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► **To cite this version:**

Morgan Deroiné, Isabelle Pillin, Gwenaël Le Maguer, Marie Chauvel, Yves Grohens. Development of new generation fishing gear: A resistant and biodegradable monofilament. *Polymer Testing*, 2019, 74, pp.163 - 169. <10.1016/j.polymertesting.2018.11.039>. <hal-03485686>

HAL Id: hal-03485686

<https://hal.science/hal-03485686v1>

Submitted on 20 Dec 2021

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Development of new generation fishing gear: A resistant and biodegradable monofilament

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Abstract

Developing biodegradable formulations or controlled-lifetime polymers is one of the issues of tomorrow. In order to reduce the impact of fishing and to fight the expansion of plastic debris in the marine environment, a new generation of monofilament, resistant and biodegradable, has been developed in this study.

The monofilament was obtained by melt-spinning extrusion, and the effect of drawing on the structure and properties of a versatile polymer, poly(butylene succinate) (PBS), was examined. The influence of the draw ratio (3.5, 4, and 4.5) and the drawing oven temperature (60, 80, and 100°C) was investigated, and the modifications obtained by drawing were monitored by means of several characterizations. The mechanical properties of the monofilament before and after drawing were examined by a tensile test. The evolution of the crystallinity and macromolecular chain orientation of the monofilament were determined by thermal analysis (DSC) and Fourier Transform Infra-Red (FTIR) spectroscopy, respectively.

A significant increase in mechanical properties was obtained on a tensile test carried out after drawing. Changes at macromolecular scale were also important: the evolution of crystallinity after drawing was observed and depended on both the temperature and the draw ratio. Then, orientation investigations explained the results obtained through the tensile test and DSC.

The results suggest that poly(butylene succinate) can be an ecofriendly alternative to traditional polyamides commonly used for fishing gear.

Keywords: poly(butylene succinate), PBS, monofilament, fishing line, biodegradable, mechanical properties, orientation

1. Introduction

The first fishing gears were produced using available resources such as cotton, flax, or hemp fibers [1]. Over the last decade, synthetic materials have appeared with the technological development of polyamides (PA) [2,3] and progressively replaced natural fibers. PA became the most commonly used

1 material for fishing gears, but their environment stability needs to be enhanced against the effects of
2 the weather, such as ultraviolet (UV) degradation [4,5]. The durability of polymers explains their
3 widespread use, but it could also be a considerable drawback in specific cases. Despite the possible
4 fragmentation of polyamides, they remain extremely persistent in the marine environment, and their
5 lifetime is estimated to be over several hundred years [6–8]. Recently, severe environmental pollution
6 by plastic debris has been observed, and their large-scale accumulation in oceanic gyres is now well
7 established [9,10]. In the long term, consequences are devastating for marine wildlife [11,12] with the
8 ghost fishing of macroplastics [13,14], the ingestion of microplastics [15,16], and so on. It is also an
9 uncomfortable reality for fishing activities such as helix blocking or sorting in the nets.

10 One of the objectives of this study is to develop an ecofriendly monofilament showing high
11 mechanical performance, such as that of the fishing lines currently available. A biopolymer commonly
12 used, poly(butylene succinate) (PBS), appears to be a realistic alternative to conventional materials.
13 PBS is an aliphatic polyester synthesized from petrochemical resources based on 1,4-butandiol and
14 succinic acid, and it is biodegradable. Its properties are comparable to those of traditional polyolefins,
15 and it is mainly used in the packaging field (flexible packaging, coated paper, disposable dishware,
16 etc.) [17].

17 Biodegradable polymers have already been investigated for marine applications. Some filaments based
18 on polylactide (PLA) exist with the innovative rope Organic® (FSE Robline) or the Elite® BioTwine
19 (LankHorst Yarns). However, PLA is able to biodegrade only under specific conditions [18].
20 Researchers working with polyhydroxyalkanoates (PHA) have shown that their biodegradation rates
21 are rather fast in marine environments [19–21]. PBS can be degraded in various environments such as
22 soil burial, activated sludge, or compost [22–24], and the biodegradation rate is strongly dependent on
23 its environmental parameters (microorganisms, nutrients, temperature, humidity). The biodegradation
24 of PBS in marine environments, according to a respirometric test such as biochemical oxygen demand
25 (BOD), has already been investigated by Kasuya et al. [25] and shows slow degradation in seawater
26 after one month of immersion at 25°C.

27 Concerning an application such as fishing gear, the monofilaments used have to be resistant and
28 efficient. In order to enhance the mechanical properties of PBS, some techniques discussed in the
29 literature involve matrix reinforcement with fillers [26] or vegetable fibers [27,28]. Blending PBS with
30 another biopolymer is also used to modulate properties [29,30]. In this study, monofilaments were
31 obtained by melt spinning, and our investigations focused upon the influence of the process
32 parameters on the final properties of the monofilament.

33 The influence of the draw ratio (3.5, 4, and 4.5) and the drawing oven temperature (60, 80, and 100°C)
34 was examined. The modifications caused by drawing on the mechanical behavior were monitored by
35 tensile tests. The spinning and drawing processes induce severe changes at a molecular scale.

1 Parameters such as crystallinity and the orientation of the macromolecular chain play an important role
2 in the determination of PBS properties and were also examined. A DSC analysis was performed to
3 monitor thermal properties and the evolution of crystallinity. A polarized Fourier Transform Infra-
4 Red, which is a powerful technique, was used to analyze the orientation [31], as the evaluation of
5 orientation in a polymer provides valuable information for greater understanding of its structure and
6 properties. In the literature, the evolution of crystallinity and orientation has already been examined on
7 PET [32–34], or PS [35,36], but little information is available on PBS. Lyoo *et al.* [37] have worked
8 on the effects of PBS polymer ratio on drawing behavior, but they investigated specific drawing zones
9 on film samples.

