

# Visualization of Polymer Chain Scission during Melt Processing Using a Mechanochromic Probe

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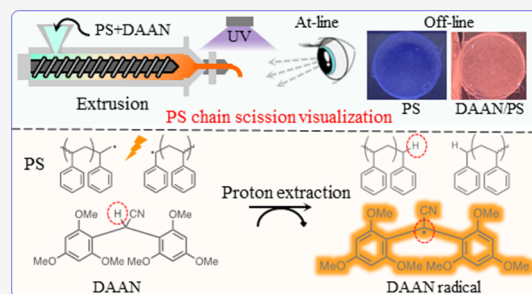


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Supporting Information

**ABSTRACT:** We thoroughly investigated polymer chain scission occurring through thermal and mechanical degradation during kneading via complex viscosity, torque, shear stress, and feeding rate measurements. We visualized polystyrene chain scission using a diarylacetonitrile derivative (DAAN-triOMe/triOMe) that can react with mechanoradicals to generate the corresponding fluorescent DAAN-triOMe/triOMe radicals. We kneaded polystyrene containing 5 wt % DAAN-triOMe/triOMe at various screw speeds and kneading temperatures using a twin-screw kneader. The results reveal that changes in complex viscosity and fluorescence intensity are correlated, indicating polystyrene chain scission and free radical generation. Mechanochromic behavior was also associated with heat-induced polymer deformation. Furthermore, the complex viscosity decreased with increasing speed and temperature. The analyses of torque, shear stress, and feeding rate revealed intricate relationships between speed, temperature, and polymer chain scission. This study highlights the effectiveness of DAAN-triOMe/triOMe in visualizing polymer chain scission using color change during both at-line and offline observations.



## 1. INTRODUCTION

Screw extrusion is the commonly used technique for melting commercial thermoplastic polymers and compounding additives or modifiers in the plastic manufacturing industry. The polymers are melted through the combined heat generated by the heater bands and shear heating created by the friction between the granules and the screw and barrel. However, the high shear and heat to which the polymer is exposed during extrusion cause thermomechanical degradation.<sup>1,2</sup> Melt processing causes considerable polymer degradation, resulting in significant changes in molecular weight, rheological properties, crystallization behavior, and yellowness, which affects the mechanical properties.<sup>3</sup> Polymer processing causes degradation, as evidenced by changes in molecular weight stemming from exposure to elevated temperatures, shear forces, and mechanical stress. Thermal and mechanical stresses generally cause irreversible damage to the material within the extruder. Such damage is caused through thermal, thermal-oxidative, thermal-mechanical, or hydrolytic degradation mechanisms.<sup>4–7</sup> Understanding polymer mechanical behavior and flow dynamics during deformation and melt processing is imperative for optimizing performance and processing parameters.

During these processes, stress visualization techniques provide invaluable insights into stress distribution patterns within polymers. Mechanochromic materials undergo reversible color changes in response to mechanical stress and thus may be used for real-time stress visualization, enabling the analysis of stress distribution in polymers without external

measuring equipment.<sup>8–12</sup> Mechanochromic materials play a crucial role in process monitoring and control by enabling real-time visual observation of stress concentrations, enabling operators to adjust processing parameters promptly for improved efficiency and quality. They aid in process optimization by identifying stress and strain areas during extrusion, allowing engineers to adjust processing parameters such as temperature and pressure to achieve a more controlled process. In quality assurance, these materials detect defects early, reducing waste and ensuring product consistency through uniform color changes across molded parts. Notably, mechanochromic polymers exhibit color change in response to mechanical stimulation and hold significant promise for detecting material damage and stress,<sup>13</sup> allowing timely replacements or repair.

