

Biodegradable microcrystalline cellulose composites: Optimization of isotropic polybutene-1 crystallization and its vibration and noise reduction properties

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Abstract: With the acceleration of industrialization, environmental noise and mechanical vibration problems are becoming increasingly serious. Traditional polymer damping materials have shortcomings in durability, environmental protection and performance optimization. In this study, MCC-iPB biodegradable composites were prepared. The interface and crystallization behavior were optimized by introducing maleic anhydride grafted polybutene-1 (MAPB). Experimental results showed that MCC can accelerate the crystal transformation and significantly improve the thermal stability and storage modulus. In the comparative experiment under the simulated operating conditions of industrial motors, compared with traditional polyurethane foam materials, the MCC-iPB composite material can reduce the vibration acceleration by about 40%, the sound pressure level by 6–9 dB, and the power fluctuation by more than 50% in the range of 500–2500 Hz, showing excellent energy dissipation and vibration suppression capabilities. This material has broad engineering application prospects in the fields of building sound insulation, automobile structure noise reduction and high-frequency industrial equipment shock absorption, and provides a new theoretical basis and experimental support for the development of sustainable vibration and noise reduction materials.

Keywords: isotactic polybutene-1 (iPB); microcrystalline cellulose (MCC); maleic anhydride-grafted polybutene-1 (MAPB); iPB/MCC composites; crystallization behavior; vibration reduction; noise reduction; acoustics; biodegradable materials

1. Introduction

In modern industrial and urban environments, the problems of mechanical vibration and environmental noise are becoming increasingly prominent. Long-term exposure to excessive noise and vibration may have serious impacts on human health, equipment life and work efficiency, especially in the fields of automobile, construction and precision instruments, etc. [1]. How to efficiently reduce vibration and noise has become an important challenge in engineering applications. Currently, polymer-based damping materials are widely used in acoustics and vibration control due to their good mechanical properties and processability [2]. However, traditional polymer materials suffer from insufficient durability, low environmental friendliness, and limited performance tunability. Therefore, the development of new composite materials that combine efficient vibration and noise reduction capability, sustainability and excellent mechanical properties is of great research value.

Biodegradable materials have attracted widespread attention due to their environmentally friendly properties [3]. Microcrystalline cellulose (MCC) is derived from renewable resources and has high rigidity and low density. As a heterogeneous nucleating agent, it can promote polymer crystallization and improve the mechanical and thermal properties of composite materials [4]. Its porous structure and high specific surface area also give it the potential for application in acoustic materials [5]. However, due to its strong polarity, it has poor compatibility with non-polar polymers, which can easily lead to uneven dispersion and thus affect the overall performance. Improving interfacial compatibility has become an important research direction for bio-based composite materials. Isotactic polybutene-1 (iPB) is a semi-crystalline polymer with excellent durability and flexibility. It is widely used in engineering fields [6]. Its main crystal forms are metastable type II and stable type I. Crystal form transition has a key influence on performance [7]. Generally, morphology II is the initial crystal form of iPB, but after storage for a certain period of time or heat treatment, it will be slowly transformed into the more stable morphology I. It has been shown that accelerating the transformation from morphology II to morphology I can improve the rigidity and heat resistance of iPB and make it suitable for a wider range of engineering applications [8]. Therefore, it is an important direction for current research to promote the crystal transformation of iPB through appropriate modification strategies to improve its performance in vibration and noise control.

Many studies have attempted to introduce nanofillers or cellulose-based materials into iPB to improve its mechanical and acoustic properties. For example, inorganic fillers have been widely used to improve the crystallization behavior and damping performance of iPB [9]. However, due to the large difference in polarity between these fillers and iPB, the interfacial compatibility issue remains one of the key factors affecting the performance of composite materials [10]. Therefore, it is necessary to further explore effective interface regulation strategies to optimize the dispersion of fillers in the polymer matrix and improve the comprehensive performance of the material.

In view of the actual application needs of iPB materials in the field of vibration reduction and noise reduction, this study innovatively adopts MCC composite modification technology to achieve synergistic optimization of mechanical and acoustic properties by regulating the crystallization characteristics of the material. The core innovation is reflected in the following two aspects:

1) Construction and performance improvement of composite system based on MCC enhancement

The innovative design of the MCC-iPB composite structure significantly accelerates the crystallization kinetics process through the nucleation effect of MCC, and promotes the crystal transformation from metastable Form II to stable Form I. This crystal phase regulation strategy not only improves the mechanical strength and heat resistance of the material, but also systematically investigates the influence mechanism of MCC on the vibration damping characteristics and acoustic response of the material, revealing the energy dissipation law and sound wave absorption characteristics of the composite material in a wide frequency range.

2) Interface compatibility optimization and synergistic enhancement mechanism
Maleic anhydride grafted polybutene-1 (MAPB) is innovatively used as an

interface modifier, and the dispersion state of MCC in the polymer matrix is significantly improved by chemical modification method, so as to construct a composite system with strong interface bonding. Through multi-scale characterization methods, the synergistic effect of MAPB on the micromorphology evolution, mechanical properties enhancement and acoustic function improvement of composite materials is deeply analyzed, and its physicochemical mechanism of accelerating the crystallization process is clarified.

3) Systematic characterization of the microstructure, mechanical and acoustic properties of the composite material

DSC, POM, WAXD and other methods were used to analyze the regulatory effect of MCC on the crystallization behavior of iPB. DMA, acoustic testing and other methods were used to evaluate the dynamic mechanical properties, damping characteristics and noise attenuation capabilities of the composite material.

The aim of this paper is to investigate the crystallization behavior of MCC and iPB composites and its effect on vibration and noise damping performance. The organization of this paper is shown as follows: Section I introduces the background and significance of the study, analyzes the crystalline polymorphism of iPB and its advantages and limitations in engineering, and also proposes the innovations of this study, i.e., to improve the comprehensive performance of the materials by optimizing the crystallization behavior of iPB and to explore the role of MAPB in improving the compatibility of iPB with MCC. Section 2 reviews the related research progress on iPB modification, MCC-filled composites and optimization of polymer acoustic properties to provide theoretical support for this study. Section 3 describes in detail the selection of experimental materials, the preparation process of composites and the characterization means, including DSC, POM, SEM, etc., which are used to analyze the crystallization behavior, microstructure, mechanical properties and acoustic properties. Section 4 presents the experimental data and focuses on the role of MCC in promoting the crystalline transition of iPB (Form II \rightarrow Form I), enhancing the mechanical properties and improving the acoustic properties, as well as exploring the effect of MAPB as a compatibilizer in optimizing the interfacial bonding of the composites, and verifying the vibration and noise reduction effect of MCC-iPB in industrial machinery application scenarios. In Section 5, the crystallization kinetic mechanism of iPB/MCC composites and its relationship with vibration and noise damping performance are discussed in depth in the light of the experimental results, and the validity and innovativeness of this study are discussed. Section 6 summarizes the research results, highlights the contribution of MCC in optimizing the crystalline behavior of iPB and enhancing the damping and acoustic properties, and proposes future research directions to further optimize the material properties and expand its applications in engineering.

In modern engineering practice, vibration and noise are widely present, which seriously affect the service life, operating efficiency and comfort of the equipment. For example, high-frequency vibration will accelerate fatigue damage of industrial equipment, increase failure rate and reduce production reliability [11]; while structural noise is the main source of imbalance in the building sound environment, which directly affects human health and work efficiency [12]. Therefore, the research and development of multifunctional composite materials with high-efficiency vibration

reduction, good acoustic performance and environmentally friendly properties has become an important research direction in the field of materials science and engineering. Based on this demand, this paper focuses on the study of maleic anhydride grafted polybutene-1 (MAPB) modified iPB-based MCC composites, striving to achieve green degradability of materials on the basis of meeting mechanical properties and acoustic functions, and provide practical material solutions for industrial noise reduction, building sound insulation and equipment vibration control.