10 In this study, we report the evolution of properties of a **potentially useful biodegradable monofilament**
11 after drawing and examine the influence of drawing on its thermal and mechanical properties.

12

13 **2. Experimental setup**

14 **2.1 Material**

15 Poly(1,4-butylene succinate) PBS, commercialized in pellet form under the grade BIONOLLE 1001,
16 was supplied by Showa Highpolymer Company (Japan). According to the manufacturer, PBS is a
17 semi-crystalline polymer characterized by a density of 1.25 g.cm^{-1} , a glass transition temperature of -
18 34°C , and a melting temperature of 114°C [38]. PBS pellets were dried at 60°C under vacuum for 12h
19 before processing.

20

21 **2.2 Preparation of the sample**

22 The monofilaments were prepared by melt-processing using a single-screw extruder with a round
23 nozzle of 2 mm of diameter (Scamex Company - France). The optimal distribution temperatures for
24 PBS spinning were $140\text{-}145\text{-}145\text{-}150^\circ\text{C}$ respectively from the feed zone to the nozzle. The speed of
25 the screw was between 5 and 20 rpm, and the monofilament was cooled via a water bath. After
26 cooling, the monofilament was pulled by a first roll (R1), then went through an oven. Drawing was
27 carried out on line by a second roll (R2). Moreover, drawing a polymer is only possible in a specific
28 temperature range, between the glass transition temperature (T_g) and the melting temperature (T_m).
29 The theoretical drawn ratio (DR_{th}) is expressed as the ratio between the speed of the second roll (V_{R2})
30 and the speed of the initial roll (V_{R1}) (Eq.1):

$$31 \quad DR_{th} = \frac{V_{R2}}{V_{R1}} \quad (Eq.1)$$

32 The final diameter obtained of undrawn and drawn monofilament is of $1.10 \pm 0.05 \text{ mm}$.

33

34 **2.3 Characterization techniques**

35 **2.3.1 Mechanical tests**

1 Tensile tests were performed on an Instron 5566A machine equipped with a 1kN load cell. The
2 monofilaments were tested according to the standard NF EN ISO 2062, under environmentally
3 controlled laboratory conditions (23°C, 50% RH). The main parameters of the test were an initial
4 length of 250 mm, a loading speed of 250 mm.min⁻¹ and specific grips for monofilament were used. At
5 least five specimens were tested for each condition, and the results were averaged arithmetically.
6 Another important parameter in the fishing sector, namely tenacity, was also analyzed. The tenacity of
7 a monofilament is the maximum strength obtained during the tensile test relative to its linear mass
8 (expressed in tex). One of the advantages of this parameter is that the diameter is not taken into
9 account, which enables comparison of all the filaments.

10

11 2.3.2 Thermal properties

12 A differential scanning calorimetry (DSC) analysis was performed on samples of about 10 mg, in
13 standard aluminum pans, using Mettler-Toledo DSC822e equipment under a nitrogen atmosphere.
14 Data were recorded at a heating rate of 20°C.min⁻¹. The samples were heated from 20 to 200°C and
15 kept at 200°C for 2 minutes. The samples were then cooled to -20°C and finally a second heating scan
16 was performed from -20 to 200°C. Thermal transition temperatures were recorded such as the melting
17 temperature (T_m) or the crystallization temperature (T_c) and also the melting enthalpy (ΔH_m) or
18 crystallization enthalpy (ΔH_c), during the first and the second heating. The degree of crystallinity was
19 determined by Eq.2:

$$20 \chi = \frac{\Delta H_m}{\Delta H_{100\%}} \quad (Eq.2)$$

21 where ΔH_m (J.g⁻¹ of polymer) is the melting enthalpy obtained during the first heating. ΔH_{100%} is the
22 melting enthalpy for PBS of 100% crystallinity, taken to be 200 J.g⁻¹ [29].

23

24 2.3.3 Polarized Fourier transform infrared (FT-IR)

25 Static polarized FT-IR spectra were recorded with a minimum of 32 scans per sample at a 4 cm⁻¹
26 spectral resolution using a Bruker Vertex 70 spectrometer equipped with Attenuated Total Reflectance
27 (ATR) module with diamond crystal. All spectra were recorded in the absorbance mode in the 4000-
28 600 cm⁻¹ region.

29 The molecular orientation of a polymer can be quantified by infrared linear dichroism (IRLD) via the
30 dichroic ratio of absorbance between two spectra: one measured with parallel polarized light (A_p) and
31 the other one with a light polarized perpendicularly (A_s) to the direction of stretching. The polarizers
32 were rotated to 0° at 90° and spectrum-recorded, thus enabling a direct measurement of the dichroic
33 ratio:

$$34 R = \frac{A_p}{A_s} \quad (Eq.3)$$

1 Considering uniaxial stretching, the orientation function, $\langle P_2 \rangle$, is related to the dichroic ratio
2 according to the following relationship [39]:

$$3 \quad \langle P_2 \rangle = \left(\frac{2}{3 \cos^2 \alpha - 1} \right) \left(\frac{R-1}{R+2} \right) \quad (Eq.4)$$

4
5 where α is the angle between the transition dipole moment of selected vibration and the main chain
6 axis of the polymer. The limiting values of $\langle P_2 \rangle$ are 0 and 1 for random and perfect orientation along
7 the stretching direction, respectively.