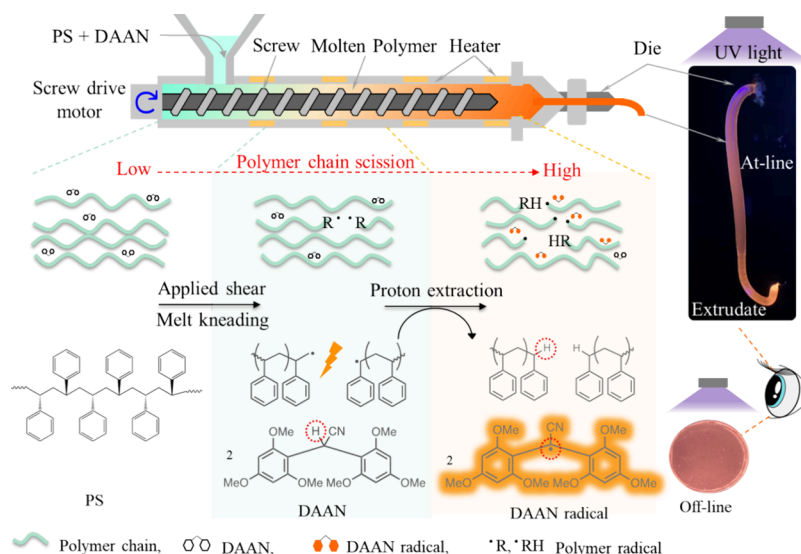
The present study investigated the impact of screw rotational speeds, kneading temperatures, and feeding rates on the generation of mechanoradicals in polystyrene (PS) blended with a diarylacetonitrile derivative (DAAN-triOMe/triOMe). In particular, fluorescence intensity, shear stress, and complex viscosity measurements were used to explore polymer

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**Scheme 1. Extrusion Process Illustrating the Visualization of Polymer Chain Scission Mechanisms using Mechanochromic Materials**



chain scission and mechanoradical generation. At-line observation of the polymer chain scission can be achieved by monitoring the color change of the extrudate during the extrusion process (Scheme 1). However, rheological, physical thermal, and mechanical properties cannot be fully assessed through the state of molten polymer. Consequently, the extrudates are prepared via compression molding as offline samples for a more comprehensive analysis. The relationship between color change and chain scission in these offline samples could provide insights into the properties relevant to *in situ* or at-line observation.

## 2. MATERIALS AND METHODS

**2.1. Materials.** Commercial-grade PS, designated grade 679 ( $M_w \sim 255,123$ ,  $M_n \sim 107,653$ , and  $MWD \sim 2.37$ ), was procured from PSJ Japan Co., Ltd. The mechanochromic probe material, DAAN-triOMe/triOMe, was synthesized according to a previously reported method.<sup>14</sup> All materials were used without additional purification.

**2.2. Experimental Procedures.** **2.2.1. Kneading Process.** PS with DAAN-triOMe/triOMe was kneaded in a twin-screw kneading extruder (LABO PLASTOMILL 4C150, Toyo Seiki Seisakusho, Ltd., Tokyo, Japan) at different temperatures, screw rotational speeds, torques, and feeding rates.

**2.2.2. Compression Molding.** Compression molding was performed using a vacuum melting heat press (Imoto Machinery Co., Ltd., IMC-11FA). The compressed samples for complex viscosity and fluorescence intensity measurements were prepared as follows: the thickness of the sample was 1 mm, preheated at 140 °C for 5 min, applying a pressure of 4 MPa for 5 min and cooling at 15 °C for 5 min. The experimental procedure of visualization and characterization of polymer chain scission is shown in Figure S1 (Supplementary data).

**2.3. Characterization.** **2.3.1. Complex Viscosity.** Rheological properties of the melt were assessed using a modular compact rheometer 302 (Anton Paar Japan K.K., Tokyo, Japan) equipped with 8 mm in diameter parallel plates. The samples were measured under a 10% strain within the frequency range of 0.1–100 rad s<sup>-1</sup> at a constant temperature of 210 °C for approximately 30 min (which is the entire measurement duration) under a N<sub>2</sub> atmosphere.

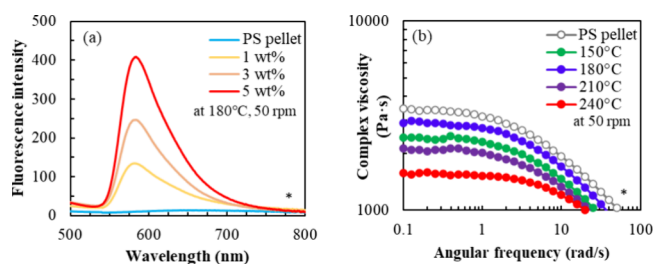
**2.3.2. Fluorescence Intensity.** Fluorescence intensity was quantified using a spectrofluorometer (Japan Spectroscopy (JASCO) Co., Ltd., FP-8550VSR) across a wavelength range of 500–800 nm.

**2.3.3. Shear Stress.** Shear stress measurements were performed using a capillary rheometer (Toyo Seiki Seisakusho, Ltd., Tokyo, Japan, CAPILOGRAPH1D) with the following specifications: barrel diameter 9.5 mm, extrusion die diameter 1.0 mm, extrusion die length 40 mm ( $L/D = 40$ ), and an operating temperature range of 150–180 °C.