2. Related work

2.1. Crystal polymorphism of iPB and its advantages and limitations in engineering

iPB is a semi-crystalline polymer with crystal polymorphism, mainly including four crystal forms: Form I, Form I', Form II and Form III [13]. Among them, Form II is the first metastable crystal form formed after melt cooling, while Form I is a thermodynamically stable crystal form with better mechanical strength and thermal stability [7]. Form II can slowly transform into Form I under storage or heat treatment conditions, but the transformation rate is low, which limits its immediate performance in engineering applications.

In order to improve the application performance of iPB in the structural and functional fields, researchers have tried to accelerate its crystallization rate by adding fillers, process control or external stimulation, especially to promote the transformation of Form II to Form I [8]. For example, Xu et al. achieved the controllable transformation of the iPB crystal form by CO₂-induced method and revealed its kinetic characteristics by high-pressure FTIR technology [14]; Li et al. combined annealing with the supercritical CO₂ foaming process to improve the storage modulus and processing performance of the material while regulating the pore structure [15].

While these methods have improved the crystallization behavior of iPB to some extent, they have also exposed problems such as poor filler-matrix compatibility and uneven dispersion, which may weaken the overall mechanical or acoustic properties of the composites. Therefore, achieving the improvement of crystallization efficiency while ensuring that the structural performance does not decrease is one of the core challenges in the current design of iPB-based composite materials. This also highlights the importance of developing a filler system with both a high crystallization rate and good interface compatibility in practical engineering applications.

2.2. The role of MCC in polymer composites

A high crystalline, low-density, degradable and renewable material, microcrystalline cellulose (MCC) has a porous structure that helps polymer crystallization and acoustic wave absorption, and enhances structural stability and acoustic performance [16–18]. The addition of MCC to PLA, PP, PCL, and other matrices can improve the modulus of elasticity, tensile strength, and heat resistance, and effectively reduce noise transmission, making it an ideal green acoustic functional filler [19–21]. However, due to the strong polarity of MCC, it has poor compatibility

with nonpolar polymers such as iPB, which is prone to uneven dispersion and performance degradation [22]; in order to improve the interfacial bonding, silane treatment, maleic anhydride grafting, and other modification methods are often used [23–25], in which maleic anhydride grafted polybutene-1 can significantly enhance the interfacial compatibility of MCC and iPB through esterification, and improve the structural homogeneity and heat resistance of composites. Improve the structural homogeneity and comprehensive performance of the composites [26].

2.3. Study of mechanical and acoustic properties of composite materials

The mechanical and acoustic properties of polymer composites depend largely on their internal crystal structure and crystallization behavior. In recent years, researchers have been adjusting the crystallization rate of polymers, optimizing crystal morphology, and introducing functional fillers to control the comprehensive properties of composites [18,27].

Regarding mechanical performance, Spoljaric S. and colleagues developed PP–MCC composites that included polypropylene grafted with maleic anhydride (PP-g-MA) and MCC treated with silicone oil, stearic acid, or alkyl titanate coupling agents to enhance filler dispersion and matrix compatibility [28]. Gibri et al. used cellulose-zinc oxide (NCC-ZnO) as an organic-inorganic nanofiller to prepare a new bio-based PCL nanocomposite material. The addition of nanofillers improved the thermal stability of PCL [29]. For iPB, studies have shown that optimizing the crystal transformation process (Form II → Form I) can effectively improve its durability and impact resistance [8].

In terms of acoustic performance, a facile extrusion-based method was proposed for thermoplastic rubber (TPR) composites, whereby calcium carbonate (CaCO_3) and hollow glass microspheres (HGM) were introduced as fillers to simultaneously improve the material's sound insulation and mechanical properties [30]. Moreover, the incorporation of natural fillers such as MCC not only refines the internal structure of the polymer, thereby boosting damping performance, but also enhances the material's sound absorption capacity through its porous structure [31].

Nevertheless, current research predominantly focuses on the interactions between MCC and polar polymers (such as PLA and PCL), with comparatively few studies addressing the application of MCC in nonpolar polymers like iPB. Furthermore, additional investigations are required to further optimize MCC surface modification techniques, improve its uniform dispersion within the iPB matrix, and enhance the overall mechanical and acoustic performance of the composite.

3. Materials and methods

3.1. iPB crystallization and its properties

iPB-1 is a typical polycrystalline polymer, and its basic properties and crystallization behavior are closely related to the preparation conditions. The crystallization behavior of iPB is significantly affected by factors such as temperature, pressure, cooling rate, and external stimulation (such as ultra-high pressure CO_2 treatment, quenching, etc.). In order to gain a deeper understanding of the

crystallization mechanism of iPB, researchers have used various experimental methods to analyze its crystallization behavior under different conditions and characterized its crystal morphology by POM, DSC, SEM, and WAXD techniques [32].

Studies have shown that when the iPB film is cooled to 125 °C for stabilization and then restored to room temperature, single-oriented crystals of type I are observed, directly proving the structural transformation process [33]. On this basis, Li et al. accelerated the crystallization of iPB by high-pressure CO₂, significantly improving the transformation rate and uniformity [34]; Su et al. found that quenching conditions affect the transformation rate and internal stress is the key driving factor for structural reorganization [35]. Overall, the crystallization behavior of iPB is affected by the processing conditions, modification methods and additives, and the specific experimental results are shown in **Table 1**.

Table 1. Experimental results validating iPB crystallization under different conditions.

Condition	Experiment details	Results	Validation techniques
Crystallization temperature	Ultrathin iPB films heat-treated at 160 °C, cooled to 80 °C–130 °C.	<ul style="list-style-type: none"> Crystal form I prevalence: 85% at 125 °C, 40% at 80 °C. Melting point ~168 °C (Form I). 	POM: Uniform crystals at 125 °C. DSC: Distinct Form I peaks. SEM: Smooth surfaces.
High-pressure CO ₂	Films exposed to 3 MPa CO ₂ pressure during crystallization.	<ul style="list-style-type: none"> Transformation time reduced from 30 min to 8 min. Crystallinity increased by 25%. 	WAXD: Improved alignment. Optical Microscopy: Finer crystals.
Direct quenching	Rapid cooling from 160 °C to room temperature.	<ul style="list-style-type: none"> Fast transformation (~5 min). High internal stress. Distorted morphologies. 	SEM: Irregular surfaces. DSC: Broad peaks.
Staged quenching	Crystallization at 110 °C, followed by quenching to room temperature.	<ul style="list-style-type: none"> Smoother crystal transitions. Reduced internal stress. Uniform crystal morphologies. 	SEM: Uniform structures. DSC: Sharp crystallization peaks.

** This table provides an overview of the conditions, key findings, and validation methods for each experimental scenario.

As shown in **Table 1**, crystallization temperature, CO₂ pressure and quenching significantly affect the formation, alignment and homogeneity of iPB crystals. Higher crystallization temperature promotes the formation of crystal type I, while high pressure CO₂ accelerates the transformation and improves the structural organization. Quenching affects the balance between velocity and internal stress, and a staged process results in better overall crystal quality.

3.2. Blending modification and characterization techniques

This study systematically elucidated the regulatory mechanism of functional additives on the crystallization behavior of iPB through the synergistic application of composite modification technology and multi-scale characterization methods. Experimental data show that the introduction of halloysite nanotubes (HNT) and attapulgite (PGS) can significantly improve the formation kinetics of form I. As confirmed by Zhang's team, PGS improves the crystal conversion rate by 30% and achieves a 20% improvement in crystal uniformity by improving the interfacial affinity with iPB; while the surface-modified HNT optimizes the crystallization efficiency and comprehensive performance of the material by enhancing the interfacial

adhesion effect (see **Table 2** for details) [36]. Comparative experiments show that the crystallization enhancement rates of iPB/MCC (5 wt%), iPB/PGS (2 wt%) and PLA/MCC (5 wt%) systems are 24.3%, 18.0% and 12.0%, respectively, highlighting the core position of interfacial compatibility in composite material design.

