

·综述·

聚对苯二甲酸-己二酸丁二醇酯复合发泡材料的 结构调控与功能化研究进展

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摘要: 聚对苯二甲酸-己二酸丁二醇酯(PBAT)是一种兼具脂肪族柔韧性与芳香族刚性的绿色生物可降解聚酯,是替代传统塑料的理想材料之一。然而,其熔体强度低导致发泡材料泡孔尺寸稳定性差的问题制约了高性能PBAT发泡材料在包装、农业、生物医学及柔性电子等领域的广泛应用。本文系统综述了PBAT发泡材料的最新研究进展,重点阐述了多相共混、功能填料复合、交联强化及分子拓扑结构调控等策略对熔体强度的强化机理;深入分析了4种发泡工艺对泡孔结构的调控规律;最后总结了PBAT发泡材料在功能包装、生态农业、生物医学等领域的研究现状,并对未来揭示多尺度结构调控机理、开发绿色智能发泡工艺等研究方向进行了展望,为开发高性能PBAT发泡材料提供理论依据和技术支撑。

关键词: 聚对苯二甲酸-己二酸丁二醇酯;生物降解;发泡材料;多尺度调控

Research Progress on Structure Regulation and Functionalization of Poly(butylene terephthalate-butylene Adipate) Composite Foaming Materials

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Abstract: Poly(butylene adipate-co-terephthalate) (PBAT) is a green and biodegradable polyester that combines the flexibility of aliphatic and the rigidity of aromatic. It is one of the ideal materials to replace traditional plastics. However, its low melt strength leads to poor cell size stability of foamed materials,

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which restricts the wide application of high-performance PBAT foamed materials in packaging, agriculture, biomedicine and flexible electronics. This paper systematically reviews the latest research progress of PBAT foamed materials, focusing on the strengthening mechanisms of melt strength by strategies such as multi-phase blending, functional filler composites, crosslinking reinforcement and molecular topological structure regulation; deeply analyzes the regulation laws of cell structure by four foaming processes; finally summarizes the research status of PBAT foamed materials in functional packaging, ecological agriculture, biomedicine and other fields, and looks forward to the research directions of revealing multi-scale structure regulation mechanisms and developing green and intelligent foaming processes in the future, providing theoretical basis and technical support for the development of high-performance PBAT foamed materials.

Keywords: Poly(butylene adipate-co-terephthalate); Biodegradable; Foaming material; Multi-scale regulation

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随着高分子材料产业的快速发展, 塑料污染已成为21世纪全球最严峻的环境挑战之一^[1~3]。塑料制品以其成本低廉、加工便捷等优势被广泛使用。然而其大部分难以自然降解^[4,5], 在环境中留存数十年甚至上百年, 导致环境和气候问题愈加严重, 对生态系统造成了持久且严重的破坏^[6,7]。为应对这一问题, 人们致力于开发可降解材料作为传统塑料的替代品^[8~12]。聚对苯二甲酸-己二酸丁二醇酯(PBAT)是由对苯二甲酸、己二酸和丁二醇共聚而成的脂肪族-芳香族线型共聚酯^[13], 兼具柔性脂肪族聚酯良好的生物降解性、高延展性和柔韧性与刚性芳香族聚酯良好的冲击性能和耐热性, 已广泛应用于缓冲包装^[14]、农业地膜^[15]、生物医学支架^[16]及柔性电子^[17]等领域, 如图1所示。同时, PBAT以其优异的生物可降解性, 可在自然环境被微生物分解为CO₂和H₂O^[18], 实现碳循环, 从而有效缓解塑料废弃物对环境的长期污染。

聚合物发泡材料因其低密度、高孔隙率和良好的比强度等特点^[19~22], 在包装、建筑和航空航天等领域具有广阔的应用前景^[23~27]。然而, PBAT的固有特性为其发泡带来挑战: 一方面, 其线性分子结构和相对较低的分子量导致熔体强度低, 在发泡过程中难以形成稳定的泡孔结构^[28]; 另一方面, 其复杂的结晶行为致使发泡窗口较窄, 气体在结晶区域的溶解度低且扩散速率慢, 不利于泡孔的均匀成核与生长^[29]。这些因素导致纯PBAT的发泡倍率低、泡孔结构差、制品收缩严重, 严重

限制了其作为发泡材料的应用。为攻克这些技术难题, 国内外研究者采用多相共混、功能填料复合、交联强化及分子拓扑结构调控等策略对PBAT进行改性^[30~35], 通过提高熔体强度、调控结晶行为和优化流变性能来改善其发泡性能。同时, 超临界流体发泡、模压发泡、挤出发泡等先进加工技术的发展, 也为制备高性能PBAT发泡材料提供了更多技术支撑。

本文系统综述了近年来PBAT发泡材料的改性及发泡技术的最新研究进展, 重点阐述了不同强化策略对熔体强度的强化机理, 深入分析了4种发泡工艺的技术特点与适用性, 最后总结了PBAT发泡材料在功能包装、生态农业、生物医学等领域的研究现状, 并对未来的研究方向进行了展望, 为开发高性能PBAT发泡材料提供理论依据和技术参考。

1 PBAT发泡性能的强化策略与机理

面对上述PBAT发泡的技术瓶颈, 通过改性强化是拓展其应用的关键前提。因此, 系统梳理并深入理解各类强化策略的作用机理至关重要。本章围绕PBAT发泡性能的强化策略与内在机理展开论述, 重点综述并剖析图2所示的4类改性方法, 深入探讨上述策略如何从分子、链段及相态等多尺度层次调控PBAT的熔体强度、结晶行为及流变特性, 进而为其发泡加工奠定坚实的材料基础。