## 3. RESULTS AND DISCUSSION

**3.1. Optimization of DAAN-triOMe/triOMe Quantity and Kneading Temperature Range.** Thermal degradation can cause polymer chain scission.<sup>5,13</sup> Therefore, optimizing the kneading temperature using a twin-screw kneading extruder was considered crucial for preventing the degradation of PS while adjusting other kneading parameters. DAAN-triOMe/triOMe was kneaded with PS to observe polymer chain scission. Samples obtained at different kneading temperatures, ranging from 150 to 240 °C,<sup>15</sup> were compression-molded. Subsequently, the compressed samples were analyzed for fluorescence intensity, and the complex viscosity of the compressed samples was determined. Fluorescence emission was chosen for measuring the changes in mechanochromic polymers because of its sensitivity to mechanical stress, noninvasive nature, real-time monitoring potential, and ability to provide quantitative insights into stress-induced changes.<sup>10,12</sup> Viscosity is associated with the molecular weight and fluidity of the polymer.<sup>16–18</sup> The fluorescence intensity of DAAN-triOMe/triOMe was examined at different concentrations: 1, 3, and 5 wt %. These tests were conducted under the following processing conditions: a kneading temperature of 180 °C, screw speed of 50 rpm, and duration of 3 min. Based on the results presented in Figure 1a, a DAAN-triOMe/triOMe concentration of 5 wt % was selected for all subsequent experiments. Importantly, no fluorescence was observed for neat PS. The PS with 5 wt % DAAN-triOMe/triOMe was subsequently kneaded at various temperatures.

The effect of heat on polymers is well-established, as it can significantly impact their behavior and properties. With increasing temperature, the thermal energy of the polymers increases,<sup>13</sup> which can lead to polymer chain scission or decomposition.<sup>3,5,7</sup> At considerably high temperatures, polymer molecules absorb sufficient thermal energy to break



**Figure 1.** (a) Fluorescence emission spectra ( $\lambda_{\text{ex}} = 365 \text{ nm}$ ) of DAAN–triOMe/triOMe/PS at 1, 3, and 5 wt % of DAAN–triOMe/triOMe, and (b) complex viscosity of DAAN–triOMe/triOMe/PS as a function of angular frequency measured at 210 °C from the kneaded samples at various kneading temperatures and a screw speed of 50 rpm. \* = Samples prepared by compression molding at 140 °C.

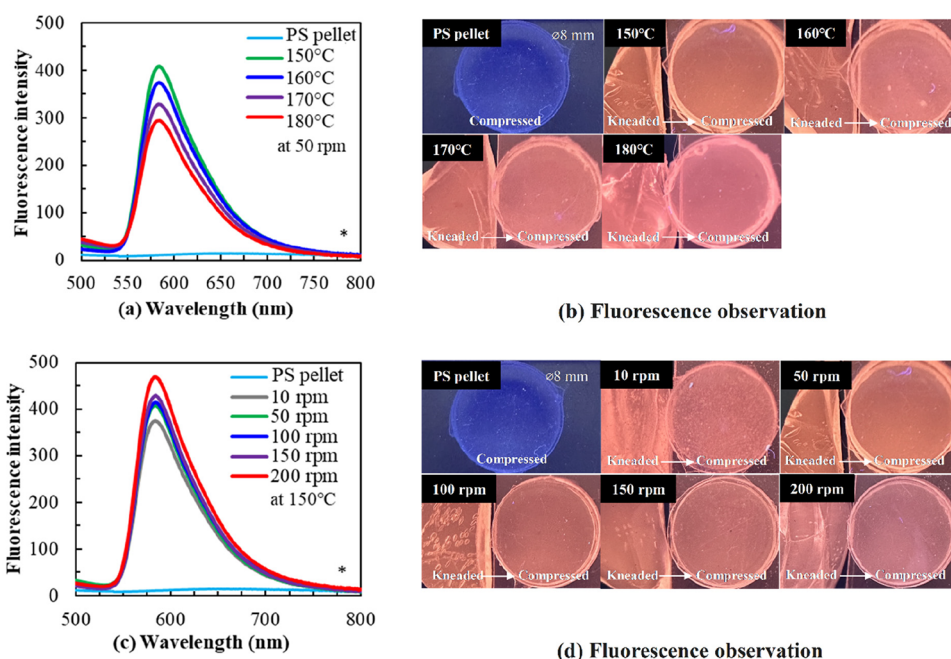
certain chemical bonds within them and generate free radicals. Consequently, the application of heat to the polymer leads to an increase in the generation of free radicals.<sup>7,13</sup> The effects of such thermally induced changes are manifold, encompassing alterations in molecular weight, weight distribution, and degree of crystallinity. Notably, the complex viscosity of PS decreases at kneading temperatures of 210 and 240 °C, indicating a reduction in molecular weight due to the thermal degradation of the polymer chain at relatively high temperatures.<sup>5,19</sup> The results indicated an optimal kneading temperature range of 150–180 °C. This range was selected due to its ability to maintain a complex viscosity value closely preserving that of neat PS. Furthermore, as depicted in Figure 4, temperatures exceeding 180 °C at a screw rotational speed of above 150 rpm result in the polymer melt temperature reaching approximately 200 °C, potentially leading to thermal degradation. This kneading temperature range (150–180 °C) with 5 wt % DAAN–triOMe/triOMe provides a suitable reference point

