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Self-Extinguishing Polypropylene with a Mass Fraction of 9% Intumescent Additive - A New Physical Way for Enhancing the Fire Retardant Efficiency

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ABSTRACT

Multilayer self-reinforced polypropylene composites, fire retarded with APP based intumescent systems, were found to have surprisingly good fire retardancy. The combination of V-0 classification with excellent mechanical properties could be realized at significantly lower additive levels than expected. Modifying the structure of the composites allowed the mechanism behind the observed synergistic effect to be understood. The outstanding efficiency recorded can be explained by the beneficial physical cooperation between the expanding process caused by intumescent fire retardants and the shrinking of the reinforcing tapes. Polymer systems with these components, when exposed to heat, form a special, compact charred surface layer, which hinders the release of pyrolysis gases and where the flame retarding action of P- and N- containing compounds occurs at smaller volume, and thus at higher concentration resulting in effective fire extinction. The observed novel synergism is promising to be efficiently utilized in the formation of cost-effective, fire retardant, self-reinforced composites.

Keywords: flame retardancy; self-reinforcement; all-PP composite, physical interaction; multilayer composites; stretched PP tapes; intumescent char

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1. Introduction

The increasing consumption of low-cost and light-weight polymeric composites in continually expanding application fields is accompanied by several serious environmental issues. Therefore, developments towards recyclable and biodegradable polymer composites with good mechanical properties and a low environmental impact need to be examined by researchers [1,2]. In addition to this, the number and danger of fire risk scenarios is significantly increasing with the continuous worldwide expansion of plastic usage, thus flame retardancy needs to be improved simultaneously with the mechanical performance of polymeric composites [3].

The preparation of well-designed self-reinforced composites (SRCs), in which the reinforcing fibers are made from the same substance as the matrix polymer, is one possible way to improve the mechanical properties of polymers without any limitation regarding recycling [4]. It has been shown recently [5] that these composites can be successfully manufactured, even from secondary raw materials.

This paper reports on the flame retardancy of multilayer polypropylene (PP) SRCs. As the PP fibers have proved difficult to flame retard effectively [6], intumescent flame retardants (IFR) were added in the matrix layers in order to diminish the flammability of the composites (made entirely of PP). The fire retardant mechanism of IFRs has been comprehensively reviewed [7,8]. These reviews state that a minimum of 15-20 wt% IFR is needed in order to achieve acceptable levels of flame retardancy in polyolefins. However, as much as 25-35 wt% of IFR is also generally used in literature [9,10,11,12]. Several chemical substances, mainly heavy metal ions and silicon-containing species, have been studied as synergetic effect additives when combined with IFR systems [11,13,14,15,16,17]. Thus the required amount of IFR can be somewhat, but not drastically, lowered.

Horrocks et al [18] [19] were the first to draw attention to the beneficial interaction of fibers and intumescent substances. They showed comprehensive evidence that cellulose based and other char-forming polymer fibers have a char promoting effect [20,21] and revealed that a so-called 'char-bonded' structure of unusually high flame and heat resistance can be formed when both the flame retarded fiber and the intumescent substance form chars through "chemically and physically compatible mechanisms" in the semi-liquid intermediate phase. *Gallo* et al. [22] showed recently that the char promoting behavior of kenaf fibers, when combined with phosphorus-based flame retardants,

can be further utilized in a well-designed, multi-component laminated composite structure. However, the possibility for using thermoplastic fibers such as polypropylene for enhancing the flame-retardant effect of an intumescent system was not yet proposed.

In this paper, the significant synergism observed between highly oriented polymer fibers and IFR systems is described. This advantageous interaction was utilized in multilayer PP SRCs, raising the possibility of the production of new, cost-effective and recyclable flame retardant composites in the future.

2. Materials and methods

2.1. Materials

Tipplen R 949A (produced by TVK Plc., Hungary) type polypropylene (MFI = 45 g/10 min) was used as the matrix material for the prepared samples. In order to reduce the flammability of the samples, Exolit AP 766 (produced by Clariant Ltd., Germany), which is an ammonium polyphosphate (APP) based IFR additive, was introduced to the matrix material. According to the product data sheet, 20-22 wt% AP 766 is sufficient in PP homopolymers to obtain the UL-94 V-0 classification. Plain-woven fabric (identification code: T-PPT-181, Stradom S.A., Poland), composed of highly stretched split PP tapes, was used as reinforcement. The reinforcing fabric have a melting temperature of $T_m = 172.4$ °C (determined by DSC), and a tensile strength of 128.8 ± 3.0 MPa measured on a 50 mm wide strip and an areal weight of 171.5 g/m².

2.2. Preparation of composites

To accurately compare the flammability properties of simple PP compounds and multilayer SRCs, concentration series with the same composition were prepared for both materials, with IFR contents of 0, 9, 13, 17 and 21 wt%.

The simple flame retarded compounds were prepared by straightforward mixing of the required amount of IFR additive with PP in a Brabender Plasti Corder PL 2000 type internal mixer at 190 °C, with a rotor speed of 30 rpm, for 10 minutes. The blends were then hot pressed to form 4 mm thick specimens in a Collin P200E type laboratory hot press.

The SRCs were prepared through several steps. The first step was the compression moulding of 180 μm thick matrix layers with IFR content of 16.3, 23.6, 30.9 and 38.2 wt% at 190 °C in a Schwabenthan Polystat 300 S laboratory hot press. The multilayered SRCs were then manufactured by laminating 11 flame retarded matrix foils and 10 woven PP fabrics using the film stacking method [23,24]. The film-stacked packages were hot-pressed to form composites (in the same hot press) at a temperature of 162 °C and a pressure of 6 MPa for 2 minutes. The SRCs had a total reinforcement content of 45 ± 1.5 wt%. Thus each SRC (considering the total mass of the SRCs) had the same flame retardant content as the equivalent simple PP compounds. (For example in the case of the SRC with an IFR content of 9 wt% 55% of the mass of the SRC was flame retarded film containing 16.3 wt% IFR, giving an overall IFR content of 0.55×16.3 wt% ~ 9 wt%.) The mean thickness of the prepared SRCs was 3.78 mm.

