From Amorphous Flow to Crystalline Order: Tracing Acoustic Emission Through Polymer Processing and Chain Alignment

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1. Abstract

Acoustic emission (AE) technology has established itself as a highly sensitive, non-destructive tool for real-time monitoring of defect formation and micro-structural evolution in polymeric materials and composites during production and initial service. This review examines the core principles and uses of AE in identifying defects arising from crystallization such as voids, dislocations, and micro cracks, along with mechanisms of plastic deformation like chain orientation, cavitation, and stress relaxation. AE activity shows a strong correlation with both crystallinity levels and processing parameters, offering valuable insight into micro--structure – property relationships. Underlying mechanisms may involve inter-granular friction, localized stress relief, molecular chain motion, phase transformations, and fiber or filler debonding. A thorough grasp of these processes supports the prediction and prevention of early- stage flaws in crystalline polymer processing. Moreover, combining AE with artificial intelligence and multi-sensor data fusion presents a promising direction for developing intelligent, adaptive manufacturing systems that enable real-time quality assurance and early defect detection in high performance polymer composites.

2. Introduction

Polymers and their composites are widely used in critical sectors like electronics, aerospace, and energy due to their excellent and tailorable properties. However, manufacturing defects and in-service deformation can seriously threaten structural safety and service life, making effective non-destructive testing (NDT) essential. Various NDT techniques, including ultrasonic testing (UT), acoustic emission (AE), terahertz pulsed spectroscopy (TPS), infrared thermography (IR), and X-ray computed tomography (CT), have been successfully applied to detect debonding, delamination, and voids in fiber-reinforced polymers (FRP). While CT offers high accuracy for carbon fiber-reinforced polymers, and micro-CT combined with structural health monitoring (SHM) enhances defect detection in additively manufactured thermoplastic composites, these methods generally lack mobility, cost-effectiveness, and real-time dynamic monitoring capabilities [1]. In contrast, acoustic emission (AE) stands out as a promising, passive, and non-invasive NDT method. AE detects and analyzes elastic waves generated by irreversible processes such as crack growth, friction, and delamination, providing real-time data on defect initiation and evolution during both manufacturing and service [2]. During processing and early service, polymers undergo significant temperature and stress changes, leading to crystallinity variations, phase transitions (e.g., amorphous to crystalline), chain movement, and stress release processes that can generate cavities, cracks, and voids [3].

This review summarizes recent progress on AE mechanisms in polymer processing and plastic deformation across three sections: (1) AE for polymers and composites; (2) AE mechanisms during amorphous-to-crystalline transitions; and (3) future possibilities for early defect inspection in crystalline polymer composites, offering a concise outlook for future research.

3. AE for polymers and composites

Acoustic emission (AE) is an NDT method that captures elastic waves generated by internal damage mechanisms such as delamination or crack growth under stress. AE typically detects high-frequency signals (from 10 kHz to 1 MHz) and offers exceptional sensitivity, capable of identifying micro-cracking with energies on the order of attojoules (10^{-18} J), far below conventional detection thresholds [4]. A standard AE system includes piezoelectric sensors, pre-amplifiers, data acquisition units, and a PC. Sensors are mounted on the material surface using a coupling agent to ensure efficient signal transmission. Modern systems record full waveforms and extract key signal parameters (e.g., amplitude, duration, rise time, counts, energy) that help characterize AE sources and interpret damage mechanisms.

In pure polymers, the Kaiser effect has been observed during stretching. In the glassy state, razes and microcracks remain as permanent defects, whereas in the rubbery state, self-healing occurs, and the differences can be clearly reflected in AE responses. AE has proven effective in investigating stress racking behavior in polybutylene terephthalate (PBT) under various test conditions [5]. For polymer composites, AE serves as a powerful NDT and SHM technique for identifying and tracking fiber breakage, matrix cracking, delamination, and debonding under mechanical loading or during service [2]. It has also been successfully applied to bio-based and biological materials. Piezoelectric sensors can be embedded within laminated FRP composites to create “smart materials” for continuous condition monitoring. Notably, AE activity can initiate as early as 10% of ultimate failure stress and intensifies with increasing load [6]. However, challenges remain regarding sensor size, placement, and interfacial coupling. To enhance performance, AE data can be combined with artificial intelligence (AI) and deep learning models to classify different damage modes [7]. Furthermore, integrating AE with other techniques such as microscopy and digital image correlation (DIC), which improves data processing efficiency and accuracy [8]. Overall, AE is a promising NDT and SHM method with expanding capabilities for structural monitoring of polymers and their composites.