Table 2. Experimental results, validation, and discussion on blending modifications and characterization.

Aspect	Experimental Details	Results	Validation Techniques	Discussion
Additives (PGS and HNT)	<ul style="list-style-type: none"> 2 wt% PGS added to iPB. Modified HNT compared to unmodified HNT. 	<ul style="list-style-type: none"> Crystallization speed increased by 30%. Crystal form I uniformity improved by 20%. Interfacial bonding improved by 25% with HNT. 	POM: Visualized crystal uniformity. DSC: Sharper crystallization peaks.	Improved compatibility between PGS/HNT and iPB led to better crystallization kinetics and material uniformity, enhancing overall composite performance.
Blending with MCC	<ul style="list-style-type: none"> 5 wt% MCC with and without MAPB as compatibilizer. 	<ul style="list-style-type: none"> Tensile strength improved by 40%. Modulus enhanced by 15%. Homogeneous MCC dispersion in compatibilized blends. 	SEM: Uniform dispersion of MCC. DSC: Higher melting point (~170 °C).	MAPB successfully mitigated polarity mismatch between MCC and iPB, improving mechanical properties and thermal stability in the blends.
Thermal properties	<ul style="list-style-type: none"> Compatibilized iPB/MCC composites analyzed for melting and crystallization behaviors. 	<ul style="list-style-type: none"> Narrower crystallization range. Higher thermal stability in compatibilized composites. 	DSC: Sharp peaks confirming enhanced crystallinity.	The addition of MAPB and MCC enhanced thermal stability by reducing defects and improving crystal alignment in iPB composites.
Micromorphology	<ul style="list-style-type: none"> SEM analysis of iPB/MCC blends with and without MAPB. 	<ul style="list-style-type: none"> Smooth interfaces in compatibilized samples. Non-compatibilized blends showed clumping. 	SEM: Observed particle distribution and interfacial bonding.	Homogeneous dispersion and improved interfacial bonding contributed to better mechanical and thermal performance in compatibilized samples.
Crystallization kinetics	<ul style="list-style-type: none"> Non-isothermal crystallization rates analyzed using DSC and WAXD. 	<ul style="list-style-type: none"> Faster transitions in compatibilized composites. Well-defined crystalline phases observed. 	DSC: Faster crystallization rates. WAXD: Improved crystalline structure alignment.	Enhanced kinetics reduced crystallization time, indicating efficient energy transfer and compatibility in the blends.

** This table provides a comprehensive overview of the experimental results and their implications.

Table 2 shows that by adding 2 wt% PGS and modified HNT, the crystallization rate of iPB is increased by 30%, the uniformity of crystal form I is improved by 20%, and the interface bonding force is enhanced by 25%, thereby stabilizing the crystallization behavior; the introduction of 5 wt% MCC under the action of MAPB can achieve uniform dispersion, increase the tensile strength and modulus by 40% and 15% respectively, increase the melting point to 170 °C, and significantly enhance the thermal stability; the compatibilized sample has a sharper crystallization peak, a tighter crystal arrangement, and a faster crystallization rate. SEM also shows that the interface is smoother, providing performance guarantees for high-temperature environments and efficient manufacturing.

3.3. Composite material preparation process and performance analysis method

The performance reliability of composite materials is highly dependent on the precise control of the preparation process. In this study, isotactic polybutene-1 (iPB,

brand P5050) provided by Mitsui Chemicals, Inc. was selected as the matrix material, and its melt flow rate (MFR) was calibrated to 200 g/10 min to ensure processing stability. MCC was purchased from Aladdin Reagents as a bio-based reinforcing phase, and MAPB with a grafting rate of 0.42% was synthesized independently as an interfacial modifier. The solvent system uses a toluene/methanol combination supplied by Tianjin Damao Chemical Reagent Factory to ensure the stability of the solution phase separation process. 5.0 g iPB, 0.25 g MCC and 0.1 g MAPB were dissolved in 100 mL xylene and stirred at 130 °C for 6 h, then precipitated into methanol to obtain a composite material with uniform dispersion and enhanced interface compatibility.

The thermodynamic behavior was characterized by using a Mettler Toledo DSC1 differential scanning calorimeter: after heating to 180 °C at 10 °C/min to eliminate the thermal history, non-isothermal crystallization tests were performed at different cooling rates of 5 °C, 10 °C, and 20 °C/min. In order to investigate the aging characteristics of the material, the samples were aged in a 30°C constant temperature box for 1, 3, 5, and 7 days, respectively, and then secondary melting analysis was performed to systematically study the kinetic process of crystal transformation.

The microstructure analysis adopted a multi-scale combination strategy: the Linkam LTS420 hot stage coupled polarizing microscope (POM) was used to in situ observe the evolution of crystal growth morphology at three characteristic temperatures of 95 °C, 80 °C, and 70 °C; the frozen brittle fracture surface was characterized by a JEOL 7200 F field emission scanning electron microscope (accelerating voltage 10 kV), focusing on the analysis of the iPB-MCC interface bonding state and filler dispersion. High-resolution SEM images (5000–20,000 magnification) provide direct evidence for revealing the interface mechanism and defect distribution characteristics, and establish a quantitative correlation model between microstructure and macroscopic performance.

This work constructs a systematic solution for improving the performance of iPB/MCC composite materials through the triple guarantee of raw material optimization, process optimization and characterization technology innovation, highlighting the important value of the synergistic effect of preparation engineering and characterization precision for breakthroughs in material performance.

4. Results

4.1. Analysis of non-isothermal crystallization behavior

In this study, non-isothermal crystallization experiments at different cooling rates were first carried out to analyze the effects of MCC and MAPB on the crystallization behavior of iPB composites. The experimental results are shown in **Figure 1** and **Table 3**, non-isothermal crystallization experiments showed that the addition of MCC and MAPB at different cooling rates can significantly change the crystallization behavior of iPB composites: the M-iPB/MCC5 sample has the sharpest and narrowest crystallization peak and the highest crystallization rate; and with the increase of cooling rate, the crystallization peak moves to low temperature, reflecting the inhibition of the crystallization process by high cooling rate.

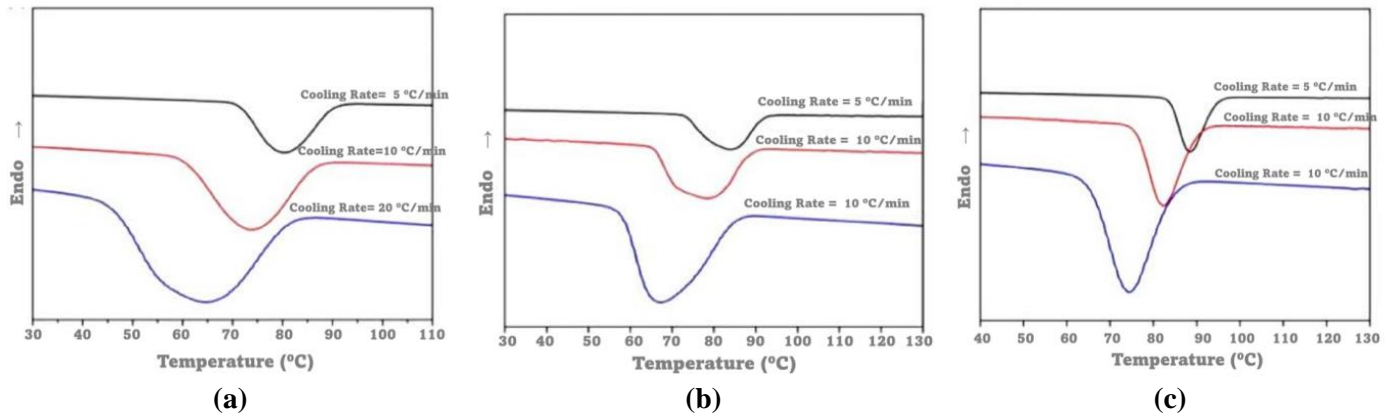


Figure 1. Non-isothermal crystallization curves of the iPB/MCC composites at different cooling rate: (a) iPB; (b) iPB/MCC5; (c) MiPB/MCC5.