To evaluate the role of molecular orientation in the flame retardant effectiveness of IFR systems, the PP fabrics used for reinforcement could be characterized with different degree of orientation. In the case of the SRCs marked RLX (i.e. relaxed) the commercially available highly stretched Stradom fabric was heat-treated at 164 °C and 0.4 MPa for 10 minutes before integration into the SRC_RLX composites, while SRCs without markings used the fabrics as received. Due to the heat-treatment the tensile strength of the relaxed fabric strip was reduced from the original value of 128.8 ± 3.0 MPa (tensile strength of the non-treated fabric) to 76.1 ± 2.2 MPa (avoiding the fusion of the PP fibers) suggesting significantly lowered degree of molecular orientation.

2.3. Characterization methods

The construction and consolidation quality of the SRC composites were inspected by reflection light microscopy (LM; Olympus BX51M) on polished cross sections of the sheets.

Comparative static tensile tests were performed on rectangular specimens of 20 mm \times 150 mm (width \times length) using a Zwick Z020 universal testing machine with a crosshead speed of 5 mm/min.

Instrumented falling weight impact (IFWI) tests were performed using a Fractovis 6785 instrument (Ceast, Pianezza, Italy) on the following settings: maximal energy: 228.64 J, diameter of the dart: 20 mm, diameter of the support rig: 40 mm, weight of the dart: 23.62 kg and drop height: 1 m. Square specimens with dimensions of 70 mm \times 70 mm were subjected to IFWI tests. From the IFWI tests the specific perforation energy (E_p [J/mm]) and the ductility factor (D_r [%]) were determined.

$$E_p = \frac{E_{max}}{h} \quad [\text{J/mm}]$$

$$D_r = \frac{E_{max} - E_{Fmax}}{E_{max}} \cdot 100 \quad [\%]$$

- E_{max} : total energy of break [J]
- h : thickness of the specimen [mm]
- E_{Fmax} : energy at maximal force [J]

All the mechanical tests were performed at room temperature and at least five specimens were tested in all cases.

The flame retardant performance of the prepared composites was characterized by limiting oxygen index (LOI) measurements according to the ASTM D 2863 standard. The LOI value expresses the lowest oxygen to nitrogen ratio where specimen combustion is still self-supporting.

Standard UL-94 flammability tests (ASTM 1356-90 and ANSI/ASTM D-635/77) were also performed. UL-94 classification is used to determine dripping and flame spreading rates.

Mass Loss type cone calorimeter tests were carried out by an instrument made by FTT Inc, using the ASTM E 906 standard method. Specimens (100 mm x 100 mm) were exposed to a constant heat flux of 50 kW/m² and ignited. Heat release values and mass reduction were continuously recorded during their burning. In all cases 3 samples of identical compositions were tested, the results reported in tables or figures correspond to the mean values obtained from these parallel measurements. The error range of the calculated experimental results was in the case of peak heat release rates (pkHRR) and time to peak heat release rates (pkHRR_{time}) lower than 15%, in the case of time to ignition (TTI) and residual mass values lower than 10%, and in the case of total heat released (tHR) lower than 5% in all cases.

3. Results and discussion

3.1. Comparison of the flammability of PP compounds and SRCs

Concentration series with increasing IFR content were prepared to compare the flammability characteristics of simple PP mixtures and multilayered SRCs. Significantly reduced flammability was

exhibited by the SRCs compared to the simple PP mixtures of the same composition. As shown in **Table 1**, the results for simple PP mixtures agreed with those in literature [8]; at least 21 wt% IFR was needed in simple PP mixtures to reach V-0 classification from standard UL-94 testing. On the contrary, SRCs with IFR content as low as 9 wt% proved to be sufficient for self-extinguishing behaviour (V-0 rating). Furthermore, SRCs consistently reached higher LOI values than simple PP mixtures despite the fact the two compounds had the same IFR concentration. This can be seen in **Figure 1**, which also makes clear that the difference between the measured LOI values increased as the additive content of the samples was increased; while the LOI of PP-IFR9 was only a few per cent lower than that of SRC-IFR9, the LOI value of SRC-IFR21 was up to 7 vol% higher than the value measured for the PP-IFR21 sample.

Table 1 UL-94 classification of PP based compounds and SRCs

PP simple compounds	UL-94 Classification*	PP multilayer SRCs	UL-94 Classification*
PP-REF	HB (30.5)	SRC-REF	HB (33.5)
PP-IFR9	HB (22.8)	SRC-IFR9	V-0
PP-IFR13	HB (19.4)	SRC-IFR13	V-0
PP-IFR17	V-2	SRC-IFR17	V-0
PP-IFR21	V-0	SRC-IFR21	V-0

*in parenthesis the average horizontal burning rates (mm/min), if measurable, are indicated

