LASER-INDUCED THERMOELASTIC WAVE TECHNIQUE TO EVALUATE HYGROTHERMAL AGING IN CFRP COMPOSITES

МЕТОД ЛАЗЕРНО-ІНДУКОВАНИХ ТЕРМОПРУЖНИХ ХВИЛЬ ДЛЯ ОЦІНКИ ГІГРОТЕРМІЧНОГО СТАРІННЯ КОМПОЗИТІВ ІЗ ВУГЛЕПЛАСТИКУ

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The interaction of heat and moisture with fiberreinforced polymer composites over a long duration is known to cause physical and mechanical degradation. In this paper, an attempt was made to evaluate physical and mechanical changes in carbon fiber–reinforced polymer (CFRP) by an unconventional nondestructive approach before and after varied duration of exposures to hygrothermal (HT) treatment at an elevated temperature (80 °C/353 K) up to 800 h. As a novel approach, laser-induced thermoelastic waves were utilized for characterization of the material. Wave characteristics, such as wave amplitude and velocity of propagation, were studied over different duration exposures of HT treatment to detect and quantify HT-induced property changes in the material. Results show that the aging effect attenuated the wave to a factor of 2.75 and significantly reduced the velocity of wave propagation by 20% compared to that of the pristine material, revealing the degradation in the material caused by HT exposure. The proposed methodology has the potential to monitor the health of fiber-reinforced polymer composite structures that have undergone hygrothermal aging.

Відомо, що взаємодія тепла та вологи з полімерними композитами, армованими волокном протягом тривалого часу, викликає фізичну та механічну деградацію. У цій статті було зроблено спробу оцінити фізичні та механічні зміни в полімері, армованому вуглецевим волокном (CFRP), за допомогою нетрадиційного неруйнівного підходу до та після різної тривалості впливу гігротермічної (ГТ) обробки при підвищеній температурі (80 °C / 353 K) до 800 год. В якості нового підходу термопружні хвилі, індуковані лазером, були використані для визначення характеристик матеріалу. Характеристики хвиль, такі, як амплітуда та швидкість поширення хвилі, були вивчені протягом різних тривалостей впливу гігротермічної (ГТ) обробки для визначення та кількісної оцінки змін властивостей матеріалу, викликаних ГТ. Результати показують, що ефект старіння послабив хвилю в 2,75 рази і значно знизив швидкість поширення хвилі на 20 % порівняно з вихідним матеріалом, виявивши деградацію матеріалу, спричинену впливом ГТ обробки. Запропонована методологія має потенціал для моніторингу стану армованих волокном полімерних композитних конструкцій, що зазнали гігротермічного старіння.

KEYWORDS: hygrothermal aging, thermoelastic waves, carbon polymer composite, CFRP

Ключові слова: гігротермічне старіння, термопружні хвилі, вуглецево-полімерний композит, вуглепластик

Introduction

Advanced composites are increasingly being used for structural applications of aerospace components. Carbon fiber– reinforced polymer (CFRP), an ultra-lightweight structural material, is widely used in the aircraft industry for its excellent engineering properties, mechanical durability, low density, and temperature and chemical resistivity. During flight, aircraft undergo rigorous fluctuations in temperature and moisture exposure, which lead to a gradual degradation of the components over a long period. This gradual degradation is known as hygrothermal (HT) aging. It induces gradual and permanent changes in composites. It can lead to water-polymer interaction, which results in swelling, subsequently altering the molecular structure along with the plasticization of polymer resin (Nogueira et al. 2001; Moy et al. 1980; Zhou and Lucas 1999; Xiao et al. 1997; Xiao and Shanahan 1998). This, in turn, deteriorates the material in terms of its engineering properties. The literature also shows that the glass-transition temperature of the material is altered by HT aging, limiting the working temperature of the material. Researchers have observed that the water absorption behavior of carbon-epoxy composite follows a Fickian law, and the rate to saturation increases with the relative humidity and temperature (Korkees et al. 2018). Consequently, a drop in mechanical properties occurs due to HT aging (Cysne Barbosa et al. 2017; Sun et al. 2011).