8 **3. Results and discussion**

9 **3.1 Mechanical properties**

10 Tensile tests were carried out on the undrawn and drawn PBS monofilament. The influence of the
11 oven temperature during drawing was first examined. The mechanical behaviors of the different
12 samples are shown in Figure 1 and the mechanical properties such as Young modulus, stress at break,
13 strain at break, and percentage gain property are summarized in Table 1.

14 Concerning the undrawn sample, an important ductility is observed. The failure strain exceeds 500%
15 (Table 1) with a low elastic modulus equal to 564 MPa, close to the mechanical properties of
16 traditional polyolefin [40]. After drawing and for all the drawing temperatures, the monofilament
17 behaviors significantly evolve compared to the undrawn PBS (Figure 1a). An initial elastic linear
18 behavior is observed with an important increase in the stress at break from 64 MPa to 267 MPa and a
19 decrease of strain in the break from 500% to 122.7%, for an oven temperature of 80°C and a drawn
20 ratio of 4 in particular (Table 1).

21 Moreover, for a constant draw ratio of 4, a small influence of the oven temperature is noted up to
22 80°C, with a slight evolution of strain at break between 60°C and 80°C from 214 MPa to 267 MPa.
23 For a drawing at 100°C, the curve behavior is lower than 80°C and for all mechanical properties, strain
24 at break reaches only 243 MPa. At 100°C, we can assume the drawing temperature is close to the
25 melting temperature of 114°C, with a possible onset of melting on chain mobility. We observe that at
26 60°C, no melting is present during drawing, and the gain in mechanical properties is similar to that
27 obtained during cold drawing. At the highest used temperature (100°C), we can assume that a tiny part
28 of PBS begins to melt. Therefore, this melt fraction shows strong mobility and could not contribute to
29 the strain. These macromolecular chains cannot crystallize in spherulites, or only in very small
30 spherulites.

31 The influence of the draw ratio is shown in Figure 1b. For these tests, the oven temperature was kept
32 constant at 80°C. A significant dependence of the draw ratio on mechanical behaviors is observed.
33 When increasing the draw ratio, the stress at break increases while the strain at break decreases, with a
34 progressive evolution of gain property as shown in Table 1. For example, Young's modulus increases

1 from 1076 to 1312 to 1483 MPa and stress at break decreases from 148 to 122.7 to 107.6 %,
2 respectively for a drawn ratio of 3.5, 4 and 4.5.

3 Hot drawing during the process induced significant changes with a potential alignment of the chains of
4 PBS along the drawing direction, which could explain the important increase of the mechanical
5 properties. Although chain mobility seems to be facilitated by the oven temperature up to 80°C, the
6 results indicate a higher influence of the draw ratio on the evolution of mechanical properties than the
7 oven temperature. The optimum processing condition is attained by the on-line spinning and drawing
8 of PBS with a draw ratio of 4.5 and an oven temperature of 80°C.

9 These tests enable reaching 60% of the strain at break of traditional monofilament in polyamide
10 (personal data). As described in the literature [41], a second drawing could help getting close to the
11 mechanical performance of PA, and we obtained promising first results.

12 However, further analyses could be investigated for greater understanding of the monofilament
13 behavior such as the evolution of crystallinity or orientation after drawing.

14 3.2 Thermal analysis

15 During the spinning process, structural changes appear at molecular level with a reorganization of
16 macromolecular chains. Therefore, the influence of the drawing temperature and ratio on the melting
17 characteristics is shown in Figure 2. Table 2 summarizes the influence of drawing on the thermal
18 transition temperature of PBS (T_m and T_c), enthalpies (ΔH_m and ΔH_c) and crystallinity (χ_c), during the
19 first and second heating scans. The evolution of crystallinity after drawing during the first heating was
20 also investigated.

21 Considering the undrawn behavior, a first exothermic peak followed by an endotherm peak are
22 observed, corresponding to the melting enthalpy. According to the literature, the PBS melting behavior
23 is well-known to be complex [42]. Indeed, PBS has a melting peak between 112 and 116°C according
24 to its molar mass and thermal history, typically 115.8°C in this study. Its melting behavior is
25 particularly interesting since it shows a complex succession of endotherms during melting. In fact,
26 multiple melting peaks were observed for PBS, varying according to the molar mass, crystallization
27 temperature, cooling rate, and so on. The multiple peak is largely discussed in the literature and is
28 generally ascribed to the co-existence of crystal melting of different stability (dual morphology
29 mechanism) and/or to the melting-recrystallization-melting process [43]. Yoo *et al.* used DSC
30 combined with WAXD to show that no crystal change occurs when PBS is crystallized at different
31 temperatures [44]. It has been concluded that the multiple melting behavior of PBS formed thermally
32 is not due to different crystal modification but can be related to a melting recrystallization process.

33 The influence of the oven temperature during drawing is shown in Figure 2a. The first exothermic
34 peak corresponding to cold crystallization disappears for each sample after drawing, for a constant

1 draw ratio. This phenomenon can be explained by a change in morphology caused by the drawing. For
2 a drawing temperature fixed at 80°C (Figure 2b), a melting peak appears at 95°C, but it disappears for
3 a drawing temperature fixed at 60°C and 100°C. Wang *et al.* named this peak T_{m2} and demonstrated
4 that it is temperature dependent [42]. Concerning the mean peak called T_{m1} , it appears to widen with
5 the increase of the drawing temperature and could correspond to a thickening of crystalline lamellae.
6 According to the enthalpy value in Table 2, during the first heating, a significant increase is observed
7 between the melting enthalpy of the undrawn and the drawn monofilaments. Moreover, the enthalpy
8 behavior of the drawn monofilament shown in Figure 2a seems to be similar regardless of the
9 temperature, which is directly related to the evolution of crystallinity from 16% for the undrawn
10 monofilament to 31.9, 33.6, and 33.1% for the drawing at a different temperature of 60, 80, and
11 100°C, respectively. During drawing, the influence of the oven temperature on crystallinity is slight,
12 and this trend is in accordance with the mechanical properties obtained in the previous tests. Lyoo *et*
13 *al.* [37] obtained similar results, as crystallinity remained nearly constant for a constant draw ratio but
14 with a different initial polymer ratio.