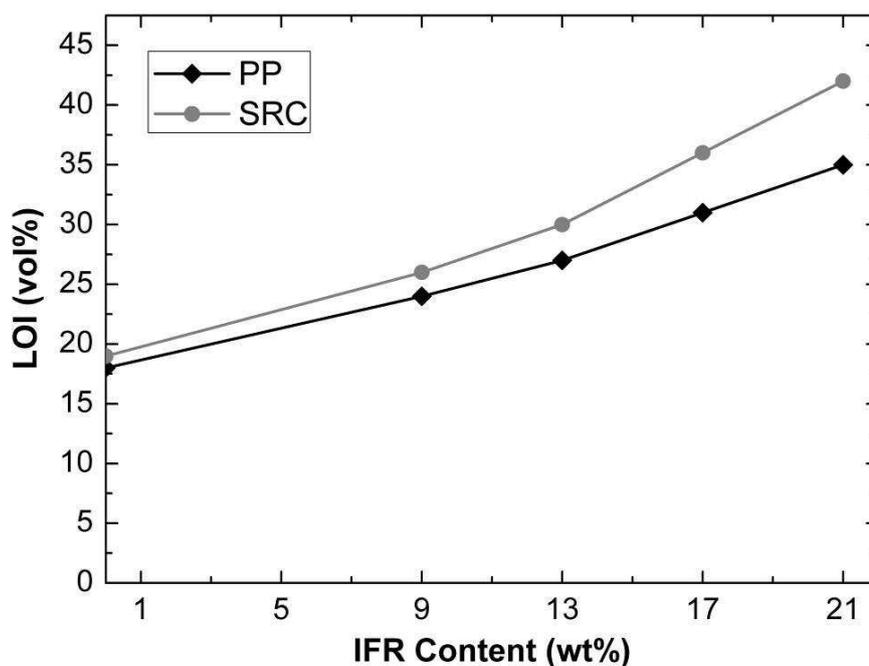


Figure 1 LOI as a function of IFR content in case of PP based compounds and SRCs

The two concentration series also had different behaviour in a mass loss type cone calorimeter. The recorded heat release rate and mass loss rate curves are presented in **Figure 2 a** and **b**, respectively. It is noticeable that, despite the identical IFR content of the corresponding samples, the SRCs consistently achieved lower values of peak heat release rate (pkHRR) than simple PP mixtures, usually by 30-45%. In the case of simple PP compounds, it was found that the time taken to reach the pkHRR ($\text{pkHRR}_{\text{time}}$) increased significantly with IFR content. In contrast, the time taken for the SRCs to reach their pkHRR was smaller. The dissimilar combustion behaviour exhibited by the two types of samples can be explained by different foam forming processes. In the case of simple, flame retarded PP mixtures, a fairly thick heat insulating foam is formed in the initial stage of burning. The heat protective character of this foam can be preserved until, depending on the IFR content, the degradation of the protective shield begins. This is indicated by the increase in heat release rate (**Fig 2 a**) and the abrupt decrease in mass loss rate (**Fig 2 b**). In contrast to this, the PP fabrics in SRCs, similarly to inorganic fabrics [25,26], hinder the development of a highly expanded foam structure and so a more compact char layer is formed on the surface of the sample. As the heat insulating property of an intumescent char mainly depends on its thickness (a thicker layer gives more insulation), the formation of compact foams in the case of SRCs is associated with higher initial heat release rates. However, compact char layers maintain more of their heat protective character than thick but weak char layers, i.e. the pkHRR is much lower for compact char layers than for thick char layers if the mass of the thick one is not higher. The dissimilar character of the foams is obvious when the photographs of the charred residues are compared. In **Figure 3** the residues of the two types of samples containing 17 wt% IFR obtained from cone calorimetric tests are compared.

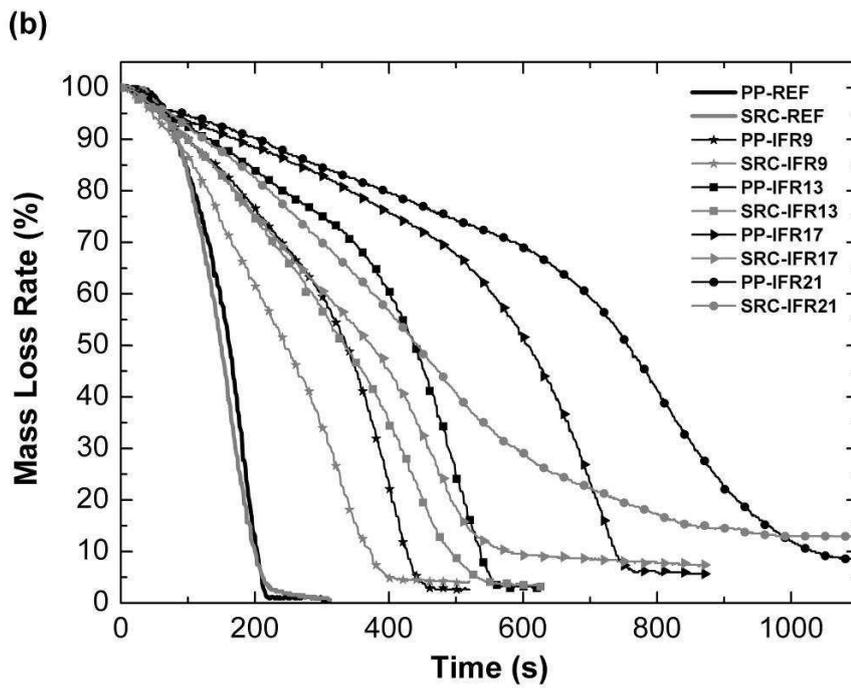
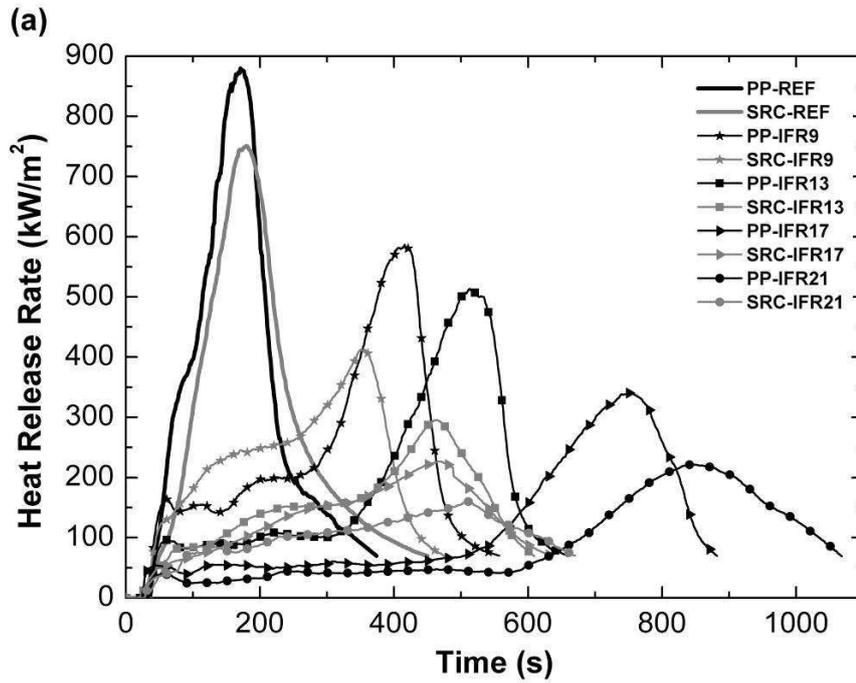


