U.P.B. Sci. Bull., Series B, Vol. 85, Iss. 1, 2023 ISSN 1454-2331

THE DEPENDENCE OF THE RACEMIC CRYSTALLIZATION OF PLLA ON THE MOLECULAR WEIGHT OF THE STEREO-COMPLEXER MACROMOLECULES

Silvia MATHE[1], Doina DIMONIE[1,2]

The possibility to increase the PLLA durability for usage as 3D printed auto items through racemic crystallization was studied by evaluating the influence of the PDLA (stereo-complexer) molecular weight and polydispersity index on the stereo-complexation of a PLLA grade designed for 3D printing. Considering all the obtained results, it was concluded that the PDLA can generates a sizeable enhancement of the PLLA functional properties and so on its durability if the molecular weight of the used PDLA varies between 4.5×10^4 *g/mol and* 20.9×10^4 *g/mol.*

Keywords: racemic nucleation, stereo-complexing, poly(lactic) acid, FTIR, 3D printing

1. Introduction

The automotive industry is constantly expanding nowadays in a constant concern to market performant, lightweight vehicles considering also the perspective of usage of renewable polymers with performances upgraded as closest as possible to the conventional ones [1,2]. Due to their low hygroscopicity, poor processability and below standards mechanical properties, the renewable base-polymers cannot be used for serial industrial manufacturing without increasing their durability [3]. Physical modification at melt processing is a good method to improve the functional properties of renewable polymers, so that, the obtained polymeric materials to be used for durable applications [3,4]. The materials with renewable base-polymers content can be shaped as vehicle parts both through classic melt processing techniques and/or 3D printing procedures [5,6,7]. The transition from 3D printed prototypes to serial production is eagerly awaited by the car manufacturers [8,9].

Presently, the poly(lactic) acid (PLA), an aliphatic polyester with unique functional properties [10,11,12,13], accounts for almost 19% of global biopolymer

---

[1] Doctoral School "Chemical Engineering and Biotechnology", University POLITEHNICA of Bucharest, Romania, e-mail: mathe.silvia@yahoo.com

[2] National Institute for Research and Development in Chemistry and Petrochemistry, Bucharest, Romania, e-mail: ddimonie@yahoo.com

production [14]. The estimated annual compound growth rate of the global market for PLA is of 15.9%, even till 2030 [15]. However, because of low glass transition temperature and crystallization rate, as well as the brittle character [16], its usages in durable applications such as 3D printed automotive components is limited [17].

To get PLA-based compounds with desired functional properties, the controlling of the morphological structure through nucleation are quite well known in the field such as: nucleation through stereo-complexation (racemic crystallization) or with nucleants (controlled crystallization) [18,19,20]. As compared to the “spontaneous” processes (crystallization without additives), the “controlled” crystallization involves the formation, in the same volume unit, of a huge number of smaller sized crystals [20,21]. Obtaining of the desired morphology in a controlled manner improves both the physical, mechanical, optical properties and the dimensional stability of the new material, as well as the cost-performance [19,20].

The lactic acid contains an asymmetric optically active carbon with two optical isomers: L-lactic acid (levo-rotatory) and D-lactic acid (dextro-rotatory) [19,22] and therefore the following enantiomers, which have the same composition, but different three-dimensional configurations, are known: poly (L-lactide) (PLLA), poly (D-lactide) (PDLA), meso poly (lactide) (meso-PLA) and racemic polylactic acid (PDLLA) [19,23,24,25].

The stereo-complexation follows the selective interactions between the -CH3 and O=C groups from the two enantiomers, PLLA and PDLA. Changes related to the adjacent functions to these groups, namely of the C-O-C, -OH or -C-O- linkages, appear also in the FTIR spectra following the racemic crystallization [26]. These interactions generate the formation with high rate of a racemized poly(lactic) acid with a semi-crystalline morphology with many small-sized crystallites [19,27,28] and enhanced functional properties and so with controlled durability [29].

The authors have proved in previous papers that the racemic crystallization of PLLA can be controlled by means of the molecular weight values and of the D-lactide sequences content of the stere-complexer macromolecules, namely of the PDLA macromolecular chains [18,19,30,31,32].

The aim of the current paper is to deepen the own study regarding the influence of the PDLA molecular weight values on the racemic crystallization level, so that to establish the optimal stereo-complexer molecular characteristics which enhance the stereo-complexation effect till a functional properties level of practical importance for 3D printed automotive items.

2. Experiment

2.1. Material, apparatus

The experiments involved the melt compounding at different blending ratio of the PLLA and PDLA (Table 1) in a laboratory Brabender (185–200 °C, 100 rpm) and shaping as sheets of 0.6 ± 0.05 of the new obtained compounds (code: sc-compounds) on a laboratory roller (100–125 °C, 25 rpm1, 25 rpm2).

Table 1

Composition of the new stereo-complexed compounds (sc-compounds)

PLA* grade, Mw, DS [3*] \ Compounds codes	**Blending Proportion for Getting Racemic Compounds, %**					
	sc-4	**sc-5**	**sc-6**	**sc-7**	**sc-8**	**sc-9**
PLLA D 850 [2*] (P_b), $4.5 \cdot 10^4$ g/mol, 0.5%	98.04	95.24	90.91	80	66.66	50
PDLA D 8052 (P_{m2}), $20.9 \cdot 10^4$ g/mol, 4.5%	1.96	4.76	9.09	20	33.33	50

* INGEO of Natura Works; [2*] Designed for 3D printing; [3*] Dextro sequences.