15 Considering the influence of the drawn ratio shown in Figure 2b, enthalpy modifications are more
16 important with a narrow peak for a ratio of 3.5 and a wider peak for a ratio of 4.5. Moreover, the
17 melting enthalpy progressively increases as a function of the drawn ratio, from 33.2 J/g for the
18 undrawn to 51.9, 67.1, and 68.5 J/g, for a drawn ratio of 3.5, 4, and 4.5, respectively. Concerning the
19 degree of crystallinity, the most important gap is obtained between a drawn ratio from 3.5 to 4, with an
20 increase from 26 to 33.6% respectively. For a ratio of 4.5, the crystallization is closed to the one
21 obtained for a drawn ratio of 4, with a value of 34.2%. From a certain rate of drawing, a limit in the
22 crystallinity fraction is reached. A similar behavior has been already observed for another biopolymer
23 such as PLA [45].

24 Hot drawing induces the chain mobility. The rearrangement of polymer chains promotes the
25 crystallinity ratio and can explain the different mechanical behaviors of the monofilament obtained
26 after drawing, with an important increase of the mechanical properties (Table 2).

27 Figure 3 shows the relation between the evolution of tenacity and crystallinity as a function of the
28 different parameters under investigation: the temperature of the oven during drawing (Figure 3a) and
29 the draw ratio (Figure 3b). Considering Figure 3a, the tenacity of the monofilaments slightly increases
30 with the drawing temperature and seems to follow the evolution of crystallinity. At 100°C, the tenacity
31 tends to stabilize at about 19 cN/tex and crystallinity around 33%. The variations induced by the oven
32 temperature parameter are slight and do not significantly influence the mean properties of the PBS
33 monofilament up to 80°C. In Figure 3b, the tenacity of the monofilament is more dependent on the
34 drawn ratio. In fact, the tenacity progressively evolves from 12.4 to 18.5 and 23.5 cN/tex, as a function
35 of the draw ratio from 3.5 to 4.5. In the literature, some authors reported similar values of PBS

1 tenacity, between 22.6 [46] and 26.9 cN/tex [47], for a draw ratio of 3.7 and 5, respectively. The hot-
2 drawing process with a draw ratio of 4.5 induces high properties for a fishing gear application.

3 4 **3.3 Orientation investigation by IR**

5
6 During the drawing step, the macromolecular chains orient in the drawing direction. At equilibrium,
7 the macromolecules have an isotropic random coil configuration. Under the effect of hot drawing, they
8 tend to take a privileged orientation. An optimized cooling at the exit of the die will allow the
9 macromolecular chains to remain oriented by minimizing the effects of relaxation. In this study, the
10 orientation induced by hot drawing has been quantified by Infrared linear dichroic (IRLD).

11 Figure 4 shows the FTIR spectra of PBS before drawing, in the parallel direction. The main
12 characteristic peaks of PBS are presented below. Two distinct peaks in the region 2980-2850
13 cm^{-1} correspond to deformation vibrations of CH_2 groups. The band in the 1713 cm^{-1} region is
14 attributed to C=O stretching vibrations of the ester group. The peak at 1155 cm^{-1} is assigned to
15 the C-O-C stretching in the ester linkages of PBS.

16 The CH_2 symmetric stretching band (2850 cm^{-1}) can be used to evaluate the PBS average orientation
17 function. The α angle is defined between the transition moment and the chain axis, and it is reported to
18 be 70° [35,48]. The absorbance values obtained as a function of the polarization are summarized in
19 Table 3, and the results of the orientation function P_2 are presented in Figure 5.

20 The orientation function of the undrawn monofilament is first analyzed. The important value obtained
21 for the undrawn monofilament, equal to 0.48, indicates an important orientation during the extrusion
22 process. The capillary flow of the polymer in the die facilitates the orientation of polymer chains along
23 the flow direction. After drawing and considering a constant draw ratio (Figure 5a), the orientation
24 function increases significantly between 60°C and 80°C, with an evolution from 0.58 to 0.73
25 respectively. These results are congruent with the evolution of the crystallinity and the mechanical
26 properties up to 80°C.

27 After drawing at 100°C, a slight increase is observed with a value of P_2 of 0.76. A stabilization
28 tendency at high temperatures is also observed, close to the melting temperature. The increase of strain
29 is related to the evolution of the orientation chain in PBS, but at 100°C, the mechanical properties of
30 the PBS monofilament are lower. This could be due to the orientation of amorphous chains that can
31 crystallize and could increase the cohesion in the material, inducing higher strain. However, at 100°C,
32 a part of PBS is melted during drawing. Therefore, some crystalline parts contributing to high strain
33 could be disordered, despite the crystallization of a small amorphous part. Moreover, this hypothesis is
34 reinforced by the shoulder observed in the melting peak, which suggests the formation of spherulites
35 with different thermal stabilities depending on their size: new spherulites appear from the amorphous

1 phase or there is an increase of lamellae thickness of the primary spherulites. Globally, the overall
2 orientation P2 can increase whereas the mechanical strain decreases with a small disruption in the
3 orientation crystalline part.