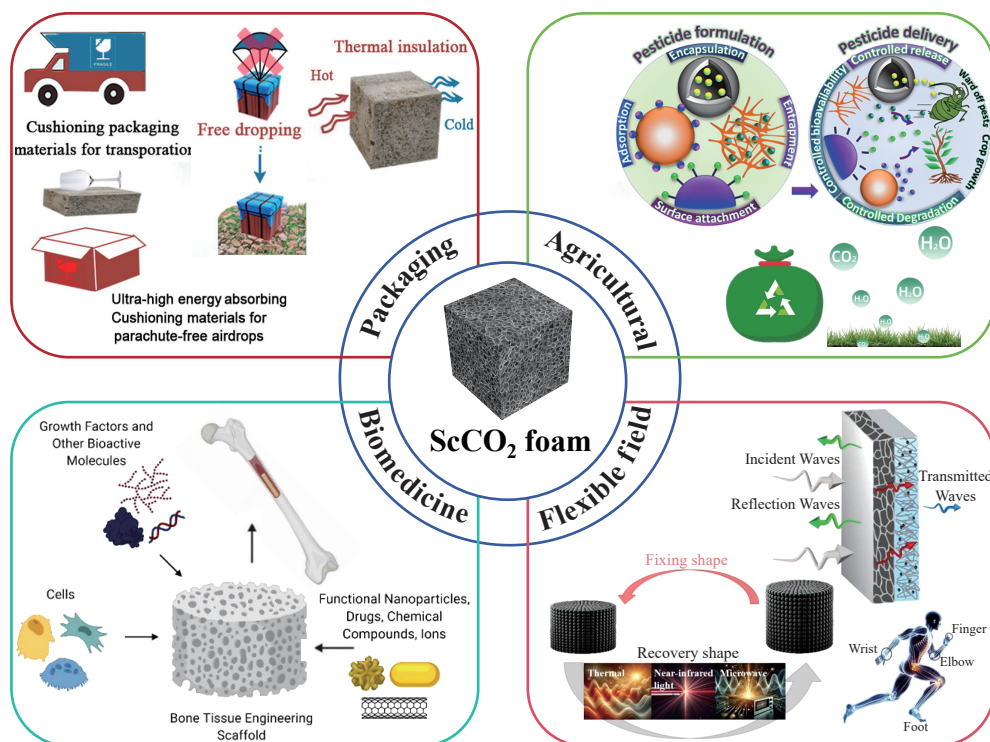


图1 PBAT泡沫的应用领域^[14-17] (2024 Elsevier版权许可; 2025 Elsevier版权许可; 2020 Elsevier版权许可; 2025 Elsevier版权许可)

Figure 1 Application field of PBAT foam (Reprinted with permission from Ref. [14]; Copyright (2024) Elsevier; Reprinted with permission from Ref. [15]; Copyright (2025) Elsevier; Reprinted with permission from Ref. [16]; Copyright (2020) Elsevier; (Reprinted with permission from Ref. [17]; Copyright (2025) Elsevier)