2.2. Procedure

In [19] it has been shown that a good stereo-complexation effect can be obtained if PLLA with Mw of $4.5 \cdot 10^4$ g/mol and 0.5% D-sequence was stere-complexed by melt compounding with PDLA with Mw of $11.6 \cdot 10^4$ g/mol and 4% D-sequence content.

In this new experiment, the same PLLA with $4.5 \cdot 10^4$g/mol and 0.5% D-lactide sequences was melt compounded, at different ratio, with PDLA with almost double molecular weight of $20.9 \cdot 10^4$ g/mol and the same D-lactide sequences content of 4.5 %. The morphological changes, occurred as results of the racemic crystallization, were studied by Fourier Transform-Infrared Spectroscopy in the Attenuated Total Reflectance mode (FTIR-ATR), considering the spectral ranges proven as highlighting the racemic nucleation through the above-described mechanism [18, 19, 20].

A first material selection was made considering the greatest stereo-complexation effect which was possible when the stereo-complexer had a molecular weight of $20.9 \cdot 10^4$ g/mol. This effect was then compared with that representing the compound selected in the previous experiment series when the PDLA had a half molecular weight, namely of $11.6 \cdot 10^4$ g/mol, and the same D-sequence content ([19]). The morphological changes and their influence on the functional properties of both selected racemized compounds have also been studied. In this way, it was possible to conclude on the significance of the molecular weight values in controlling the racemic crystallization of PLLA.

2.3. Characterization

2.3.1. Chemical Structure

The FTIR-ATR spectra were recorded on the Perkin Elmer Spectrum 100 equipment, between 4000 and 600 cm^{-1}. To obtain an optimal signal-to-noise ratio, 32 scans were performed. A clean, empty diamond crystal was used for the collection of the background spectrum. The spectral changes were studied in the following FTIR ranges: 3100–2800 cm^{-1} (-OH stretching at the end-chain, -CH3 asymmetric stretching, -CH stretching and -CH2), 1850–1680 cm^{-1} (C=O stretching), 1500–1300 cm^{-1} (-CH3, CH bending and C-O-C stretching), 1300–1000 cm^{-1} (-C-O- stretching, C-CH3 and C-O-C symmetric stretching and -OH bending) and 1000–600 cm^{-1} (-CH2 rocking and -C-C- stretching) [33].

2.3.2. Morphological structure

Scanning Electron Microscopy (SEM) micrographs were taken with an equipment Tescan Vega type, XMU model, for gold coated samples considering both the fracture section and the surface.

2.3.3. Functional Properties

Heat Deflection Temperature (HDT) was measured with a DMA Q800 equipment, using a 3-point bending clamp, the samples with dimensions of 50.0000 x 12.2300 x 3.0000 mm being heated from 20°C to 175 °C (2°C/min).

The Mechanical Behavior - Stress Strain curves were carried on a DMA Q800, following the method: DMA Controlled Force, isotherm at 30 °C, ramp force (1N/min) from 0,0001N to 18N. A tension clamp and a sample with the dimensions of 12.73 x 6.83 x 0.66 mm were used.

3. Results and discussions

3.1. Chemical changes because of stereo-complexing

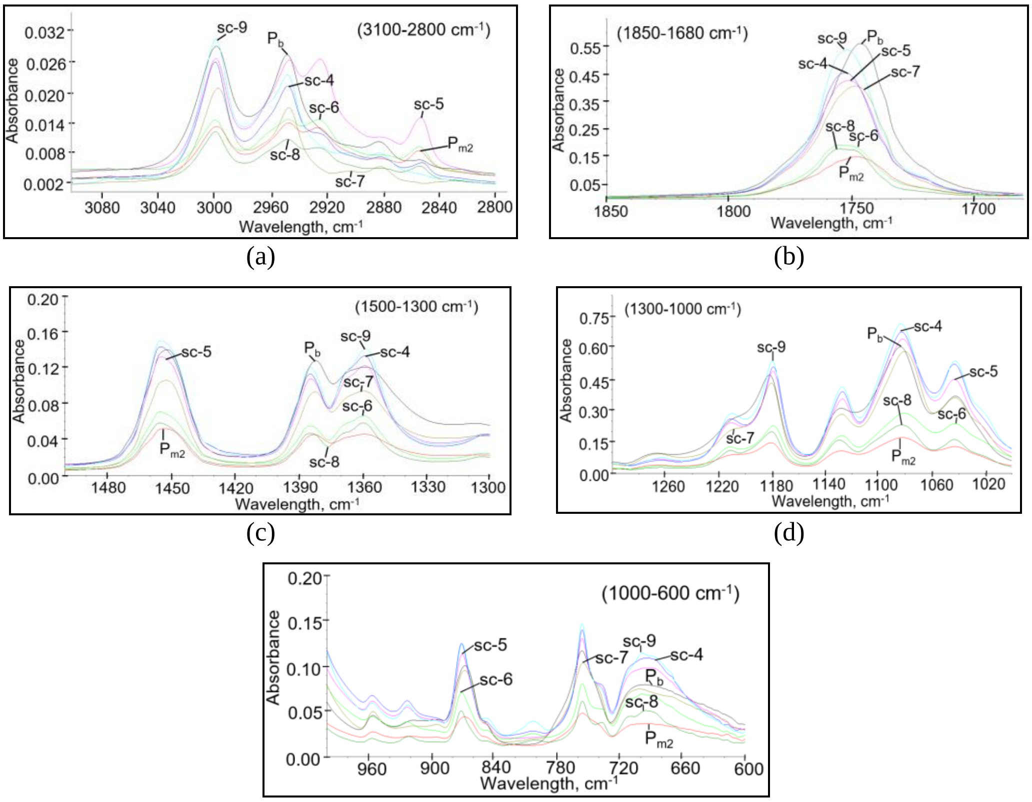
3.1.1. Compounds with stereo-complexer with high Mw

The interactions appeared between the methyl (-CH3) and carbonyl (O=C) groups when PLLA with Mw of $4.5\cdot10^4$ g/mol was compounded with PDLA with high molecular weight of 20.9·104 g/mol are reflected by the spectra presented in Fig. 1.

