Polyurethane

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Polyurethane is widely considered as the biggest polymer product which is categorized under plastics. PUs belong to a group of elastomers that are linked to a urethane material with a distinctive feature of being hard and soft parts in the macromolecule. Plastic and modular construction industries produce big quantities of PU wastes in the fabrication process during either processing or utilization of materials.

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1. Introduction

A range of research has been conducted on the ongoing discussion of the effect of chemical structure and annealing of the morphology of polyurethanes (PUs) on experimental and theoretical work on phase-separation kinetics [1]. Phase separation is the most crucial reason for the PUs' microphase separation as the powerful hydrogen link between the urethane hard parts [2]. The main components of PUs are macrodiol, diisocyanate, and chain extender [3]. The chemistry of PU synthesis depends on the reactions of isocyanate. The hydrolysis resistance of PUs and the noting of the diol chemistry on molecular weight stability in water are discussed by Gomez et al. [4].

PUs belong to a group of elastomers that are linked to a urethane material with a distinctive feature of being hard and soft parts in the macromolecule [5]. In addition, the environmental issue that involves PU recycling was a concern of researchers [6]. The synthesis of PU is the main theme of the studies in the field of working towards environmentally based materials such as PU, using the short-chain diol called diisocyanate [7]. Polyurethane is widely considered as the biggest polymer product which is categorized under plastics [8]. Plastic and modular construction industries produce big quantities of PU wastes in the fabrication process during either processing or utilization of materials [9]. The structure and properties of PU parts have been investigated to achieve better biocompatibility and are characterized by surface and bulk morphology [10]. Traditionally, PU items are equipped with many organic solvents and free isocyanate monomers [11]. In the production of PU foams, catalysts are employed in the polyaddition reaction [12]. It has been reported that two simultaneous reactions could occur during PU manufacturing that involves the isocyanates and polyols during gas liberation or a foaming reaction [13]. As an example, paints from modified PU are extensively used as topcoats for corrosion and weather resistance. The aliphatic PU is sensitive to acrylic ester comprising hydroxyl which is widely considered as having good adhesion and being aging-resistant [14]. These processes involve building up strong hydrogen links of the PU matrix, raising the rigidity of the matrix, and negatively affecting the relaxation of dipoles [15]. The particles dispersed in aqueous phase dispersion, classified as anionic PU, are binary colloidal systems, cationic, and non-ionic systems [16]. Regarding the nanomaterials, the antibacterial polyurethane activity of composite nanofibers has been assessed in food-borne pathogenic bacteria and staphylococcus aureus, using various techniques [17]. The focus is on the formation of soft, long-chain diol segments, whereas the construction of the hard segment belongs to the microdomain of segmented PU copolymers [18].

2. Polyurethane Composite

The soft segment relative to the hard segment of the lower air-interfacial polymer has made the appearance of PU in polyol structure [19]. The size of the dispersed PU particle reduces the concentration of the ionic group per unit chain length of the PU pre-polymer [20]. On the other hand, the increase of the ratio of hard to soft parts of the PU chains results in increasing the viscosity of the prepolymer [21]. The reduction of the ionic group concentration and the increase in the viscosity could cause a stiffer PU chain, lowering the solubility of the polymer, enhance the phase separation, and make coarse particles at the surface [22]. The above behavioural changes increase the hysteresis values of the quaternized polymers compared to the base PUs. The effect then causes a noticeable rearrangement surface that changes the hydration [23].

PUs are industrially crucial polymers with a range of structures and uses [24]. The acrylics PU polymer is known by a table of Newtonian rheological features [25]. Regarding the aging of the PU film, Sanchis et al. [26] have shown that the PU structure plays an important role in addressing the age issue.

The poor elasticity of the two segmented PUs was caused by their low molecular weight which, in turn, influences the morphology of the segmented PUs [27]. Hetflejš et al. [28] illustrated that the stabilizing efficiency of polymer-linked structures could be compared with that of their low-molecular-weight analogs, physically admixed with the PU. In another field, a sufficient mixing of the fluoro acrylic and PU polymers in the film properties could produce better results [29]. In this regard, it was found that modifying the ratio of PU and polyimide parts results in widening the range of properties from plastic to elastomer of the poly(urethane-imide) [30]. The solubility of the polyimide is enhanced as a result of adding isocyanate-terminated PU prepolymer, making a gelatine solution [31].