Figure 2 Comparison of a) heat release rate curves and b) mass loss rate curves recorded during the combustion of simple compounds and self-reinforced composites with identical flame retardant contents

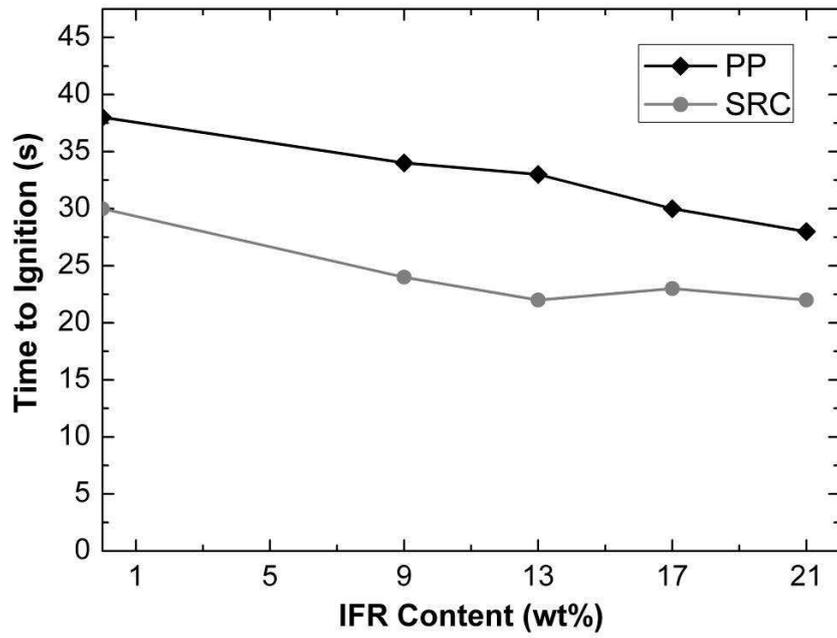


Figure 3 Charred residues of 17 wt% IFR containing samples obtained after cone calorimetric tests

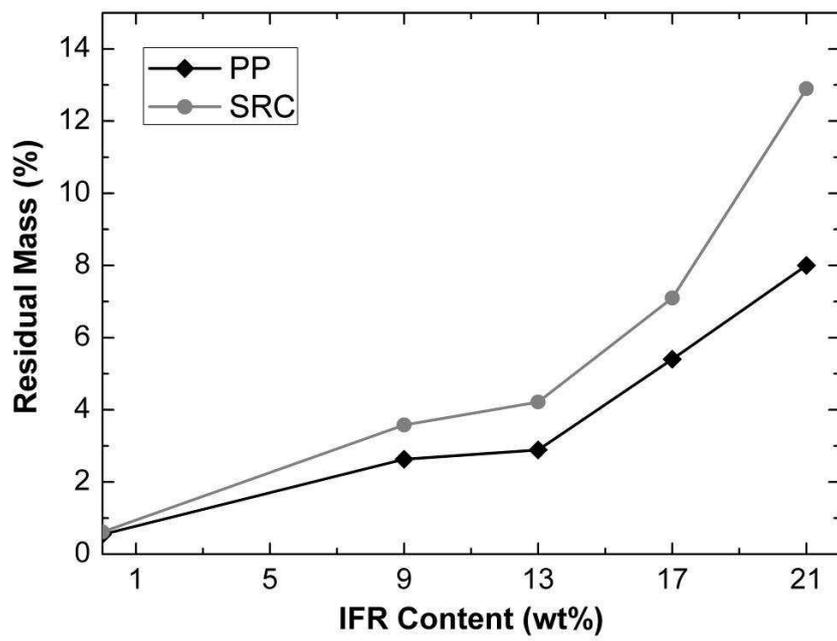
Further experimental results of the cone calorimetric combustion tests are presented in **Figure 4 a, b and c**. On average, time to ignition (TTI) for SRCs was eight seconds less than that for compounded PP mixtures (see **Fig. 4 a**). It is known that the ignitability of a composite at a given heat flux does not depend exclusively on the chemical stability of the matrix polymer and the type of fiber; their thermal conductivity, the thickness of the layers and their interactions need to be considered as well [27]. In the case of the SRCs, there are two main factors that can explain the shorter TTI. The most crucial factor is the thickness of layers; the volatilization of the thin upper layers of SRCs occurs much faster than in the case of the thick bulk of simple PP mixtures. Furthermore, the IFR additive content of the upper (matrix) layers is higher. According to *Li et al.* [28] the IFR initiated char layer formation at the initial stage of heating results in quick temperature rise and fast decomposition of PP on the surface of the samples.

