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Unlocking High-Performance Blends: Navigating the Selection of GMA and MAH as Reactive Compatibilizers

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Abstract

Glycidyl methacrylate (GMA) and maleic anhydride (MAH) are among the most extensively utilized reactive monomers for polymer blend modification. The matching degree between these monomers and polymer end groups directly determines the interface bonding quality and the comprehensive properties of the materials. In this paper, the differences in molecular structural characteristics, reaction thermodynamics, and reaction kinetics between GMA and MAH are systematically reviewed, with a particular focus on the differences in reaction efficiency and reaction mechanisms exhibited by the two monomers in polymer systems such as polyamide (PA), polyester (PBT/PLA/R-PET), polycarbonate (PC), polyolefins, and Acrylonitrile-Butadiene-Styrene (ABS). The interaction mechanisms and regulation strategies between these two monomers and processing aids (e.g., antioxidants, UV stabilizers, and flame retardants) are further investigated, while the reaction priority of their synergistic competition and optimized application schemes are clarified. Moreover, the application advances of GMA/MAH in fields such as automotive, electrical and electronic appliances, and packaging are summarized. Furthermore, current challenges in polymer systems—including insufficient monitoring of microscale reactions and poor compatibility with complex additive systems—are identified, and future directions such as the development of multifunctional composite compatibilizers and the optimization of green processing technologies are outlined. In turn, this work provides theoretical support and technical references for the precision selection, formulation optimization, and industrial application of GMA and MAH in polymer blend modification.

Keywords

GMA, MAH, Reactive Compatibilizer, Polymer Blending, Reaction

Mechanism, Processing Aids, Synergistic Competition

1. Introduction

As a core technology in polymer science, blend modification enables precise customization of material properties and effective cost reduction, thus finding extensive applications across key civilian sectors such as automotive, electronic devices, and advanced packaging. Polymers such as polyamide (PA), polyester, polycarbonate (PC), and polyolefins have emerged as the most widely used matrix materials for blend modification, benefiting from their readily available sources and excellent processability. Nevertheless, the inherent poor interfacial compatibility between these polymers remains a critical bottleneck, significantly hindering the further improvement of blend material performance [1]-[3]. Reactive compatibilizers serve as a key approach to addressing this bottleneck by undergoing *in-situ* chemical reactions with polymer end groups to form a stable interfacial layer [3]-[5].

Glycidyl methacrylate (GMA) and maleic anhydride (MAH) stand out as the preferred active components for reactive compatibilizers in polymer blend modification, owing to their key advantages of high reactivity, facile structural modifiability, and controllable cost. The epoxy groups of GMA possess ring strain-driven nucleophilic ring-opening characteristics, while the anhydride groups of MAH tend to undergo nucleophilic addition-elimination reactions. The reaction efficiency of both monomers is highly dependent on the matching degree of polymer end group properties, including acidity/basicity and the strength of nucleophilic activity [6]-[12]. Currently, numerous researchers have performed extensive investigations into the compatibilization efficiency of GMA/MAH in single polymer systems. Nevertheless, the selection principles for different systems have not been systematically summarized, the interaction mechanisms with various processing aids are still fragmented, and there is an urgent need to refine the formulation optimization and process control technologies under complex operating conditions.

Based on existing research findings and starting from the essence of molecular structures, this paper systematically analyzes the differences in reaction mechanisms and efficiencies between GMA and MAH in typical polymer systems, comprehensively elaborates on their interaction rules with processing aids, delves into the reaction priority and regulation strategies of their synergistic use, summarizes key selection criteria by integrating application scenarios in civilian fields, and outlines future research directions. It provides a reference for the R&D and industrial application of high-performance general blend materials.

2. Molecular Structures and Reaction Characteristics of GMA and MAH

2.1. Structures & Functional Group Characteristics

The epoxy ring in the molecular structure of GMA (with a strain energy of approximately 114 kJ/mol) constitutes the core source of its reactivity. The high electronegativity of the oxygen atom on the ring endows the ring carbon atoms with an electron-deficient nature, which thus requires nucleophilic attack or protonation assistance to achieve ring-opening [8] [9]; The conjugated electron-withdrawing effect of the carbonyl groups in the five-membered cyclic anhydride structure of MAH induces a significant decrease in the electron cloud density of the ring carbon atoms, forming strong electrophilic centers that readily undergo nucleophilic addition-elimination reactions with strong nucleophiles [10] [11] [13].

2.2. Differences in Reaction Essence and Thermodynamics

The nucleophilic ring-opening reaction of GMA requires a relatively high activation energy (60 - 70 kJ/mol), and thus necessitates protonation (e.g., by acidic end groups) or catalysts (e.g., quaternary ammonium salts) to lower the energy barrier [8] [9] [14] [15]; The nucleophilic addition-elimination reaction occurring at MAH has an activation energy of only 30 - 40 kJ/mol and can proceed rapidly in the presence of strong nucleophilic end groups (e.g., $-NH_2$) [10] [14]. From a thermodynamic perspective, the enthalpy change of GMA's ring-opening reaction stems primarily from ring strain relief, whereas the reaction between MAH and strong nucleophiles exhibits distinct thermodynamic advantages owing to the formation of imide structures with high bond energy (≈350 kJ/mol) [8] [10] [16].

2.3. Differences in Molecular Dynamics

From a microscopic standpoint, molecular dynamics (MD) simulations provide deep insights into the spatial configuration and kinetic behavior differences between GMA and MAH at the polymer-polymer interface. Experimental evidence suggests that MAH-grafted chains tend to self-assemble into a tightly packed layered arrangement at the interface of polar matrices such as PA6, where the anhydride moieties exhibit a pronounced interfacial enrichment effect. MD simulation results further quantify that the interfacial work of adhesion between MAH and the terminal amino groups of PA is substantially higher than that of GMA, a phenomenon ascribed to the compact molecular architecture of MAH that enables facile penetration into the interchain spaces of PA and subsequent formation of a hydrogen bond-mediated pre-complexation state [10] [17]-[21].

In contrast, owing to its longer side chain structure, GMA exhibits a larger free volume at the interface and thus adopts a random coil conformation. MD simulations reveal that, in polyester (PLA/PBAT) systems, GMA can significantly reduce interfacial tension and increase the interfacial width between the two phases via the nucleophilic ring-opening of its epoxy groups [19]. Recent studies have revealed via coarse-grained molecular dynamics (CGMD) simulations that, in PC/ABS blends, the rotational freedom of GMA's side chains endows it with stronger interfacial healing capacity than MAH under high-temperature shearing, thereby more effectively inhibiting the agglomeration of the rubber phase [22] [23].