In the aviation industries, a periodic maintenance check of aircraft structural components is performed after a certain number of flying hours. This consumes enormous amounts of time, money, and effort. Nondestructive testing (NDT) techniques in this regard can be an effective tool to detect and track the health of aged structural components. In this regard, the acoustic wave propagation parameters of the material are capable of real-time health monitoring over the whole structure. Wave propagation characteristics are strongly related to the elastic and microstructural properties of a material (Choi et al. 2018; Angulo et al. 2017; Gagar et al. 2014). Thus, slight variations in material properties caused by the aging process lead to an alteration in the wave propagation characteristics (Katunin et al. 2015; Park et al. 2014; Mouritz et al. 2000; Park et al. 2008). It was shown that the ultrasound technique shows effectiveness in evaluating aging in composite material (El Guerjouma et al. 2001). Hong and others showed the effectiveness of ultrasound wave propagation to evaluate HT aging (Hong et al. 1995). Also, the literature shows the potential ability of guided waves for successful detection and evaluation of defects/damage and progressive damages in composite structures. The symbolic time series analysis has shown a great potential in detecting barely visible indentation damages (Mustapha et al. 2016; Fakih et al. 2017).

Unconventional Thermoelastic Wave Generation in Polymer Composites. In this study, a novel approach was adopted for the generation of acoustic waves in CFRP material. Acoustic waves can be generated in composite material using a focused high-power laser beam of constant energy, which induces thermoelastic waves, which propagate in the material. The thermoelastic phenomenon is the result of the absorption of laser energy into the surface layer of the material, which results in a localized temperature increase. By setting suitable pulse energy parameters, the surface layer can be excited. This excitation of the layer results in the generation of acoustic waves. These waves are basically stress waves that are born due to the coupling between temperature and strain rate in a material. Due to the material's thermal conductivity, this heat travels through the media, generating heat waves. These heat waves create compression and rarefaction, which result in thermoelastic waves (Wang and Xu 2001; Lyamshev 1981).

Experimental Details

Fabrication of CFRP. A CFRP laminate was fabricated using bidirectional carbon fabric as the reinforcement and thermoset epoxy resin Araldite LY5052 as the matrix with a lay-up sequence of $[(0/90)_2(45)_2(0/90)_2]_s$. The schematic for laminate fabrication is shown in Figure 1. The laminate was cured at room temperature using the vacuum bagging fabrication process.

A plate thickness of 2.718 mm with a standard deviation of 0.042 mm was obtained. The laminate was cut to a size of 280 × 280 mm to fit in the hot water bath tank. The sensor positions were marked with circles. The schematic of the specimen is shown in Figure 4.

Accelerated Hygrothermal Aging To induce and accelerate the aging in CFRP, the laminate was kept in a hot water bath for HT treatment at the elevated temperature of 80 °C (353 K) for different durations up to 800 h.

The acoustic parameters were measured before HT and at time intervals of 24, 48, 72, 144, and finally at 792 h of HT treatment. A uniform temperature was maintained for the entire duration of the treatment. Moisture absorption was measured by the increase in the mass of the laminate. Mass measurements were taken nearest to the 0.0001 g. Figure 2 shows the plot of moisture absorption (m_t) against the duration of HT treatment. Initially, a rapid gain in moisture absorption was observed, and it tended to saturate as the treatment was prolonged.

Flexural Strength Tests. To evaluate the mechanical degradation occurring in the CFRP, three-point bending tests were performed at the end of each stage of HT treatment. A schematic of the setup is shown in Figure 3. Tests were performed as per ASTM D2344 M (ASTM 2016) using a universal testing machine of 25 kN capacity. The standard span-to-thickness ratio of 32:1 was adopted. The specimen length and width adopted were 120 mm and 13 mm, respectively.

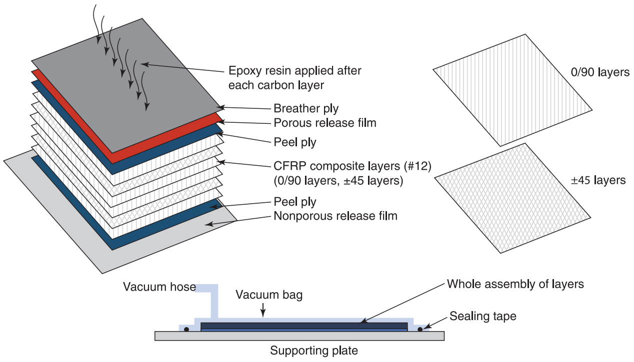

Figure 1. A schematic of composite laminate fabrication using the vacuum bagging technique.