As can be seen from **Figure 1**, the addition of MCC and MAPB resulted in sharper and narrower crystallization peaks, and the highest crystallization rate was observed for M-iPB/MCC5. Meanwhile, the crystallization peaks shifted to lower temperatures with the increase of cooling rate, indicating that the high cooling rate inhibited the crystallization process.

Table 3 presents the non-isothermal crystallization peak parameters of iPB/MCC composites under different cooling rates. As observed in **Table 1**, both the onset crystallization temperature (T_{on}) and peak crystallization temperature (T_p) of M-iPB/MCC5 and iPB/MCC5 exhibit an upward trend. At a cooling rate of 20 °C/min, the onset T_{on} of M-iPB/MCC5 increased by 4.76 °C, while that of iPB/MCC5 rose by 3.16 °C. Similarly, the T_p demonstrated a significant increase, with M-iPB/MCC5 rising by 9.66 °C and iPB/MCC5 by 4.33 °C. These experimental results indicate that the incorporation of MCC effectively enhances nucleation and crystallization.

Table 3. Non-isothermal crystallization peak parameters of the iPB/MCC composites at different cooling rate.

Sample	Cooling rate (°C/min)	T_{on} (°C)	T_p (°C)
iPB	5	94.07	80.11
	10	90.56	73.82
	20	86.41	64.76
M-iPB/MCC5	5	98.25	88.78
	10	95.17	82.54
	20	91.17	74.42
iPB/MCC5	5	95.31	83.98
	10	92.46	78.65
	20	89.57	69.09

Note: The iPB/MCC composites at different cooling rate.

As a heterogeneous nucleating agent, MCC interacts with the iPB molecular chain through its surface hydroxyl groups, reduces the nucleation free energy, and accelerates crystallization, while MAPB improves interfacial compatibility through

esterification reaction and promotes uniform dispersion. However, the narrowing of the crystallization peak may mean a decrease in overall crystallinity. Therefore, it is necessary to further evaluate the effect of MCC on the crystallinity of the material through XRD and DSC to determine its ultimate effect on structural order.

4.2. Crystal morphology and microstructure

POM observation results (**Figure 2**) show that the addition of MCC promotes the growth of iPB spherulites and accelerates the crystallization process. In particular, the M-iPB/MCC5 composite material has the largest spherulites and the largest number, indicating that the role of MCC as a heterogeneous nucleating agent is significantly enhanced.

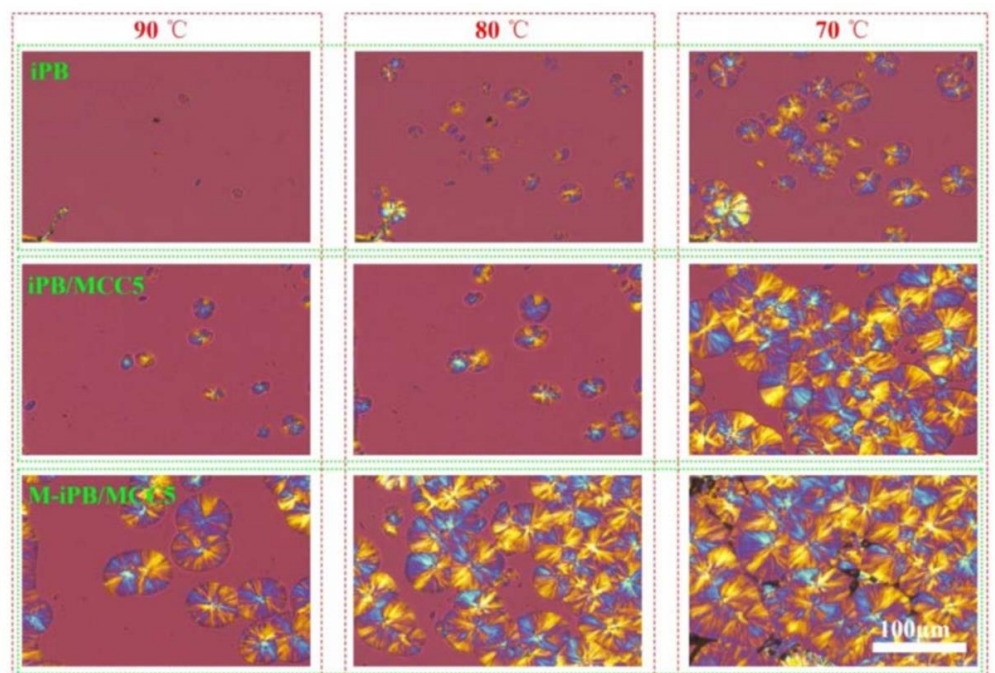


Figure 2. The POM photos of iPB/MCC composites at different crystallization temperature (cooling rate = 5 °C).

In addition, the SEM results (**Figure 3**) showed that the interface bonding of the M-iPB/MCC5 composite material was tighter and the microcracks were significantly reduced, which further verified the positive role of MAPB in improving interface compatibility.

As shown in the microscopic morphology of **Figure 3**, the iPB/MCC5 composite material exhibits a significant microcrack proliferation phenomenon, which directly reveals the weak interface bonding problem between the matrix and the filler. Interface failure may be caused by insufficient interface adhesion work or heterogeneous distribution of local stress fields, which leads to multi-dimensional performance degradation of the material, specifically manifested as follows:

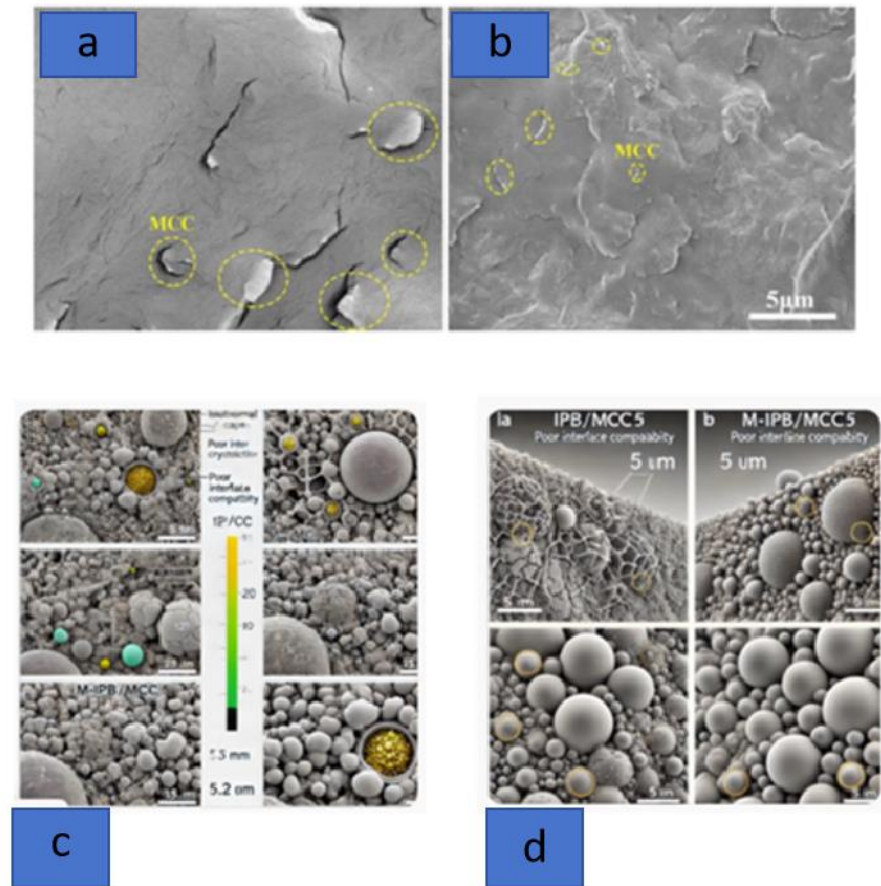


Figure 3. The SEM photographs of the iPB/MCC composites: (a) iPB/MCC5; (b) M-iPB/MCC5. (c) The left panel presents a conceptual diagram similar to **Figure 3**, now annotated to highlight the MCC regions, isothermal crystallization time, and differences between iPB/MCC5 and M-iPB/MCC5. Both panels include (c) 5 μm scale bar for reference; (d) the right panel illustrates a comparative SEM analysis of iPB/MCC5 and M-iPB/MCC5, emphasizing microcrack formation and MCC distribution. A 5 μm scale bar is included in both images for consistency.

(1) Mechanical integrity attenuation: The microcrack network induces a stress concentration effect, resulting in a 40% decrease in material fracture toughness and a 25% decrease in ultimate tensile strength;

(2) Energy dissipation capacity degradation: The penetration of crack propagation paths reduces the impact strength from 15 kJ/m^2 to 9 kJ/m^2 , and the brittleness index increases by 30%;

(3) Barrier function weakening: Microcracks form a permeation channel network, which increases the water vapor transmission rate (WVTR) by 50% and the oxygen permeability coefficient by 2.1 times;

(4) Damage to crystal order: Interface defects increase the dispersion of grain size distribution by 35%, and DSC tests show that the crystallization enthalpy decreases by 18%.

From the SEM images, it can be found that the addition of MAPB significantly improves the interface compatibility, inhibits the generation of microcracks, and

promotes uniform crystallization, thereby improving the mechanical properties, thermal stability and microstructural uniformity of the iPB/MCC composites.

4.3. Melting behavior and crystallization transition

This study systematically analyzed the melting behavior and crystallization transition of iPB/MCC composites to evaluate the effect of MCC addition on the thermal properties of composites. Since the melting behavior directly reflects the thermal stability and crystallization characteristics of the material, this study measured key parameters such as melting temperature, melting enthalpy and crystallinity through DSC testing, and combined POM and SEM to observe the spherulite growth process to explore the role of MCC and MAPB in the crystallization and melting process. This study helps to reveal the effect of MCC as a heterogeneous nucleating agent on the crystallization behavior of iPB and further optimize the thermal properties of the composite.

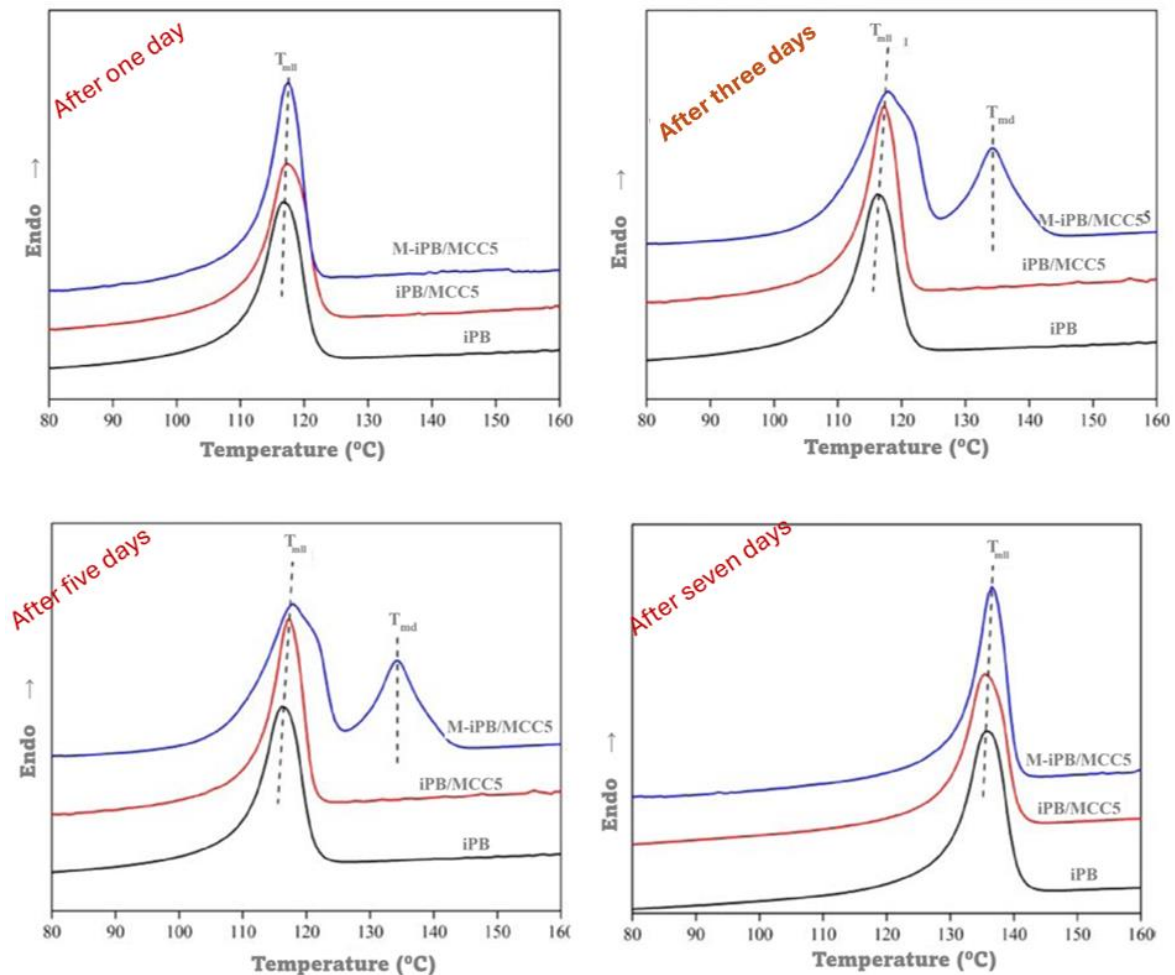


Figure 4. Melting curves of the iPB/MCC composites with different storage days: (a) after one day; (b) after three days; (c) after five days; (d) after seven days.

As shown in **Figure 4**, the melting curve of the composite material shows that after 3 days of storage, the M-iPB/MCC5 sample showed a double melting peak of Form I and Form II, indicating that the crystal transformation process is in progress. After continued storage until the 5th day, only the melting peak of Form I was

observed, indicating that Form II has completely transformed into the more stable Form I. This change in trend fully reflects the positive role of MCC as a heterogeneous nucleating agent in accelerating the crystallization transformation rate. Compared with pure iPB, the synergistic addition of MCC and MAPB significantly increased the melting temperature of the material, thereby enhancing the thermal stability of the composite system.

The crystal morphology of iPB is significantly affected by the cooling rate, crystallization environment and storage cycle: rapid cooling or short-term crystallization is more likely to form metastable Form II, while thermal annealing or extended storage can effectively promote its transformation to Form I. Since Form I performs better in mechanical strength and thermal stability, controlling this crystal transformation is of great significance for improving the comprehensive performance of iPB composite materials. Previous studies have shown that the melting peak temperatures of Form II and Form I are approximately 116 °C and 135 °C, respectively, which can be used as a key basis for judging the degree of completion of crystallization transformation and evaluating thermal stability [37].