2.4. Side Reactions and Influencing Factors

When GMA is in excess, homopolymerization tends to occur alongside hydroxy-mediated epoxy ring-opening reactions—where hydroxyl groups generated from the initial epoxy ring-opening further induce the ring-opening of residual epoxy groups and trigger cross-linking—thus resulting in a marked decrease in the melt fluidity of the system [8] [9]; MAH tends to hydrolyze to form maleic acid under processing humidity, which not only consumes its own reactivity but also may catalyze polymer degradation; additionally, residual monomers can induce material yellowing [10] [24]. Factors such as processing temperature, shear rate, system water content, and catalyst type all exert an influence on the reaction selectivity and conversion rate of both substances [15] [25]-[27].

3. Reaction Efficiency and Mechanisms of GMA and MAH in Polymer Systems

3.1. Polyamide (PA) Systems: High-Efficiency Adaptability of MAH

For PA series materials (e.g., PA6, PA66, PA6/ABS blends), the reactive end groups are dominated by strong nucleophilic amino groups (-NH_2) and supplemented by carboxyl groups (-COOH), enabling an optimal strong electrophile-strong nucleophile pairing with MAH's anhydride moieties. This reaction proceeds via two sequential steps: instantaneous nucleophilic addition of -NH_2 to the carbonyl carbon of MAH's anhydride ring at extrusion temperatures (180˚C - 240˚C, activation energy: 30 - 40 kJ/mol) to yield unstable amic acid, and subsequent dehydration at elevated temperatures to form highly stable imide structures that impart robust interfacial bonding with PA main chains without detectable reverse reactions, as illustrated in **Figure 1** [10] [11] [16]. As documented in relevant literature, the incorporation of MAH-based compatibilizers into PA6/ABS blends not only realizes super-tough room-temperature impact strength but also preserves excellent toughness at a low temperature of −10˚C [27].

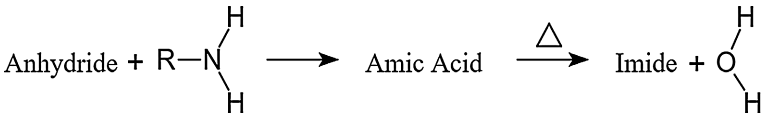

Figure 1. Schematic illustration of the reaction between MAH and amide.

The reaction of GMA with PA suffers from inherent drawbacks: the activation energy required for epoxy ring-opening (60 - 70 kJ/mol) is substantially higher than that of the MAH-amine reaction, while the hydroxyl groups produced can cause local cross-linking, damage melt processability, and prevent the full completion of interfacial reactions under typical short extrusion residence times (<3 min). In addition, investigations into broader polyamide systems including PA12 and PA610 have further validated that MAH outperforms GMA by a significant margin in both grafting efficiency and compatibilization efficacy [8]-[10] [14].

3.2. Polyester Systems: Absolute Advantages of GMA

The reactive end groups of the polyester series (PBT, PLA, R-PET, PETG, PBS, etc.) are dominated by carboxyl groups (-COOH, acidic) and supplemented by hydroxyl groups (-OH, weak nucleophiles), thus forming a highly efficient reaction system with the epoxy ring of GMA [9] [14] [28]. This highly efficient reaction is governed by a protonation-assisted ring-opening mechanism: H$^+$ donated by carboxyl groups protonates the epoxy ring oxygen atom, which not only reduces the ring strain to below 60 kJ/mol but also amplifies the electrophilicity of the ring carbon atoms, thus facilitating a nucleophilic attack by the resultant -COO$^-$. The reaction produces high bond energy ester bonds (≈330 kJ/mol) and new hydroxyl groups, where the latter fails to induce secondary cross-linking as a result of diminished electronic effects [8] [13] [29].

For biodegradable polyesters such as PLA, GMA can also scavenge the carboxyl groups (-COOH) generated by processing-induced degradation—with the post-processing carboxyl group concentration increasing by 3-5 times—and, as illustrated in **Figure 2**, achieve chain segment reconnection and chain extension, thereby enhancing the melt strength significantly [9] [28] [29]. Experimental data demonstrate that when PC/R-PET blends are modified with GMA-based compatibilizers (e.g., E-MA-GMA), both the tensile strength and heat deflection temperature (HDT) exhibit significant enhancements [30]. Since the anhydride group of MAH and carboxyl groups (-COOH) are both acidic (anhydride pKa ≈ 1.5; -COOH pKa ≈ 4 - 5), no effective reaction can occur between them. Furthermore, the conversion rate of its reaction with trace hydroxyl groups (-OH) is less than 10%, representing a reaction efficiency far lower than that of GMA [31]-[33].

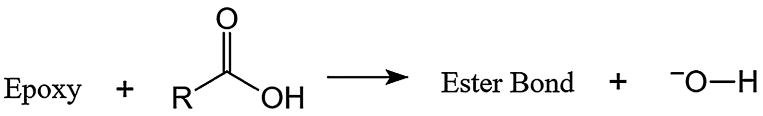

Figure 2. Schematic illustration of the reaction between GMA and polyester.

3.3. Polycarbonate (PC) Systems: Preferred Choice of GMA

The reactive end groups of PC are phenolic hydroxyl groups (-ArOH, pKa≈10, weakly nucleophilic), and the side reactions of MAH are the key to its inactivation: maleic acid generated from MAH hydrolysis can catalyze the cleavage of PC ester bonds, resulting in a reduction in molecular weight, while its reaction rate constant with phenolic hydroxyl groups ($k \approx 8 \times 10^{-2} \cdot s^{-1}$) is far lower than that of the hydrolysis reaction ($k \approx 1.2 \times 10^{-3} \cdot s^{-1}$) [10] [16] [30].

The reaction between GMA and PC can proceed efficiently under high-temperature shearing conditions. The introduction of quaternary ammonium salt catalysts (e.g., tetrabutylammonium bromide) enables the ionization of phenolic hydroxyl groups into -ArO$^-$, enhancing the nucleophilicity by several orders of magnitude; the resultant -ArO$^-$ then attacks the substituted carbon of the epoxy ring to form stable ether bonds, without any side reactions occurring. Studies have demonstrated that the addition of trace amounts of quaternary ammonium salt catalysts can increase the molecular weight retention rate of PC in PC/R-PET blends from 70% to 90% [15] [30] [34].

The differences in reaction efficiency between MAH and GMA across various polymers are summarized in **Table 1**.

