

The influence of the disc zone of a screw-disc extruder on the structure and properties of low-density polyethylene (PE-LD) extrudate

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Abstract: The article presents the results of analysis and research of the disc plasticizing mechanism operation on the mechanical, thermal, and structural properties of extruded material. The analysis of velocity distribution and trajectories of the material's displacement leads to a conclusion that the flow of polymer melt through the clearance between the discs arranges the supermolecular structure and in this way results in an extrudate with improved mechanical properties.

Keywords: screw-disc extruder, disc zone, arrangement of the polymer chains, crystallinity degree, low-density polyethylene (PE-LD).

Wpływ oddziaływania strefy tarczowej wylączarki ślimakowo-tarczowej na strukturę i właściwości wylóczyny z polietylenu małej gęstości (PE-LD)

Streszczenie: Przedstawiono wyniki badań i analizy wpływu oddziaływania tarczowego mechanizmu uplastyczniającego na właściwości wylóczanego tworzywa (rys. 1, 4). Na podstawie rozkładu prędkości i trajektorii ruchu tworzywa (rys. 2, 3) wnioskowano, że przepływ tworzywa polimerowego w szczelinie tarczowej (w stopniu zależnym od jej wymiaru, rys. 2) sprzyja porządkowaniu struktury nadcząsteczkowej (tabela 1, rys. 6, 7), dzięki czemu można otrzymać wylóczynę o właściwościach mechanicznych (tabela 2) lepszych niż uzyskane w wyniku wylóczania ślimakowego.

Słowa kluczowe: wylączarka ślimakowo-tarczowa, szczelina tarczowa, porządkowanie struktury, stopień krystaliczności, polietylen małej gęstości (PE-LD).

The main aim of this paper is to present the results and experimental data concerning polymers obtained from a mechanical process when using a disk zone of an innovative screw-disc extruder. We also study the influence of the extruder on the arrangement of the polymer chains, and therefore the structure, as well as the properties, of low density polyethylene (PE-LD) extrudate.

The construction parameters of a plasticizing system are selected according to the type of material used, its form, components and the needed form and properties of the final product. The most common plasticizing systems include screw systems. However, there have been some attempts to use disc mechanisms for plasticizing materials [1–11]. There is an extensive collection of literature concerning screw-type plasticizing mechanisms, as well as the nature of the production processes involved. However, the disc-type plasticizing mechanisms are not very popular and there are only a few publications describing

polymer processing involving disc-type extruders and the properties of the materials obtained in that way.

The authors have implemented an innovative experimental screw-disc extruder (Fig. 1) designed by engineers

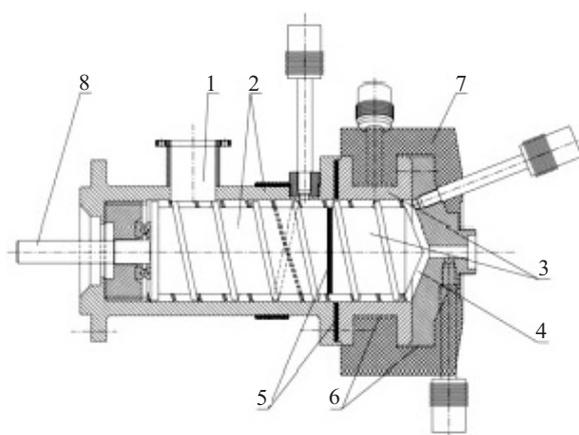


Fig. 1. Longitudinal section of plasticising system of screw-disc extruder: 1 – charging hopper, 2 – cold zone of screw and barrel, 3 – hot zone of screw and barrel, 4 – clearance between the discs, 5 – insulating separators, 6 – electric heaters, 7 – thermal insulator, 8 – drive shaft [15]

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from their department: the diameter of the screw-disc was $D = 130$ mm and the length of the screw was $L = 2D$ (screw working length $L = 260$ mm) [12–14]. The innovative extruder has a clearance between the movable face of the screw and the conical cover of the extruder. A very important feature of this device is the possibility to move the screw along its axis. As a consequence, the clearance between the discs may change from 0.1 to 6 mm, which affects the processing conditions in the disc zone of the extruder [15, 16]. The melt leaves the plasticizing system through an outlet, which is situated centrally on the axis of the screw. The rotational speed of the screw is adjustable from 12 to 40 rpm (circumferential speed $v = 0.1–15$ m/s).