The amount of charred residues obtained from combustion increased with the IFR content in the case of both simple PP mixtures and SRCs (as shown in **Fig 4 b**). In the case of SRCs, the increase is greater. Although **Fig 3** suggests larger extent of charred residue in the case of the PP mixture containing 17 wt% IFR, in fact the mass of the char corresponding to the multilayer composite (SRC-IFR17) was (owing to its more dense character) considerably (by 24%) bigger. At IFR content of 21 wt% the difference between the obtained residual masses of the two types of samples exceeded 38%. **Fig. 4 c** shows that the total heat release (THR) was typically also 25% lower for SRCs.

(a)



(b)



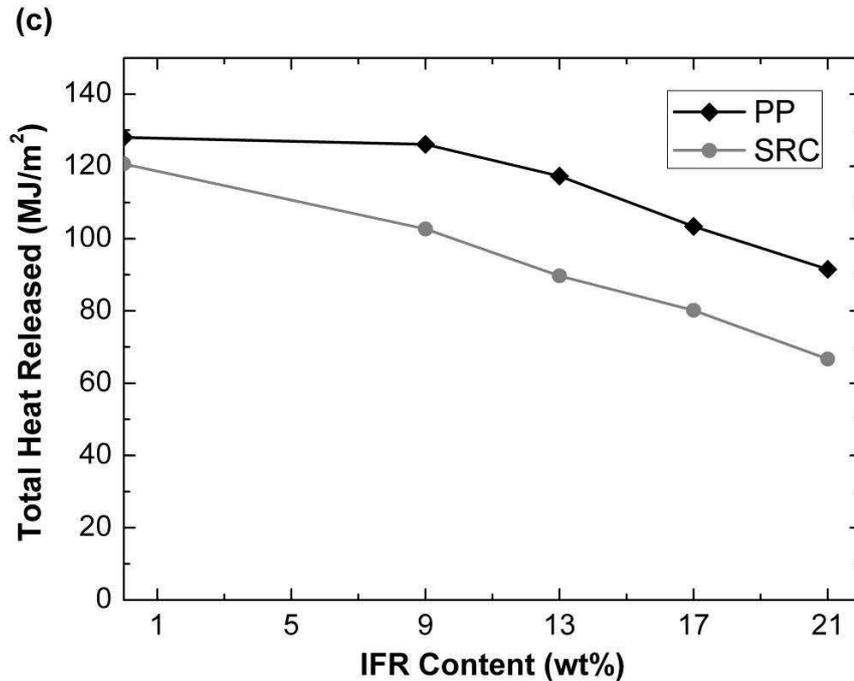


Figure 4 Results of the comparative combustion tests under 50 kW/m² irradiation of conic heater: a) time to ignition, b) residual mass and c) total heat released

According to the flammability test results, the flame retardancy of multilayered SRCs proved to be significantly superior to compounded PP mixtures. Although due to the high-grade crystallinity and orientation of reinforcing PP tapes the thermal stability (indicated also by higher T_m) and also the flammability properties (e.g. LOI) of SRCs can be somewhat increased, such improvement in flame retardancy cannot be fully ascribed to this effect. The observed char-promoting behaviour of originally non-charring PP fabrics is very surprising and required further explanation.

Hornsby et al. [29,30] proposed first the use of multi-component processing technologies, such as co-extrusion, co-injection moulding and bicomponent fiber spinning process, to achieve the necessary balance of fire retardancy and mechanical performance. By structuring fire retardant skin and unfilled core layers into multilayered composites they observed similar resistance to ignition and comparable HRR and smoke extinction area as in the case of fully fire-retardant compositions besides achieving enhancement in impact resistance. It can be concluded that only due to the multilayer structure no significant enhancement in flame retardancy was noticed. Furthermore, in contrast to our experimental results, the obtained HRR curves corresponding to their sample with laminated structure showed wavy character, indicating that no significant chemical or physical interaction occurred between the

individual layers. As in our system the chemical composition of the two types of flame retarded samples was the same, it was concluded that some kind of physical phenomenon must play the key role behind the observed mechanism, which is a completely novel issue in the field of flame retardancy. Therefore the effect of the high-strength PP fibers on the flame retardant action of the IFR system was investigated hereinafter. To this end, SRCs with identical compositions but different stages of orientation were examined; some had heat-treated reinforcing PP layers while others had the original stretched reinforcements.

3.2. Investigation of the effect of molecular orientation on the flame retardant performance of intumescent systems

Due to the heat-treatment of the highly stretched PP fabrics at 164 °C, the degree of their molecular orientation was reduced. This was confirmed by comparing the tensile strength and impact resistance of the two types of prepared SRCs.

The tensile strength and perforation energy values of the simple PP mixtures and the two types of SRCs with IFR content of 9 and 13 wt% are demonstrated by the charts in **Figure 5**. Additional mechanical test results are summarized in **Table 2**. As shown in **Figure 5 a**, the tensile strength of PP in the form of SRCs containing high-strength PP fabrics is 4 times higher than that of the simple PP mixtures. Also, the impact resistance (expressed by the perforation energy) of the un-treated SRCs exceeds considerably the performance of the PP reference (see **Figure 5 b**). It is visible that an 8-fold increase in perforation energy was achieved with SRCs, even when flame retarded. While the IFR additive content of the compounded PP mixtures negatively affected the properties of the samples (it decreased the tensile strength, significantly reduced the elongation at break and the perforation energy of the samples), no remarkable influence on the mechanical properties of the SRCs is caused by their IFR additive content (**Table 2**).

The molecular relaxation of the reinforcing fabrics reduced the tensile strength of the SRC_RLX composites by 20% compared to the original SRCs (**Figure 5 a**), and also the perforation energy was reduced by approximately 35% (**Figure 5 b**). The ductility factor (**Table 2**) of both fabric reinforced composites is considerably higher than that of PP mixtures, i.e. large amount of energy is absorbed in the crack running among the fiber/matrix interface (debonding) during impact failure. This indicates that both types of SRCs could be characterized with adequate consolidation state and the difference in

mechanical performance of SRC and SRC_RLX composites is mainly due to the difference in the degree of orientation of the reinforcing tapes. Thus, it was proven by mechanical tests that the relaxed composites represent a kind of transition, regarding the degree of molecular orientation, between the high performance SRCs and the non-reinforced compounded mixtures.