4 In Figure 5b, for a constant drawing oven temperature fixed at 80°C, the orientation function increases
5 with the draw ratio. A slight increase is observed between 3.5 and 4, but the most important value is
6 obtained for a draw ratio of 4.5 (0.85). Drawing promotes a macromolecular rearrangement with a
7 preferential alignment of the amorphous and the crystalline chains. This results in closer chain
8 segments, which increases the specific cohesion of the polymer by increasing the orientation, the
9 crystallinity, and the intensity of the molecular interactions, and leads to a significant improvement of
10 the mechanical properties up to a specific temperature of drawing.

11 These results indicate that drawing is the essential factor to obtain a resistant monofilament. A
12 compromise has to be found between the draw ratio and the temperature. For a further analysis of the
13 draw monofilament orientation, the optical birefringence could be a technique worth considering [35].

14 15 4. Conclusion

16 The aim of the study was to propose a new generation of resistant fishing gear, using a biodegradable
17 polymer. Different tests were carried out on poly(butylene succinate) monofilament. This study shows
18 that PBS is a potentially suitable polymer with versatile properties. The mechanical properties of PBS
19 are known to be closer to traditional polyolefin (PE,PP), but after drawing, significant improvements
20 were observed.

21 Both parameters under investigation, namely the draw ratio and the temperature of the oven during
22 drawing, are important to enable optimization of the monofilament properties. A high temperature
23 brings chain mobility, and the drawing carried out on line induces a preferential alignment of the
24 macromolecular chains and promotes significant evolution of PBS properties. The higher properties,
25 such as crystallinity, tenacity, and the orientation function, are obtained with a draw ratio of 4.5 and a
26 temperature of 80°C. This draw ratio induced a closer rearrangement of the chain segments, which
27 increases the specific cohesion of the polymer by increasing the crystallinity. Mechanical properties
28 are clearly promoted after drawing and get close to those of polyamides.

29 This study is a first step in the future development of a biodegradable monofilament. Poly(butylene
30 succinate) could become an eco-friendly alternative to polyamide, particularly used in fishing lines or
31 nets. Moreover, PBS could also be derived from renewable resources with the development of
32 biobased succinic acid [49,50] and 1,4-butandiol [51], but more studies still need to be carried out due
33 to the significant number of secondary products.

34 The mechanical properties could be increased via a post-drawing step or multi-stage drawing [41]. For
35 a fishing gear application, resistance to abrasion and resistance to knots are two non-negligible criteria

1 that could be examined. Ageing studies in marine environment (hydrolytic, UV, etc.) are in progress
2 and would help understand the degradation and biodegradation behaviors and predict the lifetime of
3 the monofilament [21]. Finally, as some researchers have indicated the sensitivity of PBS to ultraviolet
4 radiation [52], adjustments could be necessary to optimize the formulation.