MELT DISPLACEMENT IN THE DISC ZONE

The mechanism of the disc-type extruder contains: a rotational disc and a fixed casing with an extrusion outlet on the rotation axis of the disc (Fig. 2a). The displacement of melts due to Weissenberg's effect (accumulation of

large chains of polymer melt in the centre of the clearance between the discs) may possibly occur in the clearance between the discs.

The character of melt displacement in the clearance between the discs is the result of the superposition of two factors: pressure flux and drag flow. The pressure flux is formed by melt flowing from the outside diameter towards the centre, while the drag flow is the result of the motion of the disc in relation to the casing.

Taking into account the nature of forcing, the distribution of pressure flux velocity can be parabolic, but it is linear for a drag flow (Fig. 2b). These fluxes are perpendicular to each other and they create a displacement of the melt's particles in the clearance between the discs along spiral trajectories from the outside diameter towards the outlet (Fig. 3) [14, 16].

By comparing Fig. 3a and Fig. 3b, one can clearly observe that the trajectories of melt displacement are different, depending on the location in the clearance between the discs.

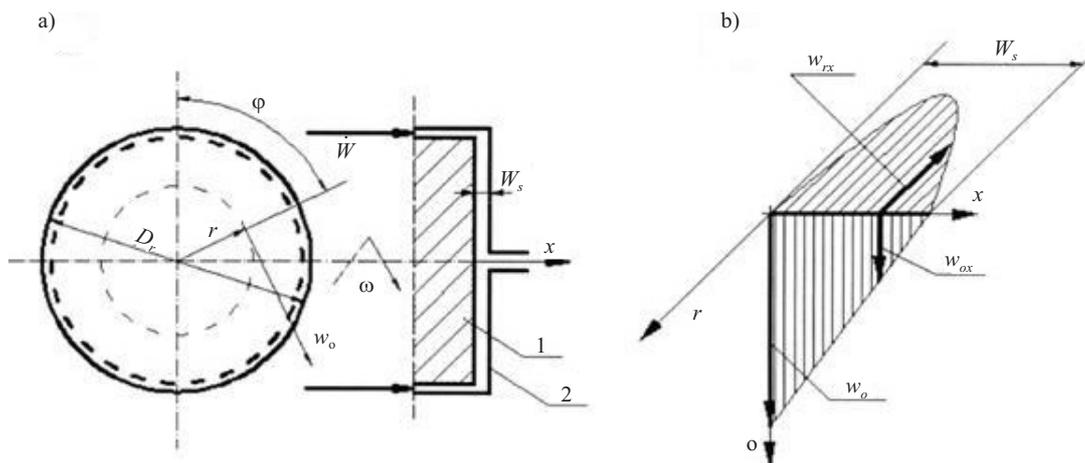


Fig. 2. Disc extruder: a) scheme, b) velocity distribution in the clearance between the discs; 1 – rotary disc, 2 – casing, w_{rx} – pressure stream rate, w_{ox} – dragged stream rate, o – peripheral direction, r – radial direction, W_s – width of the clearance between the discs, D_T – disc diameter, w_o – velocity in the circumferential direction, \dot{W} – efficiency [14, 16]

