Chemical and Process Engineering 2014, 35 (1), 121-135
DOI: 10.2478/cpe-2014-0009

A STUDY ON POLYMER PARTICLE FLOW IN A DISK ZONE OF A SCREW-DISK EXTRUDER[1]

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The paper presents the summary of research on polymer melt particle motion trajectories in a disc zone of a screw-disk extruder. We analysed two models of its structure, different in levels of taken simplifications. The analysis includes computer simulations of material particle flow and results of experimental tests to determine the properties of the resultant extrudate. Analysis of the results shows that the motion of melt in the disk zone of a screw-disk extruder is a superposition of pressure and dragged streams. The observed trajectories of polymer particles and relations of mechanical properties and elongation of the molecular chain proved the presence of a stretching effect on polymer molecular chains.

Keywords: extrusion, screw disk extrusion, flow trajectory of particles

1. INTRODUCTION

Processes that take place in a material during its processing into extruders plasticising systems affect properties of the resultant extrudate. The inside effects are associated with system design features and with processing parameters. A screw-disk extruder constructed at the Koszalin University of Technology is an interesting although not very well known solution. Between the end of the screw and the stationary cylinder cover there is a chink called the disk zone (with adjustable width). While staying in the disc zone, material is subjected to shearing and mixing (Michalska-Pożoga and Jakubowski, 2012; Rydzkowski and Michalska-Pożoga, 2010). Implementation of grooves on the inner surface of the barell, directed contrary to those on the screw, may cause grinding of polymer chains with a certain resemblance to multi-edge grinding (Macko, 2013).

Analysis of the results of experimental studies indicates that by changing the screw rotational speed and the width of the disk zone chink can affect the material macrostructure and morphology of the extrudate. It was hypothesised that, in the disk zone natural tangled chains of materials are under the influence of a tensile load, which may lead to their ordering, which will affect the properties of the resultant extrudate. The assumptions of this hypothesis are presented below.

After empirical examination analytical studies were conducted to explain effects observed during the experiment. Modelling of polymer particle flow in the disc zone of the extruder was carried out in several stages. In the first one, the conical disk zone was simplified to a flat circular disk, and in the following analysis the shape of the modelled area corresponded to a real construction of the extruder.

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[1] *The paper is a much extended version of an earlier paper of the authors published in Technical Transactions. Mechanika, 3, 273–279.*

The purpose of this article is to present a cycle of computer analysis and experimental studies confirming the phenomena occurring in disc zone of the extruder. The Analysed phenomena cause stretching of polymer chains. The stretchig affects both extrudate macrostructure and its mechanical properties.

2. SCREW DISK-EXTRUDER

The basic difference between a classical plasticising system and the screw-disk system developed in Koszalin University of Technology lies in the diameter of a screw and the proportion of its length to diameter (Figs. 1 and 2) (Diakun, 1997; Rydzkowski, 2006; Rydzkowski and Radomski, 2008). The diameter of classical screws equals several dozen millimetres and their lengths amount to 20 to 35 diameters of the screw (Fig. 2a) (Sikora, 1993). In consequence of a large diameter of a screw (130 mm Fig. 2b) it is terminated in a large flat or conical disk. An outlet of a plasticising system is located centrally in a cylinder cover. Due to the application of a special mechanism to a screw-disk extruder it is possible to change the width of this chink, so in this case we are dealing with an active element of a plasticising system. On the basis of experimental investigations and analysis of results it was found that the width of a chink affects the quality and degree of homogenisation and properties of the extrudate (Diakun, 2002; Rydzkowski, 2006; Rydzkowski and Radomski, 2008).

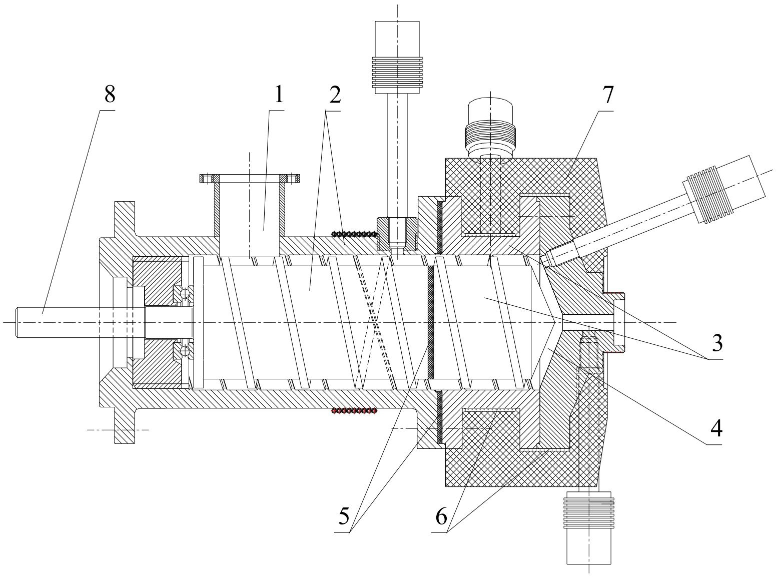

Fig. 1. Longitudinal section of the plasticising system of the screw-disk extruder;
1 – charging hopper, 2 – cold zone of the screw and barrel, 3 – hot zone of the screw and barrel, 4 – chink, 5 – insulating separators, 6 – electric heaters, 7 – thermal insulator, 8 – drive shaft
(Diakun and Michalska, 2004, Rydzkowski and Radomski, 2008)

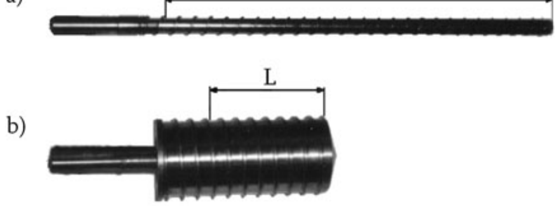

Fig. 2. Screws (*L* – screw working length): a) from single screw extruder,
b) from screw-disc extruder (Rydzkowski and Michalska-Pożoga, 2009)

Melt particle trajectories in a plasticising system result from a geometrical form and kinematics of motion elements in a system. The spiral screw channel after expanding on the flat surface can be represented as a rectangular one. Melt particle trajectories in a classical screw system take the form of screw lines resulting from pressure and dragged flow (Fig. 3) (Tadmor and Klein, 1970).

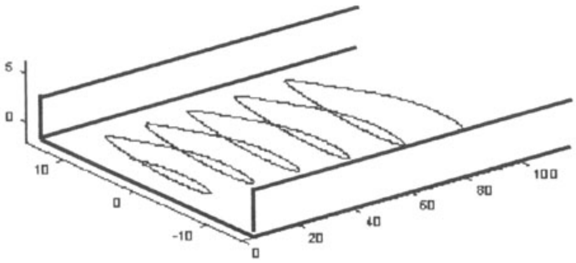

Fig. 3. Polymer particle flow trajectory in straightened screw channel (canal)
(Diakun, 2002, Rydzkowski and Michalska-Pożoga, 2009)

In the screw-disk plasticising system designed in Koszalin the situation is different. A plasticising system may be divided into two zones: a screw part and a disk zone (a frontal chink). The melt in a plasticised form occurs in principle only in a frontal chink of the extruder. A screw part mainly fulfils the function of a feed zone which is aimed at transporting a not-plasticised melt and at producing a suitable pressure in a disk zone. The plasticised melt is situated in a disk zone between a rotational conical end of the screw and an immovable disk of a cylinder cover. Therefore conditions and a type of flow are completely different as compared to a classical screw extruder construction. Trajectories result from dragged and pressure flow. The melt in a disk zone flows in the radial direction *r* from the outside wall of diameter (D_T) towards the central outlet (Fig. 4a). A flow of melt in a disk zone of a screw-disk extruder is a superposition of a pressure flux and a dragged flux (Fig. 4b) (Diakun, 2002; Diakun and Michalska, 2004).