3. Thermoplastic Polyurethane Composite

Thermoplastic polyurethanes (TPUs) are linear segmented copolymers composed of hard and soft segments separated by a microphase, which complicates the investigation of its relevant microstructure [32]. The difficulty of this investigation shortening the research of the microstructure to extension behaviour [33]. Thermoplastic polyurethane (TPU) and the thermoset PU are chemically similar to each other; however, they have different features [34]. TPU is characterized by unique physical-chemical properties due to the reformation ability from melting state which makes it elastic, highly flexible, and suitable for many industrial applications [35]. On the other hand, the sensitivity of TPU to oil is smaller than that of thermoset PU, as the latter is easy to tear with abrasive applications [36]. TPU becomes soft at high temperatures and can hold low pressure, possessing a higher tensile modulus in comparison to rubber [37].

TPU is generally described as “bridging the gap between rubber and plastics” and imparts high elasticity combined with high abrasion resistance, and, hence, becomes suitable to a variety of biomedical applications [38]. TPUs are conventionally not degradable; however, they become susceptible to hydrolytic and oxidative under vacuum [39]. The TPUs’ susceptibility to such degradation causes a problem for long-lasting biomedical implants which exploit designing biodegradable PUs [40].

TPU displays a very wide range of properties, ranging from very soft to strong, rigid thermoplastics that depend on the chemical compositions, backbone structures, and resultant microphase morphologies [41]. The 40-year investigation revealed that there are various morphological models for segmented PUs [42]. TPU has become one of the most versatile engineering thermoplastics that have constituted developing more interesting polymers due to specific structures of TPU macromolecules, interphase interactions, and microphase transformations [43]. Several researchers have addressed that blending TPU with nanomaterials enhances its physical properties and toughness [44]. The TPU’s good compatibility with polycarbonate or acrylonitrile butadiene styrene was behind using TPU as a modifier to create new blends [45]. The effect of using special additives can be seen in creating properties necessary to achieve flame retardance, antistatic, and radiation crosslinking ability [46]. Besides, exposing TPU to severe conditions results in significant structural changes depending on the structure and morphology; however, such changes deteriorate the physical properties [47].

4. Properties of Nanofiller–TPU Nanocomposites

The main application of TPU is in the medical field due to its exceptional mechanical properties and biocompatibility. The siloxane-based TPU is one of the most important nanocomposites. TPU nanocomposites were vigorously studied based on the nanofiller aspect ratio, surface modification, and percentage loading. The mechanical properties were increased at an even small amount of loading.

4.1. Morphology Properties of Nanofiller–TPU Nanocomposites

The first-ever successful attempt of dispersion of nanoclays in the TPU matrix has resulted in incredibly high interest amongst the scientific community [48]. It was seen that the morphology of clay platelets plays a crucial role in the improvement of the properties of the clay–TPU nanocomposites. The effect of hard segment content along with the amount of clay on the morphology has been discussed by Xu et al. [49]. Increased hard segment content has been seen to result in an increase of the basal spacing of the clay platelets at a lower clay content. However, the opposition has been observed to occur at higher clay contents, where increased hard segment content reduces the basal spacing. Two varieties of modified montmorillonite (MMT) have been dispersed in the TPU matrix [50]; the first is clay modified with 12 amino lauric acids and the second is clay modified with benzidine. This was done in order to study the effect of the modifier on the morphology and properties of the resulting nanocomposites [50].

Complete exfoliation was observed of up to 5% and 3% for clay modified with 12 amino lauric acid and benzidine, respectively.

4.2. Mechanical Properties of Nanofiller–TPU Nanocomposites

The mechanical properties of modified TPU are extremely important because of the usefulness of modified TPU in many engineering applications. It has been observed that the addition of nanoclay into the PU matrix improves the tensile properties to a significant degree [51]. As an example, adding 10 wt.% of modified clay increases the tensile strength, modulus, and strain at the break by more than 100% [45][49]. Young's modulus of the nanoclay–TPU nanocomposites has previously been seen to increase with the addition of modified nanoclays [52]. Nonetheless, improved Young's modulus coupled with a reduction in tensile strength and elongation at break with the addition of clay has also been reported in previous studies [53]. Besides that, the destruction of hydrogen bonds in the hard segment of TPU due to the incorporation of tethered nanoclays has also been observed [53]. The destruction in H-bonding occurs due to the H-bond formation between the carbonyl group of the TPU and the [–OH] group present on the tail of the modifier to the clay. However, modulus and tensile strength are increased by 110 and 160%, respectively, for the nanocomposite containing 5 wt.% of Cloisite®30B. The reaction of the surface [–OH] group of the MMT with the isocyanate during in situ synthesis, which leads to an improvement in tensile strength, as well as elongation at break, has been observed from experimentation [49].