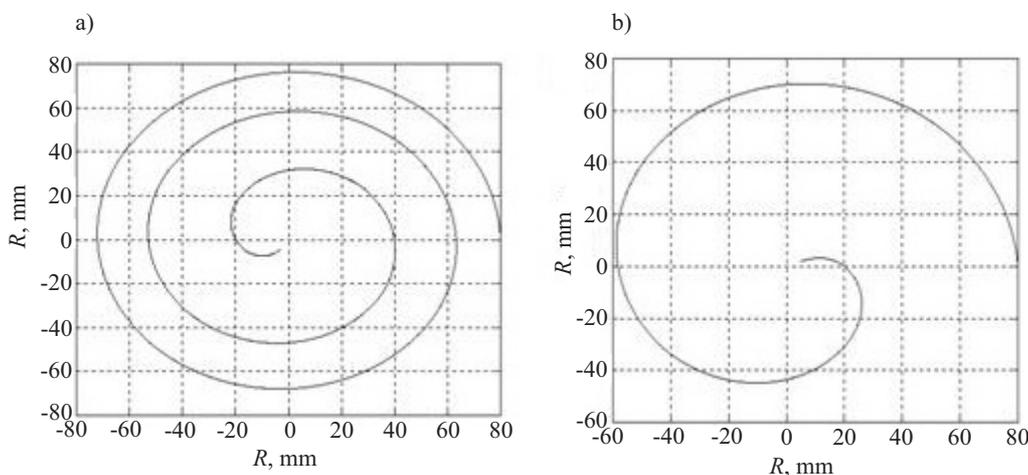


Fig. 3. The trajectories of a melt's motion in the clearance between the discs for different distances from the movable end face of the screw: a) $x = 0.2 \cdot W_s$, b) $x = 0.5 \cdot W_s$ [14]

SIMULATION OF POLYMER CHAIN CONFORMATION ARRANGING CONDITIONS IN THE CLEARANCE BETWEEN THE DISCS

The melt displacement in a flux with a velocity gradient affects the conformation of polymer chains. A velocity gradient stretches the naturally tangled polymer chains. Thus, the polymer chains will be subjected to a tension in the course of the flow. The result is an ordering of supermolecular structures. This is very beneficial because it allows the production of materials with a higher degree of supermolecular order, which increases its strength.

The authors have already presented in their papers a model simulating the conditions of polymer chain stretching [14–17]. Table 1 presents the values of distance between trajectories with respect to the conformational (Δ_M/l_K) and total length (Δ_M/l_C) of the PE polymer chain, and the values of distance between two points of the trajectories on an outlet diameter with respect to the conformational (Δ_E/l_K) and total length (Δ_E/l_C).

Table 1. Characteristic parameters of the distance between trajectories of point motion [14]

W_s mm	Parameters					
	Δ_M , nm	Δ_M/l_C	Δ_M/l_K	Δ_E , nm	Δ_E/l_C	Δ_E/l_K
3.0	51800	13.28	863.3	10300	2.64	171.6
0.3	9000	2.30	150	1800	0.46	30

Note: description in the text.

Initially, the distance between the points was expanded, reaching a maximum value Δ_M in the middle of the disc diameter. During further melt flow, the distance between the analysed trajectories was reduced and for the diameter comparable with the outlet diameter it was equal to Δ_E . If a polymer melt flows in a clearance between the discs, the particles of the melt are subjected to a tension (uncoiling the tangled polymer chain conformation), and then are recoiled in an area of a smaller diame-

ter. This second stage — the recoiling of the polymer chains in an extruder clearance between the discs — is revealed as Weissenberg's effect [14].

In the initial position (on the outer diameter of a disc), the distance between the initial points of a trajectory corresponds to the conformational length of the PE polymer chain. The larger the distance between trajectories, the more the tangled polymer chain is subjected to uncoiling. This happens because the distance between trajectories is several times larger than the dimension of a polymer particle. This effect is more evident when the value of the clearance between the discs is larger. When an extruder operates at a clearance between the discs equal to $W_s = 3.0$ mm, the distance between the points on the trajectories at the maximum point (Δ_M) can increase 13 times compared to the total length l_C (column 3 of Table 1), and at the outlet — Δ_E — it increases about 3 times compared to the total length l_C (column 6 of Table 1). This is evidence of the disc's intensive interaction leading to the uncoiling of the polymer chain during its displacement in the disc zone [14].

The melt particles in the extruder's disc zone are transferred along the ordered spiral trajectories. Due to the nature of the melt flow in a clearance between the discs, the existing tension leads to recoiling of polymer chains and their mutual arrangement. The stronger tension results in the occurrence of a higher degree of arrangement. It can be assumed that such an interaction should lead to the increased crystallinity, strength and impact hardness of the extrudate [14, 18–21].