for the exploration of other parameters that could contribute to polymer chain scission.

Based on a previous study, electron paramagnetic resonance (EPR) was employed to identify polymeric mechanoradical generated through polymer scission, facilitating a quantitative assessment of DAAN species. Notably, fluorescence became evident postgrinding. EPR measurements distinctly illustrated a signal corresponding to the formation of radical species, aligning with EPR spectra. Additionally, the fluorescence spectrum exhibited an increase in fluorescence intensity with DAAN radical quantity over grinding time. A direct correlation between fluorescence intensity and DAAN radical amount was established.<sup>20</sup> The color change and chemical mechanism are illustrated in Scheme 1.

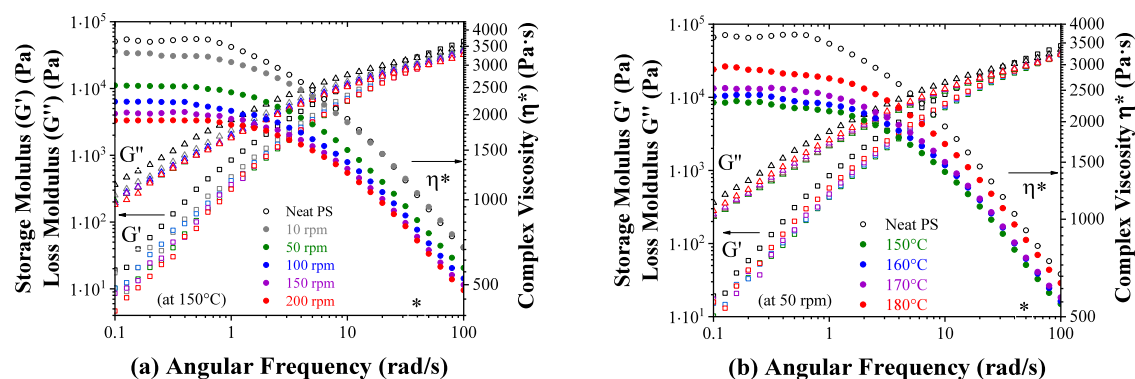
**3.2. Mechanochromic Behavior at Different Screw Speeds and Kneading Temperatures.** As previously mentioned, heat affects polymer chain scission. However, kneading temperatures in the range of 150–180 °C are considered suitable for PS. To gain further insights, the PS kneading temperatures of 150, 160, 170, and 180 °C were investigated. The rotational speed of the screw in polymer processing, particularly in extrusion and kneading, plays a significant role in polymer chain scission.<sup>2,3,15,21</sup> The screw speed determines how quickly the polymer material is transported through the processing equipment and can have a notable impact on polymer properties as a result of shear forces, heat generation, and processing time.<sup>22,23</sup> To address this, screw speeds ranging from 10 to 200 rpm were investigated to elucidate polymer chain scission mechanisms. For each kneading condition, the torque and temperature of the melt polymer were simultaneously recorded (Figure 4).

DAAN–triOMe/triOMe exhibits mechanochromic behavior when polymeric mechanoradicals abstract hydrogen radical from DAAN–triOMe/triOMe<sup>14,20</sup> and generate the corre-



**Figure 2.** (a) Fluorescence emission spectra ( $\lambda_{\text{ex}} = 365 \text{ nm}$ ) of DAAN–triOMe/triOMe/PS and the neat PS at a constant screw speed of 50 rpm at various kneading temperatures, with (b) corresponding photographs. (c) Fluorescence emission spectra ( $\lambda_{\text{ex}} = 365 \text{ nm}$ ) of DAAN–triOMe/triOMe/PS and the neat PS at different screw rotation speeds at 150 °C and, with (d) corresponding photographs. \* = Samples prepared by compression molding at 140 °C. (All photographs were acquired under fluorescence conditions at an excitation wavelength of 365 nm.)