Table 1. Underlying common mechanisms for differences in reaction efficiency between MAH and GMA in polymers.

Influencing Factors	**GMA (Epoxy Group)**	**MAH (Anhydride Group)**
Essence of Functional Group Reaction	Ring-strain-driven nucleophilic ring-opening (requiring nucleophile/protonation assistance)	Strong electrophile-driven nucleophilic addition (requiring strong nucleophiles such as $-NH_2$)
Core of End-group Matching	Acidic end groups (-COOH), weakly nucleophilic end groups (catalysts can improve conversion rate)	Basic end groups ($-NH_2$)
Key Pathways of Side Reactions	Self-polymerization/cross-linking at excess dosage (epoxy-hydroxyl secondary reaction)	Acid generation via hydrolysis (catalyzing polymer degradation), residue-induced yellowing
Activation Energy Requirement	Relatively high (60 - 70 kJ/mol, reducible via protonation/catalysts)	Relatively low (30 - 40 kJ/mol, direct reaction with strong nucleophiles)

3.4. Polyolefin Systems

General-purpose polyolefins (PP/PE) feature low cost and excellent processability yet suffer from insufficient rigidity and poor heat resistance. This drawback can be addressed via melt blending with polar engineering plastics (PA, PET and PBT) combined with modification by MAH/GMA-grafted polyolefin compatibilizers, thus achieving performance complementarity between the two types of polymers. This approach serves as a core strategy for the engineering upgrading of general-purpose plastics and the cost reduction of engineering plastics, and the resulting polyolefin-based alloys have been widely applied in the automotive, home appliance, packaging, and electronic and electrical industries.

For the preparation of polyolefin-based compatibilizers, GMA and MAH are grafted onto the molecular backbone of non-polar polyolefins (PP/PE) with an inert backbone structure via the free-radical initiated melt grafting method, thereby constructing reactive sites for subsequent compatibilization. Among these two monomers, MAH features a compact molecular structure and high electrophilicity, which endow it with high grafting efficiency onto PP/PE backbones—achieving a typical grafting ratio of 1% - 2%—when initiated by peroxides (e.g., dicumyl peroxide). This grafting process follows a "hydrogen abstraction-grafting" mechanism: peroxides decompose at processing temperatures (160˚C - 190˚C) to generate free radicals, which abstract hydrogen atoms from the polyolefin backbone to form macroradicals, and MAH then undergoes addition polymerization with these macroradicals to form grafted chains. MAH-grafted polyolefins (e.g., PP-g-MAH) are widely used in PP/PA blends due to their high grafting efficiency and low cost, as the anhydride groups can react with the -NH_2 end groups of PA to form imide linkages, significantly improving interfacial adhesion.

In contrast, GMA grafting onto polyolefins requires stricter control of processing conditions. The epoxy group of GMA is less reactive toward polyolefin macroradicals compared to MAH, and excessive peroxides may induce epoxy ring-opening side reactions. GMA-grafted polyolefins (e.g., PP-g-GMA) typically have a lower grafting ratio (0.5% - 1.2%) but exhibit higher reactivity toward polyester-based polymers. Their epoxy groups can undergo protonation-assisted ring-opening reactions with the -COOH end groups of PBT/PET, making them more suitable for PP/PBT blend systems where they enhance both interfacial compatibility and thermal stability [11] [14] [35].

3.5. ABS Systems

ABS is a ternary copolymer composed of acrylonitrile (AN), butadiene (BD), and styrene (St) segments, with reactive sites including nitrile groups (-CN) in the AN segment and residual hydroxyl groups (-OH) from polymerization initiators. MAH exhibits obvious limitations in ABS-based blends: the anhydride group of MAH can accelerate the thermal oxidative degradation of the BD segment under processing temperatures (220˚C - 260˚C), leading to a decrease in impact strength and yellowing of the material. Additionally, the reaction between MAH and the weak nucleophilic -CN/-OH groups of ABS is inefficient.

GMA, as a functional group, is more suitable in the compatibilizer for ABS/PC blends due to its unique reaction mechanism with ABS. The epoxy group of GMA can react with the terminal groups of PC, GMA can also undergo nucleophilic ring-opening reactions with the -OH groups of ABS (catalyzed by trace acidic impurities) and form dipole-dipole interactions with the -CN groups, thereby improving the interfacial adhesion between ABS and PC, and help for the thermal stability. Moreover, GMA's longer side chain structure enhances the interfacial toughness and inhibits the agglomeration of the BD rubber phase in ABS under high-temperature shearing, ensuring the retention of impact strength in ABS/PC blends [10] [30].

4. Interactions and Regulation Strategies of GMA/MAH with Processing Aids in Polymer Systems

4.1. Interactions with Antioxidants

The epoxy groups of GMA undergo ring-opening reactions with the phenolic hydroxyl groups of hindered phenolic antioxidants and the amino groups of amine antioxidants, which consumes the active components of both parties and results in a reduction in compatibilization efficiency; yet the formed grafted antioxidants can enhance the antioxidant durability. In contrast, MAH exhibits a higher reaction priority with amine antioxidants than with polymer end groups: the anhydride group of MAH undergoes nucleophilic addition–elimination reactions with primary amino groups of amine antioxidants to form stable succinimide derivatives. This specific structural formation completely deactivates the antioxidant (as the amino groups responsible for free radical scavenging are covalently bonded), leading to a significant decrease in compatibilization efficiency. In contrast, MAH only forms weak hydrogen bonding interactions with hindered phenols (e.g., 1010), exerting a negligible impact on their antioxidant activity, as illustrated in **Figure 3** [9] [14]. Thus, in GMA systems, it is advisable to reduce the dosage of hindered phenolic antioxidants (e.g., 1010), increase the proportion of phosphite antioxidants (e.g., 168) or adopt semi-hindered phenols; whereas in MAH systems, phenolic antioxidants should be prioritized and the use of amine antioxidants avoided [10] [11].