EXPERIMENTAL PART

Materials

During the experiments, we used a low-density polyethylene (PE-LD, FABS-23D022, Malen E) purchased from Basell Orlen Polyolefins Sp. z. o.o., Poland, with a melt flow rate (MFR) of 2 g/10 min, determined according to the PN-EN ISO 1872-2:2008 standard, density of 0.922 g/cm³ (PN-EN ISO 1872-2:2008), breaking stress (σ) of 14 MPa, according to PN-EN ISO 1872-2:2008 stan-

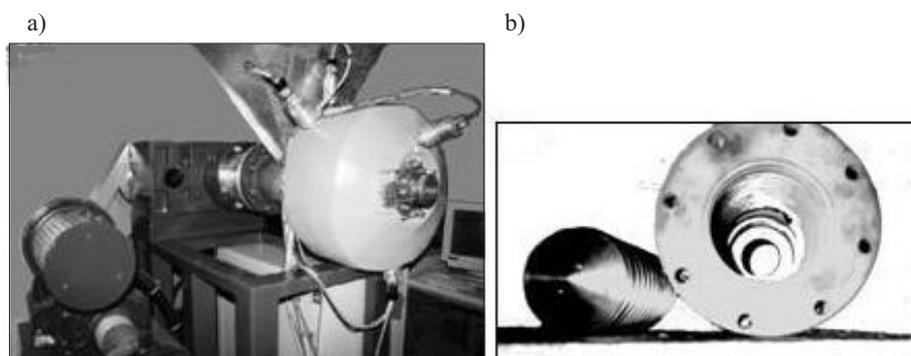


Fig. 4. Test stand: a) pilot screw-disc extruder, b) screw and barrel screw-disc extruder [15]

dard, unit elongation at rupture (ε_z) of 600 %, according to PN-EN ISO 1872-2:2008 standard and viscosity about 300 Pa·s, according to PN-EN ISO 12058-1:2003 standard.

Sample preparation

The process of extrusion was performed using the screw-disc extruder constructed in the Department of Food and Polymer Engineering, Koszalin University of Technology (Figs. 1, 4).

The screw-disc extruder with a screw diameter of $D = 130$ mm and a screw length of $L = 2D$ as operated at a screw rotational speed of 15 rpm (1.57 rad/s). The process of extrusion was performed at the temperature of the hot zone $T = 225$ °C and two dimensions of the clearance between the discs: $W_s = 0.3$ mm and $W_s = 3.0$ mm.

Methods of testing

Mechanical properties test

During the experiment, the following tests of the mechanical properties of PE-LD extrudate were made: verification of strength characteristics at static tensile testing [breaking stress σ (MPa), unit elongation at rupture ε_z (%)], impact resistance a_k (kJ/m²) and hardness examination h (°ShD).

– The determination of tensile properties was performed in compliance with standard PN-EN ISO 527-1, -2:1998. Strength characteristics were obtained using a MONSANTO universal tensile testing machine (Tensometer Type W) manufactured by Monsanto Tensometer in the UK.

The following parameters at the axial tension were applied:

- tensioning speed $v = 50$ mm/min ± 10 %
- range of measured force 2500 N.

The testing was performed at a constant ambient temperature of *ca.* 19 °C on a total number of 165 test samples.

– The impact Charpy tests were carried out according to the PN-EN ISO 179:2001 standard. Impact-test specimens were round shaped with a rectangular notch of 4 mm in depth. The specimens were cooled down for 24 h at the temperature of 3 °C. A PWS 30 type Charpy pendulum machine, manufactured by VEB Werkstoffprüfmaschine (Germany) was used to perform the impact tests. The operating range of the pendulum machine was from 0 to (150 \pm 1) J; the spacing of the supports was 40 mm. The total number of test specimens included 150 pieces.

– The hardness was examined using a ShoreD manual hardness tester with a passive pointer manufactured by Zwick Roell GmbH & Co (Germany). The measuring range of the tester was (10–100 \pm 0.99) °ShD. The load conforming to the standard for this method was (50 \pm 0.5) N. A test sample was a disc of thickness of 6 mm cut from the extruded rod. The excised samples, in order to

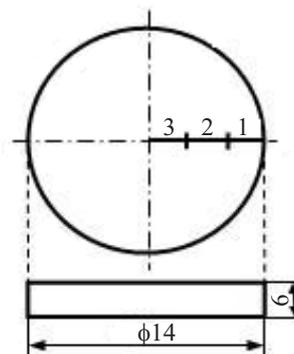


Fig. 5. The sample to determine the hardness

obtain smooth, parallel surfaces, were subjected to grinding. For each sample, three measurements were made in three areas of the sample according to the diagram shown in Fig. 5.

The hardness tests were performed according to the PN-EN ISO 868:2004 standard.

In total, 45 specimens were prepared for the tests and 135 measurements were completed.