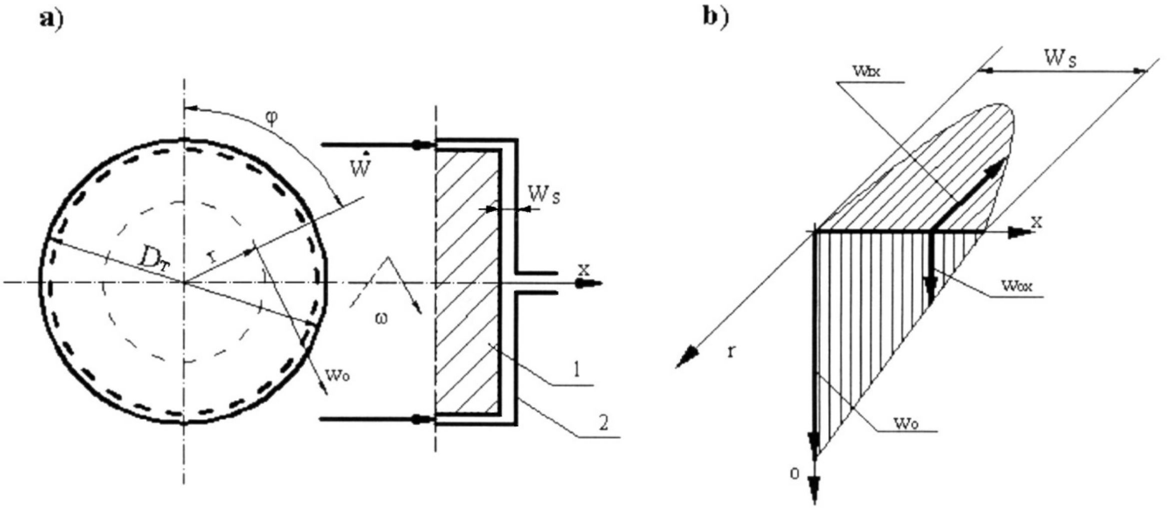

Fig. 4. Simplified disk zone: a) scheme, b) velocity distribution in the clearance between the disks; 1 – rotary disk, 2 – casing, $\mathbf{w}_{rx}$– pressure stream velocity vector, $\mathbf{w}_{ox}$ – dragged stream velocity vector, *o* – peripheral direction, *r* – radial direction, W_s – the chink, D_T – disk diameter, $\mathbf{w}_0$ – velocity in the circumferential direction vector, $\dot{W}$ – efficiency (Diakun, 2002; Diakun and Michalska, 2004; Rydzkowski and Michalska-Pożoga, 2009)

A pressure stream is the result of a forced flow through a screw system of an extruder. The melt is displaced in the radial direction *(r)* from an outer diameter of a disk chink towards the central outlet. Velocity distribution in a chink is parabolic in character, its value results from the capacity $(\dot{W})$ and is changing as a function of the radius *(r)*. A dragged stream results from a relative motion of a rotating disk and an immovable casing. The velocity of melt particles by the movable disk is equal to that of the disk. Velocity decreases along the *x* axis towards the immovable casing, where velocity of particles equals zero. Velocity distribution is linear in character.

Superposition of streams causes the spiral motion of melt particles in a chink. The nature of trajectories depends on the following factors: the capacity *($\dot{W}$)*, the width of a chink *(W_s)***,** the angular velocity **(ω)**, and the location in a disk chink *(x)* (Fig. 5).

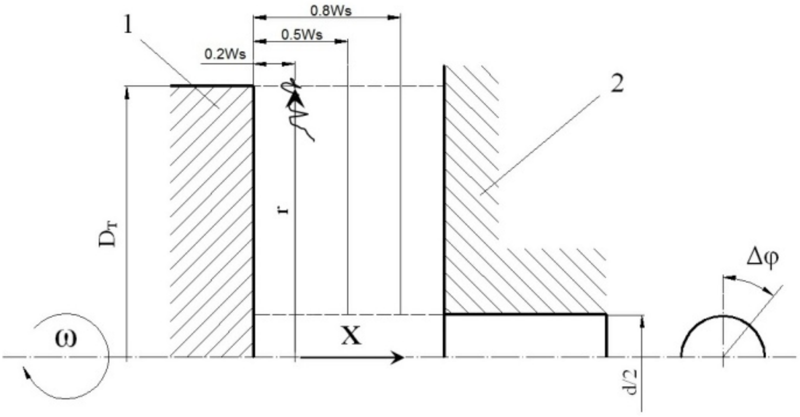

Fig. 5. Initial location of polymer chains in simulation calculations: 1 – end the screw, 2 – barell cover, W_s – the chink; *r* = $D_T/2$**-** the initial radius of a disk; *d/2*- the final radius; **ω** - the angular speed of a disk (Diakun and Michalska, 2004; Michalska-Pożoga, 2006)

3. RESULTS AND DISCUSSION

3.1. Simulation

In order to confirm theoretical nature of polymer particle flow in the disc zone of a screw-disc extruder a set of simulation studies was performed using MATLAB 7.0 program. The calculations were carried out in the program given some simplifications:

- the conical-disc zone was simplified to a flat disc (Fig. 6.),

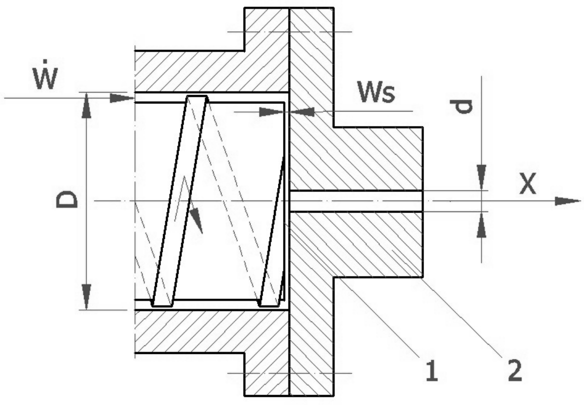

Fig. 6. The scheme of simplified disk zone: 1 – rotating disk (screw face), 2 – housing, W_s – the chink, $\dot{W}$ – flow rate, *d* – extruding die diameter, *X* – polymer material flow direction, **ω** – angular velocity, D_T – disk diameter

- pressure generated by Weissenberg's effect was neglected,
- plasticised melt has a nature of Newtonian liquid,

- flow of fluid is isothermal and laminar.