In the 3100–2800 cm^{-1} range (Fig. 1a), the following absorptions can be noticed: -OH stretching at the end-chain at 2997 cm^{-1}, -CH3 asymmetric stretching at 2995 cm^{-1}, -CH stretching at 2997 cm^{-1} and 2945 cm^{-1} and -CH2 stretching at 2944 cm^{-1}.

The 1850–1680 cm^{-1} range (Fig. 1b) show the absorption specific for C=O stretching at 1747cm^{-1}. The 1500–1300 cm^{-1} range (Fig. 1c) is specific for CH3, CH bending and C-O-C stretching as follows: -CH3 bending at 1454 cm^{-1}, -CH from CH3 bending at 1452 cm-1, -CH bending at 1375 cm^{-1}, -CH3 symmetric stretching at 1361 cm^{-1}.

In the 1300–1000 cm^{-1} range (Fig. 1d), the following absorptions had appeared: -C=O bend (1211 cm^{-1}), C-O-C asymmetric stretching (1188 cm^{-1}), -C-O- stretching (1121 cm^{-1}), -C-O-C symmetric stretching (1081 cm-1) and -C-CH3 (1042 cm^{-1}), while the 1000–600 cm^{-1} range (Fig. 1e) shows the presence of -CH2 rocking and -C-C- stretching at 870 cm^{-1}. The lowest absorption intensity of the target groups was observed for compound sc-8, which confirmed the interaction between them. 3:1 mass ratio of PLLA:DPLA favored the racemic crystallization process, leading to stronger interactions.



(a) (b)

(c) (d)

(e)

Fig. 1. FTIR spectra of the sc-4, sc-5, sc-6, sc-7, sc-8 and sc-9 compounds and those of the used PLA (base-PLLA and doubled Mw PDLA). (a) 3100–2800 cm^{-1} range; (b) 1850 –1680 cm^{-1} range; (c) 1500–1300 cm^{-1} range; (d) 1300-1000 cm^{-1} range; (e) 1000-600 cm^{-1} range

3.2. Evaluation of stereo-complexing level caused by PDLA with different molecular weight

The selected sc-8 compound obtained when the stereo-complexer PDLA had the Mw of 20.9·10^{4} g/mol, has been evaluated comparatively with the code sc-1 compound previously selected [19], when the stereo-complexer had a Mw of 11.6·10^4 g/mol (Fig. 2).

3.2.1 Chemical structure (comparatively evaluation)

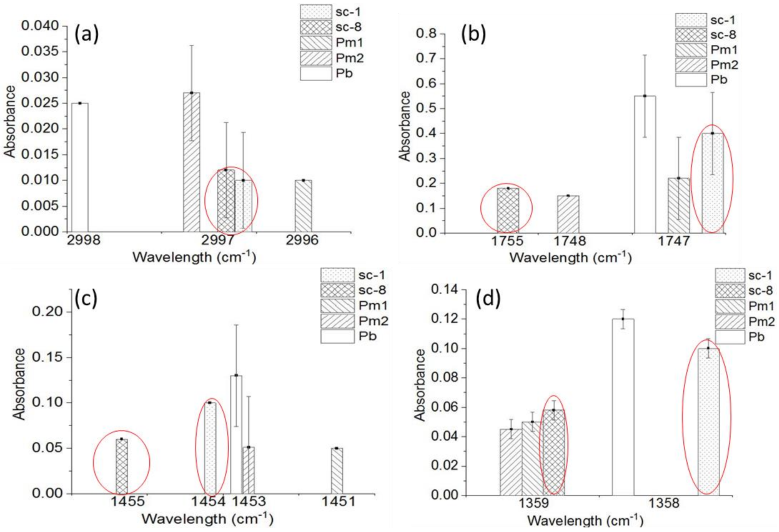
Compared to sc-1, in the case of sc-8 compound, the decrease of all the intensity absorptions, both of those involved in the racemic stereo-complexation and of those modified because of the stereo-complexation, was observed. At the same time, some of the peaks have been shifted. All the chemical structure modifications observed between the two sc-compounds are furtherly detailed.

The asymmetric methyl absorption from 2997 cm^{-1} is 16% lower in the case of sc-8 compound compared to sc-1 compound (Fig. 2a). The C=O stretching absorption from 1747 cm^{-1} is with 55% smaller and its peak is shifted with 8 cm^{-1} (Fig. 2b). The $-CH_3$ symmetric stretching from 1359 cm^{-1} is with 42% smaller and shifted with 1 cm^{-1} (Fig. 2d). The absorption of the C=O bend at 1211 cm^{-1} is with 56% smaller and shifted with 4 cm^{-1}(Fig. 2f). The -CH absorption from $-CH_3$ at 1455 cm^{-1} is with 40% smaller and its peak is shifted with 1 cm^{-1} (Fig. 2c).

Another main effect observed in the case of the sc-8 compound was the disappearance of the absorption peak from 1304 cm^{-1}, which represents the CH+C-O-C interactions, this being a result of the racemic stereo-complexation.

