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Researches on the Ultrasonic Scattering Attenuation of Carbon Fibre Reinforced Plastics with 2D Real Morphology Void Model[1]

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Abstract—In order to investigate the ultrasonic propagation in carbon fibre reinforced plastics with complex void morphology, the effective mathematical model needs to be established. The current models are oversimplified on void morphology, leading to the significant inconsistency of theoretical calculation with experimental results. In view of the problem, a real morphology void model (RMVM) was established with the idea of image-based modeling. The void morphology was extracted by digital image processing technology, and the material properties were assigned subsequently. As a result of the complex and random void morphology in RMVMs, a non-unique corresponding relationship was verified between porosity P and ultrasonic attenuation coefficient α. In the scatterplot of simulation, about 66 percent of points were plotted within the ±10% error band of fitting line, while almost all the data located at the ±20% error zone. The simulation results showed good consistency with experiments, and it proved the validity of RMVM. The investigation provides a novel model to explore the ultrasonic scattering mechanism for the composite materials containing random voids.

Keywords: carbon fibre reinforced plastics, real morphology void model, porosity, ultrasonic attenuation coefficient, non-unique corresponding relationship

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1. INTRODUCTION

Ultrasonic attenuation coefficient is frequently used to evaluate the porosity of carbon fibre reinforced plastics (CFRP) in ultrasonic nondestructive testing, and the fluctuation of coefficient is mainly attributed to the ultrasonic scattering from voids. In order to clarify ultrasonic scattering mechanism, Martin [1] in 1970s firstly presented a theoretical derivation for the relationship of ultrasonic attenuation to void diameter. The voids in model were assumed to be spheres with uniform size and regular distribution, and the ultrasonic scattering was independent of the void shape, etc. On this basis, Hale and Ashton [2] proposed a model with spherical and disc voids obeying the uniform or exponential size distribution, in which the voids exceeding 1.5% porosity were changed to be discs. Then, Hsu [3] developed a modified model of long cylindrical voids with elliptical cross-sections, and related the slope of attenuation coefficient *vs*. frequency to the porosity. The above models can be named as "definite model" for the voids with the hypothesis of fixed shape, regular size distribution and location. The theoretical calculation results of attenuation coefficients only coincided with measurements at low porosity or frequency [1–3]. The important reason was to neglect the randomness and complexity of real voids. Hsu [4] observed the void morphology, not only the three-dimensional shape and size of individual voids, but also the distribution and orientation in multiply laminated composite. The results confirmed the voids mostly occurred at the ply interfaces and elongated along the adjacent fibre direction as long as decade millimeters. The maximum height of voids was about 100 μm, and the width could be up to about 1 mm. Furthermore, the random void morphology caused the fluctuation of elastic and mechanical properties of composite materials with the same porosity [5–7].

Based on random medium theory and statistical principle, Lin [8, 9] proposed a random void model (RVM) to investigate ultrasonic scattering mechanism for CFRP with complex void morphology. Compared with definite models, the RVM could accurately describe random morphological characteristics of voids and flexibly capture the variation of ultrasonic attenuation coefficients affected by void morphology [10, 11]. However, the void morphology in RVM obtained from statistical data was still different from the real voids in composites [12], and the deviation of calculation results from experimental data increased with porosity.

A real morphology void model (RMVM) was established with the idea of image-based modeling [13]. Using digital image processing technology, the void morphology was directly extracted from a great

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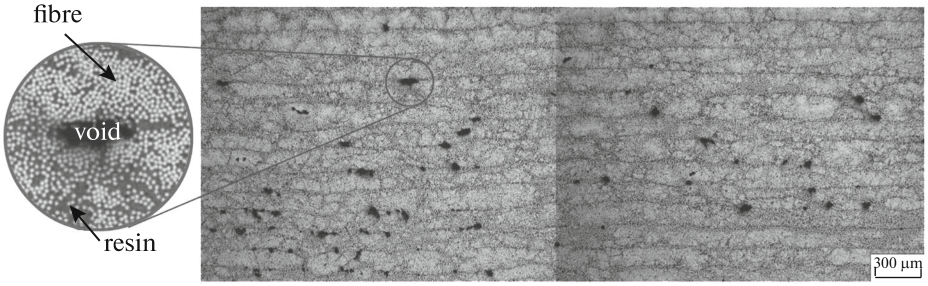

Fig. 1. Typical micrograph of CFRP containing voids.

deal of CFRP micrographs with porosity of 0.58–3.49%. Furthermore, the correlation between porosity P and ultrasonic attenuation coefficient α could be acquired by numerical calculation with RMVMs, and the model validity was proved by experiments.