Simulation tests were carried out for the following parameters:

- constant parameters include the disk radius R_T = 65 mm and the radius of a head outlet r_0 = 5 mm,
- variable parameters include the output – efficiency – $\dot{W}$ = 6.1–24.2 kg/h, the size of a chink – W_s =0.06; 0.125; 0.25; 0.5; 1; 1.5; 2; 3; 4 mm, the position of location in a chink – $x = 0.2W_s$, $0.5W_s$, $0.8W_s$ mm and the angular velocity – ω = 0.525–2.1 rad/s.

After analysing results, it was found that the trajectory of polymer particles depends on the dimension of the chink area, initial output and the distance of a particle from the front surface of the screw. The closer the particle is placed to the rotational disk the higher the concentration of spirals of their trajectories. It signifies that a longer stay of a particle in the disk zone is connected with prolonged impact of the zone on a particle (Fig. 7a and b.) (Michalska-Pożoga, 2006; Diakun and Michalska, 2004).

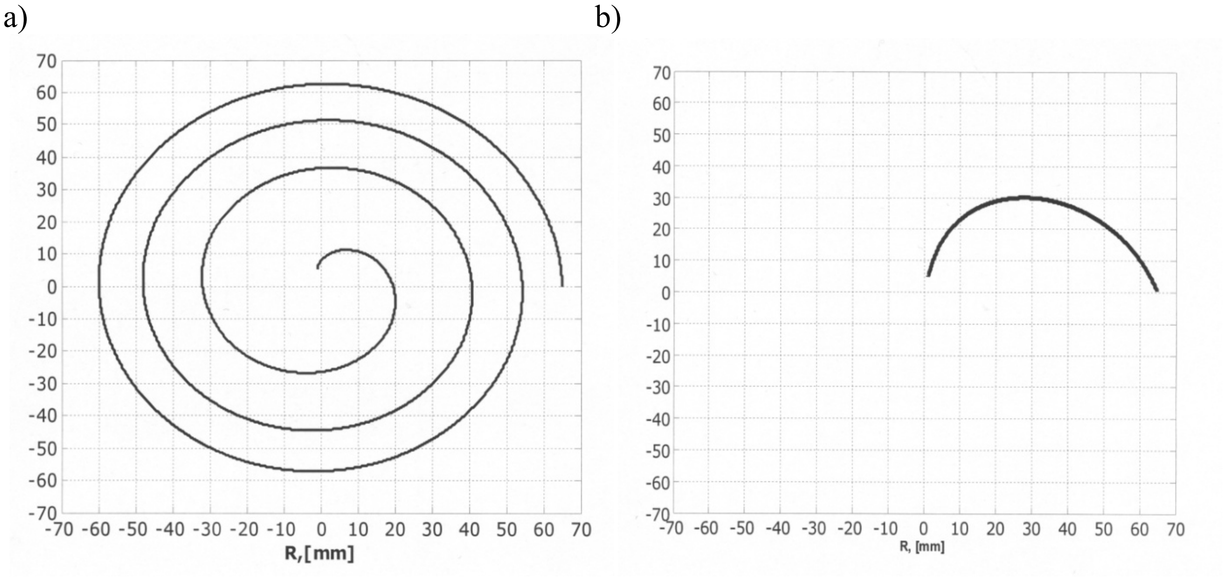

Fig. 7. Trajectory of particle motion in a screw-disk plasticising system: a) $\dot{W}$ = 16.5 kg/h, W_s = 3.0 mm, x = 0.2 mm, R_T = 65 mm, r_0=5 mm, ω = 1.03 rad/s, b) $\dot{W}$ = 13.3kg/h, W_s = 1.25 mm, x = 0.8 mm, R_T = 65 mm, r_0 = 5 mm, ω = 0.525 rad/s (Diakun and Michalska, 2004; Rydzkowski and Michalska-Pożoga, 2009)

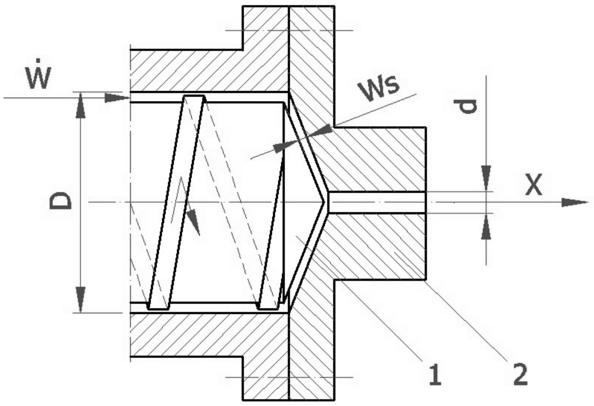

Fig. 8. The scheme of real disk zone: 1 – rotating disk (screw face), 2 – housing, W_s – the chink, $\dot{W}$ – flow rate, d – extruding die diameter, X – polymer material flow direction, ω – angular velocity, D_T – disk diameter (Michalska-Pożoga and Jakubowski, 2012)

In order to perform detailed numerical analysis without previously adopted simplification a successive stage of numerical simulation was carried out using ANSYS CFX program. With its help, an accurate spatial model of the disc zone has been developed (disc diameter D_T = 130 mm, nozzle diameter d = 10 mm, cone angle of the disc $\alpha = 133°$) (Fig. 8).

For LDPE the rheological Ostwald-de Waele power law model with parameters n = 0.41, k = 6513 Pa·s^n, Re = 1.20–6.27·10^{-5}, M = 600000 g/mol) was used. Numerical analysis was performed for the following parameters of the process: W_s = 0.3–3 mm, ω = 1.05-2.1 rad/s, $\dot{W}$ = 5.42–12.64 kg/h (Michalska-Pożoga and Jakubowski, 2012).

After analysing results, it was found that the difference in the trajectory of polymer particles movement in the disc zone is dependent on the velocity gradient (Figs. 9a and b) and that the residence time of the material in the disc zone is dependent on the output and the width of the chink (Figs. 10a and b) (Michalska-Pożoga and Jakubowski, 2012).

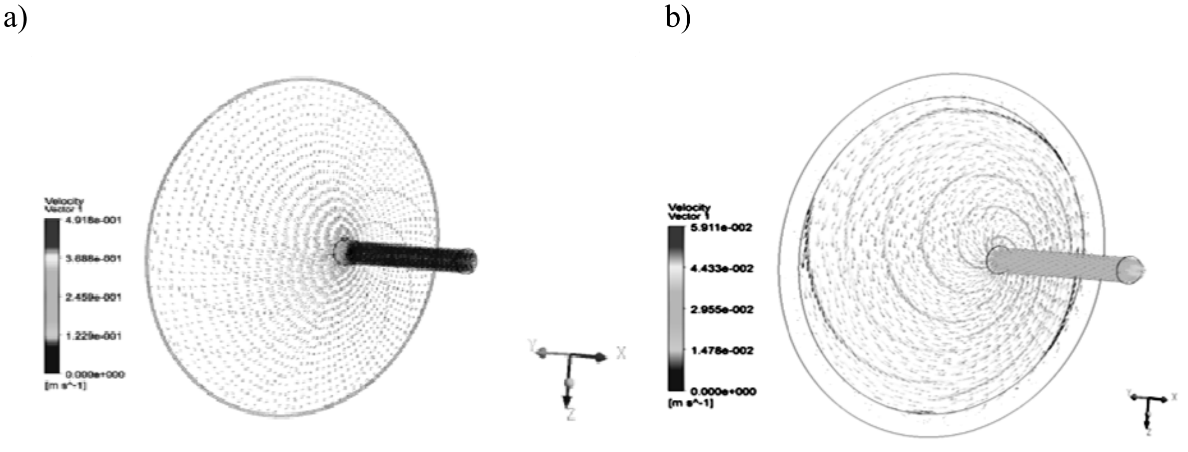

Fig. 9. Vector maps of velocity distribution prepared to disk zone of screw-disk extruder: a) W_{s1} = 0.3 mm, ω = 2.1 rad·s^{-1}, b) W_{s2} = 3.0 mm, ω = 1.05 rad·s^{-1} (Michalska-Pożoga and Jakubowski, 2012)