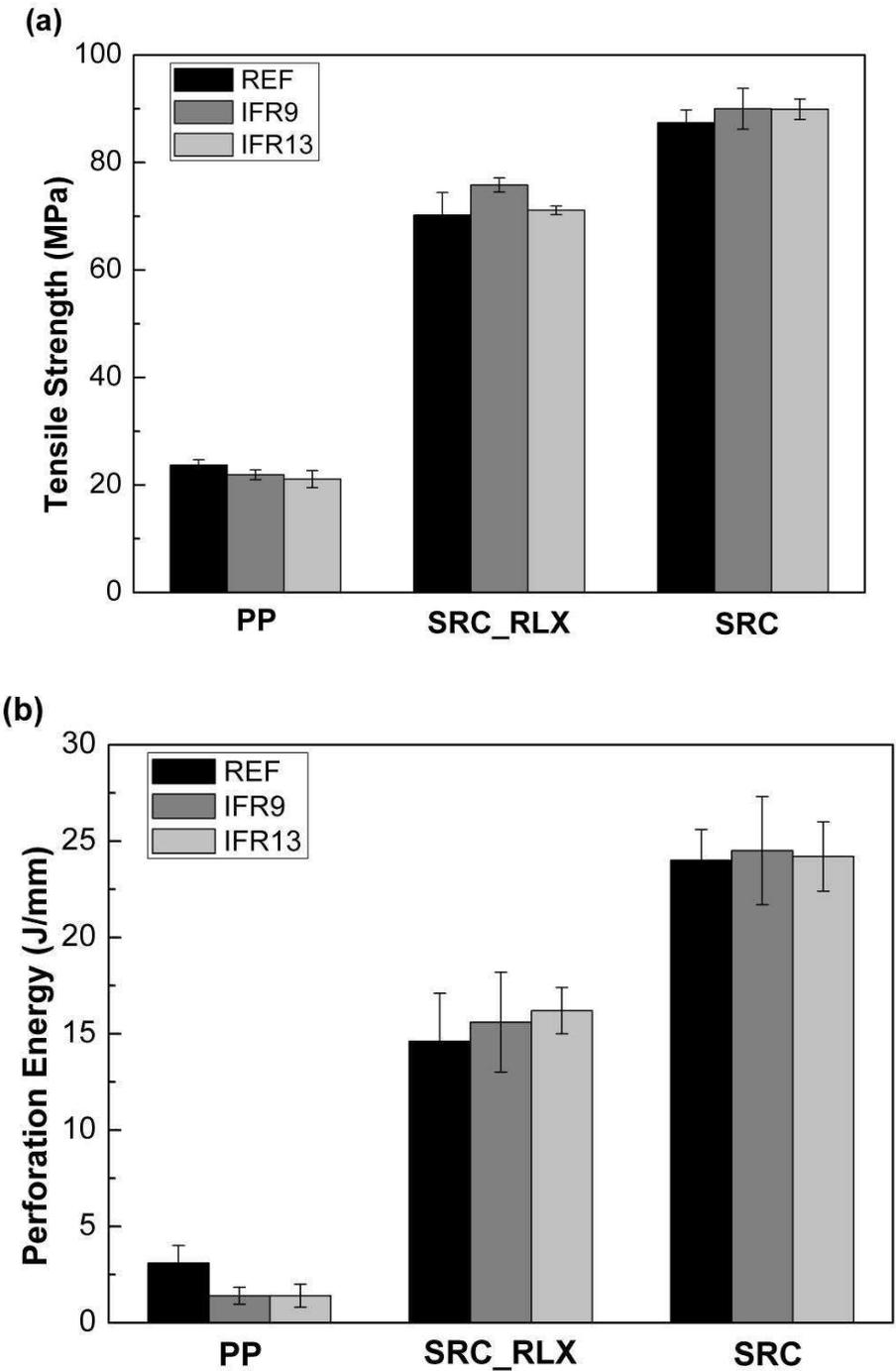


Figure 5 (a) Tensile strength and (b) perforation energy of PP compounded mixtures, SRCs and relaxed SRCs with identical IFR contents

Table 2 Elongation at break, tensile modulus and ductility factor values determined from the tensile and IFWI tests, respectively

Sample	Elongation at Break (%)	Tensile Modulus (GPa)	Ductility Factor (%)
PP-REF	41.7 ± 2.2	0.79 ± 0.04	27.6 ± 9.4
SRC-REF_RLX	25.9 ± 1.0	0.72 ± 0.05	40.3 ± 6.1
SRC-REF	23.9 ± 1.2	1.01 ± 0.07	37.7 ± 4.7
PP-IFR9	22.4 ± 1.4	0.89 ± 0.01	28.1 ± 6.9
SRC-IFR9_RLX	25.5 ± 0.1	0.98 ± 0.03	35.0 ± 4.5
SRC-IFR9	24.2 ± 0.7	1.01 ± 0.05	35.7 ± 5.1
PP-IFR13	12.4 ± 1.6	0.93 ± 0.01	33.1 ± 6.5
SRC-IFR13_RLX	23.7 ± 0.8	0.99 ± 0.03	41.4 ± 6.2
SRC-IFR13	22.6 ± 0.8	1.16 ± 0.06	37.9 ± 3.1

The flammability characteristics of these samples, with different orientation and IFR content of 0, 9 and 13 wt%, were also examined and compared. The results of the UL-94 flammability tests and LOI measurements are summarized in **Table 3**. In the case of flame retarded high performance SRCs an IFR content of 9 wt% proved to be adequate for self-extinguishment. However, when heat-treated PP fabrics were used for preparation of multilayered SRCs (relaxed SRCs), 9 wt% IFR was no longer sufficient to reach V-0 classification. Although the SRC-IFR9_RLX marked specimens did not burn horizontally, they burned completely in the vertical direction after 10 second ignition, as did the simple flame retarded PP mixture with the same additive content. The relaxed SRCs reached the V-0 rating at an additive level of 13 wt% - still much lower than the amount needed for the simple PP compounds. Analysing **Table 3**, it seems that, as well as being an intermediate state for the degree of molecular orientation between the unreinforced PP samples and the high-performance SRCs, the relaxed composites also represent an intermediate state regarding LOI values. This proves that the degree of molecular orientation of the embedded PP fibers is the key factor for the extraordinary flame retardant performance observed.