Spectral changes were also observed in the case of -C-O-C asymmetric stretching from 1180 cm^{-1}, which is with 43% smaller and shifted with 2 cm^{-1} for sc-8 (Fig. 2g). The -C-O- stretching from 1127 cm^{-1} has not moved and is with 41% smaller than the one of sc-1 (Fig. 2h).

The absorption indicating the -OH bend from 1043 cm^{-1} is with 45% smaller (Fig. 2i) and those assigned to -C-C stretching from 871 cm^{-1} (Fig. 2j) and $-CH_2$ rocking from 755 cm^{-1} are with 39% smaller (Fig. 2k).



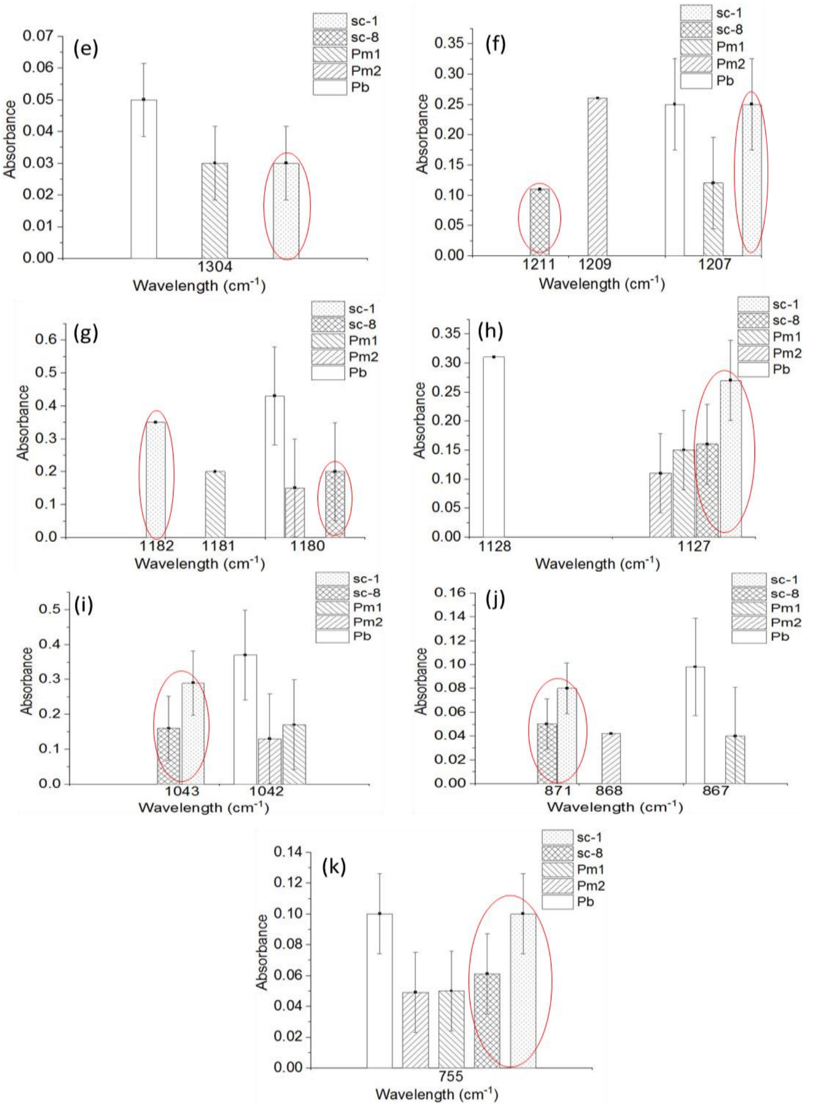
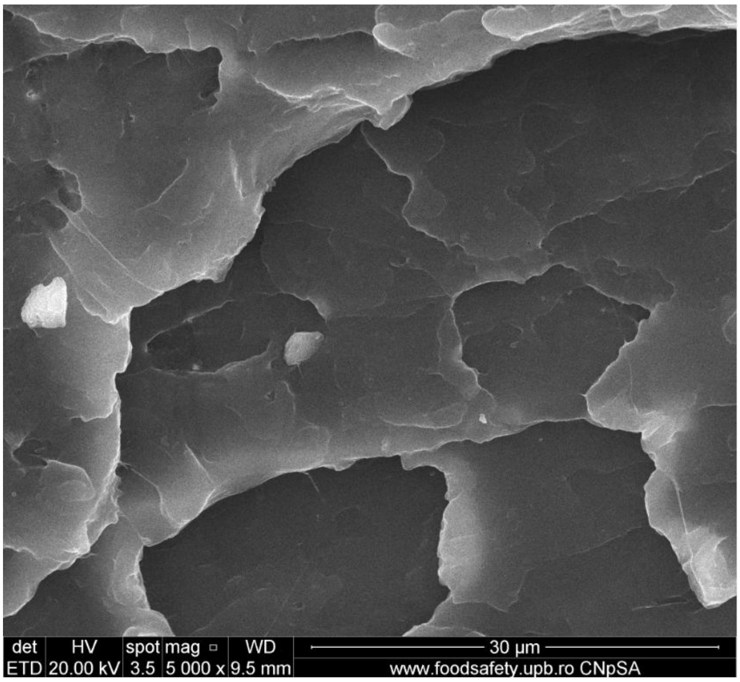