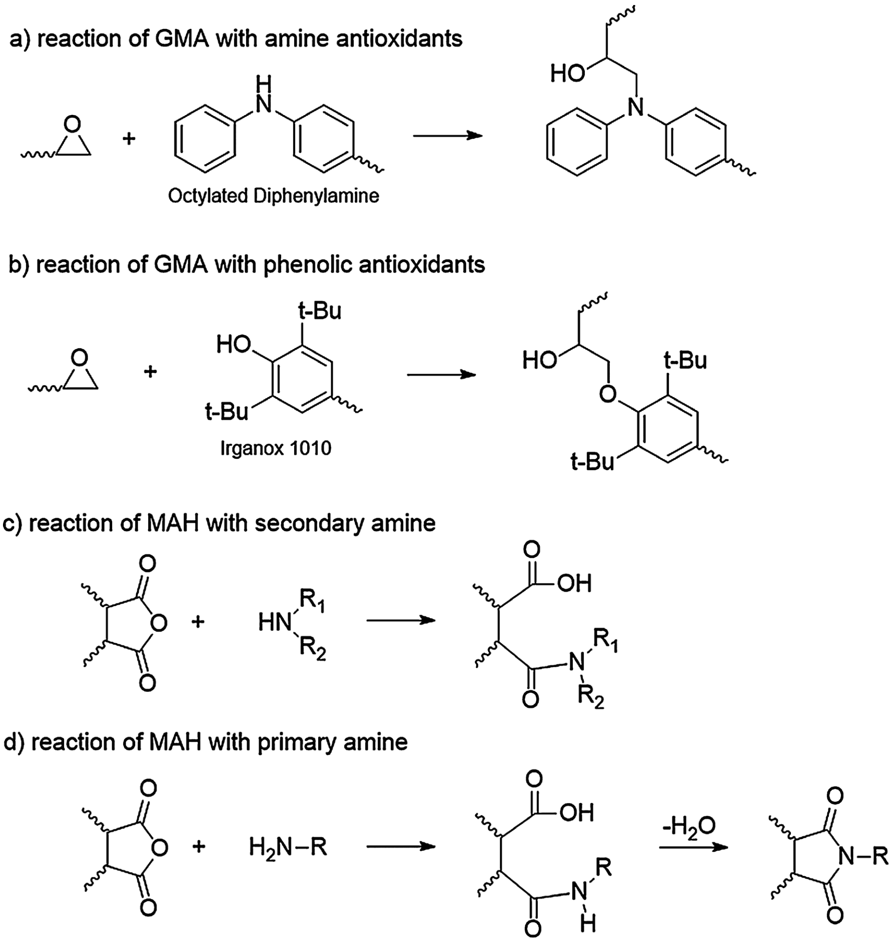

Figure 3. Reaction of GMA and MAH with antioxidants.

4.2. Interactions with UV Stabilizers

GMA can undergo ring-opening reactions with the amino groups of hindered amine light stabilizers (HALS) and the hydroxyl groups of benzotriazole-based UV stabilizers, anchoring the UV stabilizers onto the polymer chains, reducing their mobility, and thus leading to an increasing trend in the elongation at break retention rate after UV aging. However, excessive usage will competitively consume the active sites of GMA, and some reaction products tend to form quinoid structures, which induce yellowing. On the other hand, the acidity of MAH can accelerate the thermal oxidative degradation of the butadiene phase in ABS; moreover, the acidic environment generated by MAH hydrolysis will deactivate HALS and form salt precipitates, leading to a decrease in material transparency [36]-[39]. Thus, for GMA systems, triazine-based UV stabilizers free of phenolic hydroxyl groups or with high steric hindrance (e.g., UV-1577) are recommended; whereas for MAH systems, the use of HALS should be avoided, and UV absorbers (e.g., UV-327) should be prioritized.

4.3. Interactions with Flame Retardants

GMA can undergo reactions with the P-H bonds of phosphorus-based flame retardants (e.g., DOPO), the hydroxyl groups of hydroxyl-containing flame retardants (e.g., APP), and the amino groups of nitrogen-based flame retardants (e.g., melamine), thereby enhancing the flame-retardant synergistic effect. This elevates the Limiting Oxygen Index (LOI) of PC/ABS blends and enables them to achieve the UL-94 V-0 rating. However, excessive amounts of flame retardants will impair the compatibilization efficiency and even catalyze the cross-linking of GMA. As for MAH, its esterification reaction with the hydroxyl groups of phosphorus-based flame retardants facilitates the dispersion of the latter; yet its inherent acidity will catalyze the hydrolysis of organophosphorus flame retardants, leading to a reduction in flame-retardant performance [10] [40]-[45]. Reactive phosphorus-based flame retardants are recommended for GMA systems; whereas acid scavengers (e.g., hydrotalcite) can be incorporated into MAH systems to inhibit hydrolysis.

4.4. Interactions with Other Processing Aids

GMA undergoes ring-opening reactions with hydroxyl-containing lubricants (e.g., stearyl alcohol), leading to diminished lubricating efficacy; thus, fatty acid ester-based lubricants (e.g., butyl stearate) are recommended as alternatives. Whereas MAH exhibits no significant reactions with the ester groups in plasticizers, its inherent acidity may accelerate plasticizer migration, and it is therefore necessary to select acid-resistant plasticizers (e.g., epoxidized soybean oil) [10] [14].

5. Synergistic and Competitive Mechanisms of GMA and MAH in Polymer Systems and Their Application Optimization

5.1. Reaction Priority and Competitive Rules

In conventional blending systems such as PC/ABS alloys, the reaction priority sequence follows the order below under high-temperature (240˚C - 260˚C) and high-shear conditions: the reaction of MAH with trace moisture/polar additives (the highest priority) > the ring-opening addition of GMA to the terminal carboxyl groups of PC (the second priority) > the *in-situ* crosslinking between GMA and MAH (the third priority) > the direct reaction between MAH and PC (the lowest priority), as illustrated in **Figure 4** [14] [30]. This regularity is jointly governed by activation energy and functional group concentration: the high sensitivity of MAH toward polar substances leads to its preferential consumption; the protonation-catalyzed effect of the terminal carboxyl groups of PC on GMA expedites the reaction; and the electronegativity mismatch between MAH and PC renders their direct reaction difficult to proceed [9] [10].