6 Acknowledgements

7 The authors are grateful to the Bretagne Region for providing financial support for this study.

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Figures and Tables

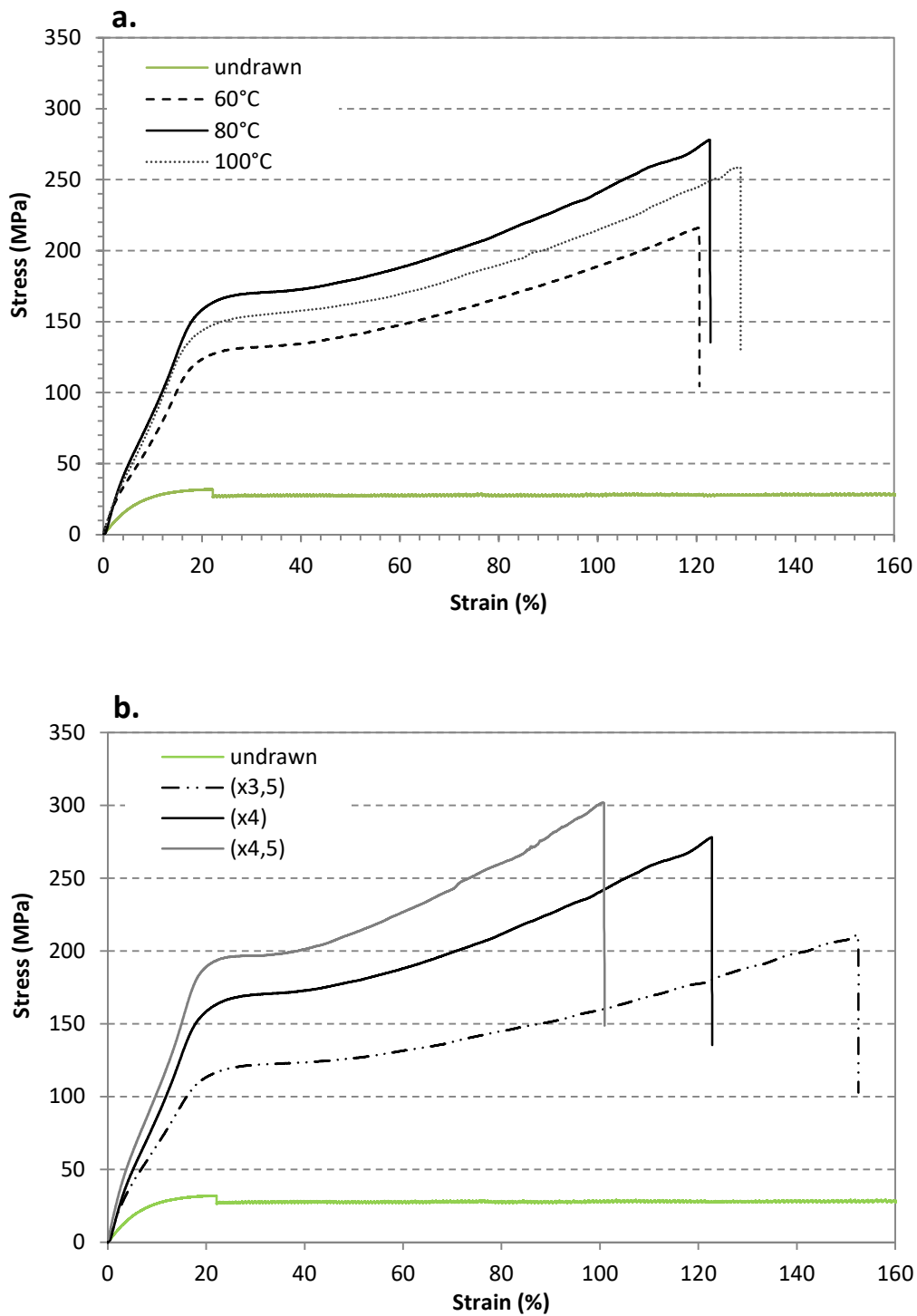


Figure 1: Evolution of the tensile behavior of the PBS monofilament drawn at different temperatures for a constant draw ratio of 4 (a) and at a different draw ratio for a constant temperature of 80°C (b). The undrawn behavior of the PBS monofilament is shown in green.

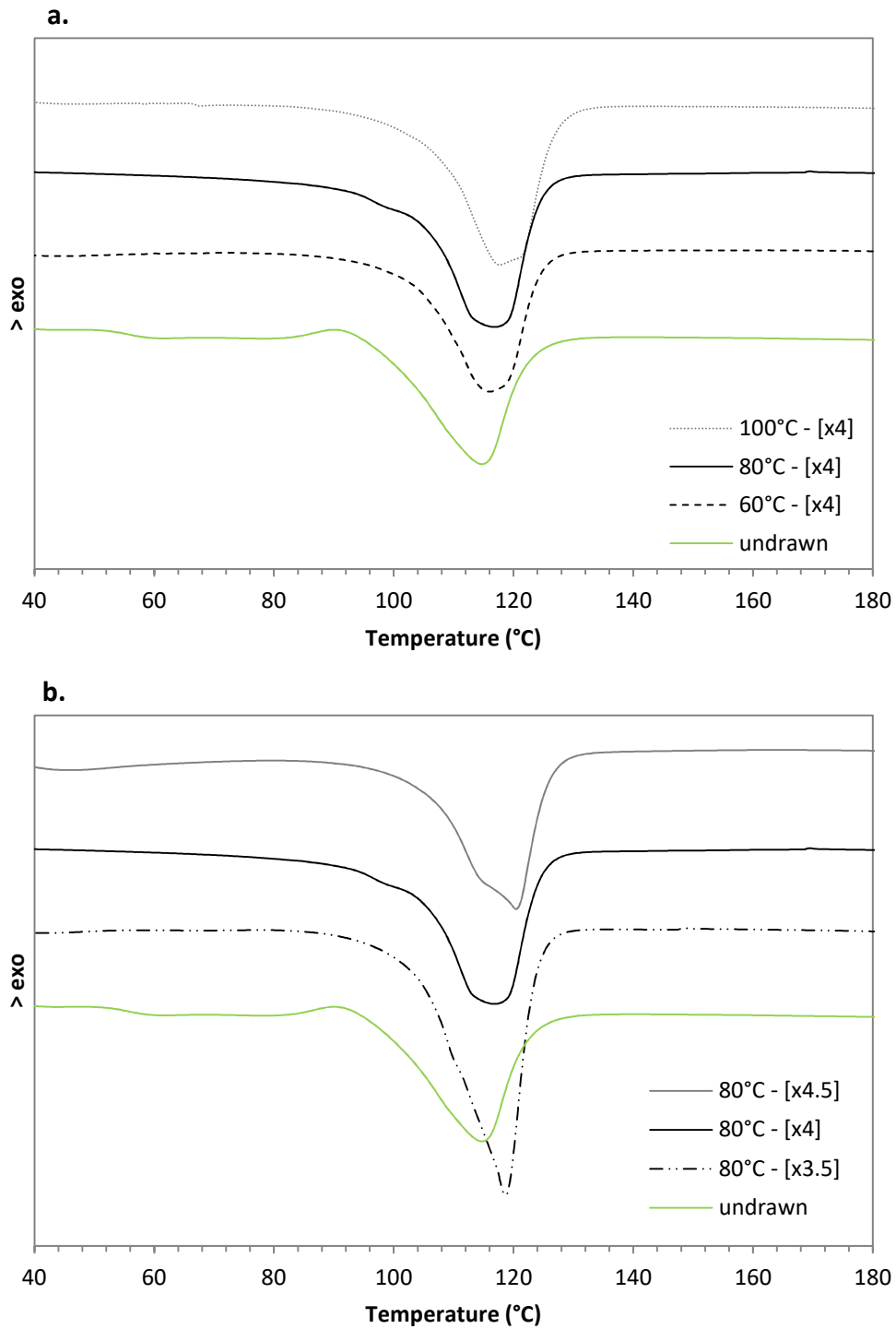


Figure 2: Evolution of the melting enthalpy behavior of the PBS monofilament drawn at different temperatures (a) and at different draw ratios (b). The undrawn behavior of the PBS monofilament is shown in green.

