The effect of extrusion conditions for a screw-disk plasticizing system on the mechanical properties of wood-polymer composites (WPC)

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Abstract: The article presents the results of research on the impact of the disk zone conditions on the mechanical properties of wood-polymer composites. The influence of three process parameters were varied: the width of the chink of disc zone (W_s), screw speed of the screw (n) and mass participation of wood fraction ($i \leq 70$ wt %). The results showed that the proper selection of conditions in the screw-disk extruder plasticizing system allowed the production of a material with better qualities.

Keywords: screw-disk extruder, wood-polymer composites, WPC, mechanical properties.

Wpływ warunków wytłaczania w ślimakowo-tarczowym układzie uplastyczniającym na właściwości mechaniczne kompozytów polimerowo-drzewnych (WPC)

Streszczenie: Zbadano wpływ oddziaływania uplastyczniającego mechanizmu tarczowego na właściwości mechaniczne kompozytów polimerowo-drzewnych (WPC). Oceniono wpływ trzech parametrów, tj. szerokości szczeliny strefy tarczowej (W_s), prędkości obrotowej ślimaka (n) i masowego udziału frakcji drzewnej ($i \leq 70$ % mas.) na właściwości wytworzonych kompozytów. Analiza wyników wykazała, że odpowiedni dobór warunków w układzie uplastyczniającym wytłaczarki ślimakowo-tarczowej pozwala na uzyskanie materiału o lepszej jakości.

Słowa kluczowe: wytłaczarka ślimakowo-tarczowa, kompozyty polimerowo-drzewne, WPC, właściwości mechaniczne.

The annual world production of wood polymer composites (WPC) is above 1.5 million tons (according to the German Nova-Institut GmbH). In Europe, the widest application of WPC was found to be as external floor elements (*e.g.* decking boards), elements of small park and garden architectures, interiors of vehicles, furniture and other consumer goods. In Asia, WPCs are used to make doorjambs, window frames and claddings [1, 2]. An increased interest in WPC products may result from the following reasons [3, 4]:

— the need to protect the environment, less consumption of polymer material (and thus their raw materials) associated with the use of wood filling, their partial biodegradability, the possibility of using post-production waste materials;

— beneficial features of ready-to-use products, favorable mechanical properties, lower water absorption and bulging, resistance to pests, no need for impregnation compared to typical wood products.

Wood polymer composites are most often produced based on polyolefin or poly(vinyl chloride) (PVC). Consequently, their manufacture employs well known methods of processing thermoplastic polymers, such as extrusion and injection [2, 5, 6]. The content of the filler in the wood polymer composites, depending on the degree of fragmentation, is in the range of 30 to 80 wt % [6—10]. The contribution of mass of the wood filler also depends on the wood material used for the warp and thus, in the case of PP, the content of the filler ranges between 20 to 40 wt %, for PE between 30 and 40 wt % and for PS 30 wt % [5, 11].

The wood fraction in WPC may play a pivotal role as a filler and, depending on the percentage contribution, also as a reinforcement. The analysis of literature reports allow us to conclude that the tensile strength and relative elongation at break, as well as impact resistance of composites, decrease with higher contributions of filler, regardless of the production method used [12—15]. To partially compensate for this effect and to improve the adhesion on the boundary line of filling-warp (reinforcing-warp), the applied filler is previously subjected to chemical modification [5, 6].

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The production of WPC in the extrusion process is related to a very time-consuming and expensive pretreatment prior to proper processing. The pretreatment, in a classic extrusion process, is based on: process of drying raw materials, mixing, homogenization in a pressure mixer or using a co-rotating twin screw extruder, followed by packaging (choice depending on the form after the process of homogenization) and re-drying prior to the proper processing [16].

To reduce the time of production of WPC, an attempt was made to eliminate several thermal pretreatment processes through the use of a screw-disk plasticizing system. Long-term studies of such a plasticizing system presented in research papers between 1990 to 2014 demonstrated the unique properties of screw-disk plasticizing systems and gave rise to the conclusions that there is a possibility to produce composites without some elements of the pretreatment [17—20]. Moreover, the production of high-filled composites without any need of prior chemical modification of the wood filler was attempted.

EXPERIMENTAL PART

Materials

Polypropylene — Malen HP456J — was purchased from Basell Orlen Polyolefins Sp. z o.o (Table 1).

Two types of wood fillers: conifer wood flour — Lignocel C 120 (size of particles 70—150 μm) (Fig.1a) and average chips of coniferous wood Lignocel 3-4 (size of particles 1500—4000 μm) (Fig.1b) were both purchased from Rettenmaier & Söhne GmbH+Co.KG and characterized by the granulometric distribution shown in Fig.1c. Evaluation of the granulometric distribution of the wood fraction was carried out by sieve analysis. Based on the obtained granulometric distribution, the equivalent diameter of the particles was calculated. Wood material was subjected to drying and extrusion at 105 °C ± 5 °C for 4 h before mixing. Determination of the particle size distribution was performed after drying the filler.

T a b l e 1. Characteristics of the matrix material (datasheet of Basell Orlen Polyolefins)

Parameters		Value
Melt flow rate (230 °C; 2.16 kg)	g/10 min	3.4
Tensile stress at break	MPa	23
Tensile strain at break	%	> 500
Tensile stress at yield	MPa	34
Flexural modulus	MPa	1400
Charpy unnotched impact strength	kJ/m^2	190
Charpy notched impact strength	kJ/m^2	4

Program and conditions of the study

The study program of extrusion was carried out according to the unsaturated (n > P), dynamic, five-level, rotatable experimental plan generated in the Experiment Planner 1.01 program. Based on the star and central experiences, the plan allows the determination of unknown coefficients from a mathematical model in the form of quadratic equations with interactions. The studies were

