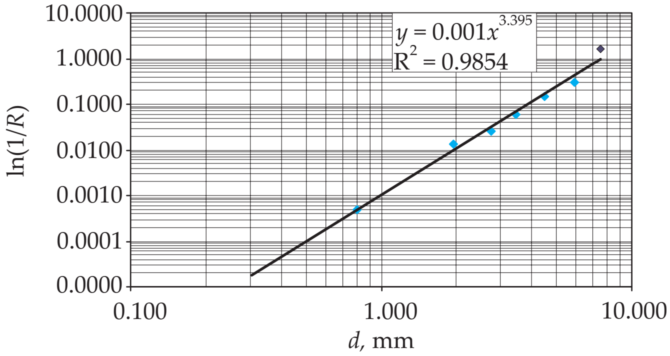



**Fig. 7. Compliance of experimental points of particle size distribution for PP – ϕ 10 mm with RRSB equation**

### Polystyrene, sieve ϕ 10 mm

The results of sieve analysis are shown in Table 8, including calculated values of the variables of RRSB equation. Compliance with the experimental point distribution curve RRSB is shown in Fig. 8.

The coefficients of RRSB equation were calculated using rectilinear regression and the least squares method and equal: $n$ = 3.331265, $d^*$ = 5.693127.

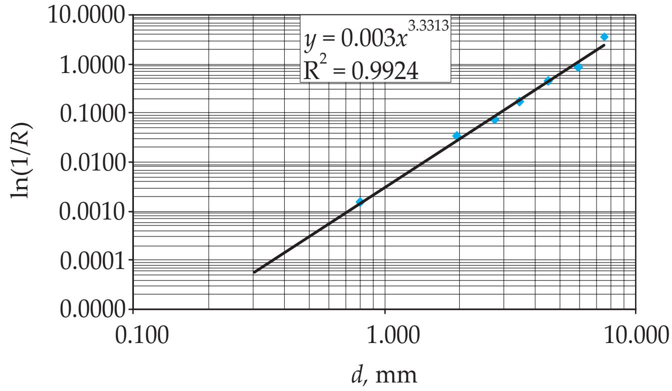



**Fig. 8. Compliance of experimental points of particle size distribution for PS – ϕ 10 mm with RRSB equation**

The sum of relative screenings for sieve was determined from the equation, and then the sum of relative screenings was determined, which corresponds to the sum function of the distribution. The collection of grains was described on the basis of the actual course sum of functions and sieves grain using two-parameter functions, searching for such a known decomposition mathematical (Fig. 9), which with the greatest approximation describe obtained curves of the sum of the distribution (on a sieve grain curve of the sum of the decomposition or aggregation sieves sifting should be straight).

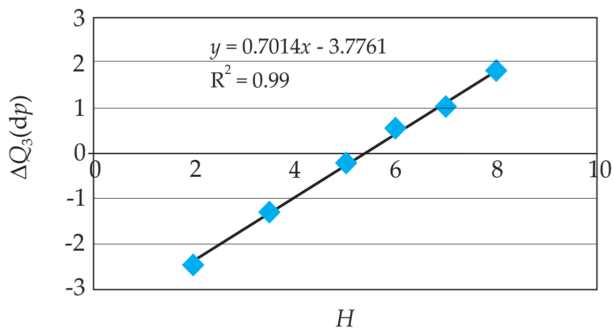



**Fig. 9. An exemplary graph of the sum of grain distributions and the normal distribution in the grid; $\Delta Q_3$(d*p*) – inaccuracy, unevenness of the function the sum distribution $Q_3$(d*p*), *H* – the sum of relative screening for sieve, $R^2$ – coefficient of determination**

Based on the determined characteristic parameters of the distribution (in case of a normal distribution, average grain size and standard deviation, characterizing the stability of distribution) and a curve the sum of the density distribution was obtained.

Each process of precision grinding, leading towards stable forms and geometric dimensions of the granules, should be carried out in accordance with the intended objective. To assess the degree of achievement of performance, the indicators are used. The effectiveness of precision grinding is determined as the ratio of the actually achieved dimensions. The granulometric distribution of the product is possible to achieve theoretically.

The overall effectiveness of the grinding geometry is given by:

$$S = W_r/W_o \tag{4}$$

where: $W_r$ – the result achieved, $W_o$ – expected outcome (less theoretically possible).

In the stable grinding, only rational cases are considered, in which the size and the $W_r$ i $W_o$ are within a defined schedule of dimensions.

Calculating the efficiency of precision grinding components of polymeric materials is based on the characteristics of the feed and product of the process (operations): mass expenditure (kg/s) and other values that are proportional to the mass expenditure.

## CONCLUSIONS

The mechanism of polymer grinding and the related system of process variables – forces and stresses are complicated. As a result, there is currently no comprehensive or universal grinding theory, and the extensive literature on this topic mostly presents the results of many tests and measurements, on the basis of which, general laws of the granulation process can not be formulated. Analyses of individual granules prove that mechanical properties have a large dispersion even for grains belonging to a narrow class.

This is mainly due to the different form of granulate (recycled form, for example: pipes), uneven distribution of structural defects and other consequences of use.

Effective identification of the geometrical stability of the product of grinding has been made using a dissecting microscope. The image from the microscope is automatically handed over to the camera with software for registration/identification and image analysis.

The optical geometrical characteristics (form and size) of the recyclate particles was performed using the software allowing automatic analysis of recorded images and estimation of geometric features of recyclate grains on the basis of digital recording.

The deterministic model is analyzed depending on energy and the grinding process [9–13]. For the purpose of assessing the stable grinding, the most important issue is the determination of a function expressing polydisperse size distribution of the material. Exemplary, the most popular function approximation is Rosin-Rammler-Sperling--Bennett (RRSB). RRSB function is suitable for the assessment of the geometrical stability of the granulate, ground recyclate of the polymer, as a fine population. Studies on the grain size distribution of recyclate plastics material were conducted on a standard unit of the screens.

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