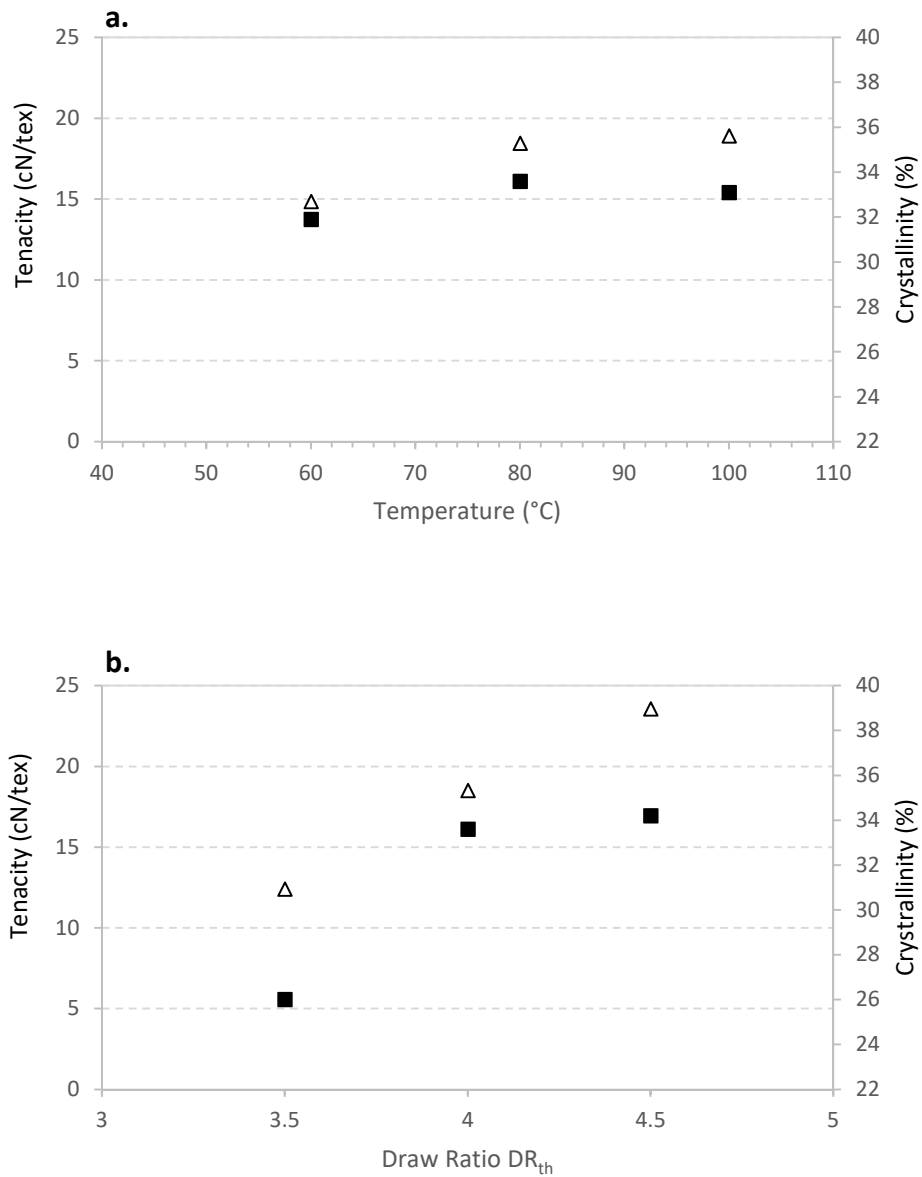


Figure 3: Relation between the evolution of tenacity (Δ) and crystallinity (\blacksquare) as a function of different parameters for the draw ratio and temperature.

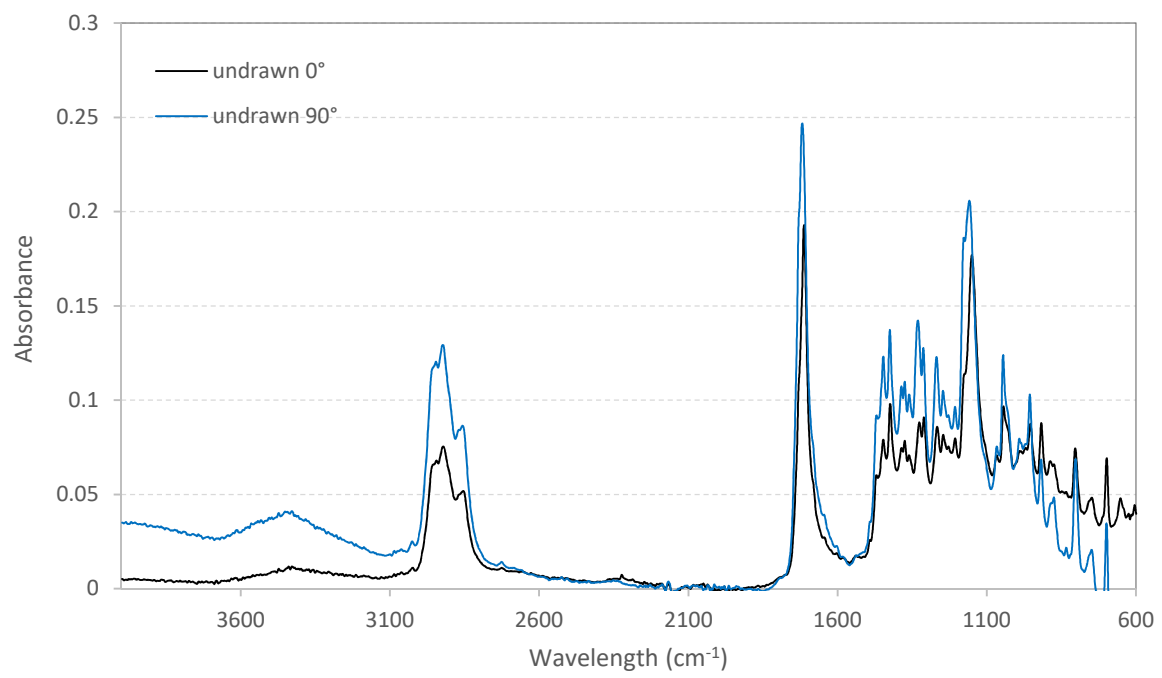


Figure 4: Polarized emission of spectrum at 0° and 90° of the PBS undrawn monofilament.