Table 3 UL-94 classification and LOI of PP simple compounds, high performance and relaxed SRCs

Sample	UL-94 Classification*	LOI (vol%)
PP-REF	HB (30.5)	18
SRC-REF_RLX	HB (33.6)	18
SRC-REF	HB (33.5)	19
PP-IFR9	HB (22.8)	24
SRC-IFR9_RLX	HB (-)	25
SRC-IFR9	V-0	26
PP-IFR13	HB (19.4)	27
SRC-IFR13_RLX	V-0	29
SRC-IFR13	V-0	30

*in parenthesis the average horizontal burning rates (mm/min), if measurable, are indicated

The results of the **UL-94 and LOI flammability tests** on the SRCs, reinforced with PP fabrics of different degrees of orientation, prove that the highly stretched tapes of the fabrics contribute to the FR effect of the IFR additives. This beneficial effect is attributed to a balanced physical interaction between the mechanism of intumescence and the shrinking of the highly oriented tapes. In this system, if exposed to an ignition source from the edges of samples, parallel to the direction of stretching (UL 94 and LOI test), all the layers of PP fabrics start to shrink in coincidence with the development of the intumescent process, thus a special compact char develops on the surface of the specimen. In this case, higher concentration of FR active compounds retains in this zone resulting in more effective fire extinguishing action.

In a **cone calorimeter**, where the heat flux is applied perpendicular to the layers of stretched tapes, the mechanism of enhancement of flame retardant efficiency and the influence of the degree of orientation differ from the above described ones. The obtained heat release rate curves in **Figure 6** and the results summarized in **Table 4** confirm the synergism between the stretched PP tapes and the IFR system as the combustion of both types of flame retarded SRCs was accompanied with significantly lower pkHRR and tHR values and greater char masses (compared to simple PP mixtures). Although the almost identical TTI values of the two types of SRCs suggest that the relaxation of fabrics do not influence the ignitibility of the multilayer composites, the embedding of heat-treated fabrics into the flame retardant matrix layers (relaxed SRCs) resulted in even lower but earlier appearance of pkHRR than in the case of original fabric reinforcement (normal SRCs) (**Figure 6 b and c**). Furthermore, in presence of the relaxed fabrics the formed charred layer was the most compact and consequently also the highest residual masses remained after combustion. The more

effective char modifying influence of the relaxed fabrics could be ascribed to its more effective barrier performance. Under the heated cone only a few upper fabric layers participate in the control of the IFR mechanism, which are thicker and denser after relaxation as shown in **Figure 7**. The relaxed composites (**Figure 7 b**) show plainer and more uniform distribution of tapes as a consequence of the pressure of 0.4 MPa applied during the heat-treatment (in order to avoid shrinkage).

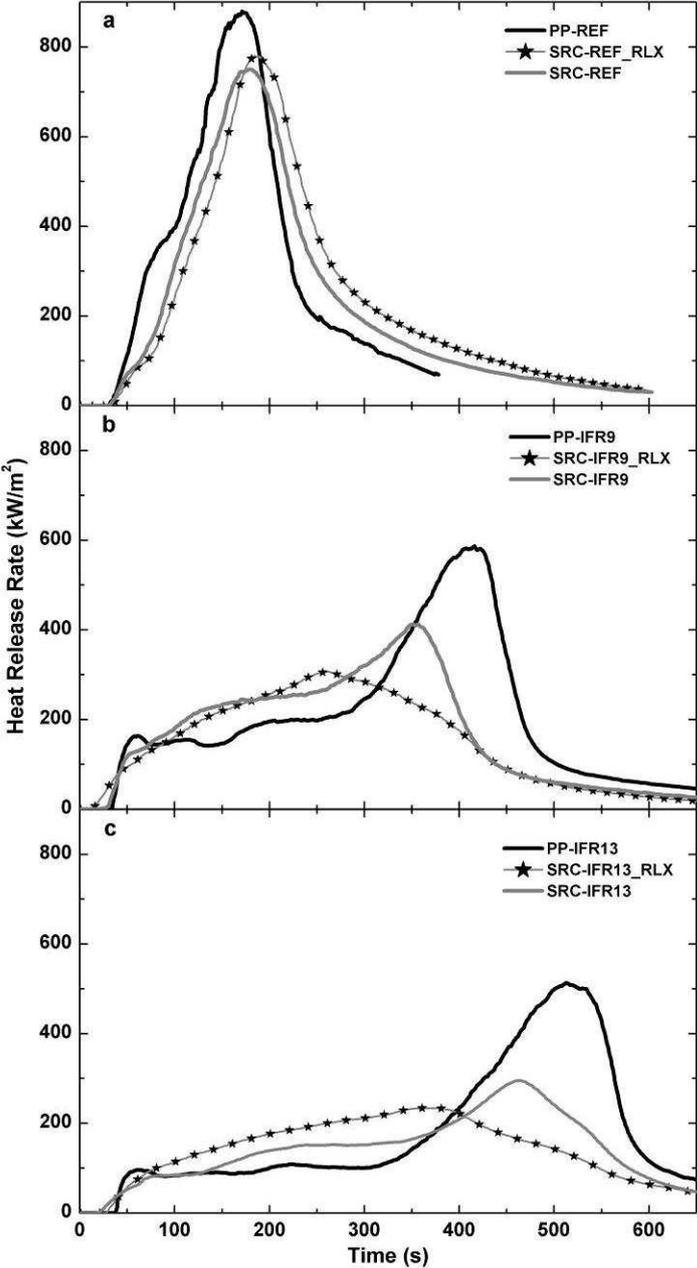


Figure 6 Heat release rate curves recorded during the burning of flame retarded simple compounds, high-performance and relaxed SRCs with IFR content of 0, 9 and 13 wt%, respectively