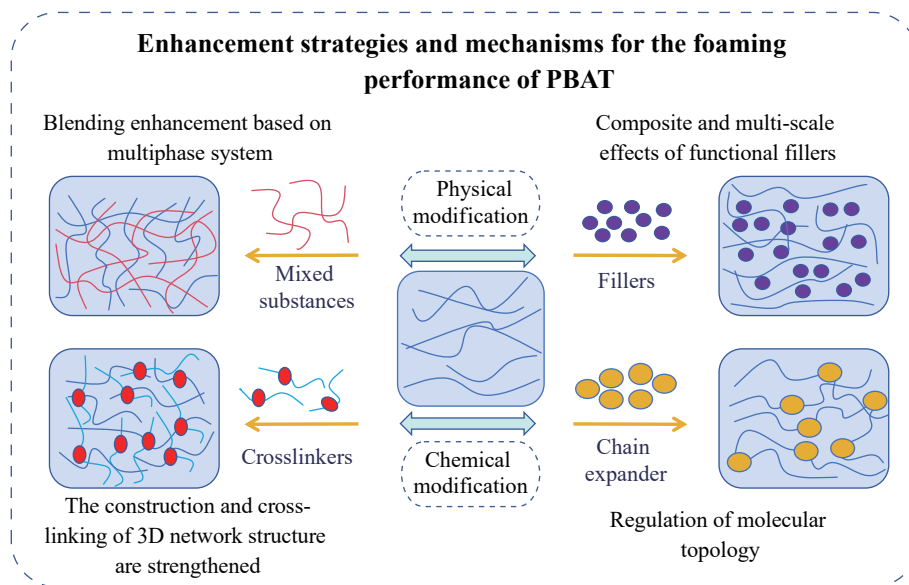


图2 PBAT的改性策略和机理

Figure 2 PBAT modification strategies and mechanisms

1.1 多相体系的共混增强

通过构建多相体系实现聚合物的共混增强与性能互补,是改善发泡材料综合性能的有效策略

之一^[36]。

针对PBAT熔体强度低且发泡后抗收缩性差的问题,研究者通过与其他聚合物构建多相体系

以改善其发泡性能。Zhu等^[37]将PBAT与聚乳酸(PLA)共混,利用PLA的刚性增强、异相成核与结晶强化作用,协同实现了发泡材料在 0.06 g/cm^3 的低密度下的高稳定性与低收缩率。Xu等^[38]在PBAT中引入聚乙烯醇(PVA),显著提高了PBAT的黏弹性和熔体强度,使发泡材料的收缩率从63.0%降至0.7%。Zhang等^[39]在PBAT中引入聚(3-羟基丁酸酯-co-3-羟基戊酸酯)(PHBV),收缩率小于5.0%。PHBV颗粒增强了泡孔壁内PBAT的结晶有序性并提供异相成核位点,二者的协同作用共同改善了发泡材料的抗收缩性能。Wang等^[40]将聚己内酯(PCL)结晶颗粒引入到PBAT基体中,发现PCL相可以改善结晶行为并促进开孔结构的形成。基于异相成核作用和特殊的开孔结构,所制备的PBAT/PCL发泡材料具有超低密度(0.04 g/cm^3)和低收缩率(<5.0%)。

通过在PBAT基体中引入聚合物构建多相体系,一方面显著提升了多相体系的熔体强度和黏弹性,为气泡的稳定生长和抵抗破裂提供了力学保障;另一方面,它们通过诱导和强化基体的结晶行为,构建了稳固的结晶网络,从而赋予发泡材料优异的尺寸稳定性和极低的收缩率,最终实现高性能发泡材料的制备。

1.2 功能填料的复合与多尺度效应

利用功能填料的复合与多尺度效应,使其通过物理或化学作用与PBAT基体结合,是调控材料发泡行为、实现性能优化与功能化的关键策略。Deng等^[41]将石墨烯纳米片(GNPs)引入PBAT中。GNPs的加入一方面限制了PBAT分子链的运动,显著增强了熔体强度,另一方面,作为高效成核剂,在引发高密度异相成核的同时,通过调控结晶行为拓宽了发泡窗口。泡孔密度提升113.4%,收缩率降至8.7%。Zhou等^[42]将碳纳米管(CNTs)和GNPs同时引入PBAT体系中,利用不同维度填料的差异构建出双峰泡孔结构(BCS)。CNTs与GNPs在PBAT中形成三维网络结构,显著提高复合材料的熔体强度,泡孔尺寸稳定性提升。Li等^[43]采用微晶纤维素(MCC)作为“骨架”嵌入PBAT体系,形成刚性骨架,显著提高熔体强度,抑制泡孔收缩,泡孔密度增至 $2.18\times 10^9\text{ cells/cm}^3$,收缩率小于3.6%。

功能填料在PBAT基体中通过构建物理交联结构,有效限制PBAT分子链运动,提升熔体强度,

为泡孔稳定生长提供力学支撑;同时,可作为高效的异相成核位点,增加泡孔密度,减小泡孔尺寸,并通过干扰基体结晶规整性来加速结晶,拓宽发泡窗口。

1.3 三维网络结构的构建与交联强化

通过构建三维网络结构对PBAT进行交联强化,是提升其熔体强度并进而调控发泡过程的有效策略。Deng等^[44]将*N*-乙烯基-2-吡咯烷酮(NVP)接枝到PBAT上。PBAT-g-NVP的长支链利用物理交联点来增强分子间作用力,提高熔体强度,同时通过化学交联网络协同抑制泡孔收缩。此外,PBAT交联网络的构建抑制了分子链的规整排列,从而降低结晶温度,协同提升了熔体强度并延缓了结晶固化,共同拓宽了发泡温度窗口。Yang等^[45]将生物基衣康酸酐接枝到PBAT主链上,并通过Zn(II)催化酯交换反应引入环氧大豆油构建可逆动态交联网络,在提高熔体强度和黏度的同时,还赋予泡孔壁自修复能力,从而将发泡材料的密度稳定在 0.05 g/cm^3 ,显著抑制泡孔收缩。Li等^[46]通过过氧化苯甲酰(BPO)引发PBAT分子链的轻度交联,形成交联网络结构,增强熔体弹性,收缩率下降57.2%。

通过构建化学交联网络、物理缠结或动态可逆网络,从分子层面增强PBAT熔体强度与弹性,从而在支撑泡孔稳定生长,拓宽发泡窗口及赋予自修复能力方面发挥协同作用,实现了发泡材料的低收缩与优异的尺寸稳定性。

1.4 分子拓扑结构的调控

通过使用扩链剂对PBAT的分子拓扑结构进行调控,是增强其熔体强度的关键途径。例如,乙烯-甲基丙烯酸缩水甘油酯共聚物(EGMA)、多单体共聚物(CE)^[47,48]及环氧扩链剂^[49]等通过与PBAT的端基反应,诱导分子链从线形到支化结构转变,从而有效提高PBAT的熔体强度并改善发泡性能。Cui等^[47]采用结晶型扩链剂EGMA对PBAT改性,不仅增加了分子链缠结密度,还通过异相成核诱导PBAT结晶,为双峰泡孔结构的可控构建提供条件,显著提高了PBAT的熔体强度、黏弹性和结晶性能,提升了泡孔尺寸稳定性,降低收缩率。Sun等^[50]设计了一种甲基丙烯酸甲酯-甲基丙烯酸缩水甘油酯(MG)共聚物对PBAT改性。MG的环氧基团与PBAT末端的羧基/羟基发生链延伸反应,形成了支化结构,有效增加