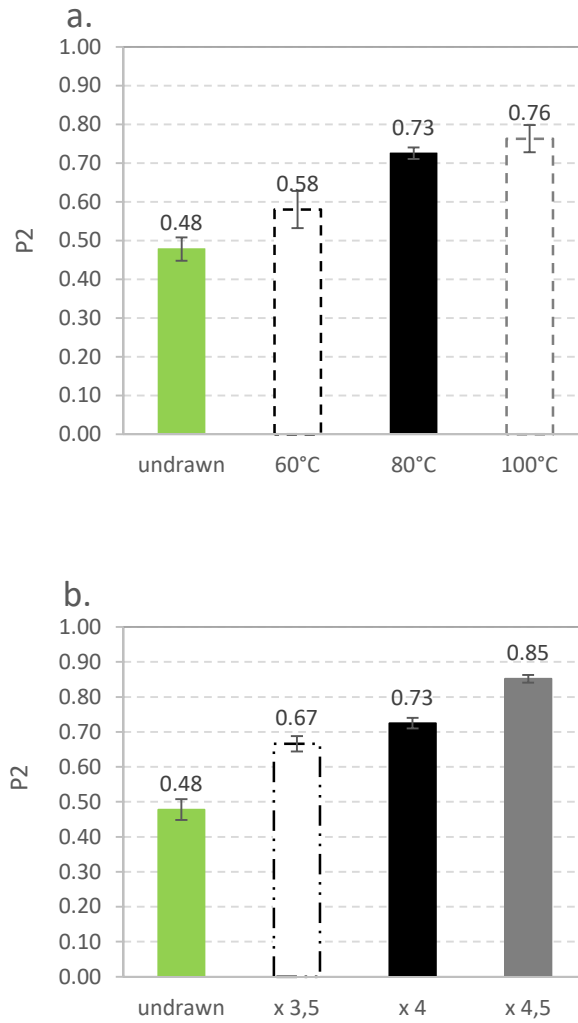


Figure 5: Evolution of the orientation function P_2 for the undrawn and drawn PBS monofilament, at different drawing temperatures (a) and at different draw ratios (b).

Table 1: Mechanical properties of PBS before and after drawing in different conditions and evolution of properties.

	Draw Ratio	Temp (°C)	E (MPa)	Gain (%)	σ_b (MPa)	Gain (%)	ϵ (%)	Gain (%)	F (N)	Tenacity (cN/tex)	Gain (%)
Undrawn	-	-	564 ± 43		64 ± 0.5		503 ± 81.2		66 ± 1	4.2	
Drawn	x4	60	1014 ± 66	+79 %	214 ± 9.9	+234 %	113.3 ± 9.9	-78 %	244 ± 15	14.9	+254 %
	x4	80	1312 ± 44	+132 %	267 ± 13	+317 %	122.7 ± 4.3	-76 %	255 ± 6	18.5	+340 %
	x4	100	1037 ± 43	+83 %	243 ± 17	+279 %	127.3 ± 6.8	-75 %	266 ± 11	18.9	+350 %
	x3.5	80	1076 ± 30	+91 %	209 ± 11	+226 %	148 ± 6.8	-71 %	262 ± 10	12.4	+195 %
	x4	80	1312 ± 44	+132 %	267 ± 13	+317 %	122.7 ± 4.3	-76 %	255 ± 6	18.5	+340 %
	x4.5	80	1483 ± 184	+162 %	302 ± 08	+371 %	107.6 ± 8.8	-79 %	247 ± 11	23.6	+461 %

Table 2: Evolution of thermal transition of PBS samples before and after drawing in different

	Draw ratio	Temp (°C)	Tm ₁ (°C)	ΔH_{m1} (J/g)	Tc (°C)	ΔH_c (J/g)	Tm _{2nd} (°C)	ΔH_{m2} (J/g)	χ_1 (%)
Undrawn	-	-	115.8	33.2	77.0	36.5	111.4	36.4	16.6
Drawn	x 4	60	118.0	63.8	77.3	54.9	113.3	49.1	31.9
	x 4	80	117.3	67.1	77.7	57.3	113.7	51.5	33.6
	x 4	100	117.3	66.3	78.0	52.2	111.7	50.1	33.1
	x 3.5	80	117.0	51.9	77.3	44.6	113.7	39.0	26.0
	x 4	80	117.3	67.1	77.7	57.3	113.7	49.0	33.6
	x 4.5	80	118.7	68.5	77.7	56.7	114.3	50.0	34.2

_{1,2} corresponding to first and second heating respectively conditions

Table 3: Representation of the absorbance obtained after polarized spectra in a parallel or perpendicular direction for the peak at 2850 cm⁻¹ and determination of the dichroic ratio R and the orientation function P2.

	Draw Ratio	Temp (°C)	A _{0°}	A _{90°}	R	P2*
undrawn	-	-	0.043	0.072	0.60	0.48
drawn	x 4	60	0.021	0.04	0.53	0.58
	x 4	80	0.021	0.049	0.43	0.73
	x 4	100	0.017	0.042	0.40	0.76
	x 3.5	80	0.021	0.045	0.47	0.67
	x 4	80	0.021	0.049	0.43	0.73
	x 4.5	80	0.014	0.04	0.35	0.85

** calculated according to the equation 4*