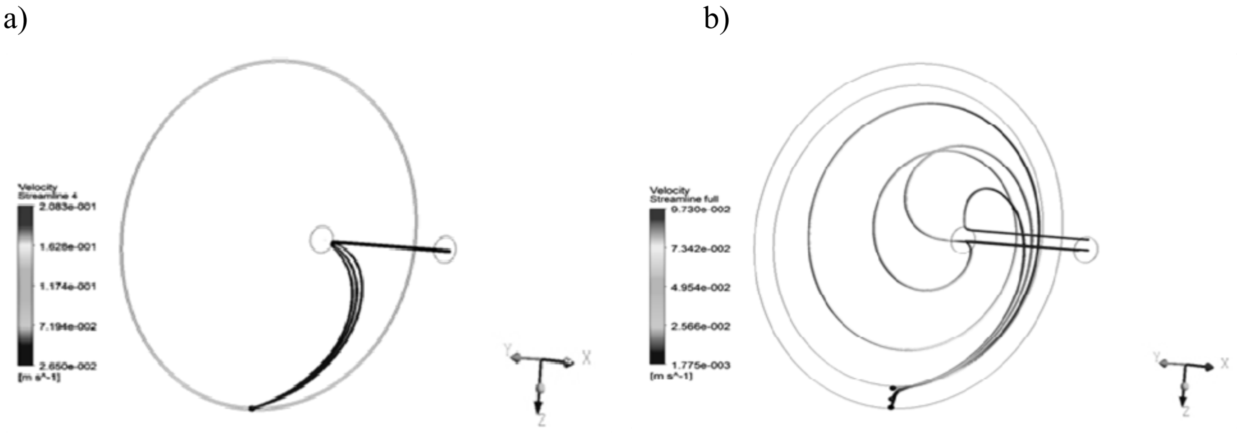

Fig. 10. Molecule of polymer material motion tracking and molecule velocity values in disk zone of screw-disk extruder: a) W_{s1} = 0.3 mm, ω = 1.05rad·s^{-1}, b) W_{s2} = 3.0 mm, ω = 2.1rad·s^{-1} (Michalska-Pożoga and Jakubowski, 2012)

3.2. Mechanism of polymer chains straightening

For the sake of simplicity polymer chains are presented in a straightened (linear) form, see Fig. 11a. However the natural conformation of a polymer chain is twisted, which is illustrated schematically in Fig. 11b.

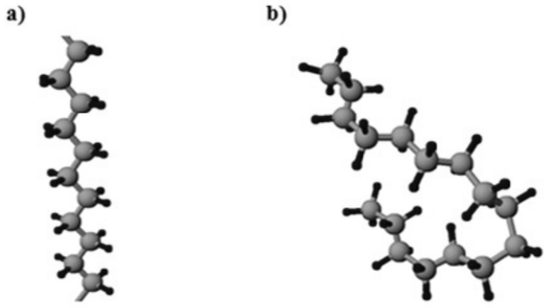

Fig. 11. Structure of a linear PE chain: a) straightened, b) twisted (Michalska-Pożoga, 2006)

The transfer of polymer melt in a flux with a velocity gradient maces the natural conformation of polymer chains to be straightened, which is illustrated schematically in Fig. 12.

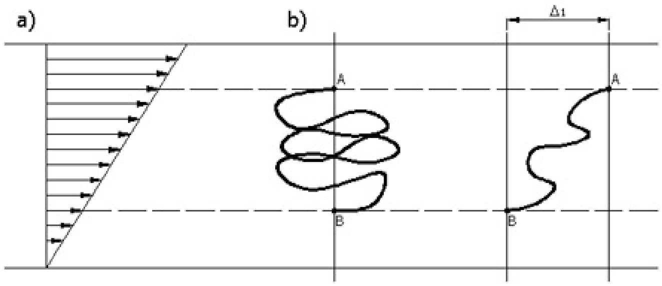

Fig. 12. Model behaviour of a macroparticle while shearing: a) velocity gradient, b) elongation of a particle *(Δ_1)*; A and B ends of a macroparticle (Michalska-Pożoga, 2006)

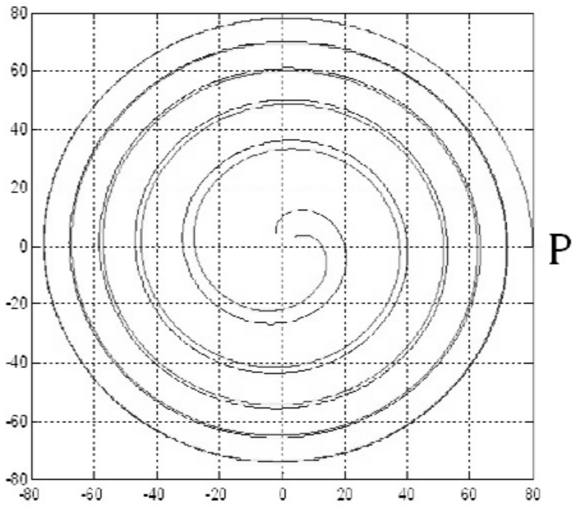

Fig. 13. Motion trajectory for two points separated by the PE-LD macroparticle conformative length at a chink depth (Diakun and Michalska, 2004; Michalska-Pożoga, 2006)

To display on a macroscopic scale the diversification of motion trajectories for two points in a disk chink of a screw-disk extruder situated at different depth *(x)* of a disk chink, a numerical analysis of two-points motion was carried out. In the place marked with the capital *P* in Fig. 13, there are two points separated by the conformative length. In the course of their motion from the outer diameter D_T = 130 mm to the head 10mm in diameter, a significant diversification of a motion track for points being analysed was observed.

Due to the action of a velocity gradient the particle is subjected to tension resulting from the diversification of motion trajectories. This gradient stretchs the polymer chains, and thus sets the polymer structure in order, which in consequence affects the functional properties of melts (Rydzkowski and Michalska-Pożoga, 2004; Michalska-Pożoga, 2006; Michalska-Pożoga and Rydzkowski, 2007; Michalska-Pożoga and Rydzkowski, 2008; Michalska-Pożoga and Jakubowski, 2012).