Differential scanning calorimetry

The degree of crystallinity [X_c (%)] was examined using a differential scanning calorimeter of DSC 822 Star type, manufactured by Mettler Toledo (Switzerland). The operational temperature range of this device was (20–500 \pm 0.2) °C.

To perform the implemented tests, a specimen was placed in an aluminium crucible, 40 · 10⁻³ cm³, with a pin. The specimen mass was determined using XS 105 analytical weighing scales with an accuracy of 0.01 g manufactured by Mettler Toledo. The tests were carried out according to the following temperature program:

- process temperature in the range of 20 to 180 °C,
- heating rate: $\beta = 5$ °C/min

The test samples were discs of thickness of 1.5 mm cut from the extruded rod. Samples for DSC were taken from the discs in accordance with the diagram shown in Fig. 5. A sample of material, weighing approximately 10 mg, was placed in the aluminum crucible.

The test was carried out according to the PN-EN ISO 11357:2009. The temperature and heat flow scales were calibrated using the melting of high-purity indium and zinc samples before testing.

Morphology observation

The morphology of the polymer was characterized by scanning electron microscopy (SEM). The samples were fractured cryogenically and then sputtered with gold. Then, the fractured samples were observed on an JSM 5500 LV type Jeol scanning electron microscope. The process of sputtering was performed in vacuum at a pressure of 1 mPa.

RESULTS AND DISCUSSION

The results presented in Table 2 show that, by changing the width of the clearance between the discs from smaller ($W_s = 0.3$ mm) to larger ($W_s = 3.0$ mm) distances, different polymer properties can be obtained.

Table 2. The influence of a screw-disc extruder's clearance between the discs on the properties of PE-LD extrudate

W_s mm	Parameters									
	σ MPa	S -	ε_z %	S -	a_k kJ/m ²	S -	h °ShD	S -	X_C %	S -
0.3	8.67	0.76	206	26.3	215.4	21.3	43.4	5.3	45.9	2.0
3.0	9.84	0.84	237	36.1	514.3	69.1	40.1	4.0	45.7	2.8

Note: σ – breaking stress, ε_z – unit elongation at rupture, a_k – impact resistance, h – hardness, X_C – crystallinity degree, S – standard deviation.

The difference in properties arises from the impact of high shear stress (when the clearance between the discs amounts $W_s = 0.3$ mm) or low shear stress, (when the clearance between the discs amounts $W_s = 3.0$ mm). When shear stresses are low, the obtained material is characterized by good homogeneity, which is especially important for the extrusion of recycled materials and mixtures. Low shear stress makes little impact on the processed material, thus avoiding the mechanical degradation of the material.

High shear stress leads to mechanical degradation of the processed material. This may provide a confirmation of expected interaction of the disc zone, namely arranging the supermolecular structure of plasticized polymer. There is a correlation between the dimension of the clearance and the extrudate's mechanical parameters.

The higher values of the strength ($\sigma = 9.84$ MPa), ultimate elongation ($\varepsilon_z = 237$ %) and the impact resistance ($a_k = 514.3$ kJ/m²) were obtained when the larger clearance was set between the discs ($W_s = 3.0$ mm). It is worth mentioning that the improvement in strength and impact resistance appeared simultaneously. However, the classical correlation, where an increase in strength corresponds to a decrease of impact resistance, was not obtained.

During the extrusion with a larger clearance between the discs ($W_s = 3.0$ mm), the supermolecular structure was arranged. That brought an expected outcome: a simultaneous increase in strength and impact resistance. The values of these parameters were significantly greater than for the extrusion with a smaller clearance between the discs ($W_s = 0.3$ mm).

In the case of a wider clearance between the discs, the melt resided in the separation zone for a longer time. Polymer chains stayed longer in the field of shear stress and were subjected to a larger velocity gradient. Figure 6 shows the change in the nature of the peripheral move-