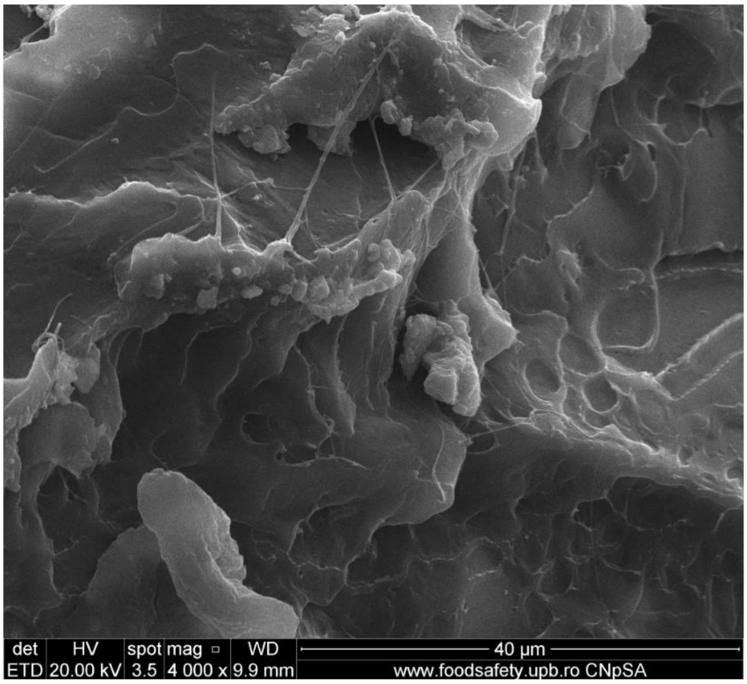
Fig. 2. The absorbance at (a) 2996–2998 cm^{-1}; (b) 1747–1755 cm^{-1} ;(c) 1451–1455 cm^{-1} ;(d) 1358–1359 cm^{-1}; (e) 1304 cm^{-1}; (f) 1207-1211 cm^{-1}; (g) 1180-1182 cm^{-1}; (h) 1127-1128 cm^{-1}; (i) 1042–1043 cm^{-1}; (j) 867-871 cm^{-1}; (k) 755 cm^{-1}.

3.2.2 Morphological changes (comparatively evaluation)

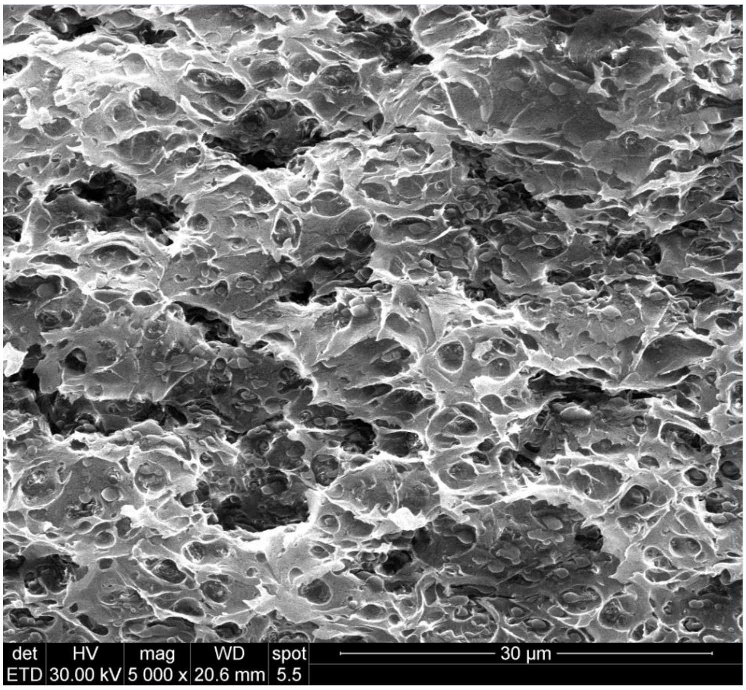
Changes in the morphological structure of the two selected compounds (sc-1 and sc-8) are presented in fig.2 which emphasize the interactions generating the racemic crystallization, proving that the stereo-complexation took place (Fig. 3).



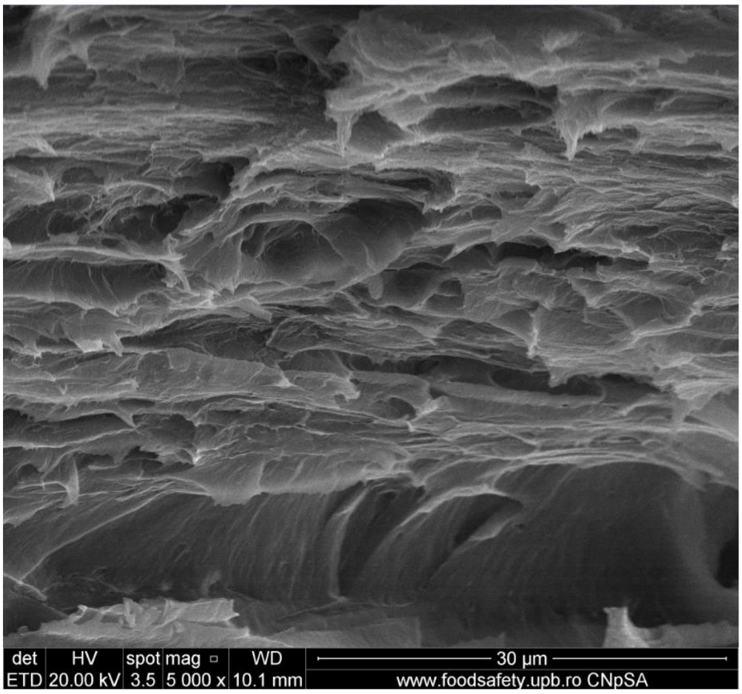
(a) P_b - Base polymer (Mw $4.5 \cdot 10^4$g/mol & 0.5% D)