**Figure 3.** (a) Complex viscosity of DAAN-triOMe/triOMe/PS measured at 210 °C from the samples kneaded at a constant kneading temperature of 150 °C at different kneading screw rotational speeds, and (b) complex viscosity of neat PS and DAAN-triOMe/triOMe/PS at a constant screw speed of 50 rpm at different kneading temperatures. \* = Samples prepared by compression molding at 140 °C.

sponding DAAN-triOMe/triOMe radical that emits orange fluorescence with a band around 580 nm. As shown in Figure 2a, b, the fluorescence intensity sequentially increases as the temperature decreases from 180 to 150 °C. This suggests that the chain scission of PS at 180 °C is less pronounced than that at 150 °C. The compression process followed for fluorescence and complex viscosity measurements was assumed to not further induce color change at 140 °C as previous study.<sup>11</sup> Thermogravimetric analysis showed that the degradation temperature of DAAN was quite high at approximately 240 °C, indicating high thermal stability (Figure S2). Furthermore, as shown in Figure 2b, d, the kneaded and compressed samples showed similar colors. Similarly, as shown in Figure 3b, the complex viscosity at 180 °C is higher than that at 150 °C, indicating a higher molecular weight and less pronounced polymer chain scission. Consequently, reduced fluorescence intensity is observed.

In contrast, fluorescence intensity increases with the screw rotational speed. In particular, at a screw speed of 200 rpm, the fluorescence intensity is 25% higher than at 10 rpm (the lowest speed). Figure 2c, d illustrates that the orange fluorescence becomes more pronounced at higher screw rotational speeds. These elevated speeds, in conjunction with higher temperatures, are believed to enhance the generation of PS radicals. The increased breakage of polymer chains, attributed to higher screw rotational speeds and the associated higher loads,<sup>23</sup> leads to greater generation of DAAN-triOMe/triOMe radicals owing to the hydrogen atom transfer reaction by the PS radicals generated during kneading.<sup>20</sup> Consequently, higher fluorescence intensity is observed at higher screw rotational speeds compared with lower rates. The observed variations in fluorescence intensity with screw rotational speeds and kneading temperatures suggest a close relationship between polymer chain scission, i.e., mechanoradical generation, and the fluorescence behavior of DAAN-triOMe/triOMe radicals.

**3.3. Complex Viscosity at Different Screw Speeds and Kneading Temperatures.** Rheological assessment of melted polymers has proven to be one of the most efficient techniques for indirectly assessing degradation changes in thermoplastic polymer materials during processing.<sup>16</sup> The viscosity of polymers is directly linked to their molecular weight, with higher-molecular-weight polymers exhibiting greater viscosity than their lower-molecular-weight counterparts.<sup>18,19</sup> Thus, complex viscosity measurements were employed to investigate polymer chain scission depending on molecular weight at various kneading temperatures.

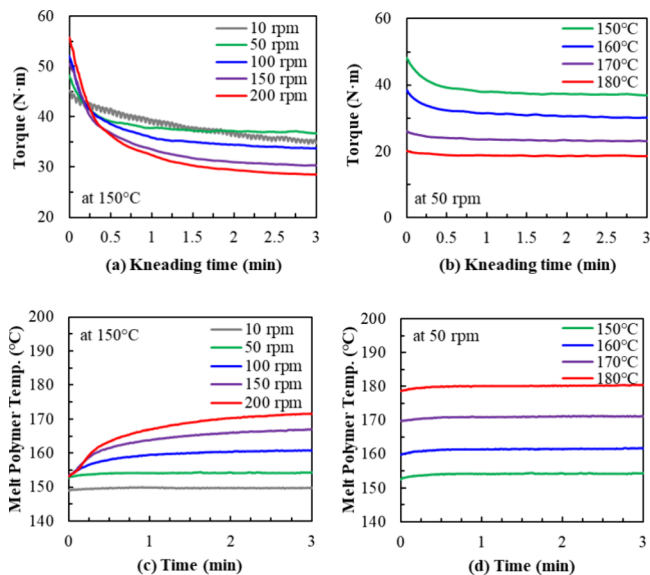
Figure 3a presents a comparison of screw rotational speeds and their impact on complex viscosity, storage modulus, and loss modulus. It is evident that as the screw rotational speed increases, the melt viscosity decreases. This observation indicates that higher screw rotational speeds promote the polymer chain scission.<sup>24</sup> As is widely recognized, shear forces and mechanical stresses<sup>22</sup> exerted on polymer chains at higher rotational speeds facilitate the rupture of molecular bonds, leading to a reduction in viscosity. Consequently, the polymer is degraded, resulting in an overall decrease in its viscosity.