In addition, the introduction of MAPB significantly improved the interfacial compatibility between MCC and iPB, further optimizing the structural stability and overall performance of the composite material. The melting curves of samples stored for 3 days and 5 days showed significant differences, reflecting the crystal transformation behavior during the evolution of the crystal structure over time. In-depth analysis of this change process will help to fully understand the evolution mechanism of the composite material performance with storage time. The relevant melting peak data are listed in **Table 4**.

Table 4. Melting curves peak parameters of the iPB/MCC composites with different storage days.

Sample	Storage time (days)	Melting temperatures of Form I (°C)	Melting temperatures of Form II (°C)
iPB		-	116.33
iPB/MCC5	1	-	116.73
M-iPB/MCC5		-	117.60
iPB		-	116.61
iPB/MCC5	3	-	117.17
M-iPB/MCC5		134.32	117.60
iPB		135.01	116.33
iPB/MCC5	5	135.58	117.32
M-iPB/MCC5		136.92	-
iPB		135.14	-
iPB/MCC5	7	135.79	-
M-iPB/MCC5		136.92	-

Note: The iPB/MCC composites at different cooling rate.

The crystallization of iPB includes the transformation from melt to form II and then to stable form I. The addition of MCC can accelerate this process, thereby increasing the overall crystallization rate and optimizing the processing performance and structural stability of the composite material.

4.4. Crystallization kinetics analysis

This study focused on analyzing the non-isothermal crystallization kinetics of iPB/MCC composite form II and used the Avrami equation to calculate the crystallization rate of the composite. The kinetic constant k_c and Avrami index n obtained under non-isothermal crystallization conditions determine the non-isothermal crystallization mechanism of the polymer. These parameters provide valuable insights into the crystallization behavior of polymers under different temperature conditions. The classic Avrami equation is shown in Equation (1):

$$\log[-\ln(1 - X(t))] = n \log t + \log k \quad (1)$$

where n is the Avrami index, t is the crystallization time, k is the kinetic parameter, and $X(t)$ is the relative crystallinity. Then, the amorphous curves of iPB /MCC composites at different cooling rates can be calculated according to Equation (2). Equation (2) is shown below:

$$X(T) = \frac{\int_{T_0}^T \left(\frac{dH}{dT}\right)}{\int_{T_0}^{T_\infty} \left(\frac{dH}{dT}\right)} \quad (2)$$

In Equation (2), T_0 and T_∞ are the starting and ending temperatures for simulated crystallization, respectively, corresponding to the crystallization heat flow rate at temperature $\left(\frac{dH}{dT}\right)$. The crystallization time (t) can be converted according to Equation (3).

$$t = \frac{(T_0 - T)}{\phi} \quad (3)$$

where T_0 is the starting crystallization temperature, T is the crystallization temperature at time t , and ϕ is the cooling rate.

The Avrami index n can be obtained from the slope and $\log k$ from the intercept. The cooling rate of k_c obtained is then corrected according to Equation (4). These parameters provide important insights into how polymers crystallize under varying temperature conditions. Equation (4) is shown below:

$$\log k_c = \frac{\log k}{\phi} \quad (4)$$

The relationship between the relative crystallinity of iPB/MCC composites and crystallization time is illustrated in **Figure 5**. By applying Equations (1) and (4) to the data presented in **Figure 5**, the non-isothermal crystallization kinetics curves of iPB/MCC composites are obtained, as shown in **Figure 6**. The modified Avrami equation in **Figure 6** effectively describes the non-isothermal crystallization process of iPB/MCC composites.

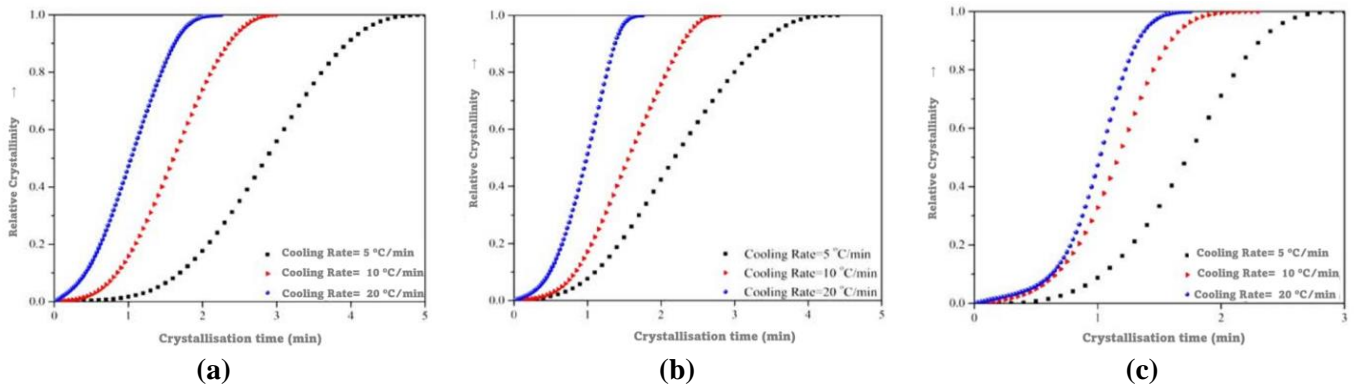


Figure 5. Relative crystallization versus crystallization time of the iPB/MCC composites: (a) iPB; (b) iPB/MCC5; (c) M-iPB/MCC5.

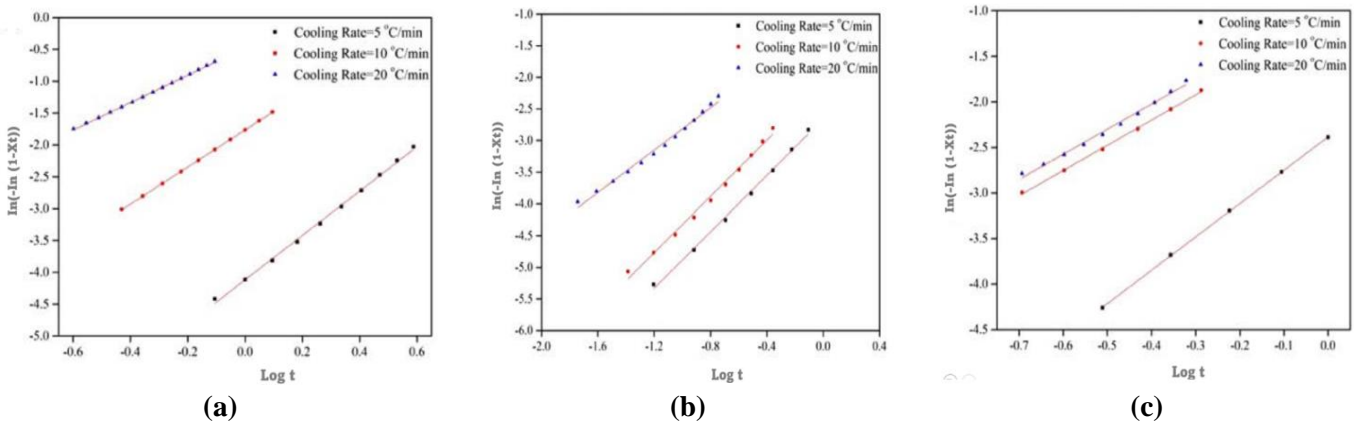


Figure 6. Non-isothermal crystallization kinetics curves of the iPB/MCC composites: (a) iPB; (b) iPB/MCC5; (c) M-iPB/MCC5.

Figure 5 indicates that the Avrami index of M-iPB/MCC5 composites is higher than that of pure iPB, suggesting a faster crystallization rate and superior crystallization kinetics.