Рис. 1. Схема виготовлення композитного ламінату з використанням методу вакуумного пакування

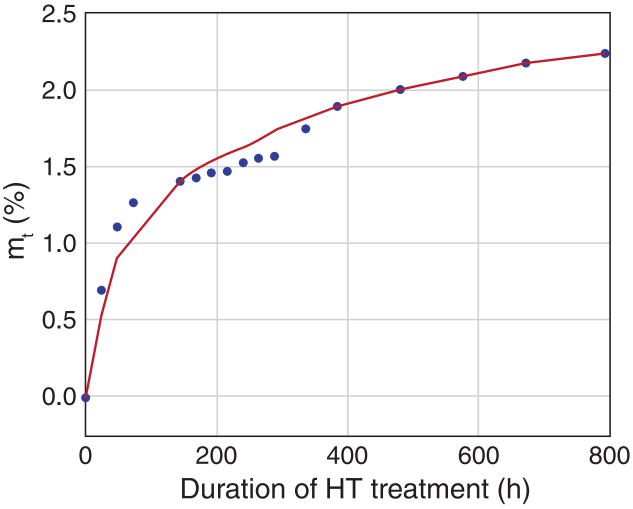

Figure 2. The moisture absorption (m_t) in the CFRP specimen for different durations of hygrothermal (HT) treatment.

Рис. 2. Поглинання вологи (mt) у зразку вуглепластику для різної тривалості гігротермічної (ГТ) обробки

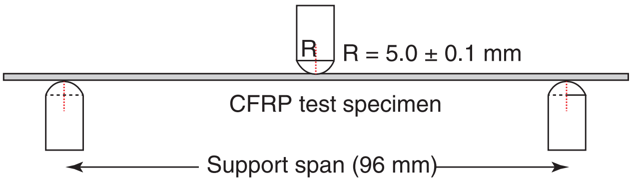

Figure 3. A schematic of the three-point-bending test.
Рис. 3. Схема випробування на триточковий вигин

The test results show the effect of HT aging on the flexural properties of CFRP (Figure 4). Overall changes in flexural modulus (E) and ultimate strength (σ_u) as a function of the duration of HT treatment were obtained and presented. It can be observed that both of these properties of composite specimens degraded considerably due to the HT treatment. The loss of ultimate strength of the specimens. The modulus was reduced by 7%, whereas the reduction in strength was found to be 26%. Also, the stiffness degradation in composite specimens was further correlated with the acoustic wave parameters obtained nondestructively.

Thermoelastic Wave Technique. In this study, the thermoelastic generation of acoustic waves by focused high-energy short-pulsed laser radiation on a composite laminate was experimentally demonstrated and its potential in evaluating the aged health of composite materials was investigated. External laser pulses (l = 1064 nm) were irradiated over the laminate surface at a normal angle. The laser energy interacted with the laminate surface, which induced rapid localized heating, and thermoelastic expansion (that is, a high strain rate and thus emission of acoustic waves). The laser energy delivered per shot was 150 mJ with a pulse duration of 10 ns and over 8 mm of beam diameter with a wavelength of 1064 nm. The resulting parameters of the waves were studied by the acoustic emission transducers.

Those were plugged over the laser irradiated side of the laminate surface using vacuum grease. The schematic of the acoustic wave propagation and positioning of the sensors is shown in Figure 5. As for the acoustic waves, attenuation is governed by the following equation: reduction in stiffness was relatively lower as compared to the

$$A_1=A_2e^{-\alpha x} \qquad (1)$$

where A_1 is the amplitude of the wave signal at the location of sensor 1, A_2 is the amplitude of the wave signal at the location of sensor 2, x is the distance between the sensors, and a is the acoustic attenuation coefficient for the composite material.

