engineering proceedings

Proceeding Paper

Evaluation of Residual Stress in Modified and Pure HDPE Materials Based on Thermal Diffusivity and Terahertz Phase Spectroscopy †

Pengfei Zhu [1], Hai Zhang [1,2,*], Carlo Santulli [3], Stefano Sfarra [1,4] and Xavier Maldague [1]

1 Computer Vision and Systems Laboratory (CVSL), Department of Electrical and Computer Engineering, Laval University, Québec, QC G1V 0A6, Canada; pengfei.zhu.1@ulaval.ca (P.Z.); stefano.sfarra@univaq.it (S.S.); xavier.maldague@gel.ulaval.ca (X.M.)
2 Centre for Composite Materials and Structures (CCMS), Harbin Institute of Technology, Harbin 150001, China
3 School of Science and Technology Geology Division (SST), Università degli Studi di Camerino, I-62032 Camerino, Italy; carlo.santulli@unibo.it
4 Department of Industrial and Information Engineering and Economics (DIIIE), University of L'Aquila (AQ), I-67100 L'Aquila, Italy
* Correspondence: hai.zhang.1@ulaval.ca
† Presented at the 17th International Workshop on Advanced Infrared Technology and Applications, Venice, Italy, 10–13 September 2023.

Abstract: Residual stress significantly affects the mechanical properties, physical properties, and durability of materials. It is meaningful to evaluate the residual stress using non-destructive methods. However, existing techniques are expensive and have low accuracy and narrow applicability. In this paper, both infrared and terahertz techniques were used to quantitatively evaluate the residual stress of high-density polyethylene (HDPE) under tensile loading. For the terahertz technique, a new theory based on stress-optics law and Poisson's effect is proposed. For the infrared technique, line-scan thermographic (LST) was used to extract the thermal diffusivity of HDPE. The residual stress caused by plastic deformation is quantitatively related to thermal diffusivity. Conclusively, THz-TDS shows an obvious improvement in residual stress detectability.

Keywords: terahertz; thermography; plastic deformation; residual stress; contactless

check for updates

Citation: Zhu, P.; Zhang, H.; Santulli, C.; Sfarra, S.; Maldague, X. Evaluation of Residual Stress in Modified and Pure HDPE Materials Based on Thermal Diffusivity and Terahertz Phase Spectroscopy. *Eng. Proc.* **2023**, *51*, 33. https://doi.org/10.3390/engproc2023051033

Academic Editors: Gianluca Cadelano, Giovanni Ferrarini and Davide Moroni

Published: 8 November 2023

1. Introduction

In recent years, the field of polymer materials science has witnessed significant advancements, coupled with a growing emphasis on recycling and sustainability. High-density polyethylene (HDPE) has emerged as a recyclable material, contributing to a greener approach and showcasing immense potential for structural building applications. Notably, HDPE demonstrates superior performance at lower temperatures, making it particularly suitable for various environmental conditions. However, the presence of residual stresses in HDPE can detrimentally impact its performance and even lead to the formation of defects within composite layers.

Traditional destructive methods used for residual stress detection pose challenges as they can introduce additional stresses and potentially reduce the overall component lifespan. Consequently, non-destructive methods have gained significant prominence in this field, assuming an increasingly vital role in accurately assessing residual stresses while preserving the integrity and longevity of HDPE components.

This paper aims to advance the measurement capabilities for assessing residual stress in HDPE by employing both infrared thermography and terahertz (THz) techniques. To enhance the efficiency of infrared thermography, a line-scan thermography (LST) method is employed. To quantify the residual stress, the Fourier transform and Laplace transform are utilized to extract the thermal diffusivity as a quantitative detection coefficient. Additionally, residual stress measurement is conducted using the THz time-domain spectroscopy (THz-TDS) method, which takes into account factors such as refractive index and sample thickness. Experimental validation is performed to assess and compare the feasibility of the proposed techniques. Ultimately, the developed approaches enable the quantitative analysis of residual stresses at different stages of damage utilizing THz-TDS and infrared thermography techniques.

2. Materials and Methods

2.1. Materials and Experimental Setup

The materials used in this paper were pure HDPE and modified HDPE with added 5% by weight of paper fiber and 5% by weight of chopped basalt. A mold was used to manufacture the specimens. The geometry of the samples is shown in Figure 1. Two pure HDPEs (the white samples) and two modified HDPEs (the gray samples) with 5% by weight of paper fiber and 5% by weight of chopped basalt were used in the experiments. The specimens were installed on the MTS® series 647 Hydraulic Wedge Grips tension machine (MTS systems, Torino, Italy). Each sample was clearly damaged during tensile tests.