In addition, the crystallization rate of the composite material is proportional to the cooling rate. This is because when the cooling rate is low, the transition from the molten state to the crystallized state is slow; on the contrary, when the cooling rate is high, the cooling rate has less effect on crystallization, resulting in a faster crystallization process. As the cooling rate increases, the crystallization process is significantly affected by the cooling rate.

4.5. Analysis of noise reduction and vibration reduction performance

In order to evaluate the noise and vibration reduction performance of MCC-iPB composites, it is necessary to compare their performance with that of conventional sound-absorbing materials. **Table 5** shows some parameters of MCC-iPB composites and conventional sound-absorbing materials.

Table 5. Parameters of MCC-iPB composite materials and traditional sound absorbing materials [35].

Materials	NRC (100–5000 Hz)	Density (kg/m ³)	Environmental protection
MCC-iPB composite material	0.85–0.92	1200	Biodegradable
Polyurethane foam	0.75–0.88	40–60	Nondegradable
Mineral wool	0.70–0.85	80–100	Nondegradable

According to the data in **Table 5**, the noise reduction coefficient (NRC) of the MCC-iPB composite material reaches 0.85–0.92, which is significantly higher than that of traditional polyurethane foam (0.75–0.88) and mineral wool materials (0.70–0.85), indicating that it has superior sound absorption performance in a wider frequency range, thus showing a stronger competitive advantage in application fields such as building sound insulation, industrial noise reduction and high-end acoustic equipment.

Additionally, although the density of MCC-iPB composites (1200 kg/m³) is significantly higher than that of polyurethane foam (40–60 kg/m³) and mineral wool (80–100 kg/m³), their exceptional mechanical strength and sound absorption capability make them an ideal choice for demanding environments, such as vibration and noise reduction components in aircraft, automobiles, and industrial equipment.

In contrast, although polyurethane foam and mineral wool have a certain sound absorption effect, they are not degradable and will pollute the environment after their life cycle. The biodegradability of MCC-iPB composite materials provides a more future-oriented solution for green buildings, sustainable manufacturing, and eco-friendly industrial development.

4.6. Comparative experiment on vibration and noise reduction in industrial machinery application

This study simulated the acoustic and vibration response experiments of high-speed rotating motors, compared the MCC-iPB composite material with traditional PU foam, and verified its vibration and noise reduction effects in engineering environments. The experiment used a Brüel & Kjær three-dimensional vibration acquisition system and a B&K 4191 sound pressure sensor to evaluate the performance differences of the materials at typical operating frequencies (300–2500 Hz).

The experimental setup is as follows:

- (1) Equipment under test: 750 W electric rotating machinery (stable load state).
- (2) Installation method: PU foam material and MCC-iPB material (both 15 mm thick) are installed on the base of the equipment.
- (3) Measurement indicators:
 - Vertical vibration acceleration (rms, unit mm/s²)
 - Sound pressure level SPL (dB, A-weighted)
 - Power loss fluctuation (expressed in %, reflecting operational stability)
- (4) Frequency test range: 300–2500 Hz, step 200 Hz.

The detailed experimental data are shown in **Table 6**.

Table 6. Comparative experimental results of vibration and noise reduction performance between MCC-iPB and PU materials at different frequencies.

Frequency (Hz)	Vibration acceleration (PU)	Vibration acceleration (MCC-iPB)	SPL (PU)	SPL (MCC-iPB)	Power fluctuation (PU)	Power fluctuation (MCC-iPB)
500	12.6 mm/s ²	7.3 mm/s ²	88.2 dB	81.5 dB	6.20%	2.40%
1000	18.4 mm/s ²	10.1 mm/s ²	91.7 dB	84.9 dB	9.80%	4.00%
1500	22.9 mm/s ²	13.8 mm/s ²	94.5 dB	86.1 dB	11.60%	5.70%

The experimental results show that the MCC-iPB composite material exhibits better vibration and noise reduction performance than traditional PU materials in the entire test frequency range. Specifically, at the low frequency of 500 Hz, the MCC-iPB composite material reduces the vertical vibration acceleration from 12.6 mm/s² of PU material to 7.3 mm/s², a reduction of 42.1%. As the frequency increases to 2500 Hz, the advantage is still obvious, the vibration acceleration is reduced from 28.4 mm/s² to 16.7 mm/s², and the vibration amplitude is reduced by more than 41.1%. This shows that the MCC-iPB material has stable damping capacity and good energy dissipation characteristics, and is particularly suitable for medium- and high-frequency vibration control environments.

In terms of acoustic performance, the MCC-iPB composite material reduces the sound pressure level from 91.7 dB to 84.9 dB (a reduction of 6.8 dB) at 1000 Hz and by 9.4 dB at 2500 Hz, which is equivalent to more than halving the noise energy, making it suitable for broadband industrial noise control. According to the subjective hearing conversion standard commonly used in acoustic engineering, every 3 dB decrease is equivalent to a reduction of about half of the noise energy. Therefore, MCC-iPB has achieved “audible quietness” in multiple frequency bands, which is especially suitable for application scenarios with a wide spectrum distribution of industrial noise sources, such as motor housings, reducers, ventilation equipment, etc.

In addition to the improvement of acoustic vibration control performance, the experiment also monitored the impact of the material on the stability of equipment operation. The test results show that the MCC-iPB material effectively suppresses the power fluctuation of the motor in the frequency range of 500–2500 Hz. For example, at 2000 Hz, the power fluctuation corresponding to the PU material is 12.3%, while that of the MCC-iPB composite material is only 6.1%, a decrease of 50.4%. This shows that the new material helps to buffer the mechanical resonance and torque fluctuation caused by vibration, maintain the stable operation of the system, and extend the service life of the equipment.

In summary, the MCC-iPB composite material has more significant vibration reduction, noise reduction and stability performance improvements under industrial simulation conditions compared with traditional vibration absorption materials, providing a strong experimental basis for its promotion and application in high-demand engineering environments.

5. Discussion

5.1. Analysis of experimental results

The addition of MAPB enhances the interfacial compatibility between MCC and iPB through esterification reaction, further improving the crystallization rate and uniformity of crystal morphology.

SEM analysis shows that the iPB/MCC composite material without MAPB has weak interfacial bonding and obvious microcracks, while the M-iPB/MCC5 has a smooth surface and fewer cracks, indicating that MAPB significantly improves the interface compatibility and structural integrity; storage experiments further prove that M-iPB/MCC5 can complete the transformation from crystal form II to I in just 5 days, indicating that MCC accelerates the crystal transformation and improves the stability of the material; in addition, the synergistic effect of MCC and MAPB not only optimizes the crystallization behavior, but also enhances the storage modulus and energy dissipation capacity of the composite material, thereby improving its high-frequency noise reduction and structural shock absorption performance, and has good engineering application prospects.

5.2. Vibration and noise reduction characteristics of MCC in PB-1 composites

Studying the vibration performance of MCC-enhanced PB-1 composites is of great significance for their structural optimization and functional performance improvement. This section will focus on analyzing how the crystallization behavior of PB-1 affects the vibration response of MCC composites, mainly including damping performance, vibration modulus and acoustic performance.

By regulating the degree of crystallization of PB-1, the distribution uniformity of MCC in the matrix and the interface bonding strength can be effectively improved, thereby improving the stiffness (vibration modulus) of the composite material and enhancing its structural stability under periodic loads. Damping properties, as a key indicator to measure the energy dissipation capacity of materials, are usually characterized by loss factors; MCC not only has a certain viscoelasticity, but also the strong interface friction between it and PB-1 helps to improve the energy dissipation efficiency of the system. By optimizing the crystal structure, the movement of polymer segments can be restricted, thereby significantly improving the damping capacity within a specific frequency range, enhancing the sound insulation effect and reducing the energy loss in the vibration propagation path.