Figure 3b illustrates the effect of different kneading temperatures on melt viscosity. Samples kneaded at low temperatures exhibit lower viscosity than those processed at higher temperatures. The higher the kneading temperature, the greater the fluidity of the polymer resin.<sup>25</sup> This phenomenon can be attributed to the increased mobility of polymer chains at higher temperatures, resulting in a decrease in shear forces. Consequently, the cleavage of molecular chains is hindered, preserving the overall molecular integrity of the polymer and, therefore, leading to a higher melt viscosity.<sup>19</sup> Due to polymer chain scission, the use of higher screw speeds or lower kneading temperatures could induce a decrease in  $G'$  and  $G''$  compared with neat PS. As a result, based on the findings, a kneading temperature of 180 °C was considered optimal at 50 rpm.

**3.4. Torque as a Function of Screw Speed and Temperature.** Torque measurements were used to investigate the reasons behind the reduced fluorescence intensity and high viscosity at higher temperatures (Figure 2). Torque measurement is a sensitive method for comparative and quantitative assessments of melt viscosity, molar mass, mechanical force, and stress to polymers in real-time during melt processing, particularly for detecting incipient degradation.<sup>26</sup> The relationship between torque and polymer chain scission involves the mechanical forces generated by screw rotation, which can induce the degradation of polymer materials. Torque was applied to study some insight into melting behavior due to polymer chain scission.<sup>27</sup> The mechanical stress from screw rotation can cleave chemical bonds within polymer chains, resulting in the formation of smaller fragments, altering the melt properties. This relationship is significant in applications where mechanical stress is applied to polymers.

In this study, the software embedded within the kneading machine simultaneously recorded both torque values and the temperature change of the melt polymer throughout each kneading process of the PS melt from the previously

mentioned experiment 3.2 under varying screw rotational speeds (at 150 °C) and kneading temperatures (at 50 rpm). As shown in Figure 4a, the torque is initially higher at higher



**Figure 4.** Torque recorded during the kneading process as a function of kneading time over 3 min at different (a) screw rotational speeds and (b) kneading temperatures. (c, d) Temperature of the PS melt.

screw rotational speeds. However, it gradually decreases as kneading progresses. This behavior was attributed to the increased load and subsequent heat generation associated with increased screw rotational speeds, as shown in Figure 4c. Under such conditions, PS experiences greater stress at higher screw rotational speeds than that at lower screw rotational speeds,<sup>28</sup> increasing the likelihood of polymer chain scission. Furthermore, the temperature of the PS melt increases as the screw rotational speed increases. The increase of the melt polymer temperature at 10, 50, 100, 150, and 200 rpm is approximately 0, 4, 11, 17, and 22 °C, respectively. At different kneading temperatures of 150, 160, 170, and 180 °C, the

temperature of the PS melt changes to approximately 4, 2, 1, and 0 °C, respectively. This indicates that higher screw speeds and lower kneading temperatures induce more heat generation due to higher shear rates. The torque values (Figure 4b) and the kneading temperature at 180 °C (Figure 4d) were constant

$$\tau = \eta \dot{\gamma} \dots \dots (1)$$

$$\dot{\gamma}_{max} = \frac{\pi(D - 2C_{t0})N}{C_{t0}}; (0 \leq \theta \leq \theta_i) \dots \dots (2)$$

$$\dot{\gamma}_{min} = \frac{\pi(D - 2C_{t0})N}{C_{t0}}; (\theta = 90^\circ) \dots \dots (3)$$