4.3. Thermal Properties of Nanofiller–TPU Nanocomposites

The thermal stability of the TPU matrix is of great importance since its degradation commences around 230–300 °C. It is important to note that a TPU matrix possesses two glass transition temperatures (T_g) corresponding to the soft and the hard segments, while it is known that the hard segment temperature T_g is not always observed due to the dominance of the soft segment and ordered hard domains [54]. It also appears that the addition of a small amount of tethered clay could increase T_g of the hard segment by 44 °C [55] while a 13 °C rise was observed in the T_g value of the soft segment with the addition of Cloisite® 20A [56]. TPU was found to exhibit two stages of degradation during decomposition. The first stage of degradation relates to the degradation of the hard segment and the second stage of degradation relates to the degradation of the soft segment [57]. In some other studies, a lower T_g of the nanocomposite, as compared to the TPU matrix, has been reported [58]. The thermal stability of the clay–TPU nanocomposite will increase after the complete decomposition of the modifier compared to that of the TPU matrix [59]. An increase in the amount of clay from 1 to 5 wt.% was reported to increase the thermal stability of the TPU matrix from 12 to 34 °C, respectively [55]. The increase in thermal stability with an increase for MMT in the TPU matrix has also been reported in previous studies [49]. The improvement in thermal stability of the clay–TPU nanocomposite was found to be directly connected to the degree of dispersion of the nanoclay in the TPU matrix [59].

5. Conclusions

Controlling the interaction between hard and soft segments through hydrogen linking plays a crucial role in featuring the amorphous structure of PU and the thermally labile thermoplastic polyurethane (TPU), which is chemically similar to PU with a better heat resistivity. TPU has become the most versatile engineering thermoplastic with exceptional mechanical properties and biocompatibility that could be utilized to develop more interesting polymers due to specific structures of TPU macromolecules, interphase interactions, and microphase transformations.

References

1. Shafeeq, V.; Unnikrishnan, G. Experimental and theoretical evaluation of mechanical, thermal and morphological features of EVA-millable polyurethane blends. J. Polym. Res. 2020, 27, 1–11.
2. Mocan, M.; Kamperman, M.; Leermakers, F.A. Microphase segregation of diblock copolymers studied by the self-consistent field theory of Scheutjens and Fleer. Polymers 2018, 10, 78.
3. Akram, N.; Zia, K.M.; Saeed, M.; Usman, M.; Saleem, S. Impact of macrodiols on the adhesion strength of polyurethane pressure-sensitive adhesives. J. Appl. Polym. Sci. 2018, 135, 46635.
4. Gomez, C.M.; Gutierrez, D.; Asensio, M.; Costa, V.; Nohales, A. Transparent thermoplastic polyurethanes based on aliphatic diisocyanates and polycarbonate diol. J. Elastomers Plast. 2017, 49, 77–95.
5. Parcheta, P.; Głowińska, E.; Datta, J. Effect of bio-based components on the chemical structure, thermal stability and mechanical properties of green thermoplastic polyurethane elastomers. Eur. Polym. J. 2020, 123, 109422.
6. Ikutegbe, C.A.; Farid, M.M. Application of phase change material foam composites in the built environment: A critical review. Renew. Sustain. Energy Rev. 2020, 131, 110008.
7. Xie, F.; Zhang, T.; Bryant, P.; Kurusingal, V.; Colwell, J.M.; Laycock, B. Degradation and stabilization of polyurethane elastomers. Prog. Polym. Sci. 2019, 90, 211–268.
8. Somarathna, H.M.; Raman, S.N.; Mohotti, D.; Mutalib, A.A.; Badri, K.H. The use of polyurethane for structural and infrastructural engineering applications: A state-of-the-art review. Constr. Build. Mater. 2018, 190, 995–1014.
9. Groover, M.P. Fundamentals of Modern Manufacturing: Materials, Processes, and Systems; John Wiley & Sons: Hoboken, NJ, USA, 2020.
10. Abbasi, A.; Mir, M.S.; Ghasemi, I.; Shahrousvand, M. Shape memory performance of green in situ polymerized nanocomposites based on polyurethane/graphene nanoplatelets: Synthesis, properties, and cell behavior. Polym. Compos. 2018, 39, 4020–4033.