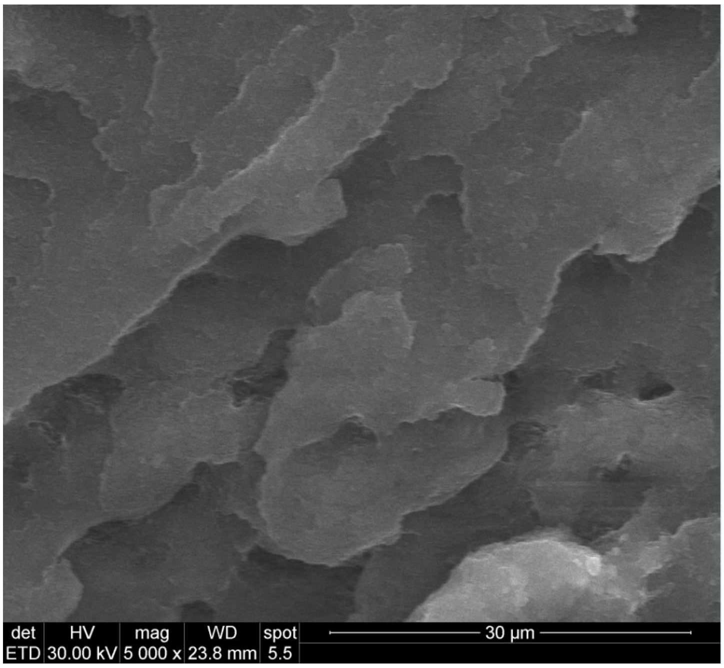
(b) P_{m1} - stereo-complexer (Mw $11.6 \cdot 10^4$ g/mol & 4% D)



(c) P_{m2} - stereo-complexer (Mw $20.9 \cdot 10^4$g/mol & 4.5% D)



(d) sc-1 - stereo-complexed compound

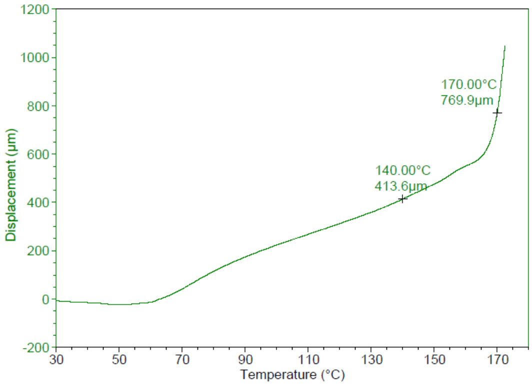


(e) sc-8 - stereo-complexed compound

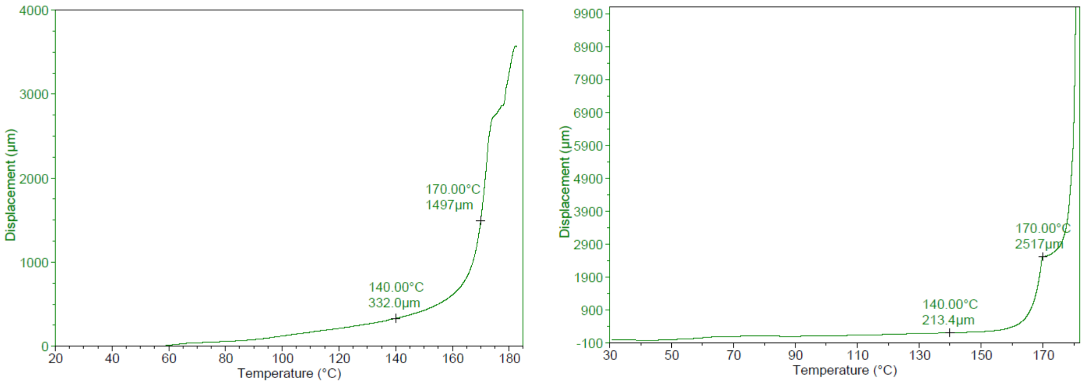
Fig. 3. SEM micrographs of (a) P_b – base polymer; (b) P_{m1} – stereo-complexer; (c) P_{m2} – stereo-complexer, (d) sc-1 – stereo-complexed compound; (e) sc-8 – stereo-complexed compound

3.3. Functional Properties

The functional properties of the selected compound sc-8 confirmed that if the PLLA (Mw of $4.5 \cdot 10^4$ g/mol) is modified with a PDLA with higher molecular weight ($20.9 \cdot 10^4$ g/mol, a compound with a heat deflection temperature of 140°C is obtained, which means better thermal behavior as the one characterizing the PLLA (Fig. 4). The thermal behavior gets worse when the PDLA with lower molecular weight was used.