了PBAT的分子量和熔体强度,泡孔尺寸稳定性提升。Zhang等^[51]将扩链剂(CE)和泡孔稳定剂(GMS)协同使用。CE的引入通过增加PBAT分子链的分子量和长度构建高熔体强度骨架,GMS作为“保护膜”保护CE构建的泡孔结构,防止泡孔收缩、合并坍塌,两者的协同效应显著提高了泡孔的尺寸稳定性,收缩率仅为8.0%。

分子拓扑结构的调控是一种基于官能团反应的化学方法,可有效地提升分子量、构建长支链结构,从而显著提高PBAT的熔体强度和黏度,改善发泡材料的尺寸稳定性。

2 PBAT 发泡工艺与泡孔结构演化

超临界流体发泡技术作为绿色制造的代表性工艺,因其以CO₂、N₂等绿色无毒的气体为物理发泡剂而备受关注^[52~54]。该技术的基本原理是通过调控发泡剂在聚合物基体中的溶解与过饱和状态,利用温度或压力的变化诱导泡孔形成,主要

过程包括以下4个阶段(图3):发泡剂的溶解与扩散、泡孔成核、泡孔生长和泡孔稳定^[55,56]。

发泡材料的综合性能依赖于微观泡孔结构(如泡孔密度、尺寸及分布等),而泡孔结构受发泡工艺的直接影响。本节重点综述4种发泡工艺对PBAT泡孔成核、生长及稳定的调控原理:间歇发泡通过控制热力学饱和条件精确调控泡孔形貌(图4a);挤出发泡在强剪切场下易形成各向异性结构(图4b);注塑发泡复杂的压力-温度历史则构建了独特的梯度泡孔结构(图4c);模压发泡则利用空间约束制备高倍率且均匀的泡孔(图4d)。

2.1 间歇发泡条件调控泡孔形貌

间歇发泡通过精确控制热力学饱和条件(温度、压力)来实现对泡孔形貌的调控。Lei等^[57]研究表明,低温低压条件下不利于气泡的高密度成核与稳定生长,会形成壁厚、分布宽且均匀性差的泡孔(如图5a和5d中);适当升高温度或增大压力可促进高密度成核并抑制粗化,使泡孔均匀细化

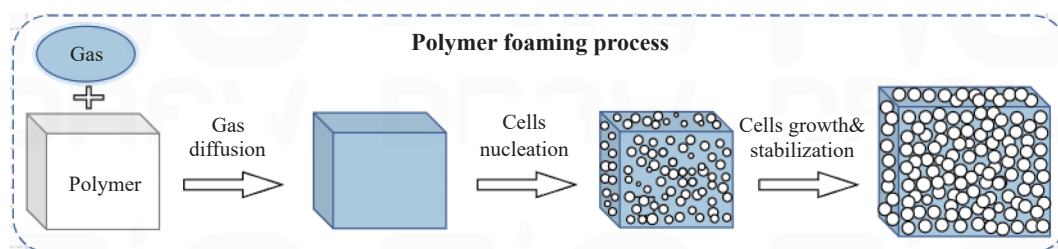


图3 聚合物发泡工艺示意图(由Figdraw 绘制)

Figure 3 Schematic diagram of polymer foaming process (by Figdraw)

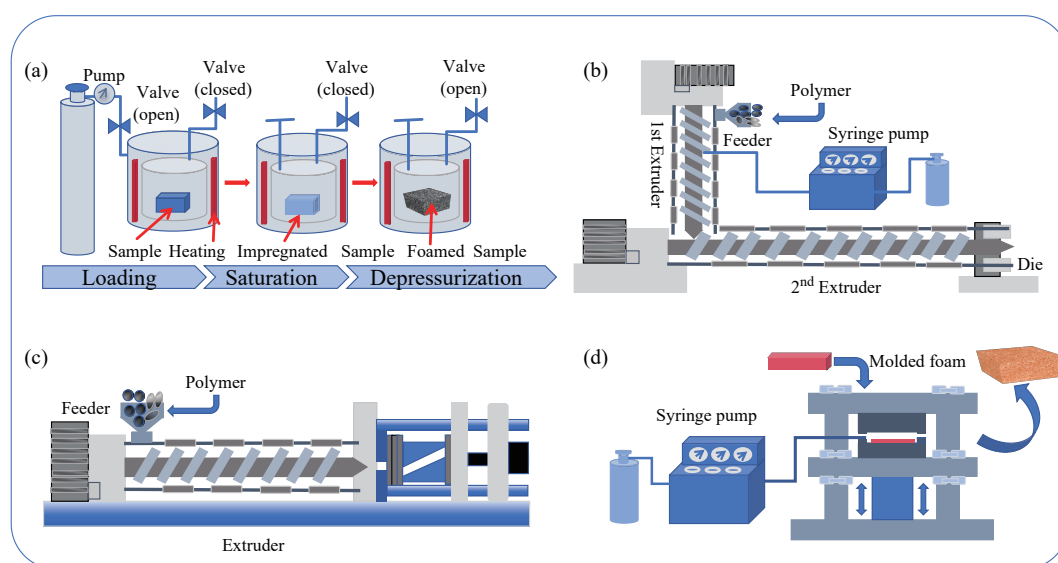


图4 发泡工艺对PBAT泡孔成核、生长及稳定的调控:(a)间歇发泡;(b)挤出发泡;(c)注塑发泡;(d)模压发泡

Figure 4 Regulation of PBAT cell nucleation, growth and stability by foaming process: (a) Batch foaming method; (b) Extrusion foaming method; (c) Injection molding foaming method; (d) Compression molding foaming method