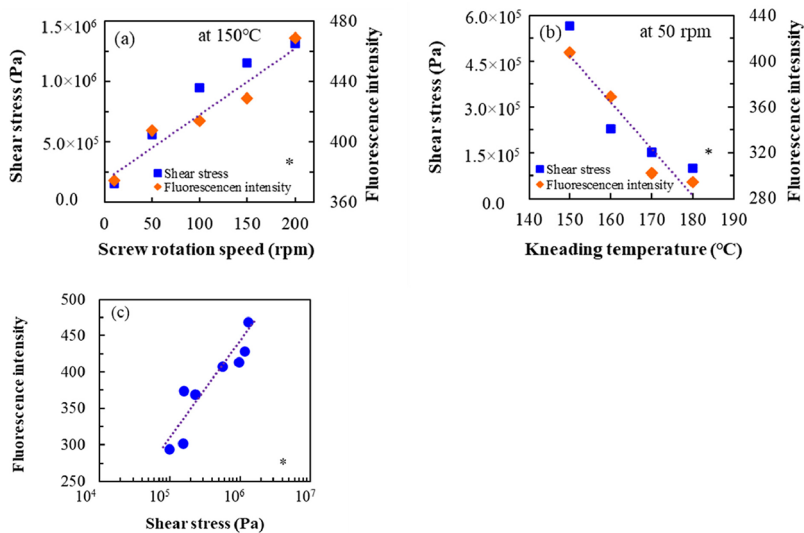
$$\dot{\gamma}_{avg} = \frac{\left[ \frac{\pi(D - 2C_{t0})N\theta_i}{C_{t0}} + \int_{\theta_i}^{\frac{\pi}{2}} \frac{\pi(D - 2C_{t0})N d\theta}{C_{t0}} \right]}{\frac{\pi}{2}}; (0 \leq \theta \leq 90^\circ) \dots \dots (4)$$

indicating no heat generated reflexing less shear stress than those of lower kneading temperatures.

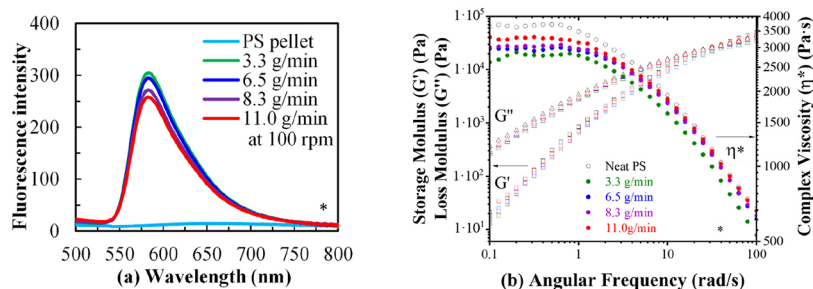
However, at lower screw rotational speeds—indicative of reduced load applied on the PS—the torque decreases with increasing kneading temperature. This observation aligns with the increased fluidity of the resin at higher kneading temperatures, leading to a decreased load on the resin. Consequently, it is presumed that polymer chain scission is less likely, consistent with the trends observed in Figures 2a and 3b.

Elevated torque within the kneading extruder can generate high shear stress on the polymer melt, increasing the likelihood of polymer chain scission, particularly for polymers sensitive to shear-induced degradation. Excessive torque and shear stress can induce chain scission, thereby reducing the molecular weight of the polymer and potentially affecting its properties.<sup>22</sup>

**3.5. Relationship between Shear stress and Fluorescence Intensity.** Elevated torque in the extruder increases the shear force and stress on the polymer melt. Thus, we elucidated the relationship between shear stress and fluorescence intensity. Shear stress was computed using Equation 1, and the average shear rate, as given in Eq (4),



**Figure 5.** Shear stress and fluorescence intensity at different (a) screw speeds and (b) kneading temperatures; (c) relationship between fluorescence intensity and shear stress. \* = Samples prepared by compression molding at 140 °C.



**Figure 6.** (a) Fluorescence intensity and (b) complex viscosity and of DAAN–triOMe/triOMe/PS measured at 210 °C from the samples kneaded at a constant screw rotational speed of 100 rpm and different feeding rates. \* = Samples prepared by compression molding at 140 °C.

was initially derived from Eqs (2) and (3) based on the screw type, as illustrated below:

Here,  $\tau$  is the shear stress,  $\eta$  is shear viscosity,  $\dot{\gamma}$  is the shear rate,  $D$  is the inner diameter of the cylinder,  $N$  is the screw rotational speed,  $C_{t0}$  is the minimum tip clearance, and  $C_{t\theta}$  is the minimum tip clearance at any angle.<sup>29</sup>

The effects of rotational speeds and their impact on shear rate were investigated at a kneading temperature of 150 °C. The results show that at a screw rotational speed of 10 rpm ( $\dot{\gamma}_{\min}$ ), the shear stress is approximately  $1.6 \times 10^5$  Pa. Conversely, at 200 rpm, it increases to approximately  $1.3 \times 10^6$  Pa ( $\dot{\gamma}_{\max}$ ), as demonstrated in Figure S3a. The determined shear rate and shear stress at various kneading temperatures but constant screw rotational speed of 50 rpm are given in Figure S3b. The obtained shear stress values at 150 and 180 °C are approximately  $5.6 \times 10^5$  and  $1.0 \times 10^5$  Pa, respectively. These findings underscore the significance of the effects of both screw rotational speed and kneading temperature on the shear rate and resin viscosity during kneading.