3.3. Experimental investigations

Attempts were made to confirm experimentally the above conclusions with regard to the form of melt motion trajectories. In case of a classical plasticising system the process of extrusion is stopped, and the plasticising system with melt inside is precooled until the melt temperature below the softening point is obtained. Then, the cylinder of a plasticising system is quickly preheated above the temperature of the melt plasticising. The melt situated in the close vicinity of the cylinder is passing into the plastic state and the screw with a layer of still solidified melt is possible to be removed (Tadmor and Klein, 1970; Wilczyński et al., 2009). These types of investigations were also conducted at the Koszalin University of Technology (Radomski, 2005).

A frontal chink situated between two conical surfaces i.e. a face of the screw and a cylinder cover provide an interesting point of a screw-disk plasticising system. The melt situated in the space confined by these elements is in the plasticised form. Therefore it is possible, like in case of a classical system, to stop an extruder with a stuffed frontal chink, cool down the melt and remove the solidified melt from the chink.

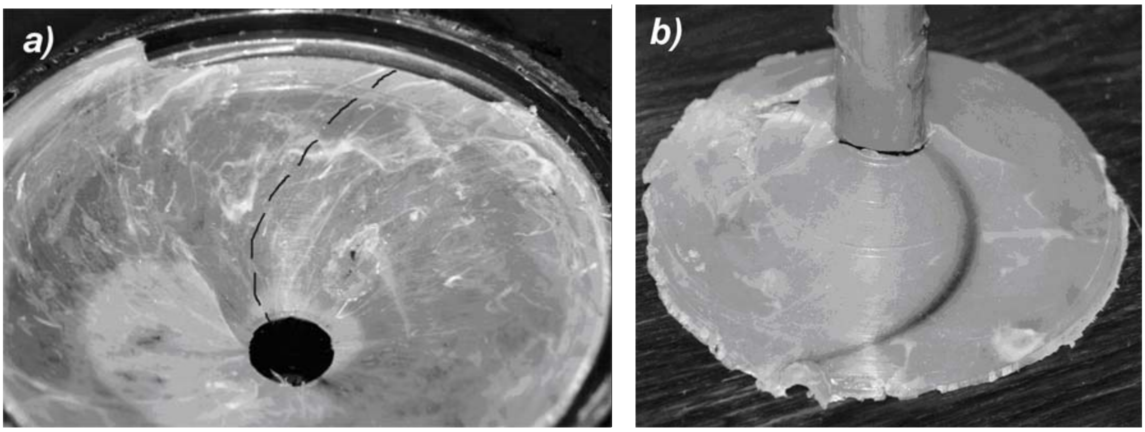

Fig. 14. Polymer disks: a) with a marked trajectory of melt motion; b) with a visible trajectory of melt motion (original figure published in Rydzkowski and Michalska-Pożoga, 2009)

During the experimental investigations in order to reveal melt particles motion trajectories, the original transparent PE-LD was plasticised with the addition of 20% marker – the mixture of yellow, blue and red PE-HD recycled stock (Figs. 14a and b). Samples (conical disks) showing a “frozen” melt during the motion in the space between the rotational screw disk and the immovable surface of the cylinder cover obtained in the process are the basis of the present investigations. The marker is visible in the form of spiral strips showing motion trajectories. Depending on the parameters of the extrusion process, samples with visible spirals showing different curvature and consolidation of melt particles trajectories were obtained. For the rotational speed of about 5 rpm and the extrusion capacity equal to 4.7 kg/h a slightly curved line presented in Fig. 9b was obtained. The experimental results are in good agreement with the numerical simulations carried out earlier and are presented in the Figs. 7b and 10a.

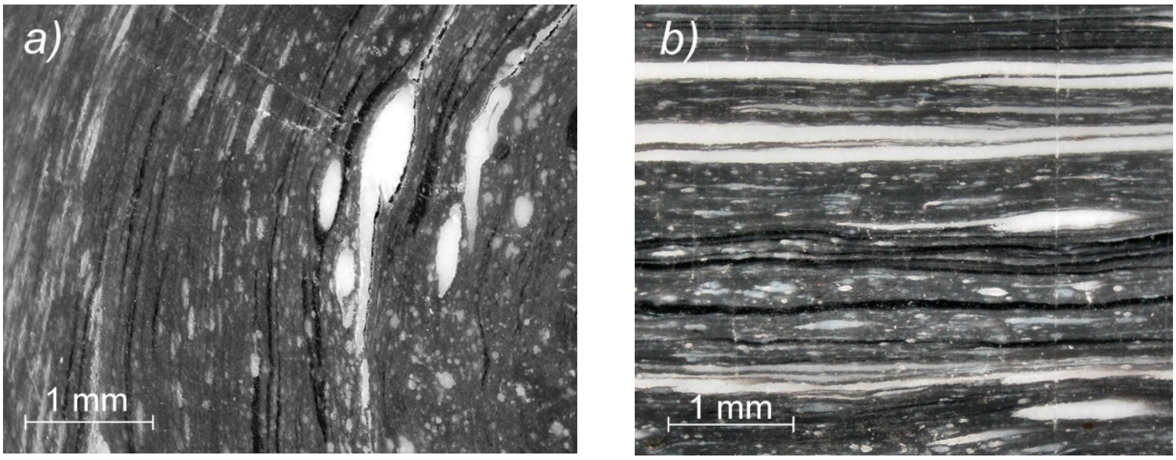

Fig. 15. Sections of extrudate obtained from mixture of polyolefins and polystyrene as a result of extrusion by W_s = 3.0 mm wide chink of the disk zone: a) cross-section, b) longitudinal section

Fig. 15 shows sections of extrudate obtained from mixtures of poliolefin recyclates. Thanks to its different colours it is possible to observe the macrostructure of extrudate. Many long and thin strips and elliptic or circular inclusions of component polymers are seen on the cross-section of the extrudate (Fig. 15a). These strips are displayed on the longitudinal section (Fig. 15b) as thin strips or long, thin areas. On the basis of the shape of the inclusions revealed in the cross- and longitudinal sections, it is possible to assume that some of them appear as thin layers while others as elliptic or circular long strings. The fact, that polymers in the melt during processing take such shapes may be evidence of an arranging influence of screw disc extrusion on the stretching of polymer chains.

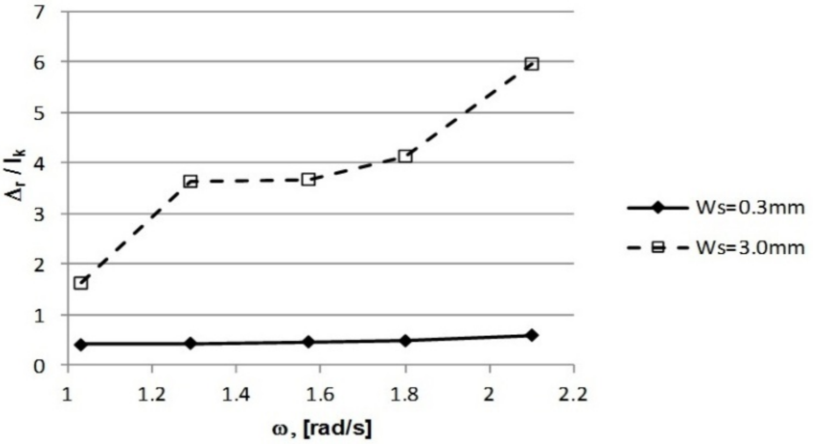

Fig. 16. The dependence of Δ_r/l_k on the angular velocity ω

Figure 16 shows a dependence of the relative elongation in the radial direction Δ_r/l_k on the angular velocity in two cases of the chink: W_s = 0.3 mm and W_s = 3.0 mm. For W_s = 3.0 mm chink, the level of ω exerts a noticeable impact on relative elongation in the radial direction Δ_r/l_k causing its growth, while in the case of W_s = 3.0 mm chink ω increase does not affect relative elongation.