Two acoustic emission transducers (sensor 1 and sensor 2) were placed diagonally with 148 mm be-

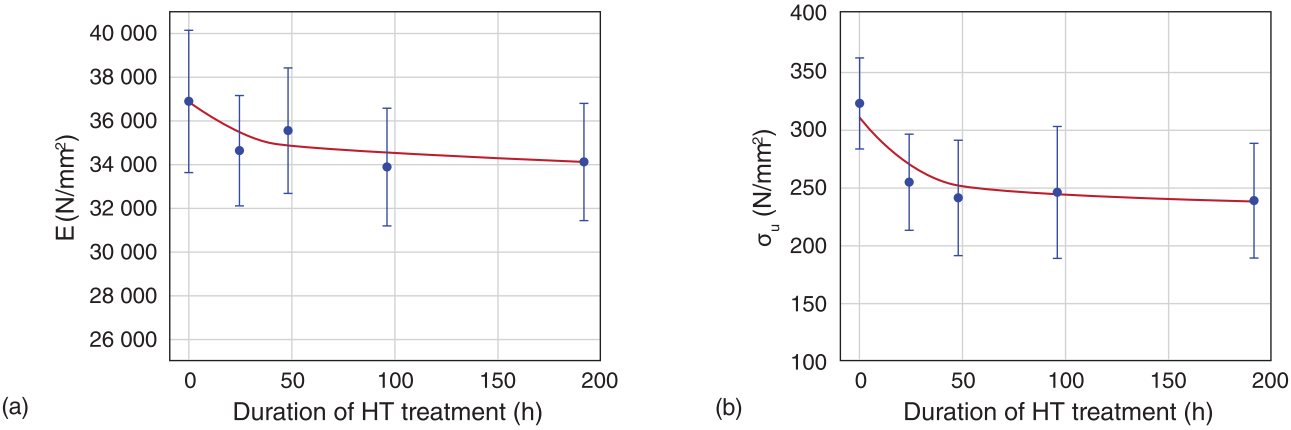

Figure 4. Plots showing mechanical degradation in CFRP with respect to the duration of HT treatment: (a) elastic modulus (E); (b) ultimate strength (σ_u).
Рис. 4. Графіки, що показують механічне руйнування у залежно від тривалості ГТ обробки: (а) модуль пружності (E); (б) межа міцності (σ_u)

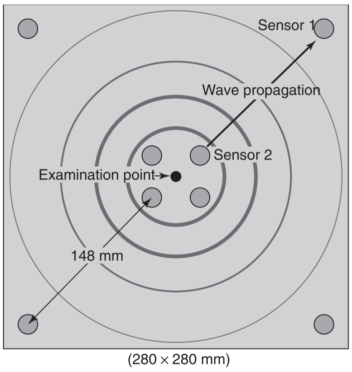

Figure 5. A schematic of wave propagation in the CFRP specimen along with the positions of the sensors.
Рис. 5. Схема поширення хвилі у зразку вуглепластику разом із положеннями датчиків

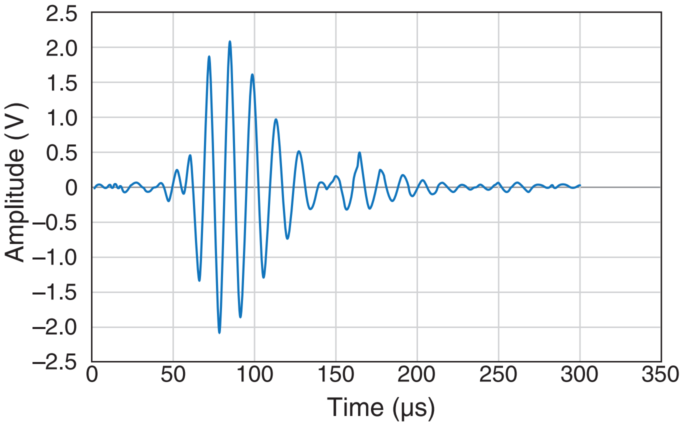

Figure 6. A typical ultrasound signal.
Рис. 6. Типовий ультразвуковий сигнал

tween them to receive the generated thermoelastic waves as shown in Figure 5. A typical ultrasound signal is shown in Figure 6. The signal amplitudes (A_1 and A_2) detected at sensor 1 and sensor 2 and the time taken by the signal to travel from sensor 1 to sensor 2 (dT) were recorded. Knowing the amplitudes measured by these sensors at their respective diagonals and the distance between them, the acoustic attenuation coefficient (a) was evaluated at each stage of HT treatment using Equation 1. Also, knowing the dT values and distance between the sensors, the wave velocity (V) was obtained using Equation 2, where x is 148 mm (distance between the sensors):

$$V = \frac{x}{dT} \qquad (2)$$

through the material, its elastic and kinetic energies were absorbed and converted into heat. The HT aging in the specimen