2. PRINCIPLE

The ultrasonic attenuation of composite materials containing voids mainly originates from the viscoelastic properties of resin and the scattering caused by voids and fibres. For different porosities, the energy loss from resin and fibres can be seen as a constant, so only the scattering attenuation caused by voids is concerned in the detection of porosity.

According to the normalization wavenumber $ka = 2\pi a/\lambda$ (where λ is the wavelength of incident wave, and a is the mean size of scatters), ultrasonic scattering mechanism is usually treated as the following three cases [14–17]:

(1) Rayleigh scattering ($ka \ll 1$): $\alpha_s = C_1a^3\lambda^{-4}$;

(2) stochastic scattering ($ka \approx 1$): $\alpha_s = C_2a\lambda^{-2}$;

(3) diffusion scattering ($ka \gg 1$): $\alpha_s = C_3a^{-1}$;

where α_s is the ultrasonic scattering attenuation coefficient; C_1, C_2 and C_3 are the constants related to elastic parameters and material density.

The above mechanism is the general expression for single scattering caused by spherical particle in elastic matrix. For the heterogeneous medium, the scattering has different frequency dependence in various directions [18, 19], and high-order scattering waves will be occurred by the nearby scatterers [20]. Under the low distribution density (the volume fraction is less than 1%), the multiple scattering between scatterers can be ignored [21]. When the volume fraction of scatterers is enhanced, the effect of multiple scattering has to be considered [22].

For typical CFRP laminates containing voids, the void widths fall within micrometer to millimeter range [4], so the multi-scale heterogeneity must be taken into account in ultrasonic scattering theory. Under the detection frequency 0.5–10 MHz, the ultrasonic wavelength is about ~300–6000 μm when the longitudinal wave velocity is 3000 m/s in CFRP. Considering the ratio of wavelength to void size, Rayleigh scattering and stochastic scattering are probably referred to CFRP containing voids at the same time. Moreover, due to the randomness of shape and position of voids, the multiple scattering of voids is hard to be predicted. The precise calculation of ultrasonic scattering attenuation is difficult to be obtained directly with analytical method in composite materials.

3. REAL MORPHOLOGY VOID MODEL

3.1. Acquisition of Micrographs

A series of 16-layered press molding unidirectional CFRP laminates were prepared by hand paste molding craft, whose thickness and fibre content were 2 ± 0.05 mm and 69 ± 3%, respectively. The CFRP laminates were scanned using ultrasonic C-scan system with a focusing immersion probe (5 MHz center frequency, 13 mm diameter). According to the amplitudes of ultrasonic echoes, some uniform regions with 6 mm diameter were selected as test areas. The ultrasonic attenuation coefficients were calculated with the method mentioned in reference [23].

After being cut and embedded, the cross-section of metallographic specimens from test areas were prepared for grinding and polishing. Finally, as shown in Fig. 1, 441 micrographs were shot for establishing RMVMs.

3.2. Pretreatment of Micrographs

The original CFRP micrographs included voids, fibres and resin, in which the voids were mainly concerned in the following research. An image processing and recognition technology, namely binarization processing, was applied to extract the gray region representing voids. However, the binarization processing easily led to the presence of incompletely filled voids and non-void noises in original micrographs (as shown in Fig. 2).

In order to eliminate the influence of noise on the extracted void morphology, the median filtering method was used to smooth original CFRP micrographs [24]. Three gray distributions given in Fig. 3 were extracted from images filtered with different sizes of window. The fluctuation of gray level decreased with the increase of window size, which was to say that the filtering effect was more and more obvious. Finally, the filtering processing with 15 × 15 window