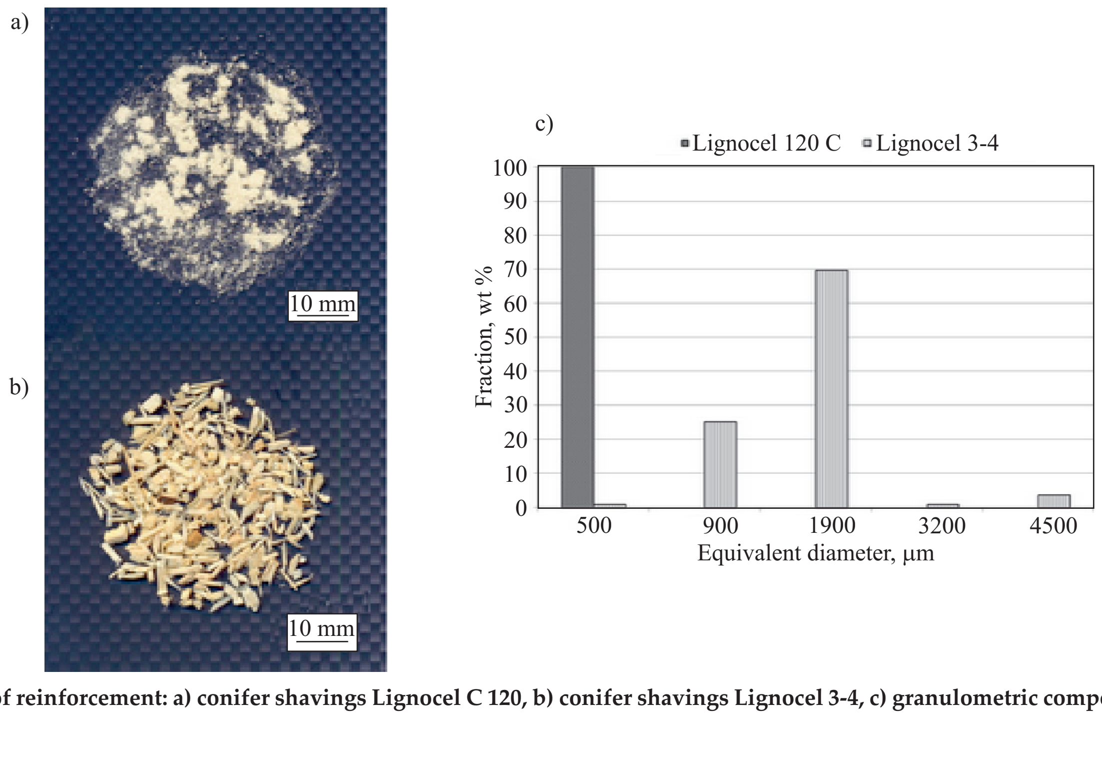

Fig. 1. Type of reinforcement: a) conifer shavings Lignocel C 120, b) conifer shavings Lignocel 3-4, c) granulometric composition of applied chips

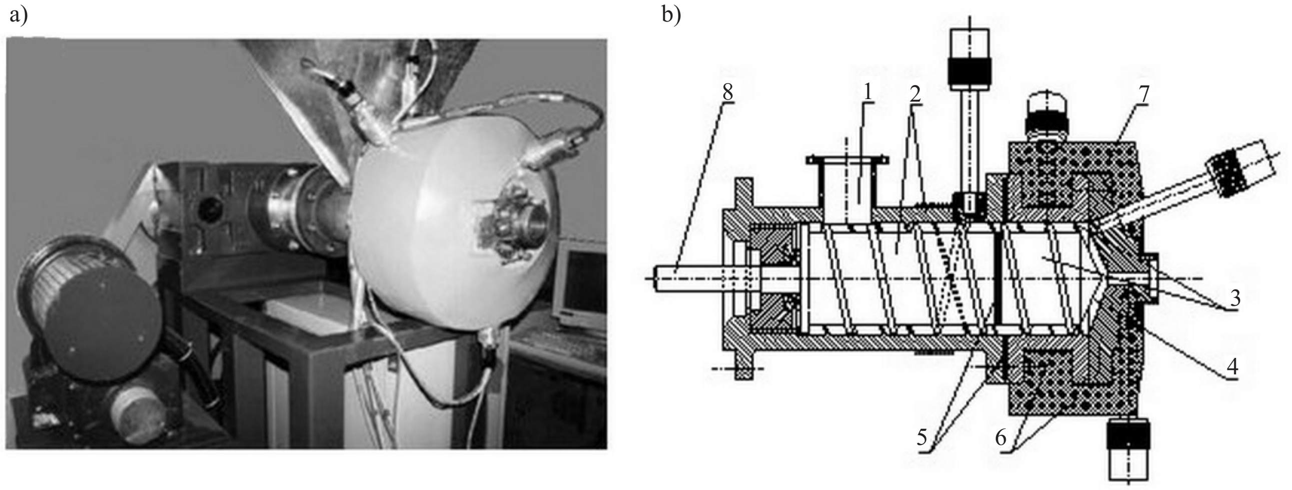

Fig. 2. Screw-disk extruder: a) general view, b) longitudinal section of the plasticizing system; 1 — charging hopper, 2 — cold zone of the screw and barrel, 3 — hot zone of the screw and barrel, 4 — chink, 5 — insulating separators, 6 — electric heaters, 7 — thermal insulator, 8 — drive shaft [15]

performed at a significance level of α = 0.05. According to this plan, the influence of three parameters on the mechanical properties of the obtained composites were evaluated, *i.e.* width of chink of screw-disk (W_s) in the range from 0.3 to 3.0 mm, screw rotational speed (n) in the range from 12 to 40 rpm and contribution of wood fractions (i) between 0 to 70 wt %. The algorithm of the program from the predetermined range selected the following values for the parameters:

— chink of screw-disk W_s [mm]: 0.3; 0.7; 1.7; 2.6; 3.0;

— rotational speed n [rpm]: 12, 16, 26, 35, 40;

— contribution of wood fraction i [wt %] 0, 10, 35, 60, 70.

T a b l e 2. The scheme of experimental parameters generated by the Experiment Planner 1.01

L.P.	Chink size W_S, mm	Rotation speed n, rpm	Fraction of the wood, i, wt %
1.	0.3	26	35
2.	0.7	16	10
3.		35	60
4.	1.7	40	35
5.		12	35
6.		26	70
7.		26	0
8.		26	35
9.		26	35
10.		26	35
11.		26	35
12.		26	35
13.		26	35
14.	2.6	16	60
15.		35	10
16.	3.0	26	35

From this data, the program selected 16 parameter combinations (Table 2) for which the extrusion process using a screw-disk extruder was carried out (Fig. 2).

The tests, shown in Table 2, were carried out for both types of filler.

In order to obtain mixtures of a certain fraction of wood, the initial mixing process was performed using a drum mixer prior to the extrusion. The premixing process lasted about 5 minutes.

The product of the extrusion process was an extrudate in the form of a rod whose segments, immediately after leaving the extrusion head, were squeezed between two plates of acid-proof steel equipped with a system of electric heaters connected to a temperature controller and a cooling system. This led to a product consisting of composite plates of a thickness of about 2 mm. From such obtained plates, using a blanking die on a hydraulic press, skull-and beam-shaped samples were obtained.