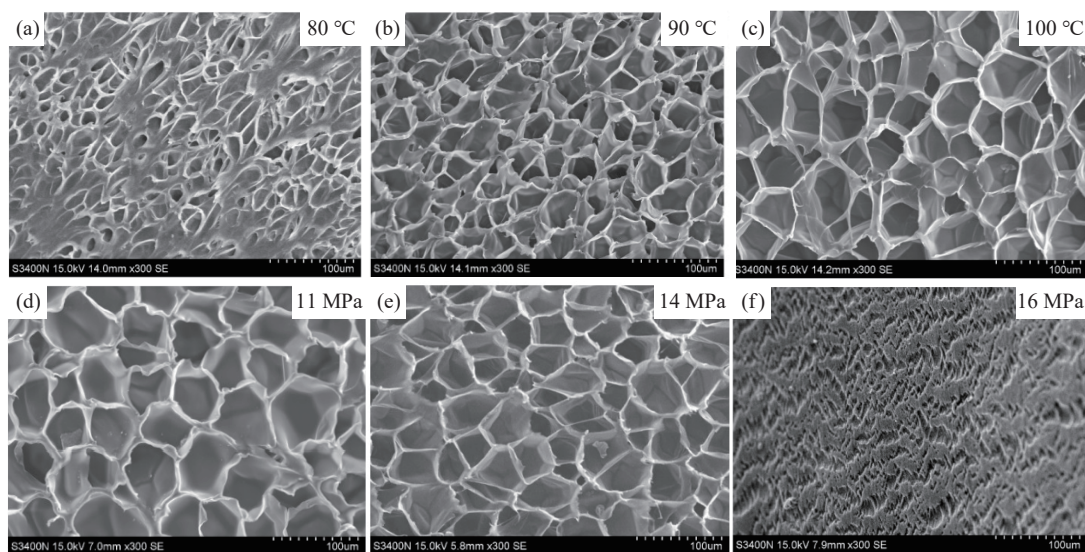


图5 不同饱和条件下泡孔结构的扫描电子显微镜图像^[57]: (a~c)不同温度下的泡孔结构; (d~f)不同压力下的泡孔结构 (2021《塑料工业》版权许可)

Figure 5 SEM images of the cellular structure at different saturation conditions^[57]: (a~c) Cell structure under different temperatures; (d~f) Cell structure under different pressures (Reprinted with permission from Ref. [57]; Copyright (2021) China Plastics Industry)

(如图5b和5e所示), 而过高的温度或压力则导致泡孔合并坍塌(如图5c和5f所示)。Wang等^[58]进一步指出, 通过优化温度与压力的协同作用: 压力升高, CO_2 溶解度增加, 成核驱动力增强, 泡孔密度显著提高, 而温度升高, CO_2 溶解度下降, 但扩散速率加快, 有利于气泡快速生长。因此, 通过不同的温度压力组合可以制备出具有不同泡孔结构的发泡材料。

在间歇发泡过程中, 泡孔形貌的调控, 本质上是体系热力学驱动力与PBAT熔体动力学行为之间竞争的结果。饱和压力主导气泡的成核密度, 为形成大量泡孔提供基础; 而饱和温度则调控泡孔的生长动力学与结构稳定性。实现均匀细密泡孔结构的关键, 在于优化压力与温度的协同作用,

以在高密度成核与泡孔稳定生长之间取得平衡。

2.2 挤出剪切诱导各向异性结构

挤出发泡过程中, 强烈的剪切历史与泡孔的各向异性结构形成密切相关。该工艺通过挤出机将PBAT、发泡剂等混合, 在高压下形成均匀的PBAT/气体均相体系, 并在模具出口处通过压力骤降使气体过饱和析出, 形成发泡材料。Zhang等^[59]发现, 在挤出过程中, 低剪切力会形成均匀的“海岛”结构, 界面张力提供额外阻力, 抑制气体扩散, 形成的泡孔尺寸较大, 分布较均匀(图6a), 各向异性较弱。随着剪切力增加, 气体沿弱结合界面快速扩散, 泡孔沿剪切方向扩展, 导致泡孔尺寸不均、坍塌或破裂, 形成明显的各向异性结构(图6b和6c)。Cai等^[60]研究指出, 低转

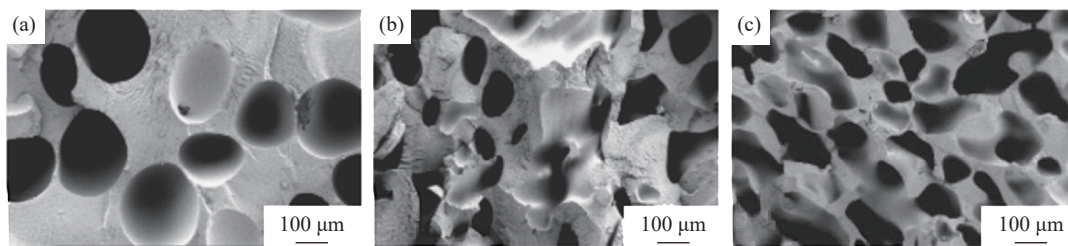


图6 E-PBAT/PPC 泡沫材料泡孔结构的扫描电子显微镜图像^[59]: (a)低剪切力下的泡孔结构; (b, c)高剪切力下的泡孔结构 (2022 Springer Nature 版权许可)