Table 4 Summary of the Mass Loss Calorimetric test results

Sample	TTI (s)	pkHRR (kW/m ²)	pkHRR _{time} (s)	Residue (mass%)	tHR (MJ/m ²)
PP-REF	38	880	171	0.5	128.0
SRC-REF_RLX	30	781	184	0.6	131.1
SRC-REF	30	751	180	0.6	120.7
PP-IFR9	34	587	416	2.6	126.1
SRC-IFR9_RLX	23	307	261	5.1	90.6
SRC-IFR9	24	413	351	3.6	102.7
PP-IFR13	33	514	513	2.9	117.3
SRC-IFR13_RLX	22	234	359	7.3	88.9
SRC-IFR13	22	295	464	4.3	89.7

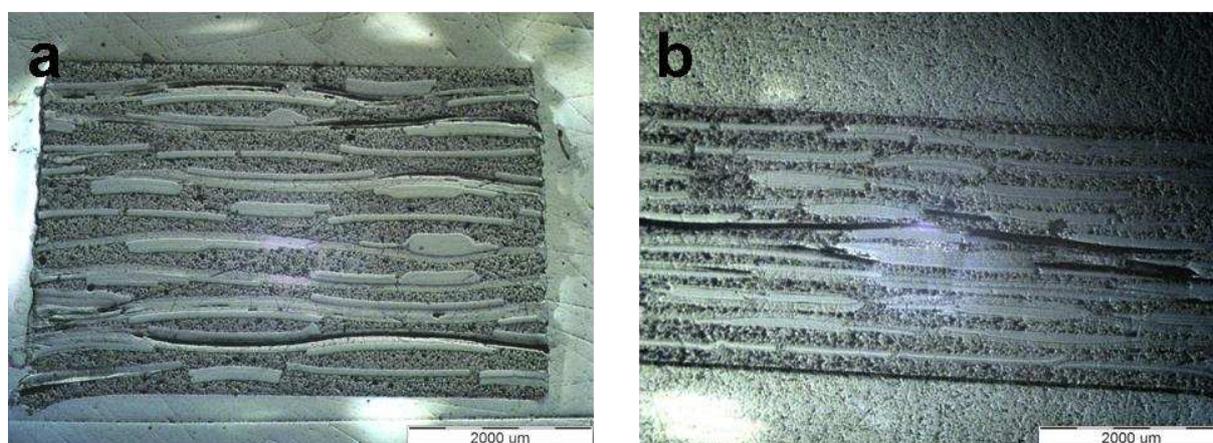


Figure 7 Light microscopic photographs of the cross section of multilayer SRCs reinforced with (a) non-treated and (b) heat treated PP fabrics

The significantly reduced rates of heat release observed in the case of multilayer SRCs can be explained by the reduced oxygen permeability and enhanced heat barrier effect of the compact char layer formed, which is similar to the ‘char bonded’ structure [20,21] reported in case of fiber-intumescent interaction earlier. It seems that the shrinkage of the highly-stretched tapes promotes the formation of a coherent network of expanding and interlinked domains by increasing the specific concentration within the surrounding matrix, as predicted by the models proposed by *Zhang* [8] and *Bourbigot* [31]. The effectiveness of the observed synergism obviously depends on the ratio of the expanding domains and the shrinking ability, which needs to be optimized in order to fully utilize the interaction.

4. Conclusion

Special synergistic flame retarding effect was observed as the result of physical interactions between APP based intumescent flame retardants and highly oriented PP fabrics in multilayer SRCs. Such interaction between a flammable polymer and a flame retardant, which is normally much less active than in the studied SRC systems, was not observed earlier. As low as 9 wt% additive concentration, less than half of the normally necessary amount of IFR, is enough to achieve V-0 classification of a PP SRC according to the UL-94 classification. This result is accompanied with noticeably higher LOI values and significantly lower heat release rates comparing to the non-oriented PP samples with the same intumescent flame retardant content. The mechanism of the improvement is based on the shrinkage of PP fabrics that keeps the char structure compact and hinders the early escape of the FR species from the char zone.

Testing SRCs with slightly relaxed PP fabrics confirmed that the degree of molecular orientation plays a key role in the char promoting effect of fibers participating in the IFR mechanism. All the characteristics of SRCs outperformed the PP mixture of same composition excepting the time to ignition, which decreased due to earlier appearance of decomposition products in the gas phase. The advantageous interaction is observable with all the applied measurements but the values and mechanisms are different. When the heat comes from the edges of the specimens (UL-94, LOI) all the stretched layers start to shrink and the compact char formed this way stops the propagation of the flame. When, however, the heat radiates perpendicular to the layers of reinforcing fabrics (cone) only the upper layers influence the mechanism of intumescence. Their effect in this case is realized in hindering the escape of active FR species and the development of a compact charred layer. The prepared flame retarded SRCs, despite the presence of IFR additives, exhibit prominent tensile properties and shock resistance: a tensile strength of 90 MPa, and perforation energy of 24 J/mm, accompanied with a ductility factor of approximately 38% is achievable.

The novel synergism displayed raises the possibility of cost-effective fire retardancy of high mechanical performance and recyclable SRCs. However, in order to utilize this potential, further investigations are necessary.

5. Acknowledgement

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