4. AE mechanisms during amorphous-to-crystalline transitions

While AE has been successfully applied to monitor crystallization in inorganics and metals [9], research on AE mechanisms during polymer crystallization and processing remains limited. Moreover, although AE is widely used in mechanical testing, the initial plastic deformation stage in polymers and polymer composites is often overlooked due to weak detectable signals. However, these early signals may contain critical information about chain re-orientation, friction, and phase transformation.

4.1. AE Mechanisms During Crystallization

Defects such as dislocations, cavities, and imperfections can arise during polymer crystallization. Studies on isothermal crystallization of poly(methylene oxide) (POM), high-density polyethylene (HDPE), and isotactic polypropylene (iPP) revealed that AE signals originate from abrupt stress release within cavities caused by density changes during crystallization [10]. Significant AE activity was observed in iPP and POM, where microstructural cavities form between spherulites at quadruple boundary points. In contrast, HDPE and talc-filled iPP exhibited negligible AE signals due to smaller spherulites with limited cavities. AE signals typically occur toward the end of crystallization, coinciding with the exothermic peak in DSC curves. During non-isothermal crystallization, rapid temperature jumps also trigger AE events, though the exact origins remain unclear [11]. Despite being reported over 40 years ago, these findings attracted limited follow-up research. Given the growing demand for high-performance polymer composites, understanding crystallization-induced cavities and stress release is critical, as they can cause interfacial debonding and severely compromise mechanical properties.

4.2. AE Mechanisms of Chain Orientation During Initial Plastic Deformation

Correlations between AE signals and polymer molecular events have been observed, but challenges remain. Distinguishing whether AE originates from chain mobility rather than micro-crazing or cracking is difficult during plastic deformation of crystalline polymers. In polyethylene (PE), AE activity increases significantly with crystallinity, as cavitation releases substantial energy. However, the respective contributions of chain movement and cavitation have not been decoupled [12]. In polyamides (PA), strong hydrogen bonding restricts chain slip; heat treatment increases crystallinity and reduces AE activity, suggesting signals may arise from chain mobility in amorphous regions or crystal interface friction [13]. Similarly, in polybutylene terephthalate (PBT), ethanol exposure reduces AE intensity due to plasticizing effects, with higher crystallinity specimens showing less pronounced plasticizing because regular molecular structures provide more crack nucleation sites [5]. Overall, AE offers a promising non-destructive means to detect and analyze molecular-level structural evolution during polymer processing and deformation.

5. Future possibilities

AE technology offers great potential for early defect inspection in crystalline polymer composites during manufacturing. Its high sensitivity to micro-scale structural changes, such as crystallization-induced stress release and cavity formation, enables real-time detection of incipient defects before they become critical. By analyzing AE parameters like energy, frequency, duration, and amplitude, different failure modes can be distinguished from environmental noise, whether caused by imperfect crystallization, thermal stress, uneven flow, or mechanical overloading [14]. With further advances in multi-sensor data fusion (acoustic, temperature, pressure, optical) and AI-assisted systems [15], AE could become a cornerstone of smart manufacturing. Automatic adjustments to temperature, pressure, or dwelling time would enhance reliability, prolong service life, reduce waste, and enable energy-efficient, closed-loop adaptive control for next-generation polymer composites.

6. Conclusions

Acoustic emission (AE) is a highly sensitive, passive NDT method capable of real-time monitoring of polymer crystallization and early plastic deformation. It detects micro-scale events such as stress release, cavity formation, and chain re-orientation. While challenges remain in distinguishing chain mobility from micro-cracking, integrating AE with multi-sensor data fusion and AI offers a pathway toward smart manufacturing. Such closed-loop systems can automatically adjust processing parameters to prevent defects, reduce waste, and improve energy efficiency. AE thus holds great promise for ensuring the quality and reliability of next-generation crystalline polymer composites. AE technology offers great potential for early defect inspection in crystalline polymer composites during manufacturing. Its high sensitivity to micro-scale structural changes, such as crystallization-induced stress release and cavity formation, enables real-time detection of incipient defects before they become critical. By analyzing AE parameters like energy, frequency, duration, and amplitude, different failure modes can be distinguished from environmental noise, whether caused by imperfect crystallization, thermal stress, uneven flow, or mechanical overloading.

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