Evaluation of Hygrothermal Aging using Wave Attenuation. The effect of HT treatment on the thermoelastic acoustic wave attenuation coefficient was found. Figure 7 presents a plot of the attenuation coefficient against the duration of the HT treatment in the CFRP specimens. This coefficient was calculated by the attenuation law using Equation 1 between the positions of sensor 1 and sensor 2. The coefficient has shown a considerable increase in the coefficient as the HT treatment was prolonged. This trend approximately follows a parabolic variation with respect to the extent of aging.

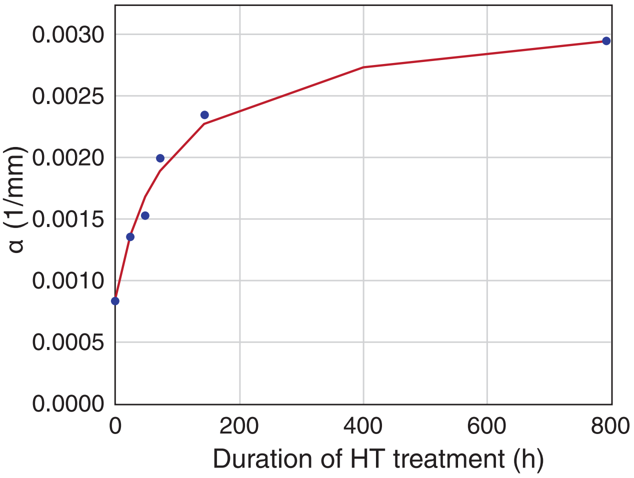

Figure 7. The effect of hygrothermal (HT) treatment on wave attenuation coefficient (a) in the CFRP specimen.

Рис. 7. Вплив гігротермічної (ГТ) обробки на коефіцієнт згасання хвилі (α) у зразку вуглепластику

A gain in the attenuation coefficient indicated an increase in the damping properties of the CFRP composite material due to the HT treatment. While the thermoelastic wave passed resulted in altering the damping and impedance properties of the CFRP composite material, which resulted in more attenuation.

To predict the mechanical degradation in CFRP using nondestructive parameters, a correlation between elastic modulus and ultimate strength with the attenuation coefficient was established. The correlation is shown in Figure 8. Both of the mechanical properties of the material show a decreasing trend with respect to the attenuation coefficient obtained. Further, by generating a rigorous database, a strong relationship can be obtained. As this coefficient was evaluated using a nondestructive approach, this methodology can be an effective tool in estimating the mechanical degradation in CFRP composite materials.

Evaluation of Hygrothermal Aging Using Wave Velocity. An attempt was made to evaluate the effect of HT aging on the velocity of acoustic wave propagation through this nondestructive approach. The time taken (dT) by the waves to travel from the position of sensor 1 to sensor 2 (averaged over four diagonals) was recorded at each stage of HT treatment. An increase in the time taken by the wave to travel the distance of 148 mm was observed. Using Equation 2, the wave velocity was determined, and its trend with the duration of HT treatment is demonstrated in Figure 9. A consistent decrease in the trend was observed. Overall, an approximate 20% decrease