Methods of testing

— The breaking stress at static tension (R_m) and the Young's modulus (E_t) were conducted in accordance with PN-EN ISO 527-1,-2:1998 on the computer-controlled TIRATEST GmbH ripper with the following parameters: tensioning speed v = 10 mm/min, the range of the measured force equal to 3 kN.

— The impact resistance (a_k [kJ/m^2]) of samples without notch was studied by the Charpy method. The studies were conducted in accordance with PN-EN ISO 179:2001 using the electronic Charpy hammer (VEB Werkstoffprüfmaschinen, Germany). In the study, a pendulum with a nominal energy of 7.5 J was used.

The evaluation of the mechanical properties was carried out in 5 replicates for each of the 16 designed combinations of variable factors established in the experimental plan (Table 2).

RESULTS AND DISCUSSION

For a full analysis of the mechanical properties of polypropylene composites with two types of fillers, *i.e.* wood chips Lignocel 3-4 and wood flour Lignocel C 120, an approximation of the test results obtained using the regression equation in the form of a second-degree polynomial with two and three interactions was constructed (Equations 1—6):

$$R_m = 12.18 + 5.44 \cdot W_s + 1.266 \cdot n - 0.504 \cdot i - 0.277 \cdot W_s \cdot n + 0.033 \cdot W_s \cdot i - 0.004 \cdot n \cdot i - 0.154 \cdot W_s^2 - 0.013 \cdot n^2 + 0.002 \cdot i^2 \quad (1)$$

$$a_k = 111.93 + 36.081 \cdot W_s - 6.195 \cdot n - 0.379 \cdot i - 1.588 \cdot W_s \cdot n - 0.180 \cdot W_s \cdot i + 0.045 \cdot n \cdot i + 5.042 \cdot W_s^2 + 0.124 \cdot n^2 - 0.006 \cdot i^2 \quad (2)$$

$$E_t = 1765.31 + 235.157 \cdot W_s - 71.55 \cdot n + 49.127 \cdot i - 68.419 \cdot W_s \cdot n - 49.498 \cdot W_s \cdot i - 3.490 \cdot n \cdot i + 429.993 \cdot W_s^2 + 3.618 \cdot n^2 + 0.565 \cdot i^2 + 1.915 \cdot W_s \cdot n \cdot i \quad (3)$$

whose interpretations are graphically presented in Figs. 3, 6 and 8.

While for chips of Lignocel C 120 type (model: second-degree polynomial with two interaction equations as:

$$R_m = 26.369 + 3.284 \cdot W_s + 0.438 \cdot n - 0.937 \cdot i - 0.215 \cdot W_s \cdot n + 0.019 \cdot W_s \cdot i + 0.009 \cdot n \cdot i + 0.358 \cdot W_s^2 - 0.002 \cdot n^2 + 0.003 \cdot i^2 \quad (4)$$

$$a_k = 7.047 - 2.612 \cdot W_s + 3.821 \cdot n - 0.063 \cdot i - 0.174 \cdot W_s \cdot n + 0.399 \cdot W_s \cdot i + 0.006 \cdot n \cdot i - 2.041 \cdot W_s^2 - 0.071 \cdot n^2 - 0.013 \cdot i^2 \quad (5)$$

$$E_t = 1476.343 - 80.238 \cdot W_s + 16.781 \cdot n - 75.358 \cdot i - 2.938 \cdot W_s \cdot n + 8.427 \cdot W_s \cdot i + 1.215 \cdot n \cdot i + 14.147 \cdot W_s^2 - 1.036 \cdot n^2 + 0.274 \cdot i^2 \quad (6)$$

whose interpretations are graphically presented in Figs. 4, 7 and 9.

The models were consistent with the experimental results obtained and the correlation coefficients for all the tested parameters ranged from 0.95 to 1.

Based on the obtained equations, a series of three-dimensional curves describing the character and strength of the impact of the disk zone (W_s [mm]), rotational speed (n [rpm]) and contribution of wood mass fraction (i [wt %]) on the mechanical properties of the WPC obtained were plotted.

Analyzing the results presented in Fig. 3, we concluded that an increased content of wood additive in the form of medium size chips of Lignocel 3–4 coniferous wood led to a decreasing trend in the value of the strength of the obtained WPC. A similar relationship was observed by TabkhPaz M. *et al*. [2]. Regardless of this general trend, preferred areas of interactions between extrusion parameters (chink in the disk zone W_s and the rotational speed n) on the strength properties (R_m) of the obtained composites were observed. It was noted that if we have a low degree of filling composites (up to 10 wt % of wood fraction — Fig. 3b), high values of strength (similar to the strength of the material used for the warp) were obtained in the interaction area of low, W_s, *i.e.* 0.3—0.9 mm and high values, n (26—40 rpm). In the case of extrusion with such parameters, extrusion is carried out at high values of shear rate, which may significantly influence the degree of ordering and structure of the material, as well as the uniform distribution of the wood fraction, with its simultaneous high compatibilization with the matrix. With increasing contributions of the wood fraction (Fig. 3c and 3d), the area of the preferred mechanical properties is shifted towards high values of W_s and low values of n (Fig. 3d). One may observe the formation of two areas of the preferred interaction (two maxima) for the high degree of filling composites (> 50 wt % — Fig. 3d).

Here, we observe a twofold impact, namely: a summary of high rotational speed and low value of the chink forms the conditions for short-term, intensive shear mixing interaction, while low rotational speed and high value of the impeller are a gentle, long-term mixing interaction. Analyzing the results shown in Fig. 3, it was also noted that the extrusion via the screw-disk plasticizing system gives high values of R_m (up to 20 MPa), even for intermediate-filled composites (up to 35 wt % — Fig. 3c).

Different correlations were observed when the wood fraction was used as filler in the form of conifer wood flour (Lignocel C 120) (Fig. 4). Analyzing the results of tensile strength (R_m), it was found that the preferred impact areas of extrusion parameters (W_s and n), regardless of the contribution of wood fraction, can be found only in the impact area of low values of impeller, *i.e.* 0.3—0.9 mm and high speed values (from 29 to 40 rpm). No change in the nature of the function with increasing wood fraction contribution (Fig. 4b—d) was found. Based on these analyzes, one can conclude that to obtain a high degree of homogeneity of the material and a good distribution of the filler, in the case of dusty wood fraction in the form of flour, high values of shear rate are essential. The consequence of these intensive efforts should be to obtain satisfactory properties of the composite. The present analyzes confirm the results presented in the study conducted by Rydzkowski (2014) [21].