However, in Fig. 17 it was noticed that an increase in the angular velocity ω results in the same increase of relative elongation in the circumferential direction Δ_{obw}/l_k for both the chink W_s = 0.3 mm and W_s = 3.0 mm. The data values in the graph overlap.

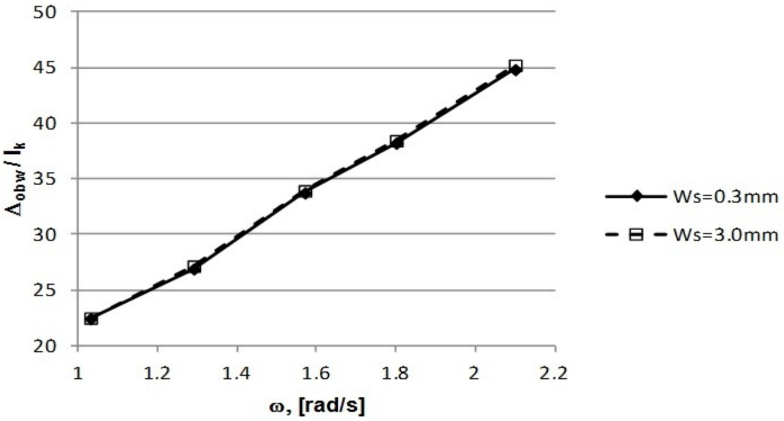

Fig. 17. The dependence of Δ_{obw}/l_k on the angular velocity ω

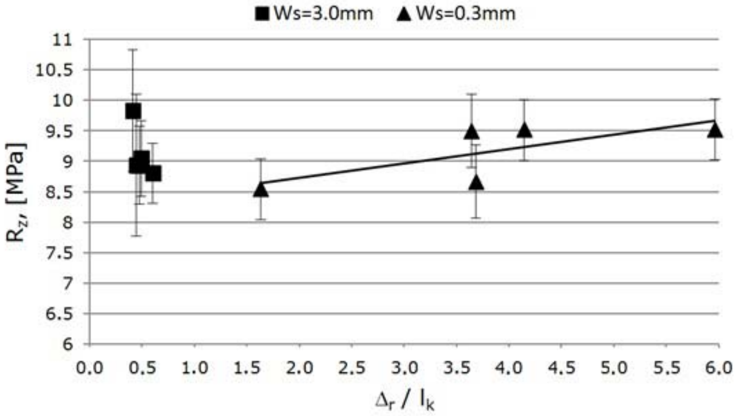

Fig. 18. Dependence of the breaking stress of tensile strain in the radial direction Δ_r/l_k for W_s = 0.3mm and W_s = 3.0 mm

Analysing the impact of the degree of ordering in the radial direction Δ_r/l_k on tensile strength for W_s = 0.3 mm (Fig. 18) the tensile strain continues to rise and is several times larger than that for the chink W_s = 3.0 mm. In the case of W_s = 3.0 mm chink a small variation of elongation was observed in the radial direction and which could hardly be taken for a clear trend. The obtained values indicate that a higher degree of ordering increases the strength of the polymeric material.

However, considering the impact of the degree of ordering in the circumferential direction on the value of the tensile strength shown in Fig. 19, it is noted that if chink equals W_s = 0.3 mm with the growth of a value of Δ_c/l_k strength value continues to rise, while for the W_s = 3.0 mm chink, an increase in the value of Δ_c/l_k the strength value is declining. Differentiation of the nature of the trend line may result from the apparent effect of shear stress. It follows from the discussion that the degree of ordering can affect not only the value of the elongation of the polymer chains (degree of ordering), but also the conditions under which the extrusion process is carried out. Therefore, shear stress differs considerably in the chinks W_s = 0.3 mm and W_s = 3.0 mm. It follows then that the value of the total elongation has the greatest impact on the circumferential component of extension.

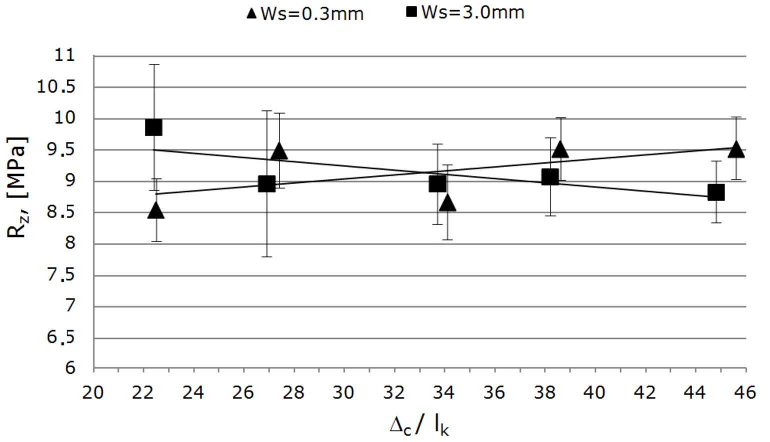

Fig. 19. Dependence of the breaking stress on the overall relative elongation Δ_c/l_k for chinks $W_s = 0.3$ mm and $W_s = 3.0$ mm

Analysing Fig. 20 which shows the effect of the degree of ordering on the elongation at break it was observed that with the increase of the degree of ordering in the radial direction Δ_r/l_k for chink $W_s = 0.3$ mm elongation at break was declining. However, for $W_s = 3.0$ mm chink a small variation of elongation in the radial direction was observed.