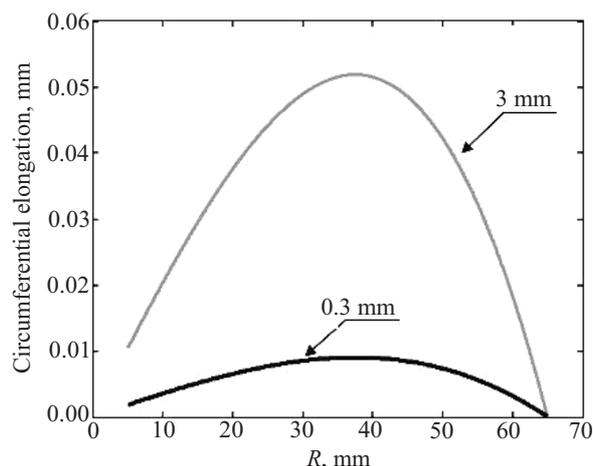


Fig. 6. The difference between the circumferential elongation (Δ_{obw}) on the radius of the disc for different values of the clearance between the discs (W_s)

ments on the radius of the disc for different values of the disc-zone clearance between the discs (W_s). It can be stated that the flow of material from the outer diameter to the center of the shield (decrease of R_T), up to a certain value of the disc diameter, induces an increase of Δ_{obw} and, past that value, further reduction of R_T results in a decrease of Δ_{obw} . This is due to the fact that despite the increase in the angular difference of the trajectory, for a small radius, the R_T circumferential elongation decreases, aiming to zero (in the center of the disc $R_T = 0$). Relating this to act on the polymer chain, it can be concluded that up to a point subjected to a development, and

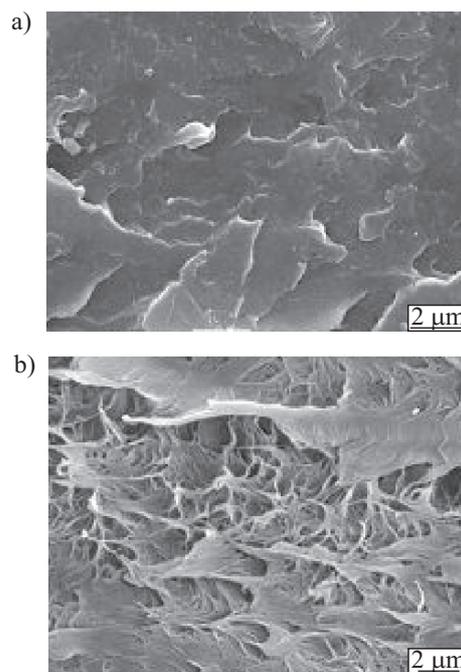


Fig. 7. The fracture's structure of an extrudate sample obtained from a screw-disc extrusion with the following size of clearance between the discs: a) $W_s = 0.3$ mm, b) $W_s = 3.0$ mm

then, by approaching the edges of the outlet opening (decreasing particle distance from the edge of the outlet channel) occurs again curled. The postulated phenomenon is consistent with the Weissenberg effect.

The influence of the clearance dimensions on the melt structure is illustrated in the fracture photographs taken by scanning microscopy (Fig. 7). The picture of the extrudate, obtained with a small clearance between the discs (Fig. 7a), shows that its fracture is fragile. The higher crystallinity is demonstrated by larger fragments of a crystalline phase, not bonded crystallites. The fracture shown in the Fig. 7b proves that an increased crystallinity is accompanied by a ductile fracture, which demonstrates the interconnection of crystalline domains and is a reason for the better mechanical properties.

The samples obtained in a screw-disc extrusion reveals much lower strength than those specified by the manufacturer in the material characteristic charts. This means that the potential properties of the melt have not been fully utilized in the process of extrusion. The course according to Fig. 6 that, the disc zone has a positive impact on the melt's supermolecular structure arranging process only to a certain value of the disc diameter (D_T). In the area of smaller disc zone's diameters takes place another recoiling of polymer chains, disrupting the positive effects obtained in the area with large disc diameters. The authors have developed an idea how to solve that problem and they have applied for a patent.

CONCLUSIONS

The nature of the melt particle displacement in the disc zone of a screw-disc extruder may bring about the uncoiling of polymer chains and arranging of their mutual locations, which should improve the strength properties of extrudate.

By extrusion using an experimental screw-disc extruder, the effect of the disc zone was confirmed. The effect leads to an increase in crystallinity of extrudate and possibility of increasing both its strength and impact resistance.

Strength tests and microstructure studies show that the polymer's structure arrangement level has an influence on the properties of the material. It has been observed that the influence change depending on the value of the clearance between the discs applied during the process. This is due to the shear stress and recoiling of the polymer chains. The small clearance between the discs causes a high shear stress and high recoiling of the polymer chains, while the large clearance between the discs creates low values of shear stresses.

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