Figure 5 shows the variation of function along with the diagonal of Fig. 3 and Fig. 4. In terms of wood fraction in the form of medium-sized chips, it was observed that, with the increase in its quantity, the area of preferred impact is variable (Fig. 5a). In terms of composites characterized by a fill of i = 10 wt %, the preferred area was obtained among low W_s and high n values. For composites characterized by a fill of i = 35 wt %, this area was extended in parallel across the whole diagonal plane presented in Fig. 6c moving the area of intensity to the area of high W_s and low n values for composites of i = 70 wt %. In contrast, for the wood fraction in the form of flour, it was noted that the change of percentage contribution does not lead to any movement of the preferred area of influence (Fig. 5b).

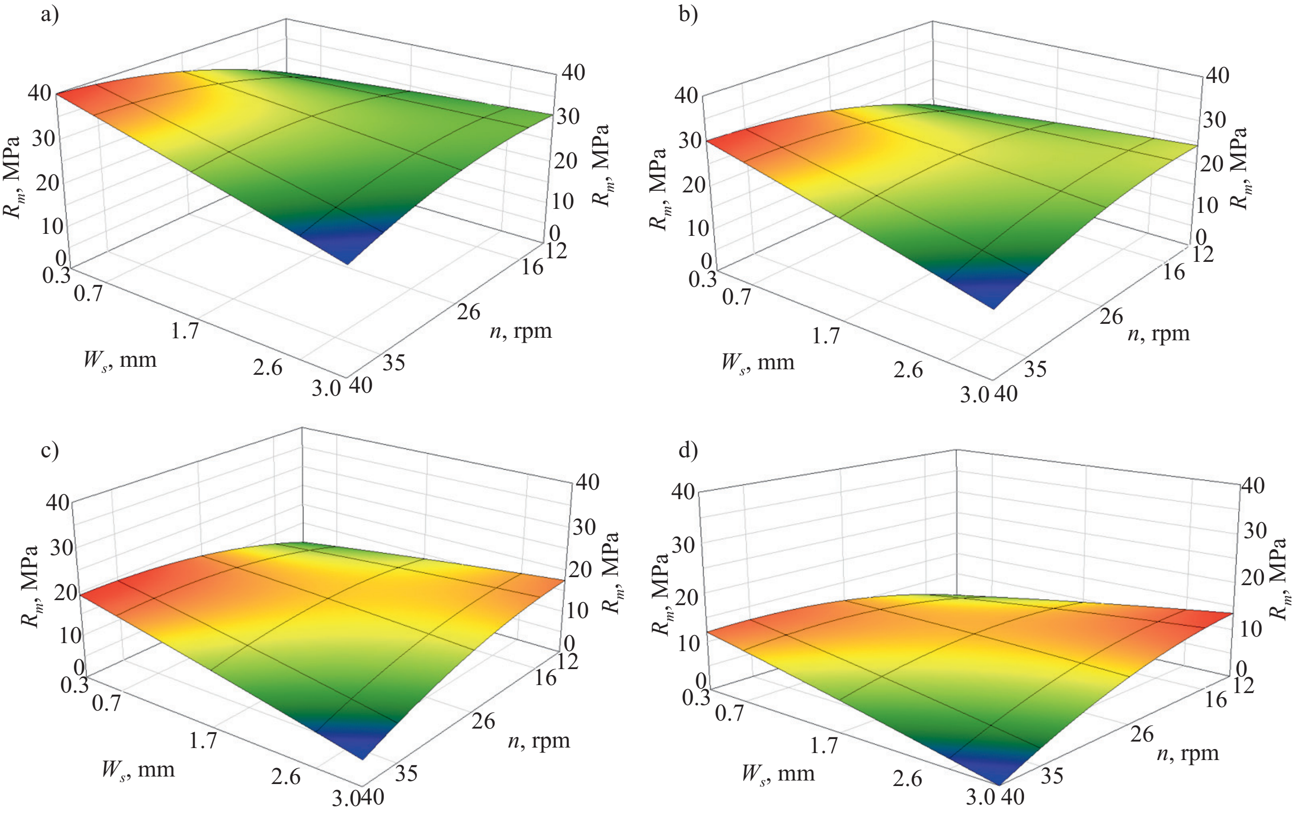

Fig. 3. The dependence of R_m on the value of chink width and the speed of the screw to: a) unfilled, b) low degree of filling (up to 10 wt % of wood fraction), c) medium degree of filling (up to 35 wt % of wood fraction), d) high degree of filling (> 50 wt % of wood fraction) of WPC composites with the chips Lignocel 3-4 type