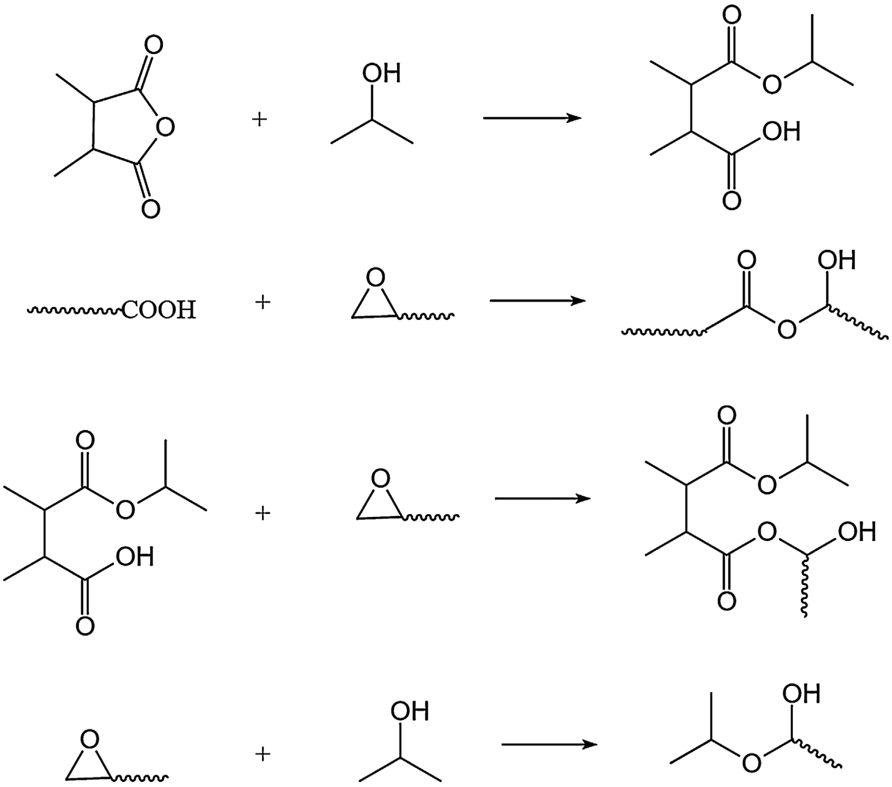

Figure 4. Reaction sequence and mechanism of anhydride and GMA in the system.

Notably, variations in shear rate can significantly alter this reaction priority sequence by regulating mass transfer and diffusion kinetics. At low shear rates (<200 s^{-1}), diffusion limitations become dominant: trace moisture in the system tends to aggregate at the interface rather than uniformly disperse, reducing the collision frequency between MAH and moisture molecules. Meanwhile, the prolonged diffusion time allows MAH to migrate toward the polymer end groups (e.g., -COOH of PC), increasing the probability of MAH-polymer reactions. Under such conditions, the reaction priority may shift to: ring-opening addition of GMA to PC terminal carboxyl groups > reaction of MAH with PC terminal carboxyl groups > reaction of MAH with moisture/polar additives > *in-situ* crosslinking between

GMA and MAH. This shift is particularly pronounced in systems with low moisture content (<0.1 wt%), where diffusion limitations override the thermodynamic advantage of MAH-moisture reactions. Conversely, at moderate shear rates (300-500 s^{-1}), the balance between diffusion and reaction kinetics maintains the original priority sequence, while at ultra-high shear rates (>1000 s^{-1}), excessive shear-induced chain scission may generate additional polar groups, further influence the priority of these reactions [10] [46].

5.2. Synergistic Effect

Appropriate blending of GMA and MAH (typically at a mass ratio of 3:1 to 5:1) enables the formation of a reactive interfacial layer, which enhances impact strength while significantly improving the heat distortion temperature (HDT). However, when their mass ratio approaches 1:1, severe gelation tends to occur, resulting in the loss of melt processability and a drastic reduction in elongation at break. In addition, GMA can scavenge the acidic species generated by MAH hydrolysis to inhibit polymer degradation, whereas MAH is capable of consuming the hydroxyl groups formed by excessive GMA to mitigate the risk of over-crosslinking, thus exhibiting a complementary synergistic effect [47] [48].

5.3. Application Optimization Strategies

In polymer modification, the selection of primary compatibilizers is generally determined by the type of polymer terminal groups: MAH is preferred for PA systems, while GMA is the optimal choice for polyester/PC systems. A small amount of the other type of compatibilizer is added as a supplement (accounting for 20% - 30% of the primary compatibilizer dosage). In terms of processing conditions, the processing temperature should be controlled (230˚C - 250˚C for GMA systems and 220˚C - 240˚C for MAH systems), along with a dwell time of 2 - 3 min. For MAH systems, the relative humidity of the processing environment must be strictly controlled below 5%. A small amount of catalyst (e.g., 0.1% - 0.3% quaternary ammonium salt catalyst) can be incorporated into PC systems, whereas 0.5% - 1% acid scavenger is recommended for MAH systems. Furthermore, the selection of additives such as antioxidants and UV absorbers is also a key factor for high-performance modification (as shown in **Table 2**) [10] [11] [14] [15] [30].

Table 2. Optimization strategies of compatibilizers and additives for polymer modification systems.

Conflict Factors	Solutions	Recommended Directions
GMA vs. Hindered Phenolic Antioxidants	Replace with low-activity phenols/phosphites	Reduce the dosage of 1010, increase the proportion of phosphite 168, or adopt semi-hindered phenols.
GMA vs. UV Absorbers	Replace with triazine-based absorbers	Use absorbers free of phenolic hydroxyl groups or with high steric hindrance (e.g., UV-1577) to reduce reaction activity.
MAH vs. PC Matrix	Control the grafting ratio and perform acid removal	If MAH must be used, ensure an extremely low grafting ratio and add acid scavengers (e.g., hydrotalcite) to mitigate polymer degradation.

6. Application Progress of GMA/MAH in Polymer Systems

6.1. Automotive Field

When PA/ABS blends are applied to automotive interior components, the incorporation of MAH-based compatibilizers can increase the impact strength by more than 40%, thereby satisfying the requirements for low-temperature toughness [27] [49]; When PC/PBT (PET) alloys are applied to automotive exterior components, GMA-based compatibilizers can suppress the transesterification reaction, increase the heat distortion temperature (HDT) to above 180˚C, and significantly improve the weather resistance [2] [50]-[52].

6.2. Electronic and Electrical Field

When PC/ABS alloys are used for electronic device housings (e.g., laptop casings, router shells), the synergistic application of GMA and reactive phosphorus-based flame retardants (e.g., DOPO) can achieve a flame retardant rating of UL-94 V-0 while maintaining favorable impact strength and tensile strength. The addition of GMA also improves the dielectric strength, suitable for the insulation requirements for electronic enclosures. When PLA/PBS biodegradable materials are applied to packaging (e.g., chip carriers), GMA-based compatibilizers can enhance the melt strength and increase the tensile modulus, enabling the materials to meet the dimensional stability requirements of blow molding and injection molding processes [4] [9] [30].

6.3. Packaging Field

When PA/EVOH blend barrier materials are applied in food packaging, MAH-based compatibilizers can improve interfacial adhesion, resulting in a reduction of the oxygen transmission rate (OTR) by more than 30%. When PLA blend materials are used in food-contact packaging, GMA-based compatibilizers can enhance the stability of mechanical properties without the release of hazardous substances [11] [34] [48].