Figure 6 SEM images of the cellular structure of E-PBAT/PPC foam: (a) Cell structure under low shear force; (b, c) Cell structure under high shear force (Reprinted with permission from Ref. [59]; Copyright (2022) Springer Nature)

速下剪切力较弱,熔体强度高,不利于泡孔生长,形成的泡孔壁较厚,各向异性较弱。随着剪切力增强,熔体强度下降,更多 CO_2 参与成核过程,泡孔生长限制变弱,泡孔密度增加。当剪切速率过高时,泡孔出现合并坍塌现象,形成明显的各向异性取向结构。

在挤出发泡过程中,剪切历史是诱导泡孔形成各向异性结构的关键因素。强烈的剪切作用使PBAT/气体均相体系中的分子链沿流动方向取向,导致熔体强度呈现方向性差异——沿流动方向的强度高于垂直方向。该差异使气泡在垂直方向上生长阻力较小,从而被优先拉长,形成纺锤形或椭圆形泡孔。最后,快速冷却过程将这种由剪切诱导的取向结构固化,形成具有高度各向异性的泡孔形貌。

2.3 注塑发泡条件构建梯度结构

注塑发泡是传统注塑技术的延伸,注塑发泡过程中复杂的压力-温度历史直接决定了梯度泡孔结构的构建。Dong等^[61]研究显示,当PBAT/气体均相熔体从高压料筒注入低压模具型腔后,压力急剧下降以及近模壁的熔体因冷却快而黏度骤增,抑制了气泡的成核与生长,形成致密的皮

层。随着不断注入熔体,模腔内压力不断升高,芯部熔体冷却速率减缓,为泡孔均匀生长提供有利环境,从而构建出“皮-芯”梯度泡孔结构(如图7a所示)。Gao等^[62]采用二次开合模工艺,在熔体注射填充模具之后,施加较高的保压压力将泡孔重新溶解回熔体中,再次形成均相体系。保压结束后,瞬间打开模具,模腔内部压力骤降,芯层泡孔同时大量的成核和生长,使得泡孔结构更加均匀(如图7b和7c所示)。

注塑发泡过程中,泡孔结构由熔体经历的“压力-温度历史”共同决定:压力主导泡孔的成核与初始形态,温度控制泡孔的生长与定型。最终,模腔内形成非均匀的压力-温度耦合场,构建出从致密皮层到多孔芯部的梯度泡孔结构。

2.4 模压空间约束构筑可控结构

模压发泡利用模具特有的空间约束,通过控制模腔内的膨胀空间,使泡孔在受限环境中生长,获得高倍率、均匀细密的泡孔结构。Gao等^[63]研究表明,随着模腔压力升高, CO_2 溶解度增大、成核驱动力增强,泡孔密度增加、尺寸下降(如图8所示)。Zhai等^[64]利用模压发泡高压抑制气体非均匀成核,开模瞬间触发爆发式成核,模具的限制不

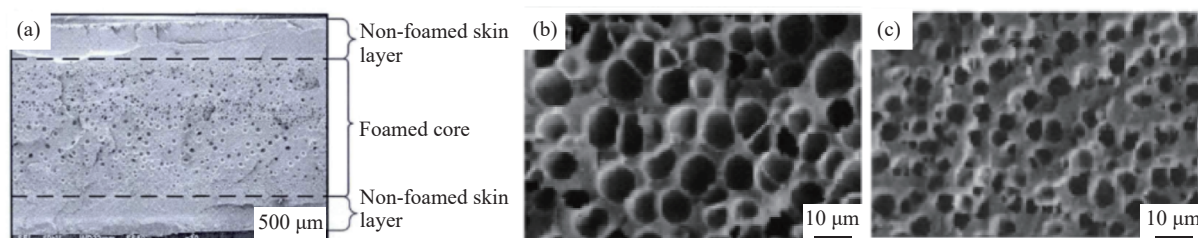


图7 注塑发泡泡孔结构的扫描电子显微镜图像^[61,62]: (a)梯度泡孔结构(2016 Sage 版权许可); 保压15 s (b)和20 s (c)的泡孔结构(2023作者版权许可)

Figure 7 SEM image of the cellular structure of injection-molded foam: (a) Gradient cell structure (Reprinted with permission from Ref. [61]; Copyright (2016) Sage); Cell structure with 15 s (b) and 20 s (c) holding pressure (Reprinted with permission from Ref. [62]; Copyright (2023) the Author(s))

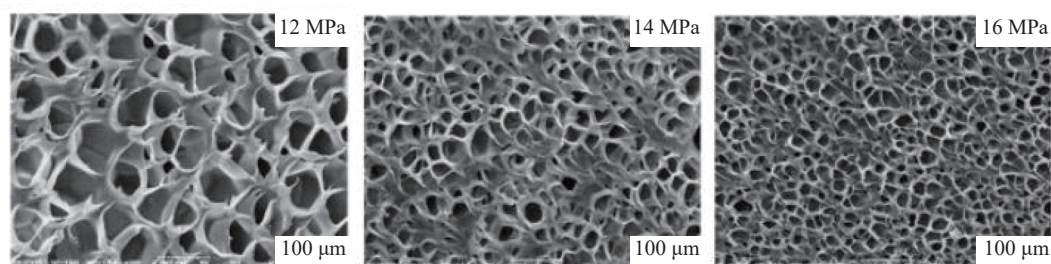


图8 模压发泡条件下不同发泡压力下的泡孔结构的扫描电子显微镜图像^[63](2022作者版权许可)

