Porosity Estimation of Composites Using Acoustic Attenuation

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Keywords: composite, ultrasonic nondestructive testing, porosity, acoustic attenuation.

Abstract. Ultrasonic techniques for measuring void content were discussed and the composites used for the whole fuselage composite aircraft AG300 were chosen as experimental specimens, including 10 unidirectional carbon fiber laminates and 10 textile glass fiber sheets. The ultrasonic RF signals were processed using Hilbert transform and spectral-filter and then used to calculate the acoustic attenuation. The relationship between attenuation coefficient and porosity was calibrated by sampling experiment based on metalloscope. The calibrated formula was then used to estimate the porosity of the rest specimens. The results indicate that the porosity values estimated by the calibrated formula are in good agreement with the values determined by metalloscope.

Introduction

As composites have the advantages of light weight, high specific strength and stiffness, outstanding designability and etc., they are widely used today especially in aviation industry. For example, the proportion of composites in advanced airliner A380, A787 and A350 can be up to 25%, 50% and 53% respectively, and composite content in the fourth-generation fighter of China could reach 30%. The specifically what I want to say is that the whole fuselage composite aircraft AG300 independently developed by AVIGENERAL Aircraft Industry contains more than 85% composites.

With the development of general aircraft industry and the wide application of composites, people give more attention to the quality inspection. Because of the unique production processes of composite, there are inevitably various flaws within the material, such as voids, porous, layers, inclusions and so on. Voids are the most common flaws in composite and will decrease mechanical property and reliability seriously. Studies[1, 2] indicate that while in the range of 0 to 4% the porosity increases every 1% will lead to decline 5~15% in interlaminar shear strength and will also degrade performance of tensile strength, bending strength and compressive strength. People want to find effective methods to estimate porosity in composites, including destructive testing methods and non-destructive testing (NDT) technologies. Ultrasonic testing (UT) such as acoustic attenuation, sound velocity or acoustic impedance is a special and effective NDT method[2~5]. In this study, the use of ultrasonic techniques for measuring void content was discussed and the experimental data showed that the ultrasound testing results were in agreement with the metallographic detection.

Methods

In 1975, the British scholars Stone and Clarke studied the ultrasonic attenuation in carbon fiber reinforced plastics[2] and presented a relationship between acoustic attenuation coefficient α and the porosity P_V as follows:

$$\begin{cases} \alpha = 0.0794 f^{1.27} P_V{}^2 & (P_V < 1.5\%) \\ \alpha = 0.87 f^{1.55} P_V{}^2 & (P_V \geq 1.5\%) \end{cases} \tag{1}$$

where f represents the ultrasonic frequency. Stone and Clarke's study is regarded as a classic formula up to now and has been quoted once and again. In 1976, Martin took Stone's study as lessons and presented a new attenuation model[3] by equation (2) where a, λ and g represents void size, ultrasound wavelength and a parameter related to ultrasonic velocity in composites, respectively.

$$\alpha = \frac{8\pi^4}{3}\frac{ga^3}{\lambda^4}P_V \tag{2}$$

However, Martin's somewhat idealized model will induce large errors in the condition of high porosity. In 1988, Hale and Ashton suggested a method by comprehensively considering the shape, size and distribution of voids[4] and the formula is shown as follows where A is a constant related to material characteristics, R and r represents the largest and smallest void radius respectively. Hale's model is difficult for practical application as the void size is unknown in most cases.

$$\alpha = Af^4 P_V\left(1-P_V\right)^2 \frac{4}{7}\frac{\left(R^7-r^7\right)}{\left(R^4-r^4\right)} \tag{3}$$

A new interesting idea was proposed recently that the acoustic attenuation coefficient α_P caused by voids was a porosity-related function[5] :

$$\alpha_P = C_0 + C_1 P_V + C_2 P_V^{\,2} \tag{4}$$

where C_0, C_1 and C_2 are parameters related to material characteristics. When Given the ultrasound frequency in ultrasonic testing, the parameters will be constants in same batch and same type of composite. In this experimental study the novel model was investigated. The frame work of this study is shown in Fig.1.

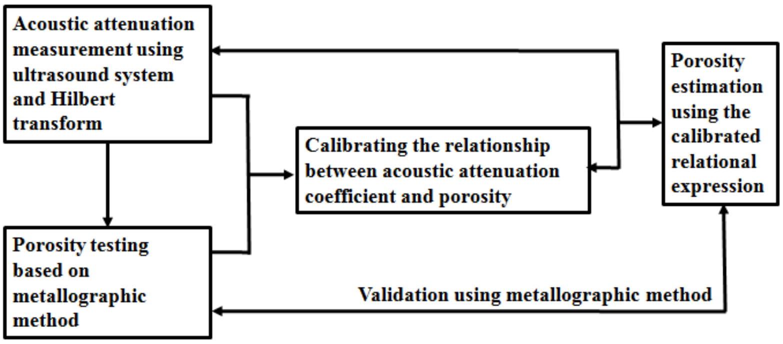


Fig.1 Skeleton diagram for ultrasonic estimation of composite porosity

In the stage of measuring acoustic attenuation, the Hilbert transform and spectral-filter were used to process the ultrasound echo signals. It's an useful method as Hilbert transform has advantages of high resolution, no energy leak and etc. After the first and second bottom waves were obtained, the acoustic attenuation coefficient could be calculated using the following formula:

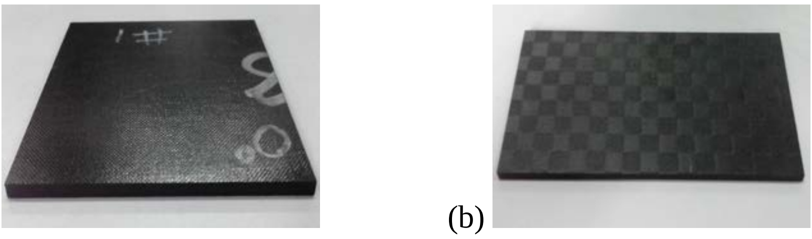
$$\alpha_P = \frac{1}{2\mathrm{t}}\left[20\ln\frac{U_1}{U_2} - 20\ln\frac{Z_W + Z_C}{Z_W - Z_C}\right] \tag{5}$$

where U_1 and U_2 represents amplitude of the first and second bottom waves respectively, $Z_W = 1.5\times10^6\ \mathrm{kg}/(\mathrm{m}^2\cdot\mathrm{s})$ represents the acoustic impedance of water at room temperature, and Z_C represents the acoustic impedance of composites. Water was chosen to be the ultrasound couplant on upper surface of composites. The reflection loss of interface between upper surface and water is compensated in (5), but the reflection loss of interface between lower surface and air is ignored because of the reflection can be regarded as a perfect reflection. The porosity can be calculated using equations (4) and (5).

Experiments and results

10 unidirectional carbon fiber laminates and 10 textile glass fiber sheets were used in the study and rectangular plates were chosen in order to obtain the acoustic impedance conveniently. Vernier

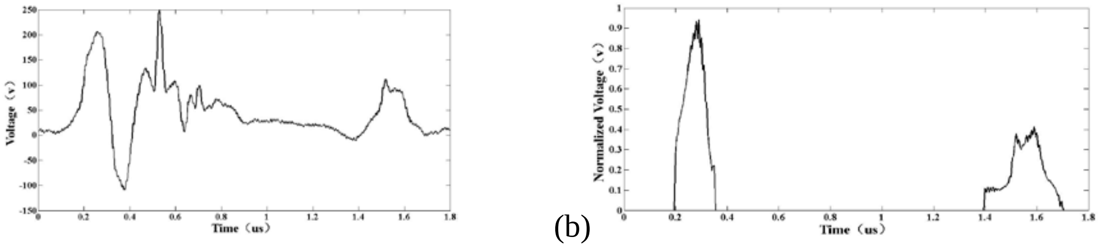
caliper with precision of 0.02mm and electronic scale with precision of 0.01g were used respectively to measure size (length, width and thickness) and mass of the specimen. The measurement implemented repeatedly to reduce errors. The acoustic impedance can be calculated by $Z_C = \rho_C \cdot u_C$ where density ρ_C can be gotten by size and mass, and sound velocity u_C can be obtained by thickness and the ultrasonic echoes of first and second bottom waves.



(a) (b)

Fig. 2 Two types of specimen. (a) unidirectional carbon fiber; (b) textile glass fiber

The ultrasound system was composed of CTS-1002, Trasonic probe (5MHz , 10mm) and UltraVision DS4034 oscilloscope. Fig. 3(a) shows an original ultrasound echo RF signal including the first and second bottom waves and Fig. 3(b) shows the normalized signal processed by Hilbert transform and spectral-filter. The figures indicate that the signal in Fig. 3(b) presents the first and second bottom waves and the acoustic attenuation so much better and clearer.



(a) (b)

Fig. 3 An ultrasound echo signal. (a) original RF echo; (b) normalized signal processed by Hilbert transform and spectral-filter

After the ultrasound testing, 5 samples of each type of the specimen were chosen randomly to determine porosity using Leica DM 2700M metalloscope. The samples were cut into $8\text{mm}\times16\text{mm}$ pieces along different profiles using a high precision cutter GTQ-50003, and then the sections were polished carefully using MP-2B with 600 meshes coarse grinding and 2000 meshes fine grinding. Finally, the smooth sections were embedded into an epoxy resin matrix stage which would be put on the metalloscope slide to determine porosity. Fig. 4 shows some of the metallographic pictures in which the voids were filled with green color automatically using the professional software package of Leica system. The pictures indicate that small voids appear spherical or spheroidicity in shape and large voids appear strip in shape which is in agreement with previous scholars' study.