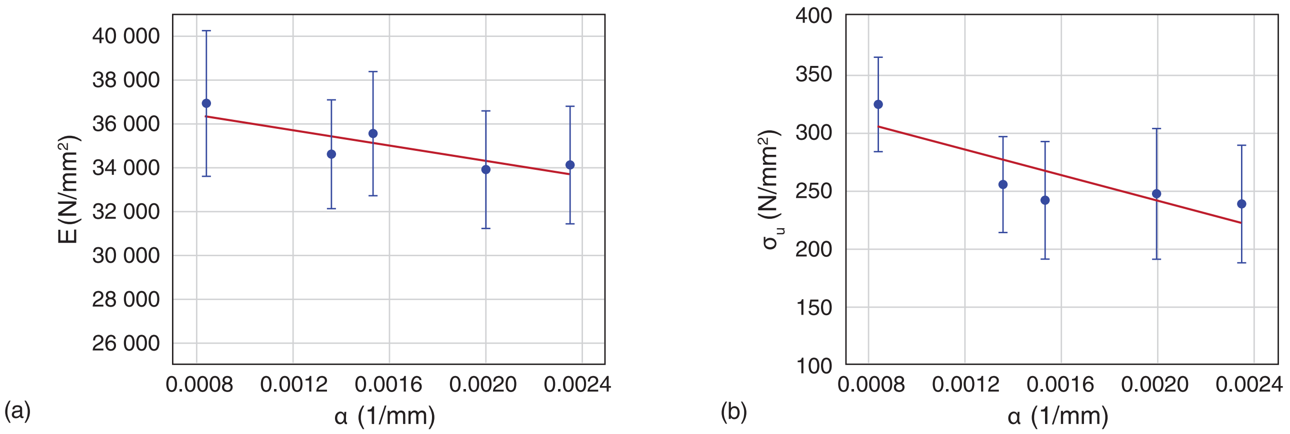

Figure 8. The correlation between mechanical parameters and attenuation coefficient (a) of CFRP: (a) elastic modulus (E); (b) ultimate strength (σ_u).

Рис. 8. Кореляція між механічними параметрами та коефіцієнтом згасання (α) вуглепластику: (а) модуль пружності (E); (б) межа міцності (σ_u)

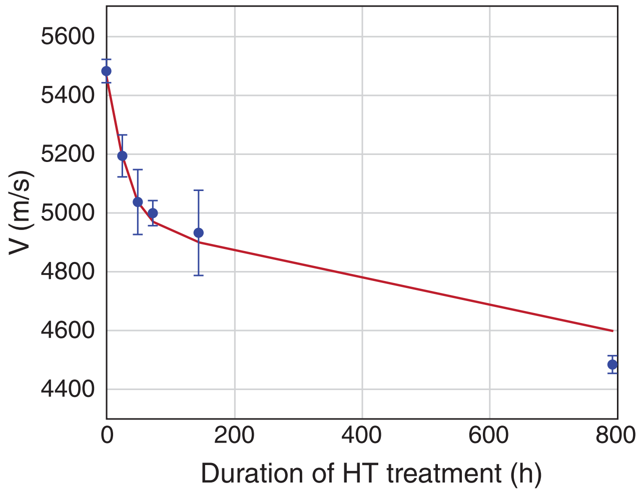

Figure 9. The effect of hygrothermal (HT) treatment on the velocity of thermoelastic wave propagation (V).

Рис. 9. Вплив гігротермічної (ГТ) обробки на швидкість поширення термопружних хвиль (V)