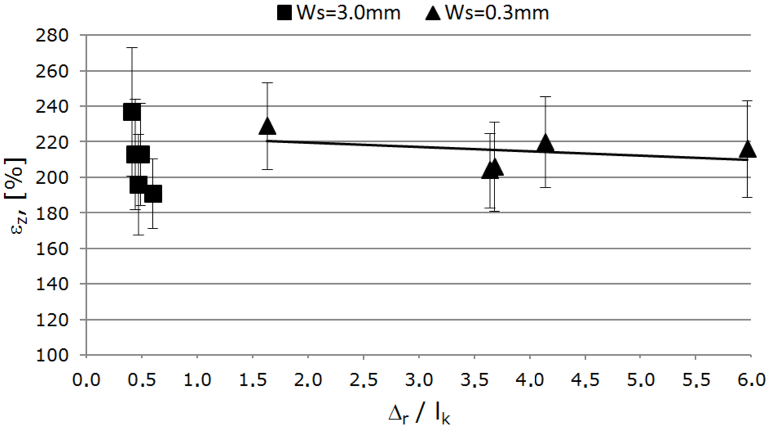

Fig. 20. Dependence of the relative extension at break on elongation in the radial direction Δ_r/l_k

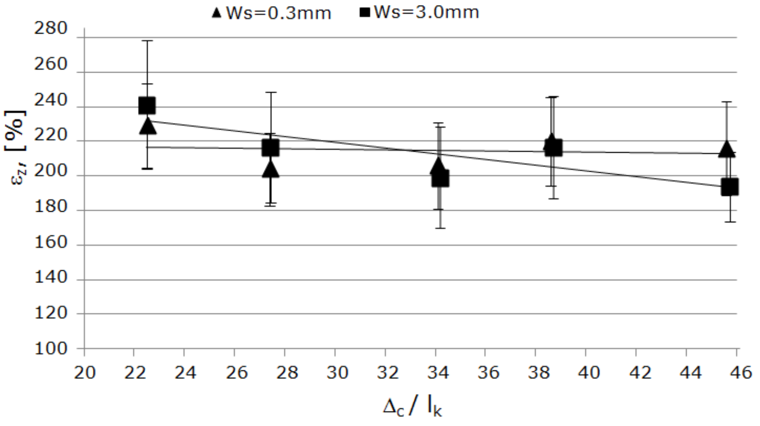

Fig. 21. Dependence of relative extension at break on the degree of ordering of the total $\Delta c/l_k$ for chinks $W_s = 0.3$ mm and $W_s = 3.0$ mm

A relative dependence of tensile extension on the total degree of ordering Δ_c/l_k is presented in Fig. 21. It can be noted that extrusion with the small chink $W_s = 0.3$ mm gives stable results, while with the chink $W_s = 3.0$ mm a clear trend of decreasing elongation at break test can be observed. Regardless of the chink width it was noticed that a higher degree of polymer chains ordering reduces the value of elongation at break.

It is natural that the higher is the strength of the material the more rigid it becomes, which ultimately leads to reduced elongation at fracture. It would be useful to obtain a material with a maximum value R_z (high resistance), and ε_z (very flexible). Such characteristics were achieved for a sample obtained from the chink $W_s = 3.0$ mm, the peripheral speed **v** = 0.06 m/s and low ordering ratio $\Delta_{obw}/l_k = 22.43$. With such process conditions the resulting material is characterised by the highest value of tensile strength ($R_z = 9.84$ MPa) and the highest value of relative extension at break ($\varepsilon_z = 237\%$). Similarly, samples characterised by the preferred features are obtained by the chink $W_s = 0.3$ mm, the peripheral speed **v** = 0.13 m/s and the large complete ordering $\Delta_c/l_k = 45.6$.

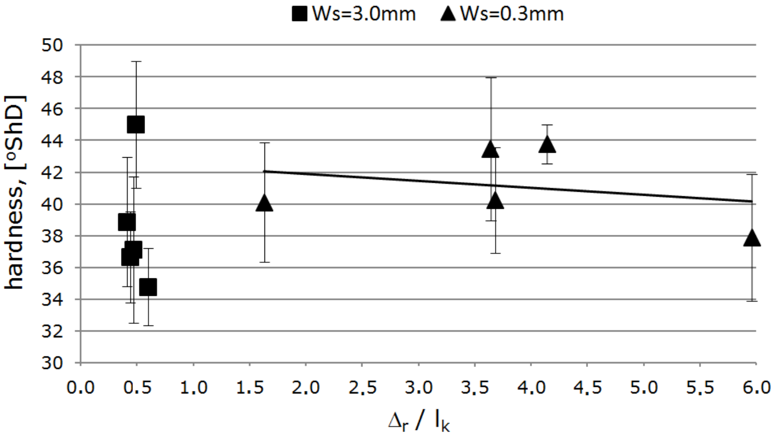

Fig. 22. The dependence of the hardness on relative elongation in the radial direction Δ_r/l_k

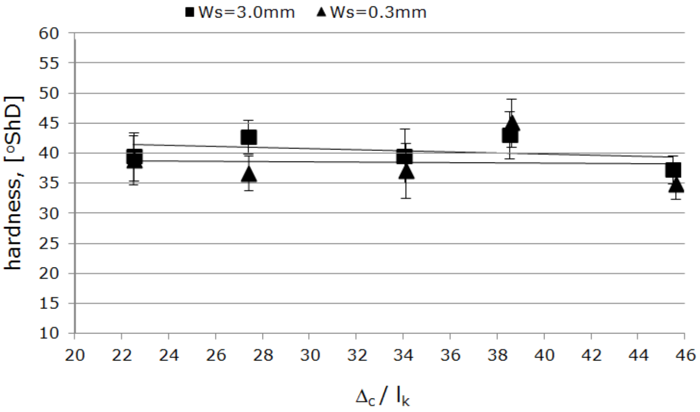

Fig. 23. Dependence of hardness of elongation in the circumferential direction Δ_{obw}/l_k for chinks $W_s = 0.3$ mm and $W_s = 3.0$ mm

This material has high tensile strength ($R_z = 9.53$ MPa) and a high value of elongation at break at $\varepsilon_z = 216\%$. Further analysis of the results showed that there were also samples with unfavorable characteristics. These samples were obtained at large chink $W_s = 3.0$ mm, the peripheral speed **v** = 0.1 m/s and with a high degree of ordering in the circumferential direction at $\Delta_{obw}/l_k = 33.73$. This material has low tensile strength ($R_z = 8.94$ M Pa) and a low value of elongation at break ($\varepsilon_z = 196\%$).

Analysing Fig. 22 it can be noted that the value of hardness, for chink value of $W_s = 0.3$ mm tends to decrease with the increasing degree of ordering in the radial direction Δ_r/l_k. The degree of ordering of polymer chains in the peripheral direction slightly affects hardness values (Fig. 23).

The nature of hardness regardless of the relative elongation Δ_c/l_k was the same as the circumferential extension Δ_{obw}/l_k. Samples extruded with a large chink $W_s = 3.0$ mm and an average degree of ordering of at $\Delta_{obw}/l_k = 38.2$ had high hardness (43.77°ShD). Samples obtained from the chink $W_s = 3.0$ mm and high ordering in the circumferential direction ($\Delta_{obw}/l_k = 44.81$) are characterised by an average value of hardness, which amounted to 37.88°ShD. However, the minimum hardness (34.77°ShD) was measured for samples extruded at chink $W_s = 0.3$ mm, with the highest degree of ordering ($\Delta_{obw}/l_k = 45.2$). The properties of the extrudate were affected not only by the size of the extended polymer size (degree of ordering) but also the shear stress, τ. The reason for chink diversity effect is the fact that a small value of chinks does cause large shear stress, while a large chink value results in smaller shear stress. High shear stress can induce growth of the actual degree of ordering of polymer chains, but also causes mechanical degradation.