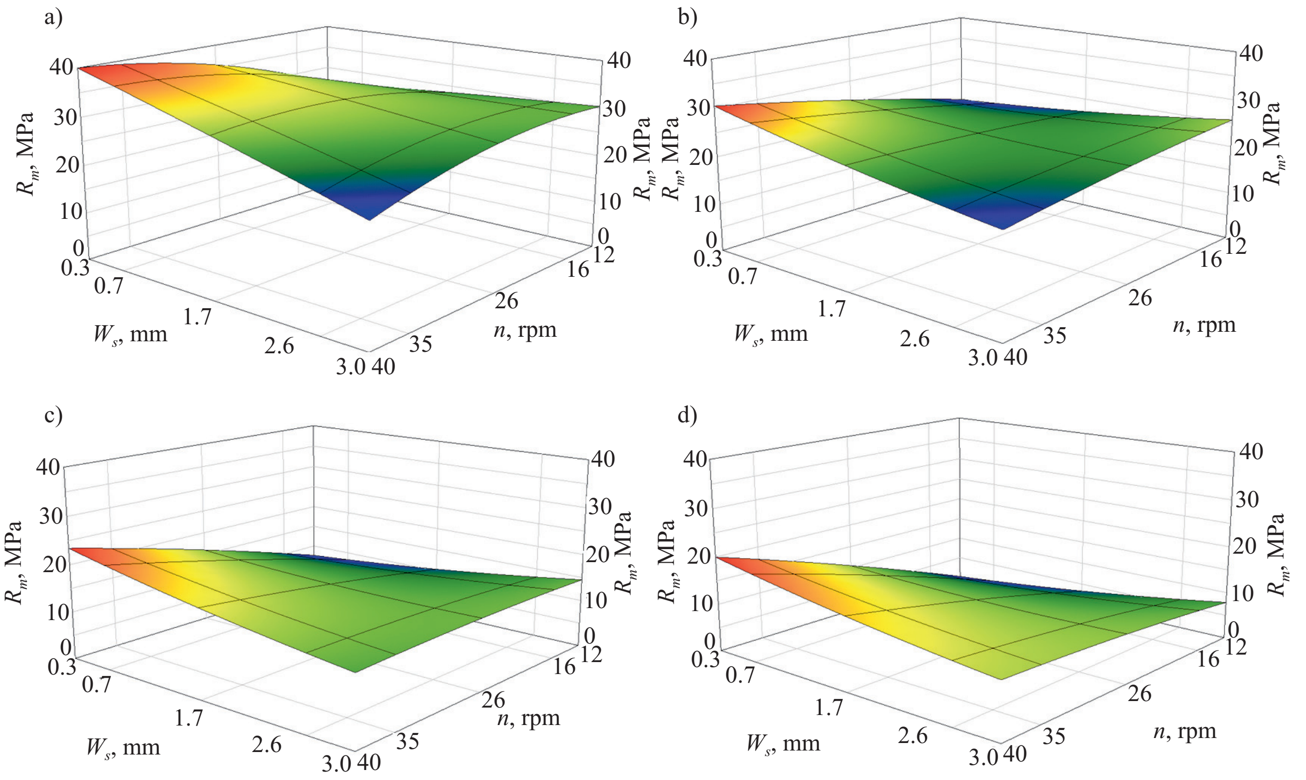

Fig. 4. The dependence of R_m on the value of chink width and the speed of the screw to: a) unfilled, b) low degree of filling (up to 10 wt %), c) medium degree of filling (up to 35 wt %), d) high degree of filling (> 50 wt %) of WPC composites with the chips Lignocel C 120 type

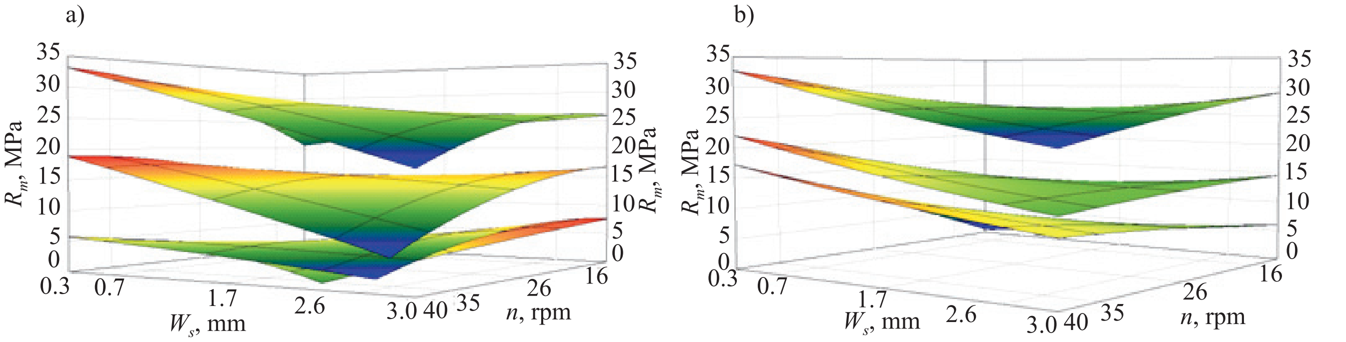

Fig. 5. Profile of impact of extrusion parameters on R_m depending on the content of wood filler: a) composite of polypropylene/medium-sized chips Lignocel 3-4, b) a composite of polypropylene / flour Lignocel C 120

Moving to the analysis of the results of WPC impact resistance (a_k) (Fig. 6), it was observed that the preferred area of impact of extrusion parameters on the discussed feature, regardless of the contribution of wood fraction, was formed in terms of the interaction of high value of impeller width (from 2.0 mm to 3.0 mm) and low values of rotational speed (from 12 to 18 rpm). For these parameters, low values of shear rate and shear stress were observed. These conditions affect the material to a minor extent; it stays longer in the plasticizing system, which gives time for the distribution and ordering of the wood fraction. In this area, the difference in the value of resilience between the individual contributions of wood fraction was established at a maximum of about 26 wt %.

Analyzing the obtained results of WPC impact resistance with wood fractions in the form of conifer wood flour (Lignocel C 120) (Fig. 7), an extension of preferred interaction areas was observed, unlike for the composites of the medium-sized chips of Lignocel 3–4 type. The area of preferred interaction of extrusion parameters a_k, changes with the increase in the contribution of wood fraction. For materials of low degree of filling, this area was determined by parameters: value of chink (W_s) within the range 0.3—1.9 mm and the rotation speed *(n)*