7. Challenges and Prospects

7.1. Current Research Challenges

In polymer systems, real-time monitoring methods for the microscopic reaction mechanisms of GMA/MAH are inadequate, and *in-situ* characterization techniques to clarify dynamic reaction processes are lacking. Moreover, methodologies for evaluating reaction selectivity and conducting quantitative analysis of GMA/MAH in complex additive systems are scarce. Specific examples of such complex additive systems include PC/ABS alloy systems containing a combination of hindered phenolic antioxidants (1010), triazine-based UV stabilizers (UV-1577), reactive phosphorus flame retardants (DOPO), and fatty acid ester lubricants (butyl stearate); PLA/PBS biodegradable blend systems with semi-hindered phenol antioxidants, benzotriazole UV absorbers (UV-327), and hydrotalcite acid scavengers; and others. The effects of these complex systems are highly complex, and there is a lack of methodologies for qualitative analysis. Additionally, technologies for enhancing reaction efficiency under green processing conditions (*i.e.*, low temperature, low shear rate, and solvent-free conditions) remain to be broken through [10] [14] [30] [34].

7.2. Future Research Directions

Developing multifunctional compatibilizers suitable for polymer systems (e.g., GMA-MAH composite grafted compatibilizers) that integrate functions such as compatibilization, antioxidation, and flame retardancy; utilizing molecular simulation techniques (e.g., DFT calculations) to predict reaction efficiency and interfacial interactions—specifically, DFT can quantify the activation energy discrepancies between GMA (60 - 70 kJ/mol) and MAH (30 - 40 kJ/mol) in reactions with different polymer end groups, verify the effect of protonation/catalysts on reducing GMA's energy barrier, and clarify the thermodynamic advantage of MAH-imide formation (≈350 kJ/mol) to resolve uncertainties in Section 2.2—for guiding the rapid optimization of formulations; developing *in-situ* characterization technologies to reveal microscopic reaction mechanisms and the evolution law of interfacial structures; and expanding application research in bio-based polymer systems to adapt to green development requirements will become the research hotspots.

8. Conclusions

The difference in reaction efficiency between GMA and MAH in polymer systems stems from the matching degree between their functional group characteristics and polymer end group types: With its strong electrophilicity, MAH is compatible with the highly nucleophilic end groups ($-NH_2$) of PA, exhibiting excellent compatibilization effects in PA-based blend systems; in contrast, GMA reacts efficiently with the acidic/weakly nucleophilic end groups of polyesters and PC through the proton-induced ring-opening mechanism of its epoxy ring, making it the preferred compatibilizer for such systems. The interaction between the two and processing additives presents dual effects of "competitive consumption" and "functional synergy", which can only be balanced through precise selection and dosage regulation. When used synergistically, controlling their ratio and processing conditions enables the synergistic improvement of interfacial properties and thermomechanical properties.

Future research could focus on the *in-situ* characterization of microscopic reaction mechanisms in polymer systems, the development of multifunctional compatibilizers, computer simulation-aided selection, and the optimization of green processing technologies. It aims to promote the application of GMA/MAH in new types of civil blend materials and provide technical support for the R&D of high-performance polymer blend materials.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Jamaludin, N.A., *et al.* (2015) Mechanical and Thermal Properties of SEBS-g-MA Compatibilized PET/PC Nanocomposites. *Journal of Applied Polymer Science*, **132**, Article No. 42356.

[2] Duan, H., Tang, J.J., Li, C.H., *et al.* (2017) Influence of Compatibilizers on PC/R-PET Alloys. *China Plastics Industry*, **45**, 31-35.

[3] Shi, P., Tang, J. and Duan, H. (2021) Influence of Different Tougheners on the Properties of PC/PBT Alloy. *Journal of Materials Science and Chemical Engineering*, **9**, 70-82. https://doi.org/10.4236/msce.2021.911005

[4] Zhao, T., Yu, J., Pan, H., Zhao, Y., Zhang, Q., Yu, X., *et al.* (2023) Super-Tough Polylactic Acid (Pla)/Poly(butylene Succinate) (PBS) Materials Prepared through Reactive Blending with Epoxy-Functionalized PMMA-GMA Copolymer. *International Journal of Biological Macromolecules*, **251**, Article ID: 126150. https://doi.org/10.1016/j.ijbiomac.2023.126150

[5] Duan, H., Shi, P., Fan, Z., Liu, D. and Xia, Q. (2024) Enhancing PLA/PBAT Blends Properties with High Epoxy-Functional Polymer as a Compatibilizer. *Journal of Physics*: *Conference Series*, **2888**, Article ID: 012009. https://doi.org/10.1088/1742-6596/2888/1/012009

[6] Essabir, H., El Mechtali, F.Z., Nekhlaoui, S., Raji, M., Bensalah, M.O., Rodrigue, D., *et al.* (2020) Compatibilization of PA6/ABS Blend by SEBS-g-MA: Morphological, Mechanical, Thermal, and Rheological Properties. *The International Journal of Advanced Manufacturing Technology*, **110**, 1095-1111. https://doi.org/10.1007/s00170-020-05888-5

[7] Hu, L. and Vuillaume, P.Y. (2020) Reactive Compatibilization of Polymer Blends by Coupling Agents and Interchange Catalysts. In: *Compatibilization of Polymer Blends*, Elsevier, 205-248. https://doi.org/10.1016/b978-0-12-816006-0.00007-4

[8] Chen, D., Wang, H. and Li, Y. (2017) Reactive Compatibilization: Formation of Double-Grafted Copolymers by in Situ Binary Grafting and Their Compatibilization Effect. *ACS Applied Materials & Interfaces*, **9**, 33091-33099. https://doi.org/10.1021/acsami.7b08699

[9] Xu, P., Zhang, C., Niu, D., Yang, W., Chen, S., Liu, T., *et al.* (2023) Highly Toughened Poly(lactic Acid)/Poly(butylene Adipate-Terephthalate) Blends *In-Situ* Compatibilized by MMA-co-GMA Copolymers with Different Epoxy Group Content. *International Journal of Biological Macromolecules*, **243**, Article ID: 125017. https://doi.org/10.1016/j.ijbiomac.2023.125017