11. Utomo, R.N.C.; Li, W.-J.; Tiso, T.; Eberlein, C.; Doeker, M.; Heipieper, H.J.; Jupke, A.; Wierckx, N.; Blank, L.M. Defined Microbial Mixed Culture for Utilization of Polyurethane Monomers. ACS Sustain. Chem. Eng. 2020, 8, 17466–17474.
12. Zhu, S.; Chen, K.; Xu, J.; Li, J.; Mo, L. Bio-based polyurethane foam preparation employing lignin from corn stalk enzymatic hydrolysis residues. RSC Adv. 2018, 8, 15754–15761.
13. Saleh, S.; Yunus, N.Z.M.; Ahmad, K.; Ali, N. Improving the strength of weak soil using polyurethane grouts: A review. Constr. Build. Mater. 2019, 202, 738–752.
14. Athavale, S.P. Hand Book of Pressure Sensitive Adhesives and Coatings: Pressure Sensitive Adhesives Technology; Notion Press: Chennai, India, 2018.
15. Kariduraganavar, M.Y.; Tambe, S.M.; Tasaganva, R.G.; Kittur, A.A.; Kulkarni, S.S.; Inamdar, S.R. Studies on nonlinear optical polyurethanes containing heterocyclic chromophores. J. Mol. Struct. 2011, 987, 158–165.
16. Shin, E.J.; Choi, S.M. Advances in waterborne polyurethane-based biomaterials for biomedical applications. Novel Biomater. Regener. Med. 2018, 1077, 251–283.
17. Pant, B.; Park, M.; Ojha, G.P.; Kim, D.-U.; Kim, H.-Y.; Park, S.-J. Electrospun salicylic acid/polyurethane composite nanofibers for biomedical applications. Int. J. Polym. Mater. Polym. Biomater. 2018, 67, 739–744.
18. Gaaz, T.S.; Sulong, A.B.; Akhtar, M.N.; Raza, M.R. Morphology and tensile properties of thermoplastic polyurethane-halloysite nanotube nanocomposites. Int. J. Autom. Mech. Eng. 2015, 12, 2844–2856.
19. Maji, P.K.; Bhowmick, A.K. Structure–property correlation of polyurethane nanocomposites: Influence of loading and nature of nanosilica and microstructure of hyperbranched polyol. J. Appl. Polym. Sci. 2013, 127, 4492–4504.
20. Son, S.-H.; Lee, H.-J.; Kim, J.-H. Effects of carboxyl groups dissociation and dielectric constant on particle size of polyurethane dispersions. Colloids Surf. A Physicochem. Eng. Asp. 1998, 133, 295–301.
21. Babaie, A.; Rezaei, M.; Sofla, R.L.M. Investigation of the effects of polycaprolactone molecular weight and graphene content on crystallinity, mechanical properties and shape memory behavior of polyurethane/graphene nanocomposites. J. Mech. Behav. Biomed. Mater. 2019, 96, 53–68.
22. Jabbari, E.; Khakpour, M. Morphology of and release behavior from porous polyurethane microspheres. Biomaterials 2000, 21, 2073–2079.
23. Grapski, J.A.; Cooper, S.L. Synthesis and characterization of non-leaching biocidal polyurethanes. Biomaterials 2001, 22, 2239–2246.