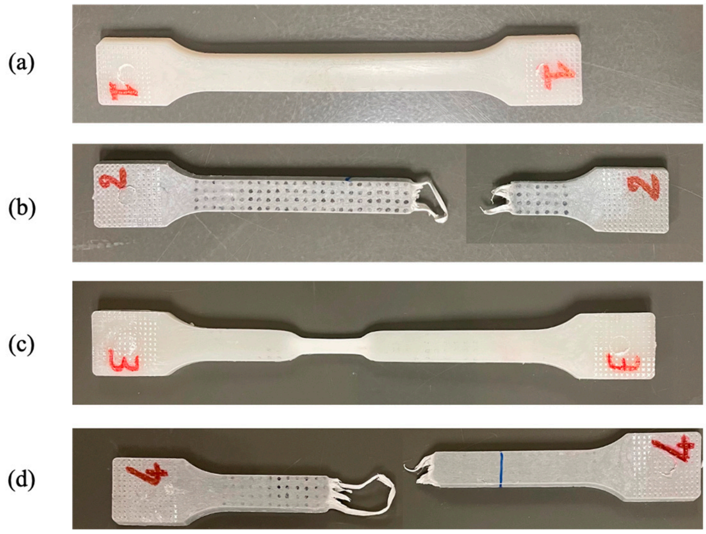


Figure 1. Specimens processed by tensile: (**a**) specimen 1 in plastic stage; (**b**) specimen 2 in fracture stage; (**c**) specimen 3 in necking stage; (**d**) specimen 4 in fracture stage.

Line-scan thermography and terahertz time-domain spectroscopy were used in this work. For infrared thermography, a line laser and a mid-wave infrared camera (640 × 512 pixels, 28 fps sampling rate) were utilized. The scanning speed is 10 mm/s. THz system was manufactured by Menlo Systems GmbH, Munich, Germany (1.2 GHz frequency resolution, 100 MHz repetition rate). The scanning step was set at 0.5 mm.

2.2. Thermal Diffusivity Measurement

For every pixel in LST, it can be considered subjected to a short pulse of energy distributed according to the function of pulsed thermography based on the dynamic-to-state data reconstruction technique [1]. Then, the Fourier transform is in the coordinates, and Laplace transform is in time. The heat conduction can be calculated [2]

$$\log\left(\frac{\theta(k_n,t)}{\theta(0,t)}\right) = c(k_n) - \alpha k_n^2 t \tag{1}$$

where $k_n = 2\pi n/(N \cdot \Delta x)$, n is an integer from 0 to $N-1$, N is the number of pixels in the temperature profile line, and Δx is the pixel dimension. From Equation (1), it is possible to find an interesting property that the thermal diffusivity can be obtained by the slope of the logarithm of the ratio of the Fourier transform of the surface temperature sequence to its zero-frequency component.

2.3. Stress Evaluation Based on THz Technique

According to stress-optic law, when a pressure or tension is applied to an object, the refractive index of the object changes. For uniaxial tensile, the phase difference caused by stress can be given as [3]

$$\Delta\delta_s = \frac{2\pi f d A \sigma_1}{c} \tag{2}$$

where f denotes frequency, d is specimen thickness, A is stress-optic constant, σ_1 denotes stress along tensile direction, and c is the light speed.

According to the Poisson effect, when the sample is applied to uniaxial tension or compression, the sample expands or contracts in the other two directions. The phase difference caused by the Poisson effect can be given as

$$\Delta\delta_d = -\frac{2\pi \mu d f N_0 \sigma_1}{cE} \tag{3}$$

where μ is the Poisson ratio, and E is the elastic modulus of the specimen. Considering the influence of the refractive index and the sample thickness, the relationship between the phase variation and the principal stress can be given as

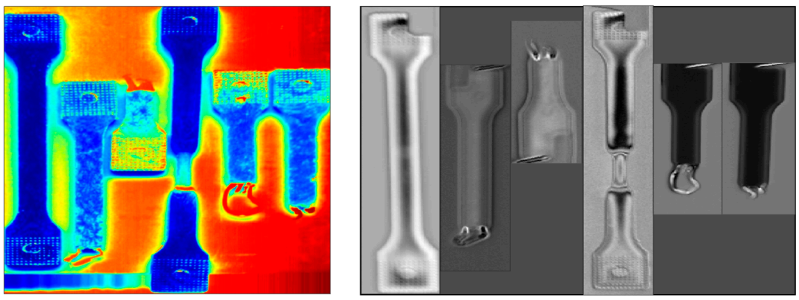
$$\Delta\delta = \Delta\delta_s + \Delta\delta_d = \frac{2\pi d f \sigma_1}{c}\left(A - \frac{\mu N_0}{E}\right) \tag{4}$$

Equation (4) shows that the phase difference is linear with the frequency when the stress is constant. Because the other coefficients are relevant to the material and, therefore, do not change, the line slope between phase difference and frequency is proportional to the stress.