[10] Anjos, E.G.R.d., Marini, J., Montagna, L.S., Montanheiro, T.L.d.A. and Passador, F.R. (2020) Reactive Processing of Maleic Anhydride-Grafted ABS and Its Compatibilizing Effect on PC/ABS Blends. *Polímeros*, **30**, No. 4. https://doi.org/10.1590/0104-1428.09220

[11] Debbah, I., Krache, R., Aranburu, N., Fernández, M. and Etxeberria, A. (2018) Effect of SEBS-g-MAH Addition on the Mechanical, Rheological, and Morphological Properties of Polycarbonate/Acrylonitrile-Butadiene-Styrene Blends. *Journal of Elastomers & Plastics*, **50**, 611-633. https://doi.org/10.1177/0095244317753652

[12] Duan, H., Shang, X., Wu, X., Ma, L., Xing, C. and Zhu, J. (2025) Epoxy-Based Chain Extenders in Polylactic Acid (PLA): A Comprehensive Review of Structure, Performance, and Challenges. *Journal of Materials Science and Chemical Engineering*, **13**, 20-44. https://doi.org/10.4236/msce.2025.131003

[13] Joynal Abedin, F.N., Fizal, A.N.S., Alkarkhi, A.F.M., Khalil, N.A., Ahmad Yahaya,

A.N., Hossain, M.S., *et al.* (2024) Synergistic Reinforcement with SEBS-g-MAH for Enhanced Thermal Stability and Processability in GO/rGO-Filled PC/ABS Composites. *Polymers*, **16**, Article No. 2554. https://doi.org/10.3390/polym16182554

[14] Zeng, J.B., Li, K.A. and Du, A.K. (2015) Compatibilization Strategies in Poly(lactic Acid)-Based Blends. *RSC Advances*, **5**, 32546-32565. https://doi.org/10.1039/c5ra01655j

[15] Bubmann, T., Seidel, A., Ruckdäschel, H. and Altstädt, V. (2021) Transparent PC/PMMA Blends with Enhanced Mechanical Properties via Reactive Compounding of Functionalized Polymers. *Polymers*, **14**, Article No. 73. https://doi.org/10.3390/polym14010073

[16] Ryu, S.C., Kim, J.Y. and Kim, W.N. (2018) Relationship between the Interfacial Tension and Compatibility of Polycarbonate and Poly(acrylonitrile-butadiene-styrene) Blends with Reactive Compatibilizers. *Journal of Applied Polymer Science*, **135**, Article No. 46418. https://doi.org/10.1002/app.46418

[17] Zhang, W., Gomez, E.D. and Milner, S.T. (2017) Predicting Flory-Huggins χ from Simulations. *Physical Review Letters*, **119**, Article No. 17801. https://doi.org/10.1103/physrevlett.119.017801

[18] Yeung, C. and Herrmann, K.A. (2002) Molecular Dynamics Simulation of Reactive Compatibilization of Polymer Blends. *Macromolecules*, **36**, 229-237. https://doi.org/10.1021/ma021229x

[19] Zakizadeh, M., Jalali-Aarani, A. and Garmabi, H. (2025) Experimental Investigation and Molecular Dynamic Simulation of *In-Situ* Compatibilization of Biodegradable PLA/PBAT Blend as a Shape Memory Material. *Journal of Polymers and the Environment*, **33**, 4713-4728. https://doi.org/10.1007/s10924-025-03677-3

[20] Yan, Z., Ma, Z., Deng, J. and Luo, G. (2021) Mechanism and Kinetics of Epoxide Ring-Opening with Carboxylic Acids Catalyzed by the Corresponding Carboxylates. *Chemical Engineering Science*, **242**, Article ID: 116746. https://doi.org/10.1016/j.ces.2021.116746

[21] Tikekar, M.D., Delaney, K.T., Villet, M.C., Tree, D.R. and Fredrickson, G.H. (2022) A Phase Field Model for Dynamic Simulations of Reactive Blending of Polymers. *Soft Matter*, **18**, 877-893. https://doi.org/10.1039/d1sm01686e

[22] Lyu, Y., Yin, H., Chen, Y., Zhang, Q. and Shi, X. (2020) Structure and Evolution of Multiphase Composites for 3D Printing. *Journal of Materials Science*, **55**, 6861-6874. https://doi.org/10.1007/s10853-020-04505-w

[23] Zhou, Y.G., Zou, J.R., Wu, H.H. and Xu, B. (2019) Balance between Bonding and Deposition during Fused Deposition Modeling of Polycarbonate and Acrylonitrile-butadiene-Styrene Composites. *Polymer Composites*, **41**, 60-72. https://doi.org/10.1002/pc.25345

[24] Wang, Y., Li, Y., Wang, W., Lv, L., Li, C. and Zhang, J. (2019) Recycled Polycarbonate/Acrylonitrile-Butadiene-Styrene Reinforced and Toughened through Chemical Compatibilization. *Journal of Applied Polymer Science*, **136**, Article No. 47537. https://doi.org/10.1002/app.47537

[25] Hentati, F. and Masmoudi, N. (2024) The Impact of Injection Molding Process Parameters on Mechanical Properties and Microstructure of PC/ABS Blends Using Taguchi Approach. *Polymer Bulletin*, **81**, 10659-10679. https://doi.org/10.1007/s00289-024-05212-1

[26] Hentati, F., Hadriche, I., Masmoudi, N. and Bradai, C. (2019) Optimization of the Injection Molding Process for the PC/ABS Parts by Integrating Taguchi Approach and CAE Simulation. *The International Journal of Advanced Manufacturing Tech-*

nology, **104**, 4353-4363. https://doi.org/10.1007/s00170-019-04283-z

[27] Aparna, S., Purnima, D. and Adusumalli, R.B. (2016) Review on Various Compatibilizers and Its Effect on Mechanical Properties of Compatibilized Nylon Blends. *Polymer-Plastics Technology and Engineering*, **56**, 617-634. https://doi.org/10.1080/03602559.2016.1233280

[28] Duan, H., Zhu, C. and Fan, Z. (2023) Eliminating the Thermal Degradation of Polylactic Acid by the Modification of a Macromolecular Epoxy-type Chain Extender. *Journal of Applied Polymer Science*, **141**, e54769. https://doi.org/10.1002/app.54769

[29] Zhao, H., Hu, S., Xia, X., *et al.* (2021) Structure and Properties of Chain Extender-Compatibilized PBAT/PLA Blend Systems. *Engineering Plastics Application*, **49**, 131.