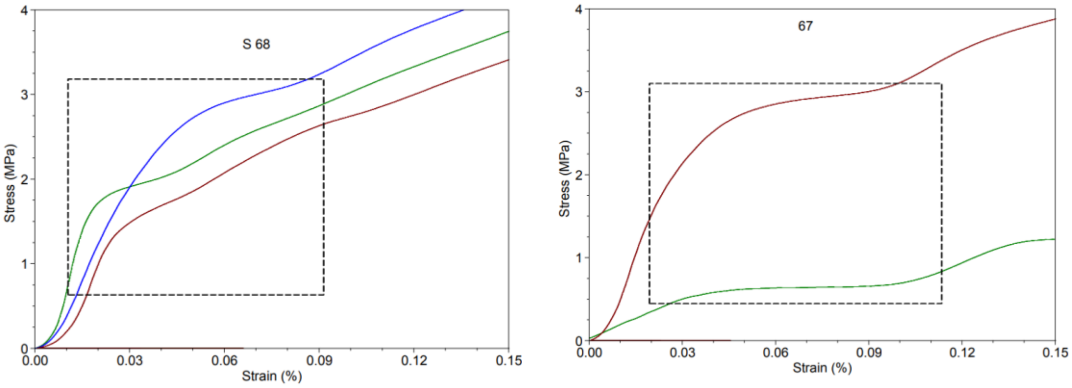
(a)



(b) (c)

Fig. 4. HDT Curve for (a) base-polymer; (b) sc-1 (using stereo-complexer with Mw 11.6·10^4 g/mol and 4% D); (c) sc-8 (using stereo-complexer with Mw 20.9·10^4 g/mol and 4.5% D)

The stress-strain curves (Fig. 5) recorded for the 2 selected sc-compounds obtained by using the stereo-complexers P_{m1} (11.6·10^4 g/mol) and P_{m2} (20.9·10^4 g/mol) shows that, the fracture has changed, following the stereo-complexation, from brittle to ductile, being much more obvious in the second situation (Fig. 5b). It can be stated that a better control of the parameters that influence the samples obtaining will improve the mechanical properties.



(a) (b)

Fig. 5. Stress-strain curves for: (a) sc-1 (using stereo-complexer with Mw 11.6·10^4 g/mol); (b) sc-8 (using stereo-complexer with Mw 20.9·10^4 g/mol)

6. Conclusions

The aim of the current paper was to establish the optimal stereo-complexer molecular characteristics of PDLD with selected molecular weight and polydispersity index which in stereo-complexation with a PLLA grade designed for 3D printed, enhance the racemic crystallization till a functional properties level of practical importance for 3D printed automotive items.

The realized studies proves that the stereo-complexation depends on the molecular weight and the polydispersity index of the stereo-complexer (PDLA), and for the selected PDLA the generated structural and morphological changes are as follows:

- Decreasing in the characteristic FTIR peaks intensity with 16-56%, shifting of the main peaks with 1-8 cm^{-1} and disappearance of the peak from 1304 cm^{-1}.
- Changes of the SEM morphologies mainly at the interfaces which turned into zones with individual structure.
- The increasing of the HDT from 60^{0}C till 140^{0}C.
- The conversion of the breaking character from brittle to a ductile one.

The obtained results had proved that in case of PLLA with molecular weight of $4.5\cdot10^4$ g/mol and 0,5 polydispersity index, the better racemic crystallization effect was registered with a PDLA with molecular weight of $20.9\cdot10^4$ g/mol and 4,5 polydispersity index.

Funding: The work on this paper was supported by: A. Cohesion funds of the European Union POC-A1- A1.2.3-G-2015- P_40-352 – SECVENT 81/2016, “Sequential processes of closing the side streams from bioeconomy and innovative (bio)products resulting from it”, Subsidiary project 2608/2022, Government of Romania, Ministry of Research and Innovation and through B. no. 40/PCCDI/2018/project 5.

REFERENCES

[1]. Global Lactic Acid and Polylactic Acid Market Size 2017 by End-Use [Lactic Acid (Industrial, Food and Beverages, Pharmaceuticals, Personal Care) and Polylactic Acid (Packaging, Agriculture, Electronics, Textiles)], by Region and Forecast from 2018 to 2025, Adroit Market Research, 2019

[2]. F. Thewihsen, S. Karevska, A. Czok, C. Pateman-Jones and D. Krauss, “If 3D printing has changed the industries of tomorrow, how can your organization get ready today?”, EY global 3D printing survey, 2016

[3]. A. Zarski, K. Bajer, J. Kapusniak, “Review of the Most Important Methods of Improving the Processing Properties of Starch toward Non-Food Applications”, Polymers 2021, 13, 832

[4]. T. Mekonnen, M. A. Dubé, “Renewable Polymers: Processing and Chemical Modifications”, Processes 2019, 7, 398

[5]. S. A. Ashter, “Introduction to Bioplastics Engineering”, Elsevier Inc., 2016

[6]. A. S. Elakkad, “3D Technology in the Automotive Industry”, International Journal of Engineering Research & Technology (IJERT), Vol. 8 Issue 11, 2019, 248-251

[7]. N. Shahrubudin, T.C. Lee, R. Ramlan, “An Overview on 3D Printing Technology: Technological, Materials, and Applications”, Procedia Manufacturing 35 (2019), 1286–1296

[8]. F. Eckes, “Impact of 3D Printing on Supply Chain Relationships - A Study within the German Automotive and Logistics Sector”, JÖNKÖPING University, 2016

[9]. S. M. Gutiérrez, “How Additive Manufacturing is shaping Global Supply Chains”, TecnoCampus, 2021

[10]. E. Castro-Aguirre, F. Iniguez-Franco, H. Samsudin, X. Fang, R. Auras, “Poly(lactic acid)—Mass production, processing, industrial applications, and end of life”, Adv. Drug Deliv. Rev. 2016, 107, 333–366

[11]. D. Notta-Cuvier, J. Odent, R. Delille, M. Murariu, F. Lauro, J.M. Raquez, B. Bennani, P. Dubois, “Tailoring polylactide (PLA) properties for automotive applications: Effect of addition of designed additives on main mechanical properties”, Polymer Testing, 2014