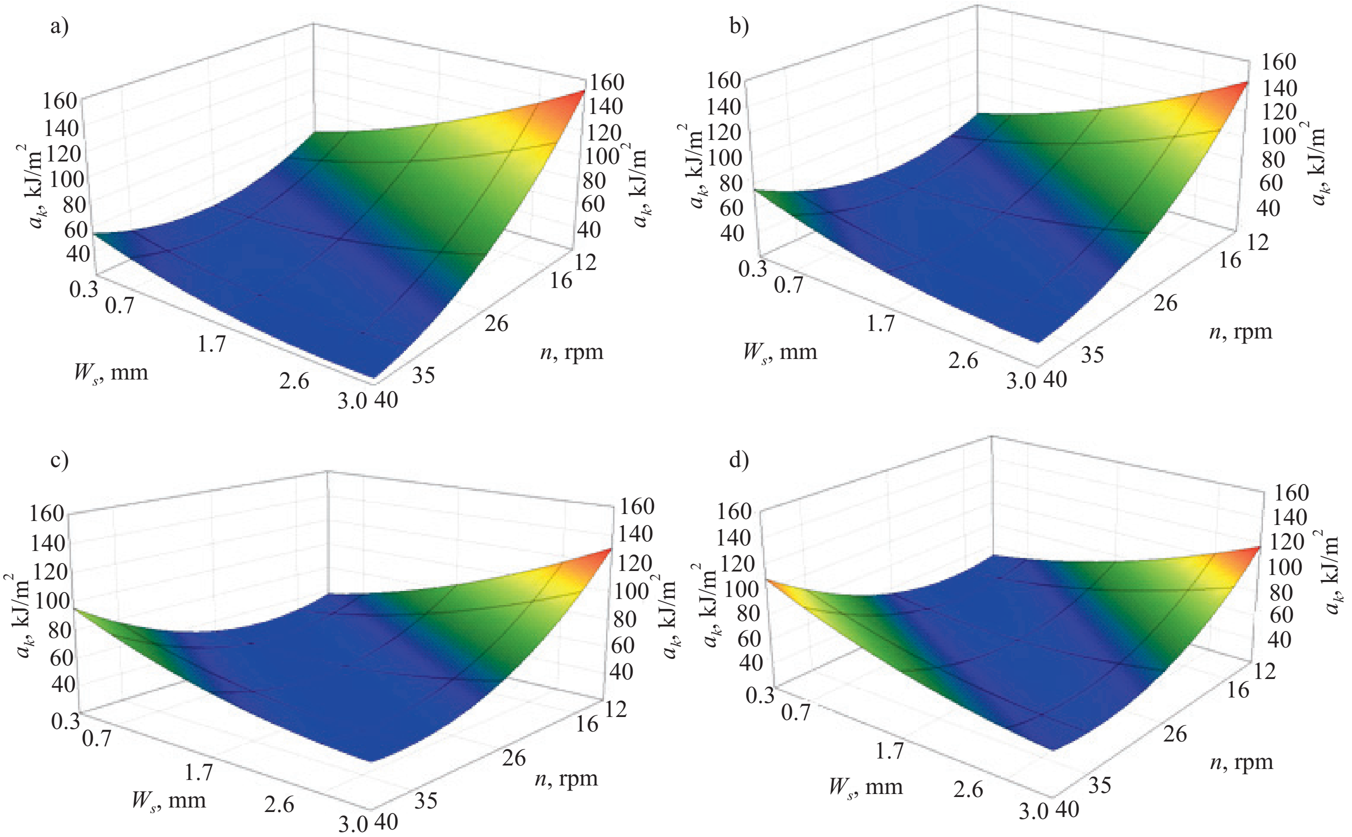

Fig. 6. The dependence of a_k to the value of chink width and the speed of the screw to: a) unfilled, b) low degree of filling (up to 10 wt %), c) medium degree of filling (up to 35 wt %), d) high degree of filling (> 50 wt %) of WPC composites with the chips Lignocel C 3-4 type

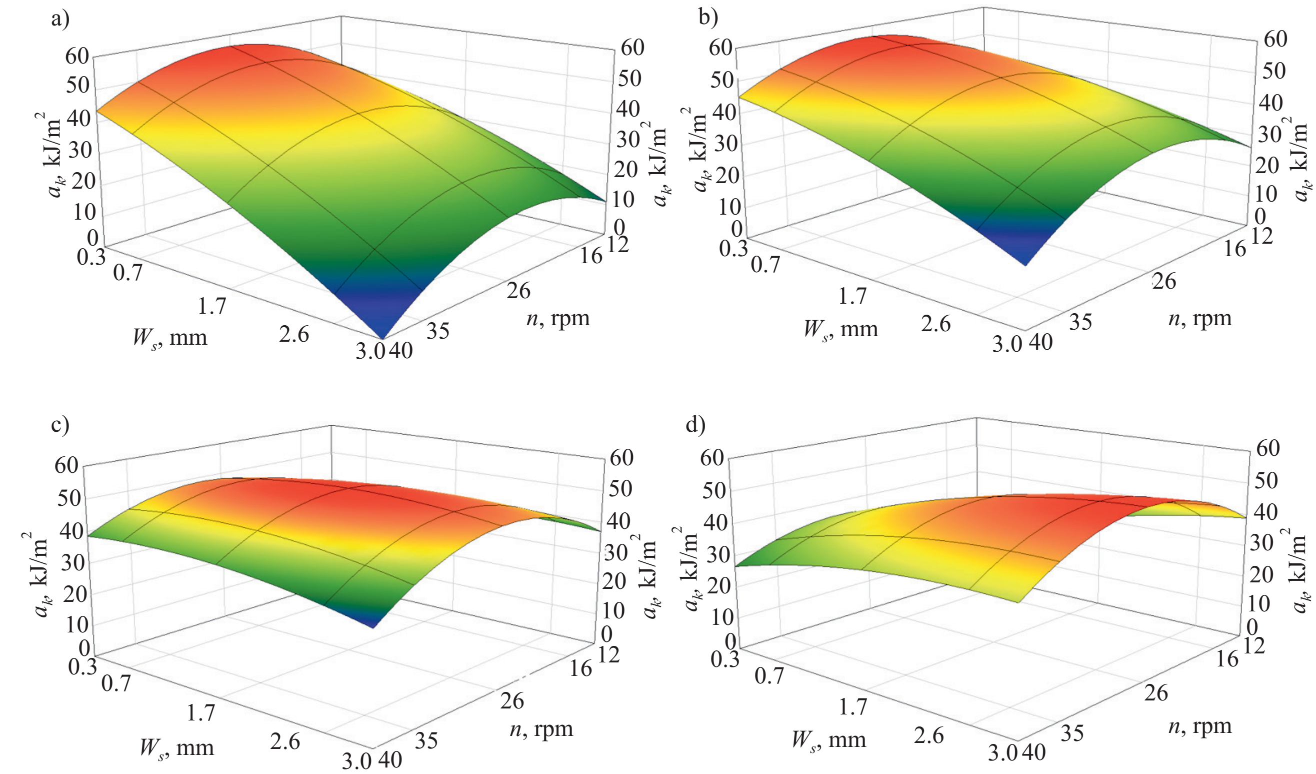

Fig. 7. The dependence of a_k to the value of chink width and the speed of the screw to: a) unfilled, b) low degree of filling (up to 10 wt %), c) medium degree of filling (up to 35 wt %), d) high degree of filling (> 50 wt %) of WPC composites with the chips Lignocel C 120 type