24. Golling, F.E.; Pires, R.; Hecking, A.; Weikard, J.; Richter, F.; Danielmeier, K.; Dijkstra, D. Polyurethanes for coatings and adhesives–chemistry and applications. Polym. Int. 2019, 68, 848–855.
25. Bhavsar, R.A.; Nehete, K.M. Rheological approach to select most suitable associative thickener for water-based polymer dispersions and paints. J. Coat. Technol. Res. 2019, 16, 1089–1098.
26. Sanchis, M.; Calvo, O.; Fenollar, O.; Garcia, D.; Balart, R. Characterization of the surface changes and the aging effects of low-pressure nitrogen plasma treatment in a polyurethane film. Polym. Test. 2008, 27, 75–83.
27. Marcano, A.; Fatyeyeva, K.; Koun, M.; Dubuis, P.; Grimme, M.; Marais, S. Recent developments in the field of barrier and permeability properties of segmented polyurethane elastomers. Rev. Chem. Eng. 2019, 35, 445–474.
28. Hetflejš, J.; Šabata, S.; Podešva, J.; Kovářová, J.; Prokůpek, L.; Netopilík, M.; Spěváček, J.; Sýkora, J. Novel stabilisers acting simultaneously as molecular-weight regulators in soluble elastomeric polyurethanes. Polym. Degrad. Stab. 2010, 95, 579–586.
29. Li, J.-W.; Lee, H.-T.; Tsai, H.-A.; Suen, M.-C.; Chiu, C.-W. Synthesis and Properties of Novel Polyurethanes Containing Long-Segment Fluorinated Chain Extenders. Polymers 2018, 10, 1292.
30. Didenko, A.; Smirnova, V.E.; Popova, E.N.; Vaganov, G.V.; Kuznetcov, D.A.; Elokhovskii, V.; Ivanov, A.G.; Svetlichnyi, V.M.; Yudin, V.E.; Kudryavtsev, V.V. Heat Resistance and Dynamic Mechanical and Rheological Properties of a Blend of Crystallizing Polymers Polyimide and Copoly (urethane—imide), at Identical Chemical Structure of the Imide Blocks in the Initial Polymers. Russ. J. Appl. Chem. 2020, 93, 45–56.
31. Zuo, M.; Takeichi, T. Preparation and characterization of poly (urethane–imide) films prepared from reactive polyimide and polyurethane prepolymer. Polymer 1999, 40, 5153–5160.
32. Jouibari, I.S.; Haddadi-Asl, V.; Mirhosseini, M.M. A novel investigation on micro-phase separation of thermoplastic polyurethanes: Simulation, theoretical, and experimental approaches. Iran. Polym. J. 2019, 28, 237–250.
33. Andrew, J.J.; Srinivasan, S.M.; Arockiarajan, A.; Dhakal, H.N. Parameters influencing the impact response of fiber-reinforced polymer matrix composite materials: A critical review. Compos. Struct. 2019, 224, 111007.
34. Wang, S.; Liu, Z.; Zhang, L.; Guo, Y.; Song, J.; Lou, J.; Guan, Q.; He, C.; You, Z. Strong, detachable, and self-healing dynamic crosslinked hot melt polyurethane adhesive. Mater. Chem. Front. 2019, 3, 1833–1839.
35. Xiang, D.; Zhang, X.; Li, Y.; Harkin-Jones, E.; Zheng, Y.; Wang, L.; Zhao, C.; Wang, P. Enhanced performance of 3D printed highly elastic strain sensors of carbon nanotube/thermoplastic

polyurethane nanocomposites via non-covalent interactions. Compos. Part. B Eng. 2019, 176, 107250.

36. Varnava, C.K.; Patrickios, C.S. Polymer Networks One Hundred Years after the Macromolecular Hypothesis: A Tutorial Review. Polymer 2020, 215, 123322.
37. Szefer, E.; Stafin, K.; Leszczyńska, A.; Zając, P.; Hebda, E.; Raftopoulos, K.N.; Pielichowski, K. Morphology, dynamics, and order development in a thermoplastic polyurethane with melt blended POSS. J. Polym. Sci. Part. B Polym. Phys. 2019, 57, 1133–1142.
38. Princi, E. Rubber: Science and Technology; Walter de Gruyter GmbH & Co KG.: Berlin, Germany, 2019.
39. Yuan, S.; Shen, F.; Chua, C.K.; Zhou, K. Polymeric composites for powder-based additive manufacturing: Materials and applications. Prog. Polym. Sci. 2019, 91, 141–168.
40. Herzberger, J.; Sirrine, J.M.; Williams, C.B.; Long, T.E. Polymer design for 3D printing elastomers: Recent advances in structure, properties, and printing. Prog. Polym. Sci. 2019, 97, 101144.
41. Solouki Bonab, V. Polyurethane (PU) Nanocomposites Interplay of Composition Morphology and Properties; Case Western Reserve University: Cleveland, OH, USA, 2019.
42. Asensio, M.; Costa, V.; Nohales, A.; Bianchi, O.; Gómez, C.M. Tunable structure and properties of segmented thermoplastic polyurethanes as a function of flexible segment. Polymers 2019, 11, 1910.
43. Ren, M.; Zhou, Y.; Wang, Y.; Zheng, G.; Dai, K.; Liu, C.; Shen, C. Highly stretchable and durable strain sensor based on carbon nanotubes decorated thermoplastic polyurethane fibrous network with aligned wave-like structure. Chem. Eng. J. 2019, 360, 762–777.
44. Lin, W.; Qu, J.-P. Enhancing impact toughness of renewable poly (lactic acid)/thermoplastic polyurethane blends via constructing cocontinuous-like phase morphology assisted by ethylene–methyl acrylate–glycidyl methacrylate copolymer. Ind. Eng. Chem. Res. 2019, 58, 10894–10907.
45. Lu, F.; Liu, Y.; Wang, F.; Mai, Y.-l.; Li, D.-y. Effect of Organo-Modified Montmorillonite on the Morphology and Properties of SEBS/TPU Nanocomposites. Polym. Eng. Sci. 2020, 60, 850–859.
46. Müller, K.; Bugnicourt, E.; Latorre, M.; Jorda, M.; Echegoyen, Y.; Lagaron, J.M.; Miesbauer, O.; Bianchin, A.; Hankin, S.; Bölz, U. Review on the processing and properties of polymer nanocomposites and nanocoatings and their applications in the packaging, automotive and solar energy fields. Nanomaterials 2017, 7, 74.
47. Kim, K.-S.; Choi, S.B.; Kim, D.U.; Lee, C.-R.; Kim, J.-W. Photo-induced healing of stretchable transparent electrodes based on thermoplastic polyurethane with embedded metallic nanowires. J. Mater. Chem. A 2018, 6, 12420–12429.