[30] Nishino, K., Shindo, Y., Takayama, T. and Ito, H. (2016) Improvement of Impact Strength and Hydrolytic Stability of PC/ABS Blend Using Reactive Polymer. *Journal of Applied Polymer Science*, **134**, e44550. https://doi.org/10.1002/app.44550

[31] Gao, T., *et al.* (2025) Research Progress in Modification of Polycarbonate. *China Plastics*, **39**, 37.

[32] Nagarajan, V., Mohanty, A.K. and Misra, M. (2017) Blends of Polylactic Acid with Thermoplastic Copolyester Elastomer: Effect of Functionalized Terpolymer Type on Reactive Toughening. *Polymer Engineering & Science*, **58**, 280-290. https://doi.org/10.1002/pen.24566

[33] Abdul Razak, N.C., Inuwa, I.M., Hassan, A. and Samsudin, S.A. (2013) Effects of Compatibilizers on Mechanical Properties of PET/PP Blend. *Composite Interfaces*, **20**, 507-515. https://doi.org/10.1080/15685543.2013.811176

[34] Vieyra, H., Molina-Romero, J.M., Calderón-Nájera, J.d.D. and Santana-Díaz, A. (2022) Engineering, Recyclable, and Biodegradable Plastics in the Automotive Industry: A Review. *Polymers*, **14**, Article No. 3412. https://doi.org/10.3390/polym14163412

[35] Li, S., Xiao, M., Wei, D., *et al.* (2009) Melt Grafting of Glycidyl Methacrylate-Styrene Multi-Monomer onto Powdered Polypropylene. *Journal of East China University of Science and Technology* (*Natural Science Edition*), **35**, 44-50.

[36] Wang, X., Sun, C., He, L., Liu, Y., Sun, Q., Dong, L., *et al.* (2024) Synthesis and Properties of a Novel Reactive and Low-Migration-Resistant Antioxidant and Its Application in Rubber Composites. *ACS Omega*, **9**, 15401-15409. https://doi.org/10.1021/acsomega.3c10301

[37] Al-Malaika, S. and Eddiyanto, E. (2010) Reactive Processing of Polymers: Effect of Bifunctional and Tri-Functional Comonomers on Melt Grafting of Glycidyl Methacrylate onto Polypropylene. *Polymer Degradation and Stability*, **95**, 353-362. https://doi.org/10.1016/j.polymdegradstab.2009.11.006

[38] You, B., Zhou, D., Liu, L., Zen, M. and Ren, X. (2013) Preparation of Hals-Functional Core-Shell Nanoparticles and Their Application in Poly(butylene Terephthalate). *Polymer-Plastics Technology and Engineering*, **52**, 946-953. https://doi.org/10.1080/03602559.2013.763376

[39] Kikuchi, T., Ohtake, Y. and Tanaka, K. (2012) Discoloration Phenomenon Induced by the Combination of Phenolic Antioxidants and Hindered Amine Light Stabilizers. *Nippon Gomu Kyokaishi*, **85**, 283-288. https://doi.org/10.2324/gomu.85.283

[40] Wang, X., Cheng, W. and Li, J. (2019) The Effect of Flame Retardants on the Flame Retardancy and Adhesion Properties of Bisphenol A Epoxy Resin. *Development and Application of Materials*, **34**, 93-97.

[41] Yang, X., Shi, J., Zhou, Y., *et al.* (2024) Enhancing the Flame Retardancy of Epoxy

Resin via Phosphorus-Based Flame Retardant-Intercalated Mg-Al Hydrotalcite. *Chinese Journal of Applied Chemistry*, **41**, No. 8.

[42] Lin, K., Wang, L. and Deng, H. (2025) Preparation of Flame Retardant DOPO-BZA and Its Enhancement on Flame Retardancy of Epoxy Resin. *Acta Materiae Compositae Sinica*, **42**, No. 11.

[43] Zhang, C., Duan, H., Wan, C., Liu, C., Zhao, H. and Ma, H. (2022) Simultaneously Improving the Thermal Stability, Mechanical Properties and Flame Retardancy of Epoxy Resin by a Phosphorus/Nitrogen/Sulfur-Containing Reactive Flame Retardant. *Materials Today Communications*, **30**, Article ID: 103108. https://doi.org/10.1016/j.mtcomm.2021.103108

[44] Abbasi, A., Shakeri, A. and Abbasi, A. (2018) Synthesize and Characterization of Flame Retardant Copolyesters PET/Phosphorus Compound. *Journal of Vinyl and Additive Technology*, **25**, 262-270. https://doi.org/10.1002/vnl.21688

[45] Suwanniroj, A. and Suppakarn, N. (2022) Influence of Glycidyl Methacrylate Grafted Poly(butylene Succinate) (PBS-g-GMA) on Flame Retardancy and Mechanical Properties of Water Hyacinth Fiber/Ammonium Polyphosphate/Poly(butylene Succinate) Composites. *Journal of Applied Polymer Science*, **139**, e53063. https://doi.org/10.1002/app.53063

[46] Lee, H.I., Lee, H.K., Kim, D.S., Choi, S.J., Kim, S.H., Yoo, J.J., *et al.* (2014) Effects of the High Shear Rate Processing on the Thermal Properties of PC/ABS Blends. *Polymer Korea*, **38**, 320-326. https://doi.org/10.7317/pk.2014.38.3.320

[47] Song, L., Zhang, Q., Hao, Y., Li, Y., Chi, W., Cong, F., *et al.* (2022) Effect of Different Comonomers Added to Graft Copolymers on the Properties of PLA/PPC/PLA-g-GMA Blends. *Polymers*, **14**, Article No. 4088. https://doi.org/10.3390/polym14194088

[48] Wilkie, C.A. and Morgan, A.B. (2024) Fire Retardancy of Polymeric Materials. CRC Press.

[49] Yan, J., Wang, C., Zhang, T., Xiao, Z. and Xie, X. (2024) Super Tough PA6/PP/ABS/SEBS Blends Compatibilized by a Combination of Multi-Phase Compatibilizers. *Materials*, **17**, Article No. 5370. https://doi.org/10.3390/ma17215370

[50] Song, Z., Liu, D., Xu, J., *et al.* (2014) Study on the Compatibility of High-Impact PET/PC Alloys. *Plastics Industry*, **42**, 29-34.

[51] Liu, R., Li, L., Yin, B., *et al.* (2010) Effect of E-MA-GMA on the Compatibility of PC/PET Blends. *Synthetic Resins and Plastics*, No. 1, 21-23.

[52] Li, W., Wang, Y. and Wang, B. (2014) Effect of Transesterification Inhibition on the Properties of PC/PBT Blends. *Plastics Manufacturing*, No. 3, 74-80.