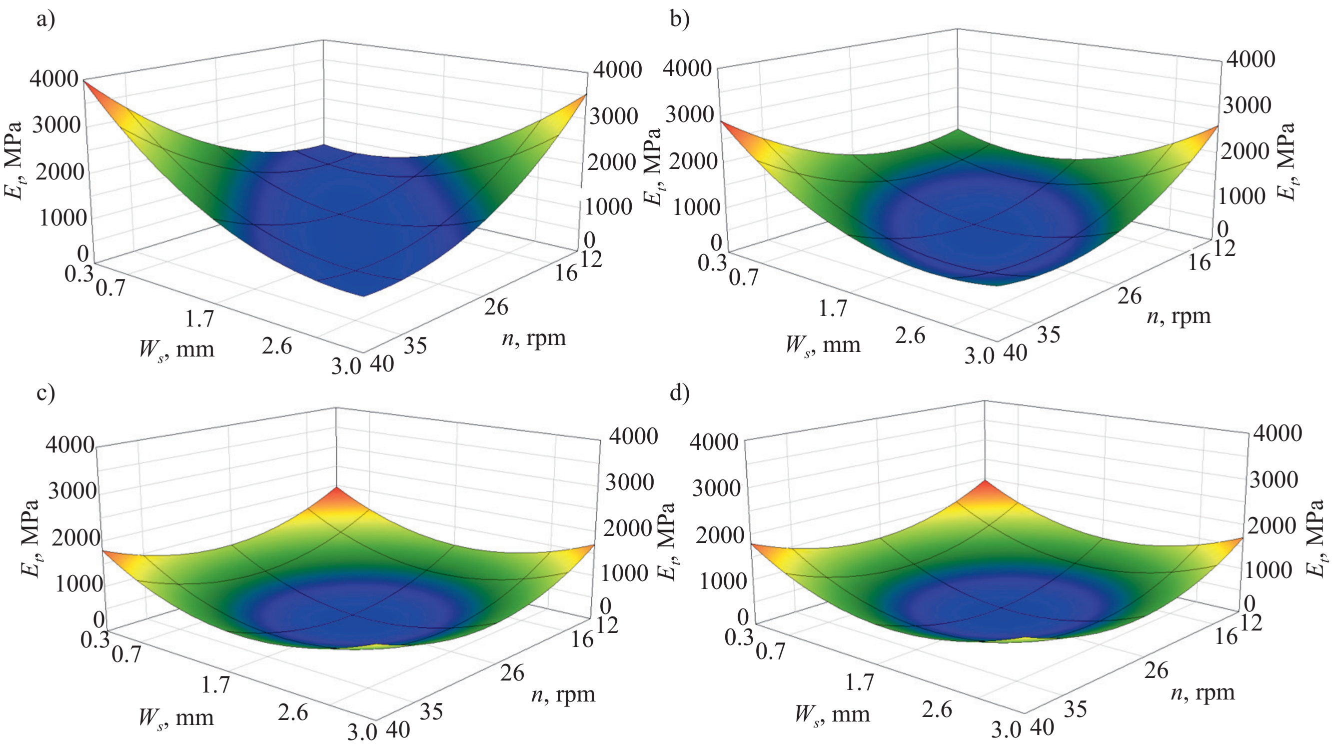

Fig. 8. The dependence of E_t to the value of chink width and the speed of the screw to: a) unfilled, b) low degree of filling (up to 10 wt %), c) medium degree of filling (up to 35 wt %), d) high degree of filling (> 50 wt %) of WPC composites with the chips Lignocel C 3-4 type

from 12 to 40 rpm (the whole range of the analyzed speeds) (Fig. 7b).

For composites of medium degree of filling, this area is W_s in the range from 0.3 to 3.0 mm (the whole analyzed

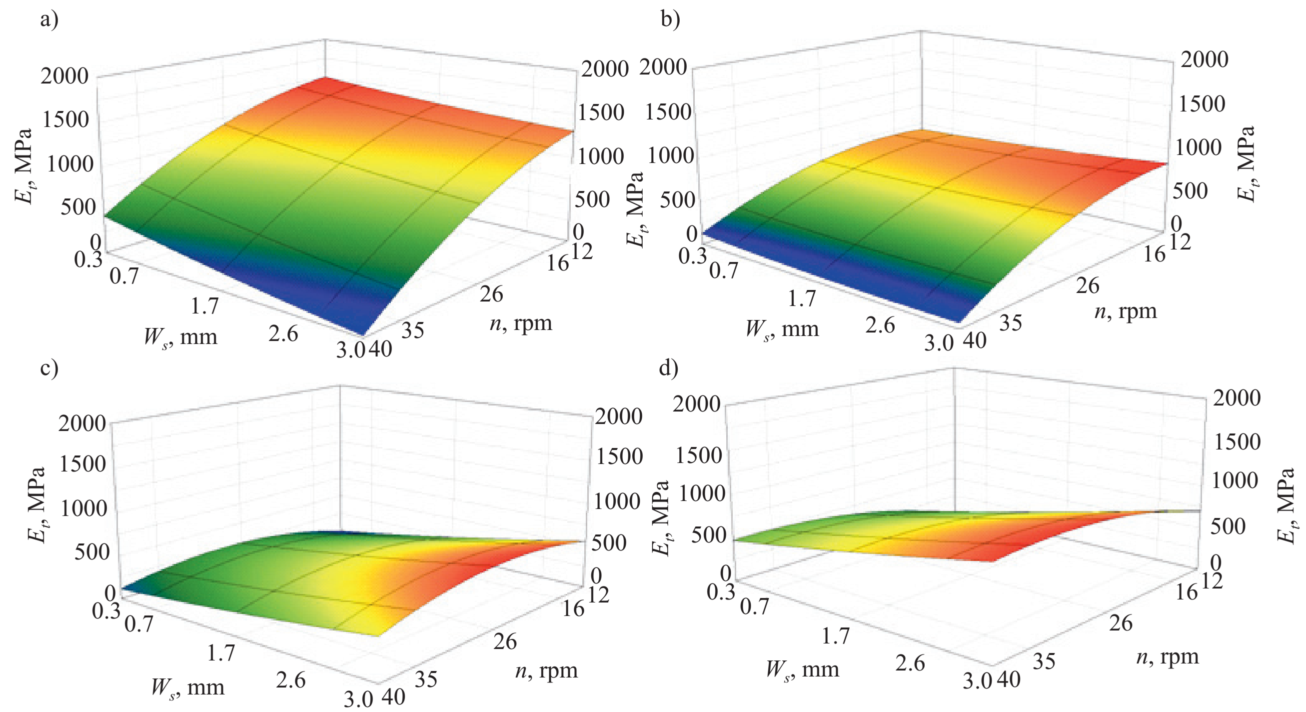

Fig. 9. The dependence of E_t to the value of chink width and the speed of the screw to: a) unfilled, b) low degree of filling (up to 10 wt %), c) medium degree of filling (up to 35 wt %), d) high degree of filling (> 50 wt %) of WPC composites with the chips Lignocel C 120 type

width of chink of screw-disk) and *n* from 16 to 35 rpm (Fig. 7c), while for the composites with a high degree of filling, this area is determined by W_s values in the range from 2.0 mm to 3.0 mm and *n* from 16 to 35 rpm (Fig. 7d). In these areas, there was no significant difference in the values of the resilience between the individual wood fraction contributions.