Figure 5c shows a notable correlation between shear stress and fluorescence intensity. This implies that the application of shear stress to the PS results in a discernible change in its fluorescence intensity. DAAN–triOMe/triOMe radicals in the PS matrix emit fluorescence in response to mechanical stress. Consequently, an increase in shear stress leads to a corresponding change in the fluorescence intensity of the PS.

With increasing applied shear stress, molecular chains of PS undergo cutting or scission. This indicates that higher shear stress causes mechanical deformation of the PS, leading to the breakage of the molecular chains.<sup>30</sup> The correlation between shear stress and fluorescence intensity can also aid the understanding of mechanical scission and molecular changes.

**3.6. Relationship between Feeding Rates and Fluorescence Intensity.** The negative correlation between feeding rate and residence time within an extruder is significant in polymer processing. A longer residence time may increase the shear and thermal degradation of the polymer, ultimately impacting material properties.

Figure 6 shows the effect of feeding rate on the duration of shear and heating during the processing of the material in the kneading extruder. At lower feeding rates, shear is applied for an extended period, leading to molecular chain scission. Conversely, with increasing feeding rate, as shown in Figure S4a, the polymer experiences shear for a shorter time, reducing the likelihood of molecular chain scission.<sup>31,32</sup> Consequently, Figure 6b exhibits a relatively higher fluorescence intensity at lower feeding rates, coinciding with the lower complex viscosity in Figure 6a. The impact of the feeding rate on the duration of shear plays a critical role in determining the extent

of molecular chain scission within the polymer during kneading. These findings significantly contribute to the understanding of polymer scission behavior and have implications for the optimization of kneading parameters to achieve desired material properties.

#### 4. CONCLUSIONS

This study has explored relations among heat, mechanical forces, and polymer chain scission using the mechanofluorescent probe in polymer processing. The effect of heat on polymers became evident through observable alterations in their properties and behavior at elevated temperatures. High temperatures induced increased fluidity, leading to either polymer chain scission due to the cleavage of chemical bonds and the generation of free radicals. Correlations between fluorescence intensity and various parameters were clarified. We found that higher screw rotational speeds enhanced fluorescence intensity because of intensified polymer chain breakage, as confirmed by a set of experimental data from complex viscosity, torque, shear stress, and fluorescence intensity measurements, all these results are related to each other. In contrast, suitable kneading temperatures were associated with reduced fluorescence owing to nonradical adduct formation. The mechanochromic behavior of DAAN–triOMe/triOMe under the effects of heating and shear resulted in the generation of mechanoradicals and fluorescence emission, providing insights into the effect of mechanical stress on polymer behavior. The relationship between shear stress, shear rate, and polymer scission revealed that higher shear stress corresponds to increased fluorescence intensity, reflecting polymer chain scission and deformation. Additionally, this study underscores the significance of residence time in the kneading extruder, where longer residence times promote the scission of molecular chains.

The insights obtained in this study are pivotal for optimizing polymer processing conditions. They will guide the selection of appropriate temperatures and shear rates, which are essential for achieving desired material properties. Furthermore, this study proposes a visual indicator of stress distribution and molecular chain scission, offering researchers a valuable tool for studying the mechanical behavior of polymers during deformation and flow. Additionally, the findings of this study contribute to the understanding of polymer chain scission, which is crucial for the development of advanced materials. Moreover, this study lays a strong foundation for further exploration of polymer behavior under different processing conditions. It facilitates advancements in the visualization of polymer scission and degradation, providing immense value in material science and engineering.



## ■ ASSOCIATED CONTENT

### SI Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acs.macromol.3c02182>.

Experimental procedures of visualization and characterization of polymer chain scission; thermogravimetric analysis (TGA) graph of DAAN degradation temperature; relationship of screw speeds and shear rates as well as shear rates and shear stresses at different temperatures; output volume of different feeding rates at 100 rpm and different screw rotational speeds at a constant feeding rate of 8.3 g/min, 3 min (PDF)

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### Notes

The authors declare no competing financial interest.

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## ■ ABBREVIATIONS

PS, polystyrene; DAAN–triOMe/triOMe, diarylacetonitrile derivative with six methoxy groups

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