[12]. V. Nagarajan, A. K. Mohanty and M. Misr, “Perspective on Polylactic Acid (PLA) based Sustainable Materials for Durable Applications: Focus on Toughness and Heat Resistance”, ACS Sustainable Chem. Eng. 2016

[13]. R.A. Ilyas, S.M. Sapuan, “Polylactic Acid (PLA) Biocomposite: Processing, Additive Manufacturing and Advanced Applications”, Polymers 2021, 13, 1326

[14]. E. Balla , V. Daniilidis et al., “Poly(lactic Acid): A Versatile Biobased Polymer for the Future with Multifunctional Properties—From Monomer Synthesis, Polymerization Techniques and Molecular Weight Increase to PLA Applications”, Polymers 2021, 13, 1822

[15] Precedence Research, “Polylactic Acid Market (By Raw Material: Corn starch, Sugarcane & sugar beet, Cassava, and Others; By Application: Packaging, Agriculture, Transport, Electronics, Textiles, Others) - Global Industry Analysis, Size, Share, Growth, Trends Analysis, Regional Outlook and Forecasts, 2021 - 2030”, Globe Newswire, Ottawa, 2021

[16]. Y. Feng, P. Ma, P. Xu, R. Wang, W. Dong, M. Chen, C. Joziasse, “The crystallization behavior of poly(lactic acid) with different types of nucleating agents”, Int. J. Biol. Macromol. 2018, 106, 955–962.

[17]. A. Bouzouita, “Elaboration of polylactide-based materials for automotive application: Study of structure-process-properties interactions”, Ph.D. Thesis, Université de Valenciennes et du Hainaut-Cambresis, Université de Mons, Mons, Belgium, 2016.

[18]. S. Mathe, D. Dimonie, M. Cristea, “Thermal analysis and polarized light microscopy as methods to study the increasing of the durability of PLA designed for 3D printing”, Int. J. Polym. Anal. Charact. 2021, 26, 253–264.

[19]. D. Dimonie, S. Mathe, M. Iftime, D. Ionita, R. Trusca, S. Iftimie, “Modulation of the PLLA Morphology through Racemic Nucleation to Reach Functional Properties Required by 3D Printed Durable Applications”, Materials 2021, 14, 6650.

[20] D. Dimonie, C. Vasile, R. Coserea, S. Garea, F. Andrei, “Characterization of the nucleation efficiency based crystallization behaviour and other polypropylene properties”, Materiale Plastice 2, 46, 2009

[21]. J. McGinty, N. Yazdanpanah, C. Price, J. Horst and J. Sefcik, “Nucleation and Crystal Growth in Continuous Crystallization”, The Handbook of Continuous Crystallization, 2020

[22]. V. P. Martino, R. A. Ruseckaite and A. Jiménez, „Thermal and mechanical character-ization of plasticized poly (l-lactide-co-d,l-lactide) films for food packaging”, Journal of Thermal Analysis and Calorimetry, Vol. 86, 3, 707–712, 2006

[23]. L. Xiao, B. Wang, G. Yang, M. Gauthier, “Poly (Lactic Acid)-based biomaterials: Synthesis, modification and applications”, Biomed. Sci. Eng. Technol. 2012, 11, 247–282.

[24]. R. Ahmed, “Poly(Lactic Acid) Stereocomplex Formation in the Melt: Limitations and Prospectives”, Ph.D. Thesis, Technische Universiteit Eindhoven, The Netherlands, 2011.

[25]. G. Kister, G. Cassanasand M. Vert, “Effects of morphology, conformation and configuration on the IR and Raman spectra of various poly(lactic acid)s”, Polymer Vol.39 No.2, pp. 267-273,1998

[26]. J. Zhang, H. Sato, H. Tsuji, „Infrared Spectroscopic Study of CH3···OC Interaction during Poly(l-lactide)/Poly(d-lactide) Stereocomplex Formation”, Macromolecules 38(5), 2005

[27]. A. Gupta, Akhilesh K. Pal, E. M. W. V. Katiyar, „Effects of Amphiphilic Chitosan on Stereocomplexation and Properties of Poly(lactic acid) Nano-biocomposite", Scientific Reports (2018) 8:4351

[28]. M. Eleuteri, M. Bernal, M. Milanesio, O. Monticelli, A. Fina, "Stereocomplexation of Poly(Lactic Acid)s on graphite nanoplatelets: From functionalized nanoparticles to self-assembled nanostructures" Front. Chem. 2019, 7, 176.

[29]. Y. Srisuwanand, Y. Baimark, „Mechanical properties and heat resistance of stereo-complex polylactide/copolyester blend films prepared by in situ melt blending followed with compression molding", Heliyon. 4(12), 2018

[30]. S. Mathe, B. Gîrbaciu and D. Dimonie, "DSC study of cold crystallization process characterizing the stereocomplexed PLA compounds", PRIOCHEM, 15th Edition, 2019, Bucharest

[31]. B. Girbaciu, M. Cristea, D. Ionita, S. Mathe and D. Dimonie, "Physical modification of PLA for increasing its durability (Polarizing Light Microscopy Study)", PRIOCHEM, 15th Edition, 2019, Bucharest

[32]. S. Mathe, D. Dimonie, "Study of increasing durability of PLA designed for 3D printing through nucleation with sulphonic ester derivate as nucleating agent", PRIOCHEM, 16th Edition, 2020, Bucharest

[33]. Z. Qiu, Z. Li, "Effect of orotic acid on the crystallization kinetics and morphology of biodegradable poly(L-lactide) as an efficient nucleating agent", Ind. Eng. Chem. Res. 2011, 50, 12299–12303.