48. Mokhothu, T.H.; Mtibe, A.; Mokhena, T.C.; Mochane, M.J.; Ofosu, O.; Muniyasamy, S.; Tshifularo, C.A.; Motsoeneng, T.S. Mechanical, Thermal and Viscoelastic Properties of Polymer Composites Reinforced with Various Nanomaterials. In Sustainable Polymer Composites and Nanocomposites; Springer: Berlin, Germany, 2019; pp. 185–213.
49. Xu, J.; Cheng, L.; Zhang, Z.; Zhang, L.; Xiong, C.; Huang, W.; Xie, Y.; Yang, L. Highly exfoliated montmorillonite clay reinforced thermoplastic polyurethane elastomer: In situ preparation and efficient strengthening. RSC Adv. 2019, 9, 8184–8196.
50. Chen, T.-K.; Tien, Y.-I.; Wei, K.-H. Synthesis and characterization of novel segmented polyurethane/clay nanocomposites. Polymer 2000, 41, 1345–1353.
51. Wang, X.-C.; Zhu, Q.-S.; Dong, B.-B.; Wu, H.-H.; Liu, C.-T.; Shen, C.-Y.; Turng, L.-S.; Geng, T. The effects of nanoclay and deformation conditions on the inelastic behavior of thermoplastic polyurethane foams. Polym. Test. 2019, 79, 106043.
52. Yeh, S.-K.; Liu, Y.-C.; Chu, C.-C.; Chang, K.-C.; Wang, S.-F. Mechanical properties of microcellular and Nanocellular thermoplastic polyurethane nanocomposite foams created using supercritical carbon dioxide. Ind. Eng. Chem. Res. 2017, 56, 8499–8507.
53. Amirkiai, A.; Panahi-Sarmad, M.; Sadeghi, G.M.M.; Arjmand, M.; Abrisham, M.; Dehghan, P.; Nazockdast, H. Microstructural design for enhanced mechanical and shape memory performance of polyurethane nanocomposites: Role of hybrid nanofillers of montmorillonite and halloysite nanotube. Appl. Clay Sci. 2020, 198, 105816.
54. Sarver, J.; Kiran, E. Foaming of Polymers with Carbon Dioxide–The year-in-review–2019. J. Supercrit. Fluids 2021, 173, 105166.
55. Adak, B.; Butola, B.S.; Joshi, M. Effect of organoclay-type and clay-polyurethane interaction chemistry for tuning the morphology, gas barrier and mechanical properties of clay/polyurethane nanocomposites. Appl. Clay Sci. 2018, 161, 343–353.
56. Bocchio, J.A.; Escobar, M.M.; Amado, J.C.Q. Ablative properties of polyurethanes reinforced with organoclay. Polym. Eng. Sci. 2020, 60, 630–635.
57. Magnin, A.; Pollet, E.; Phalip, V.; Avérous, L. Evaluation of biological degradation of polyurethanes. Biotechnol. Adv. 2020, 39, 107457.
58. Arenas, J.P.; Castaño, J.L.; Troncoso, L.; Auad, M.L. Thermoplastic polyurethane/laponite nanocomposite for reducing impact sound in a floating floor. Appl. Acoust. 2019, 155, 401–406.
59. Khalifa, M.; Anandhan, S.; Wuzella, G.; Lammer, H.; Mahendran, A.R. Thermoplastic polyurethane composites reinforced with renewable and sustainable fillers—A review. Polym. Plast. Technol. Mater. 2020, 59, 1751–1769.

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