The last of the strength parameters analyzed was the Young's modulus (E_t) (Fig. 8 and Fig. 9). Analyzing the results for the WPC with wood fraction in the form of medium size chips (Fig. 8) it was found that, regardless of the percentage contribution of wood fraction, higher E_t values are located in the two extreme ranges of the values of the extrusion parameters, *i.e.* small values of W_s (from 0.3 to 0.7 mm), high *n* (from 35 to 40 rpm) and high values of W_s (from 2.6 to 3.0 mm) and low *n* (12 to 16 rpm). In these areas, we can obtain a material of low elasticity but of high strength. In contrast, material of high elasticity can be obtained in areas of average values of the extrusion parameters, namely: W_s in the range from 1.1 to 2.6 mm and *n* from 20 to 35 rpm. Analyzing the curves (Fig. 8b—d), it was also noted that, with an increasing fraction of wood, the area of impact of the parameters in which the material of low elasticity is obtained decreases.

The value of the modulus of elasticity E_t for composites filled with wood flour (Fig. 9), regardless of its contribution, did not exceed the borderline for the E_t of warp material (1400 MPa) and ranged from 500 to 800 MPa. High E_t values occur in different areas of interaction of extrusion parameters and depend on the percentage contribution of wood fractions.

For composites with a low degree of filling, this area determines the value of chink width in the range from 0.3 to 3.0 mm and a rotational speed from 12 to 26 rpm. For composites with a medium degree of filling, this area determines high values of chink, from 2.4 to 3.0 mm and *n* value within the range 16 to 35 rpm, while for the composites with a high degree of filling, these are large values of the chink (from 1.7 to 3.0 mm), *i.e.* from 12 to 40 rpm for the whole range of the analyzed rotational speed.

The structural analyses of the obtained composites used in this article will be presented in the next publication.

CONCLUSIONS

— The conditions in the screw-disk system that plasticize the extruder allow the production of high-quality WPC and positively influence their properties.

— By changing the width of the chink of the screw-disk (W_s) and the rotational screw speed (*n*) of the extruder, one can control the processing conditions in the chink of the screw-disk. A combination of high rotational speed and low value of crevice forms the conditions for intense shear-mixing effects in a short time, while the low rotational speed and high value of the chink is a gentle, long-term mixing impact.

— It is possible to control and thus design the properties of the composite obtained by controlling the parameters of the extrusion in the screw-disk plasticizing system of the extruder, *i.e.* the chink width (W_s) and the rotational speed (*n*), depending on the amount and the type (form, particle size, origin) of the filler used.

— The preferred impact area of the extrusion parameters also depends on the form and size of the particles in the used filler. When using a material with medium size particles, we have an opportunity of more flexible control of the screw-disk extrusion process in contrast to dusty materials (wood flour).

— In the screw-disk system, it is possible to produce wood-polymer composites characterized by good performance without the use of compatibilizer sand without time-and energy-intensive pretreatment of the input material.

REFERENCES

[1] Baunemanna R.: „Materials from the press conference International Trade Fair No. I for Plastics and Rubber Worldwide", Warsaw 2013.

[2] TabkhPaz M., Behravesh A.H., Shahi P. Zolfaghari A.: *Polymer Composites* **2013**, *34*, 1349. http://dx.doi.org/10.1002/pc.22549

[3] Zajchowski S., Tomaszewska J.: *Teka Komisji Budowy i Eksploatacji Maszyn, Elektrotechniki, Budownictwa* — OL PAN **2008**, 183—188.

[4] Jeziórska R., Zielecka M., Szadkowska A. *et al*.: *Polimery* **2012**, *57*, 192. http://dx.doi.org/10.14314/polimery.2012.192

[5] Błędzki A.K., Gassan J.: *Progress in Polymer Science* **1999**, *24*, 221. http://dx.doi.org/10.1016/S0079-6700(98)00018-5

[6] Cyga R., Czaja K.: *Przemysł Chemiczny* **2008**, *87*, 932.

[7] Borysiak S., Doczekalska B.: *Polimery* **2009**, *54*, 820.

[8] Błędzki A.K., Sperber E.V.: „Wood and Natural Fibre Composites", Institut für Wekstofftechnik Kunststoff- und Recyclingtechnik, Kassel 2005.

[9] Głowacka L., Zajchowski S.: *Inżynieria i Aparatura Chemiczna* **2005**, *3*, 26.

[10] Gozdecki C., Zajchowski S., Kociszewski M. *et al*.: *Polimery* **2011**, *56*, 375.

[11] Faruk O., Błędzki A.K., Fink H.P., Sain M.: *Progress in Polymer Science* **2012**, *37*, 1552. http://dx.doi.org/10.1016/j.progpolymsci.2012.04.003

[12] Ares A., Bouza R., Pardo S. G. *et al*.: *Journal of Polymers and the Environment* **2010**, *18*, 318. http://dx.doi.org/10.1007/s10924-010-0208-x

[13] Zajchowski S., Ryszkowska J.: *Polimery* **2009**, *54*, 74.

[14] Borysiak S., Paukszta D.: *Molecular Crystals and Liquid Crystals* **2008**, *484*, 379. http://dx.doi.org/10.1080/15421400801901464

[15] Kazemi Y., Cloutier A., Rodrigue D.: *Polymer Composites* **2013**, *34*, 487. http://dx.doi.org/10.1002/pc.22442

[16] Sikora R.: „Przetwórstwo tworzyw wielkocząsteczkowych", Wydawnictwo Edukacyjne Żak, Warszawa 1993.

[17] Rydzkowski T., Michalska-Pożoga I.: *Chemical and Process Engineering* **2014**, *35*, 121. http://dx.doi.org/10.2478/CPE-2014-0009

[18] Michalska-Pożoga I., Diakun J.: *Polimery* **2014**, *59*, 845. http://dx.doi.org/10.14314/polimer.2014.845

[19] Diakun J., Michalska-Pożoga I.: *Polimery* **2004**, *49*, 42.

[20] Rydzkowski T., Michalska-Pożoga I.: „Recycled Polymers: Chemistry and Processing, vol. 1", Smithers Rapra Technology Ltd. 2015, pp. 115—160.

[21] Rydzkowski T.: „Teoretyczne i doświadczalne podstawy efektywnego wytłaczania ślimakowo-tarczowego w recyklingu materiałów i kompozytów polimerowych", Wydawnictwo Uczelniane Politechniki Koszalińskiej, Koszalin 2012.

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