Figure 8 SEM images of pore structures at different foaming pressures under mold foaming (Reprinted with permission from Ref. [63]; Copyright (2022) the Author(s))

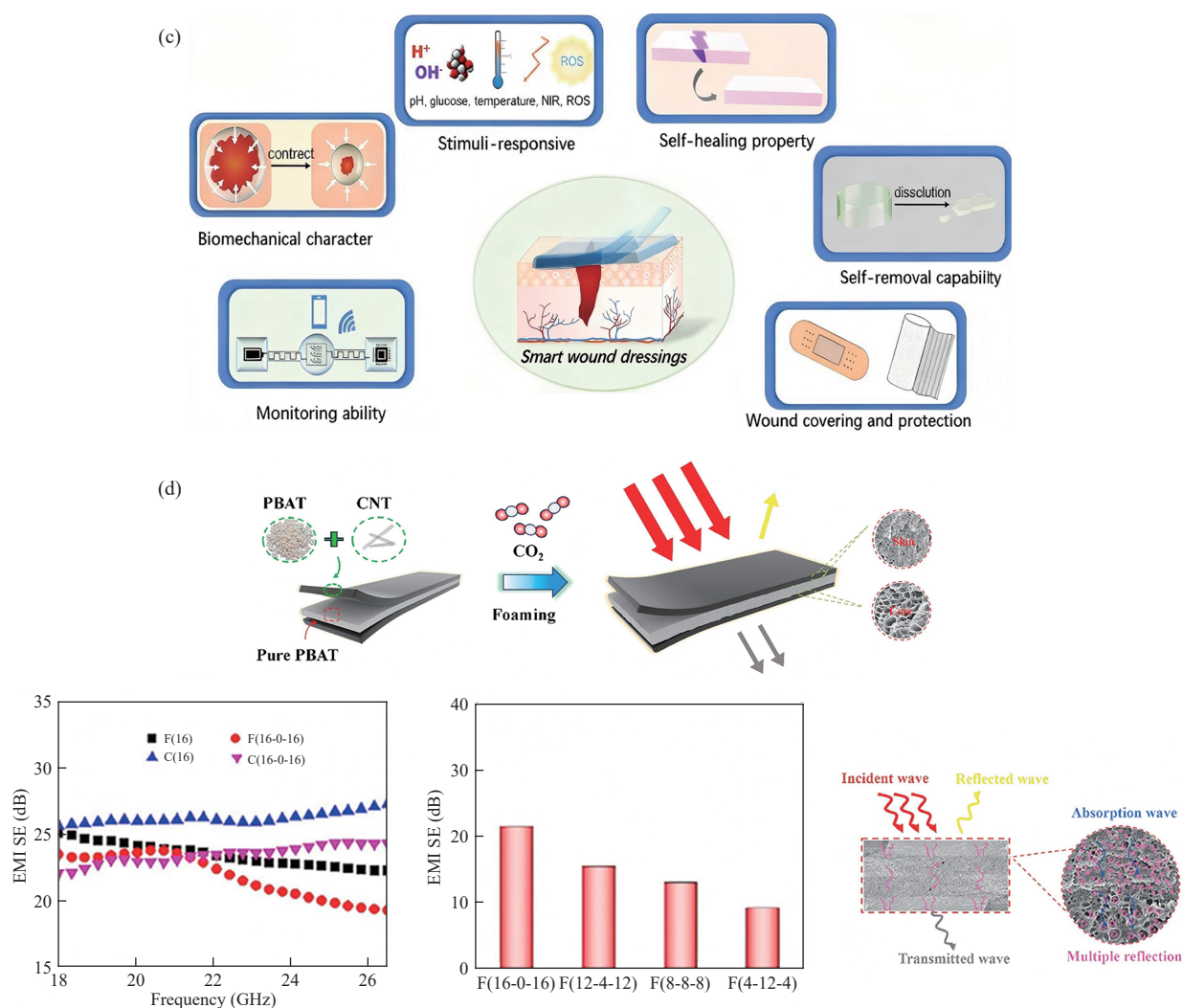


图9 (a)多功能包装发泡材料^[71] (2024 Elsevier 版权许可); (b)刺激响应性泡沫材料^[72] (2023 Elsevier 版权许可); (c)智能泡沫在伤口敷料中的应用^[73] (2021 Elsevier 版权许可); (d) PBAT 泡沫材料在电磁屏蔽领域中的应用^[74] (2024 Elsevier 版权许可)

Figure 9 (a) Multifunctional packaging foam material (Reprinted with permission from Ref. [71]; Copyright (2024) Elsevier); (b) Stimulating responsive foam material (Reprinted with permission from Ref. [72]; Copyright (2023) Elsevier); (c) Application of smart foam in wound dressings (Reprinted with permission from Ref. [73]; Copyright (2021) Elsevier); (d) Application of PBAT foams in the field of electromagnetic shielding (Reprinted with permission from Ref. [74]; Copyright (2024) Elsevier)