For extrusion with a small chink $W_s = 0.3$ mm the shear rates $\dot{\gamma}$ in range of 450−910 s^{-1} is obtained. In this case, shear stress $\tau_{0.3}$ is calculated in the range from 0.185MPa to 0.227 MPa. However, for extrusion at a high chink $W_s = 3.0$ mm the shear rate $\dot{\gamma}$ in range of 45−91 s^{-1} is obtained. In such a case shear stress $\tau_{3.0}$ is calculated in the range from 0.086 MPa to 0.109 MPa. As we can see there is a wide variation of shear rate and stress. Shear stress for chink $W_s = 3.0$ mm is similar to that taking place in a screw extruder, and for the chink $W_s = 0.3$ mm it is comparable to that in a co-rotating twin-screw extruder.

The analyses confirm the convergence of obtained melt trajectories with extrudate supermolecular structure, visible in the form of bands and ropes on longitudinal and cross sections. The results also confirmed the effect of stretching on mechanical properties of extrudate. The above results prove the correctness of analysis and conclusions presented by Diakun and Michalska (Diakun and Michalska, 2004). Those conclusion assume the occurrence of a stretching effect on a polymer molecular chain during its residence in the disc zone of a screw-disk extruder.

4. CONCLUSIONS

- The motion of the melt in a disk zone of an extruder is a superposition of pressure and dragged streams. Trajectories of melt particles in a conical chink form spirals and depend on the extrusion capacity as well as the position of particles along the width of a chink.
- Velocity gradient transfers the ends of polymer chains along different trajectories.
- It was found from the analysis of calculation results that velocity gradient may cause the conformation length to be extended from a few to several dozen times.
- Particle trajectories in a disk zone of a screw-disk extruder obtained from simulation (Figs 7a, 10b and 13) in the form of complete spirals are difficult to be produced under conditions of real extrusion (Fig. 14).
- The presence of long, thin strips of components in the extrudate (obtained from a mixture of polyolefins) is a macroscopic confirmation of an impact of the existing conditions in the extruder disc zone on arranging the structure of polymer chains.
- The dimension of the circular chink of the disc zone can significantly affect shear stress.
- Large values of shear stress cause stretching of polymer molecular chains that organize the material structure.

- It was observed that the tested material achieves high values of mechanical properties by extrusion at small dimensions of the chink.
- Arranging the structures of polymer chains may exert an influence on the supermolecular structure and the functional properties of melts.

SYMBOLS

D	screw diameter, mm
L	working length of a screw, mm
o	peripheral direction
$\dot{W}$	efficiency/ flow rate, kg/h
x	axial direction
d	circumferential direction, mm
X	polymer material flow direction
k	consistency ratio, $\mathrm{Pa \cdot s^n}$
n	flow exponent
D_T	disk diameter, mm
w_{rx}	pressure stream velocity vector, m/s
w_{ox}	dragged stream velocity vector, m/s
w_o	velocity in the circumferential direction vector, m/s
W_s	width of a chink, mm
R_T	disk radius, mm
r_0	outlet radius, mm
l_k	conformative length of a macromolecule, nm
R_z	breaking stress, MPa
r	radial direction, mm
v	peripheral speed, m/s
Re	Reynolds number
M	molecular weight, g/mol
PE-LD	low density polyethylene
PE-HD	high density polyethylene

Greek symbols

α	cone angle of the disc, °
$\dot{\gamma}$	shear rate, $\mathrm{s^{-1}}$
Δ_r/l_k	the relative elongation in the radial direction relative to the conformational length
Δ_c/l_k	relative elongation in relation to the conformational length
Δ_{obw}/l_k	the relative elongation in the circumferential direction relative to the conformational length
Δ_r	macromolecules elongation in the radial direction, nm
Δ_c	total elongation of macromolecules, nm
Δ_{obw}	macromolecules elongation in the circumferential direction, nm
ε_z	unit elongation at rupture, %
ω	angular velocity, rad/s

REFERENCES

Diakun J., 1997. Experimental, autothermal screw-disk extruder as a result of optimisation and simulative calculations. *8th Seminar on Plastics in Machine Design.* Cracow, 2-4 October 1997, 75–81.

Diakun J., 2002. The way of microcomponent distribution in the worm and disk system of a screw-extruder. *Inż. Ap. Chem.*, 41, 45–46.

Diakun J., Michalska I., 2004. Simulation of polyethylene macromolecules shifting in a disc zone of an extruder. *Polimery*, 49, 42–48.

Macko M., 2013. Economic-energetic analysis of multi edge comminution of polymer recyclates. *Przem. Chem.*, 92, 8, 1499–1502.

Michalska-Pożoga I. 2006. *Influence of a plasticizing mechanism of a screw-disk extruder on mechanical properties of extrudate*. PhD thesis, Koszalin University of Technology, Koszalin, Poland.

Michalska – Pożoga I., Rydzkowski T., 2008. Estimation of mechanical properties of PP obtained by screw and screw-disc extrusion, In: Koszkul J., Bociaga E. (Eds), *Polymers materials and processing*. Czestochowa University of Technology, Częstochowa, 125-131.

Michalska – Pożoga I., Rydzkowski T., 2007. Selected rheological and mechanical properties of PE recyclate mixture with different concentration of original LD – PE obtained by screw-disk extrusion. *7th International conference Advances in Plastics Technology*, Katowice, Poland.

Michalska-Pożoga I., Jakubowski M., 2012. Use of the computational fluid dynamics in a numerical analysis of molecular motion and polymer material pattern of flow in screw-disk extruder zone. *Przem. Chem.* 91, 9, 1808–1812.

Radomski G., 2005. Comparison of homogenization of polymers during the extrusion in screw extruder or screw-disk extruder. *Polimery*, 50, 374–378.

Rydzkowski T., Radomski G., 2008. Mixing ratios obtained using screw-disk-type and screw extruders; selected properties of reglanulate and the original material mixtures. *Plast. Rubber Compos.: Macromol. Eng.*, 37(8), 376–380. DOI: 10.1179/174328908X356473.

Rydzkowski T., 2006. The influence of screw – disc extrusion on LD-PE properties. *Europa/Africa Meeting of the Polymer Processing Society*. Pretoria, South Africa.

Rydzkowski T., Michalska – Pożoga I., 2004. The properties change of LDPE in result of multiple extrusion on the basis of DSC investigations. In: Koszkul J., Bociaga E. (Eds), *Polymers materials and processing*. Częstochowa University of Technology, Częstochowa, 259–264.

Rydzkowski T., Michalska-Pożoga I., 2009. The movement trajectories of particles of material in disc zone of screw-disc type extruder. *Technical transaction: Mechanika 3*, Cracow University of Technology, 273–279.

Rydzkowski T., 2012. *Theoretical and experimental basis of effective screw-disc extrusion in recycling of polymeric materials and composites*. Wydawnictwo Uczelniane Politechniki Koszalińskiej, Koszalin.

Sikora R., 1993. *Macromolecular materials processing*. Wydawnictwo Edukacyjne, Warszawa, 13–21; 146–158.

Tadmor Z. and Klein I., 1970. *Engineering principles of plasticating extrusion*. Van Nostrand Reinhold Book Co., New York.

Wilczyński K., Lewandowski A., Wilczyński J. K., 2009. Melting in polymer processing. *Technical Transactions. Mechanics 3*, 381–385 (in Polish).

Received 11 March 2013
Received in revised form 02 February 2014
Accepted 13 February 2014