3. Results and Discussion

3.1. Raw Data

The detection results of LST and THz-TDS are shown in Figure 2. For specimen 1, it is abnormal in the THz image and normal in the LST image. For specimens 2 and 4, there is high contrast in the fracture area. For specimen 3, the signal intensity of the neck area is larger than other areas. Furthermore, there is an obvious red color at the bottom of the neck area in LST.



(a) (b)

Figure 2. Detection results: (**a**) infrared thermography and (**b**) terahertz time-domain spectroscopy.

3.2. Residual Stress Measurement

Figure 3 shows the measurement results of residual stress for specimen 1 and specimen 3. There is an obviously higher residual stress in the middle area of specimen 1 using the THz technique, while LST cannot detect the residual stress. For specimen 3, the residual stress can be detected via both THz and LST techniques. In addition, the variance of residual stress in the region of interest is identical. Therefore, both THz and LST techniques can detect the residual stress. The THz technique has higher detectability.

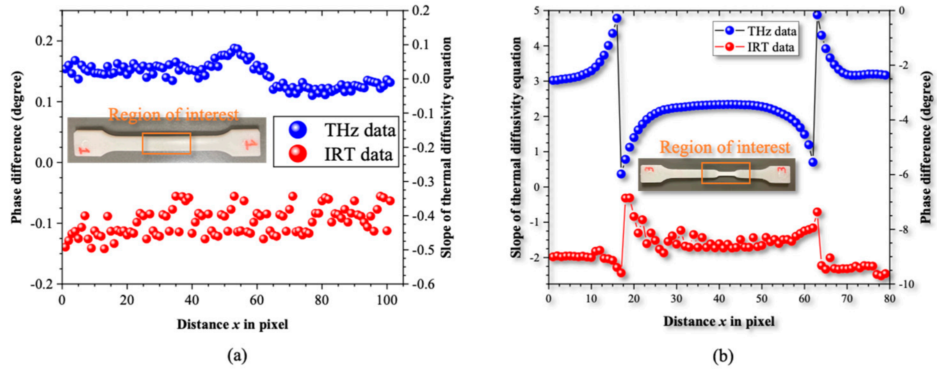


Figure 3. Residual stress measurement: (**a**) specimen 1 and (**b**) specimen 3.

4. Conclusions

The characterization of residual stress was performed in this work using the LST and THz-TDS techniques. The thermal diffusivity and the phase difference are quantitatively related to residual stress. Experimental validation was conducted to assess the effectiveness of our proposed methods in measuring residual stress in the HDPE specimens. Notably, the THz-TDS technique exhibited superior capabilities by detecting residual stress in the sample at the early plastic stage, where the unrecoverable strain was minimal. This highlights the broader detection scope of the THz-TDS technique in comparison to IRT. Subsequent stress measurement utilizing the aforementioned techniques showcased significant consistency in the neck area. Overall, the results obtained using the implemented techniques demonstrate the efficacy of both IRT and THz-TDS in detecting and quantifying residual stresses in HDPE.

Author Contributions: Data curation, P.Z.; investigation, P.Z., H.Z., C.S. and S.S.; writing—original draft preparation, P.Z.; writing—review and editing, H.Z., C.S. and S.S.; resources, C.S. and S.S.; supervision, H.Z. and X.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Natural Sciences and Engineering Research Council (NSERC) Canada through the Discovery and CREATE 'oN DuTy!' program as well as the Canada Research Chair in Multipolar Infrared Vision (MiViM). This research was also supported by the National Key Laboratory of Science and Technology on Advanced Composites in Special Environments through the Open-end Research Fund program (no. 6142905213301).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Oswald-Tranta, B.; Sorger, M. Scanning pulse phase thermography with line heating. *Quant. InfraRed Thermogr. J.* **2012**, *9*, 103–122. [CrossRef]
2. Bison, P.; Grinzato, E.; Marinetti, S. Local Thermal Diffusivity Measurement. *Quant. InfraRed Thermogr. J.* **2012**, *1*, 241–250. [CrossRef]
3. Song, W.; Li, L.; Wang, Z.; Wang, S.; He, M.; Han, J.; Cong, L.; Deng, Y. Experimental Verification of the Uniaxial Stress-Optic Law in the Terahertz Frequency regime. *Opt. Lasers Eng.* **2014**, *52*, 174–177. [CrossRef]