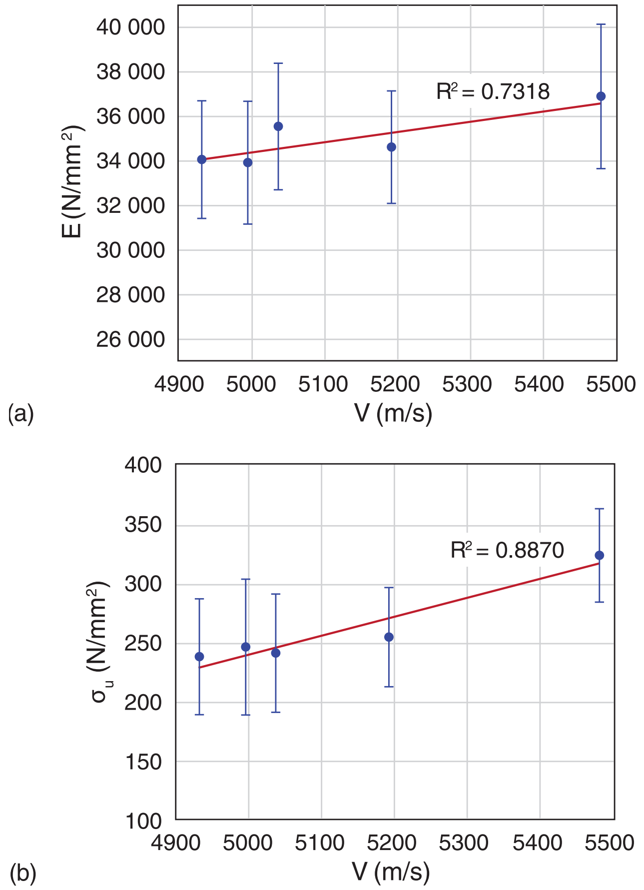

Figure 10. The correlation between mechanical parameters of CFRP and thermoelastic wave velocity (V): (a) elastic modulus (E); (b) ultimate strength (σ_u).

Рис. 10. Кореляція між механічними параметрами вуглепластику та швидкістю термопружної хвилі (V): (а) модуль пружності (E); (б) межа міцності (σ_u)

in the velocity of wave propagation was found over 800 h of the treatment. The rate of velocity decrement was found to decrease as the aging prolonged. As the aging resulted in lowering the elastic properties of CFRP, a decrease in the wave velocity was expected and the same is observed in Figure 9.

Further, a correlation of the elastic modulus and ultimate strength of CFRP with acoustic wave velocity was obtained. Figure 10 presents the trend of the mechanical properties withthe velocity of wave propagation. Both of the properties show an increasing trend with respect to the wave velocity obtained. This indicates that the reduction in the velocity of propagation signifies a decrease in the health of the material. A straight-line fit goes fairly well with the data. With a rigorous database, a strong correlation can be made to evaluate the aged health of CFRP just by analyzing the wave parameters through this nondestructive approach.

Conclusion

An unconventional and unique NDT approach was presented through this study. Through the experiments, HT aging has shown a significant effect on the thermoelastic wave propagation characteristics in CFRP laminates. The aging was characterized on the basis of two thermoelastic wave parameters: wave amplitude and wave velocity. The attenuation, evaluated through wave amplitude, and wave velocity have shown significant changes as a result of aging. Thus, a gain in the attenuation coefficient and a decrease in the wave velocity can be effective parameters for monitoring the aging of this type of structure, as these have been correlated with mechanical properties of CFRP. This technique has the advantage of being a noncontact simulation of waves, which can be further developed into an effective health monitoring tool to form a strong relationship between the thermoelastic properties of CFRP and the extent of degradation due to HT aging. Hence, by listening to the sound, the aged health of CFRP composite material can be effectively evaluated through this novel and unconventional NDT technique.

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08.02 – 11.02 Wels, Austria	iCT - 11th Conference on Industrial Computed Tomography 2022	FHOÖ
15.03 – 17.03 Erfurt, Germany	Fachtagung ZfP im Eisenbahnwesen	DGZfP
05.04 – 07.04 Київ, Україна	XIV Міжнародна спеціалізована виставка «Київський технічний ярмарок»	Міжнародний виставковий центр
24.04 – 27.04 Florence, Italy	Analysing Art 2022: New Technologies – New Applications	BINDT
03.05 – 06.05 Stuttgart, Germany	Control 2022	Schall Messen
11.05 – 12.05 Київ, Україна	Конференція і виставка «Неруйнівний Контроль-2022»	Асоціація «ОКО»
30.05 – 01.06 Київ, Україна	VI Міжнародна конференція «Титан 2022: Виробництво та застосування»	ІЕЗ ім. Є.О. Патона НАНУ, МАС
30.05 – 03.06 Incheon, Korea – postponed	20th World Conference on Non-Destructive Testing (WCNDT 2020)	KSNT
04.07 – 07.07 Palermo, Italy	10th European Workshop on Structural Health Monitoring	
10.07 – 15.07 Berlin, Germany	26th International Conference on Structural Mechanics in Reactor Technology	iASMiRT, DGZfP, TÜV NORD, swissnuclear, TU Kaiserslautern

Початок. Продовження дивись на стор. 57