能化设计使其能够在完成保墒、增温、抑草等农艺功能后,可以在土壤环境中快速降解,避免造成白色污染。研究表明,新型土壤可生物降解的PBAT (如Ecovio M 2351)在农业应用中表现出显著优势^[75]。该材料在收获后经简单犁地处理即可快速破碎与降解,极大简化了农田清理工序,同时避免了塑料残留对土壤结构的破坏^[76]。Wufuer等^[77]关于PBAT农艺效能的研究,证实了其在真实农田环境中的降解性与适用性,为PBAT发泡材料(如育苗钵)等一次性农用制品的应用提供信

心。Singh等^[78]研究发现多孔结构赋予材料的高负载能力与可控释放特性,是开发高效农业泡沫的核心优势。通过发泡制备的PBAT育苗钵,其内部的多孔结构不仅能协同调控根区的水分、气体和温度环境,为幼苗生长提供理想的微环境,还可掺入有机肥料或益生菌等活性成分,通过构建刺激响应机制实现可控释放^[72](如图9b所示)。该策略能有效协调肥效的缓释和土壤微生态的改善^[79],从根本上避免了传统塑料育苗钵带来的残留污染问题。

3.3 生物医学多孔结构仿生与药物控释

PBAT在生物医学领域的应用得益于其可调控的多孔结构、可预测的降解周期及良好的生物相容性^[80]。在组织工程方面,通过仿生设计制备的三维多孔支架可模拟天然细胞外基质的微观结构,从而有效促进细胞黏附、增殖和分化,在支持组织再生的同时有效抑制细菌感染。Hsieh-Chih等^[81]系统综述了先进多孔材料的合成策略及其在促进组织再生、同时抑制细菌感染方面的多功能应用。在药物控释载体领域^[82],PBAT多孔结构巨大的比表面积和孔隙可高效吸附或包裹药物分子,通过调控PBAT的结晶度与亲疏水平衡,可实现药物的局部、持续和可控释放^[83]。Niculescu等^[84]综述了泡沫敷料在渗液管理、抗菌抗炎等多功能整合方面的最新进展。这类智能敷料的核心,在于能够响应伤口微环境的变化(如pH值、酶或温度),动态释放生长因子、抗生素或抗炎药物^[85,86]。Luo等^[87]和Dong等^[73]系统阐述了智能伤口敷料的设计原则,其中由生物可降解材料(如PBAT)构成的多孔泡沫基质,因其可降解性和负载能力而被视为极具前景的载体平台(图9c)。

3.4 新兴应用中的多功能一体化构建

PBAT材料在新兴领域的应用体现了多功能一体化的设计理念,通过材料组成和结构的创新设计,同时实现多种功能的集成,拓展了其在高端领域的应用前景。在绿色隔热方面,通过调控PBAT发泡倍率和泡孔结构,可制备出导热系数低、隔热性能优异的环保型保温材料^[40]。这些材料不仅能有效阻止热量传递,提高建筑物的能源效率,还能在使用寿命结束后完成生物降解。在柔性器件领域,PBAT材料的功能化设计聚焦于柔性和导电功能的集成。Chen等^[74]将PBAT与碳纳米管等导电填料复合,制备出兼具良好柔韧性、可降解性与屏蔽功能的发泡材料(如图9d所示)。Hu等^[88]制备了可生物降解的PBAT/PCL形状记忆发泡材料,该材料具备多重刺激响应能力和优异循环稳定性,在智能柔性器件领域展现了巨大的应用潜力。

4 结论与展望

系统综述了可生物降解PBAT材料的改性策略、发泡工艺及其多功能应用的最新研究进展。针对PBAT本身熔体强度低、结晶行为复杂及发

泡窗口窄等固有挑战,研究指出,通过多维度改性策略(如构建可降解多相体系和动态交联网络)可协同优化其流变与结晶行为,为高性能发泡奠定材料基础;不同发泡工艺与泡孔结构间存在明确的“构效关系”,合理选择间歇、挤出、注塑或模压发泡技术可精准调控泡孔形态与宏观性能;在此基础上,PBAT发泡材料的应用已从传统缓冲包装拓展至生态农业、生物医学及绿色柔性器件等新兴领域,展现出多功能集成与环境降解协同的巨大潜力。

尽管PBAT发泡材料的研究已取得显著成果,但其迈向大规模产业化与高值化应用仍面临诸多挑战,未来研究可从以下方面重点展开:

(1)深入多尺度机理研究。借助先进原位表征和分子模拟,揭示气泡成核/生长动力学、填料-基体界面作用及降解过程中结构-性能演变规律。

(2)开发绿色、精准、智能化的发泡新工艺。探索超临界CO₂与化学发泡剂的协同体系,推动3D打印/增材制造技术与发泡工艺的融合,实现复杂结构功能部件的一体化成型与定制化生产。

(3)拓展高端应用与完善全生命周期评价(LCA)。设计开发适用于高温隔热、智能响应等尖端领域的PBAT功能发泡材料,并建立系统完整的LCA体系,科学评估其全链条环境影响。

(4)推动标准体系建设与产业化协同。建立与完善可降解发泡材料的性能测试标准、降解认证体系和回收再利用渠道,通过产学研协同创新,推动PBAT发泡材料从实验室走向市场,为国家“双碳”目标提供实质性支撑。

总而言之,PBAT发泡材料的突破与发展,是一项贯通产学研用的系统性工程,必须通过基础研究的深化、核心工艺的革新、应用场景的开拓以及产业政策的协同,才能完全释放其绿色潜力,最终跨越从实验室到产业的鸿沟,为国家“双碳”目标与绿色循环经济提供坚实支撑。

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