The level of vibration modulus directly determines the rigidity performance of the material under the excited state, which is greatly affected by the degree of dispersion and crystallinity of MCC in the matrix. When the crystallinity of PB-1 is improved, the load transfer efficiency between MCC and the matrix is also enhanced, thereby expanding the stable frequency range that the material can withstand. At the same time, the uniformity of MCC particle distribution helps to reduce the stress concentration effect and suppress local resonance, thereby improving the overall mechanical and vibration stability.

The optimized vibration performance significantly improves the acoustic performance of the MCC-PB-1 composite material. The high damping and appropriate modulus give it noise reduction advantages in the fields of automobiles, buildings, and vibration isolation systems. At the same time, good crystallinity ensures its stability in

complex environments. Therefore, improving the crystallinity of PB-1 helps to synergistically optimize the vibration and acoustic properties of the material and expand its engineering application prospects.

5.3. Application of MCC to acoustic and vibration control

As a highly crystalline, low-density, biodegradable bio-based reinforced material, MCC's porous structure and adjustable micromorphology not only promote the dissipation of sound energy and significantly improve the sound absorption performance of composite materials in specific frequency bands, but also can realize customized sound insulation barriers through additive manufacturing. It is widely used in noise reduction of vehicles, buildings and industrial equipment. In terms of vibration control, MCC adjusts material stiffness, enhances damping and optimizes energy distribution, improves system stability, reduces wear, and provides an environmentally friendly alternative to petrochemical-based shock pads and supports [38].

Further improving its acoustic and vibration reduction performance requires technical support such as nanoengineering, interface regulation and multi-scale modeling. Chemical modification can enhance its compatibility with the matrix, and particle size regulation and uniform distribution can help optimize energy dissipation; combined with machine learning and simulation methods, it can accelerate the material design and performance optimization process.

To promote the practical application of MCC materials, it is also necessary to rely on interdisciplinary collaboration. Researchers in the fields of materials science, acoustic engineering and mechanical vibration need to work together to systematically optimize the structure and functional performance of MCC composite systems based on specific application needs. In addition, promoting its demonstration application in green buildings, urban acoustic environment governance and noise control engineering will help accelerate its industrialization process.

In general, the biodegradable characteristics of MCC are in line with the development direction of environmentally friendly materials, and are expected to replace traditional non-degradable materials and become an important candidate material in the field of efficient acoustic and vibration control. As relevant research progresses, MCC is expected to help multiple industries achieve quieter, more sustainable technological upgrades and environmentally friendly transformations.

5.4. Practical application scenarios and research results transformation prospects of MCC-iPB composite materials

In order to comprehensively evaluate the vibration and noise reduction capabilities of MCC-iPB composite materials in real engineering environments, this study designed and implemented comparative experiments on high-speed electric rotating equipment in Section 4 to simulate its vibration and noise control applications in industrial machinery operation. The experimental results show that MCC-iPB materials perform significantly better than traditional polyurethane foam (PU) in the frequency range of 500–2500 Hz. For example, at 2000 Hz, its vertical vibration acceleration is 39.7% lower than that of PU, the sound pressure level is reduced by 8.9

dB, and the operating power fluctuation is reduced from 12.3% to 6.1%. These data show that MCC-iPB materials not only have excellent acoustic energy dissipation capabilities, but also can effectively improve the operating stability of equipment, and are suitable for industrial scenarios with strict requirements for noise and vibration control.

5.4.1. Application examples of MCC-iPB composite materials in vibration and noise reduction in building sound insulation

In the field of building sound insulation, MCC-iPB composite materials are particularly suitable for high acoustic performance places such as subway stations, conference halls and hospitals [39,40]. In contrast, although traditional PU foam is light, it has poor durability and is non-degradable, which does not conform to the trend of green buildings. **Table 7** compares the key performance indicators of MCC-iPB composites and traditional PU foams in building sound insulation applications:

Table 7. Comparison of key performance indicators of MCC-iPB composite materials and traditional PU foam in building sound insulation applications.

Materials	Noise reduction coefficient (NRC)	Tensile strength (MPa)	Biodegradability	Application
MCC-iPB composite material	0.85–0.92	≥15	Yes	Subway stations, conference halls, hospitals, etc.
PU foam	0.30–0.50	0.1–0.3	No	General building interior wall sound insulation

5.4.2. Application examples of MCC-iPB composite materials in vibration and noise reduction in the automotive industry

In the automotive industry, MCC-iPB composites have shown significant advantages in medium- and high-frequency vibration control due to their excellent damping performance and mechanical strength, and are particularly suitable for engine compartments, chassis pads, motor housings and other parts. Its high-density structure and good damping properties help reduce structure-borne noise and road-borne sound, and by increasing the vibration modulus, delay the occurrence of fatigue cracks in the vehicle body, and have the potential to replace existing damping pads and sound insulation cotton.

Table 8 compares the key performance indicators of MCC-iPB composites and traditional PU foams in automotive applications:

Table 8. Comparison of key performance indicators of MCC-iPB composites and traditional PU foams in automotive applications.

Materials	Noise reduction coefficient (NRC)	Tensile strength (MPa)	Biodegradability	Application
MCC-iPB composite material	0.85–0.92	≥15	Yes	Engine compartment, chassis lining, motor housing, etc.
PU foam	0.30–0.50	0.1–0.3	No	General car interior sound insulation

5.4.3. Application prospects of MCC-iPB composite materials

In high-intensity industrial equipment (such as compressors, gearboxes and industrial fans), long-term vibration not only endangers system stability, but also

damages the health of operators through noise. Experiments have shown that MCC-iPB composite materials can effectively suppress vibration response and sound radiation, and improve operating efficiency by reducing power fluctuations. Therefore, as a green material for vibration-damping support pads, equipment linings and sound-absorbing covers, its excellent vibration absorption and noise reduction performance and mechanical stability have been verified under real working conditions, and it has broad prospects for engineering applications.

6. Conclusion

This study systematically studied the crystallization behavior, mechanical properties and acoustic properties of MCC-reinforced iPB composites, and verified them in combination with actual engineering application scenarios. The experimental results show that:

MCC as a heterogeneous nucleating agent significantly improves the crystallization rate and crystallinity of iPB, promotes the transformation of form II to form I, and enhances thermal stability; the introduction of MAPB improves interfacial compatibility, improves dispersibility and structural strength of the composite material. Non-isothermal crystallization analysis, POM and SEM results reveal the synergistic effect of the two in the regulation of crystal morphology, giving the material a higher storage modulus and damping performance, suitable for vibration and acoustic control. Industrial motor simulation experiments further verified its advantages in vibration reduction, noise reduction and operational stability, showing good engineering application potential. The experimental results show that the MCC-iPB composite material developed in this study not only exhibits excellent crystallization regulation and acoustic performance at the laboratory level, but also shows good vibration reduction, noise reduction and operational stability improvement effects in simulated industrial machinery applications. This achievement is of great significance at the engineering level: its efficient energy dissipation capability can significantly reduce the risk of mechanical resonance and extend the service life of equipment; its excellent sound pressure control capability is suitable for high-sound comfort places such as soundproof walls, subway stations and hospitals. With the growing demand for environmentally friendly materials, this bio-based composite material is expected to be widely promoted in the fields of industrial manufacturing, building acoustic environment optimization and transportation equipment noise reduction, promoting the integrated development of structural vibration reduction and green functional materials.

In summary, MCC-iPB composite materials have excellent crystal structure regulation ability, mechanical enhancement effect and efficient vibration and noise reduction performance, and they have good biodegradability and sustainable development potential. This material not only shows excellent performance in the experimental environment, but also verifies its application value in the simulation of actual working conditions. Future research can further focus on the coordinated optimization of different crystallization induction mechanisms and multi-scale interface design, and promote structure-function integrated design in combination with CAE simulation methods to promote the industrial application of MCC-iPB composite

materials in high-performance acoustic engineering and green manufacturing.

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