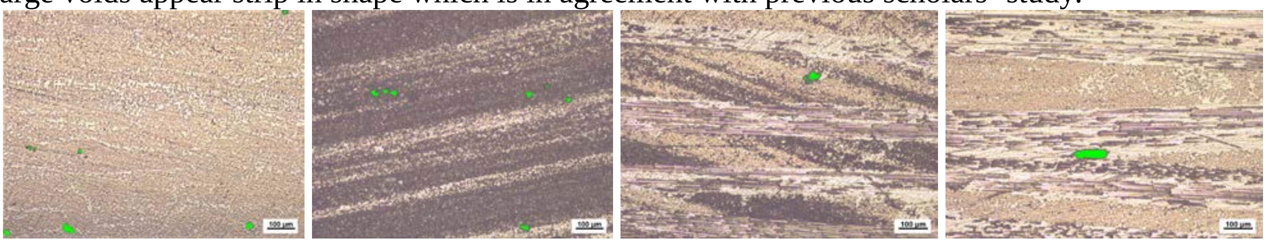


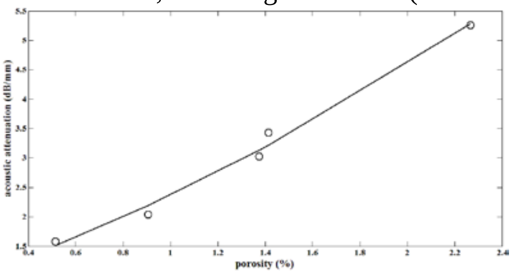
Fig. 4 Metallographic pictures where green areas represent voids (scale: 100μm)

The results of the sampling experiment were given in table 1, where α_P represents the acoustic attenuation coefficient obtained by ultrasound system and P_V represents the porosity determined by metalloscope. According to the values, the parameters C_0 , C_1 and C_2 in equation (4) were calibrated by least square method. The fitting curves of equation (4) of each type of composite were shown in Fig. 5. The calibrated formula was then used to estimate the porosity of the rest specimens by means of acoustic attenuation obtained using ultrasound system. These specimens were also tested by metalloscope to validate the model. The comparison of the porosity values of the rest composites obtained by the two methods were given in Fig. 6 which indicates the results agree well.

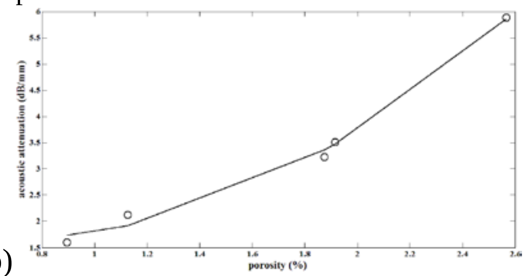
Table 1 Results of ultrasound and metallographic testing

Number *	α_P (dB/mm)	P_V Average value (%)	P_V Variance	Number *	α_P (dB/mm)	P_V Average value (%)	P_V Variance
01-3.00-1	3.024	1.375	0.038	02-4.35-1	1.601	0.895	0.606
01-2.98-1	3.428	1.415	0.743	02-4.33-1	2.122	1.126	0.041
01-3.01-1	5.258	2.266	0.535	02-4.33-2	3.512	1.915	0.023
01-3.03-1	2.040	0.906	0.543	02-4.36-1	5.885	2.566	0.843
01-2.97-1	1.582	0.514	0.420	02-4.35-2	3.224	1.875	0.300

* **numbering method:** I – II – III, I: composite type i.e. 01 means unidirectional carbon fiber laminate and 02 means textile glass fiber sheet, II: average thickness (unit mm), III: repeat times of the same thickness.

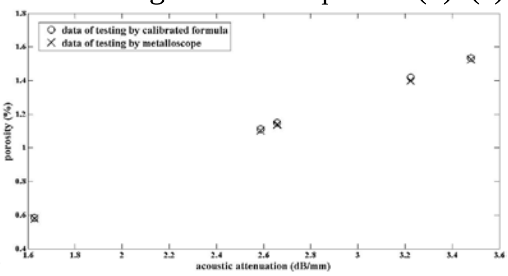


(a)

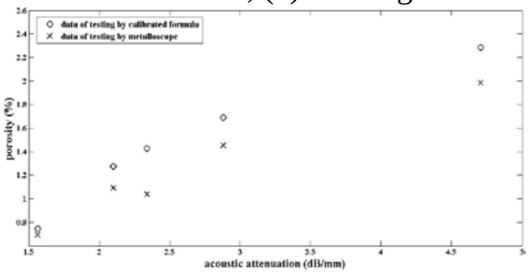


(b)

Fig. 5 The fitting curves of equation (4). (a) unidirectional carbon fiber; (b) textile glass fiber



(a)



(b)

Fig. 6 The comparison of the porosity values obtained by calibrated formula and metalloscope. (a) unidirectional carbon fiber; (b) textile glass fiber

Discussion and conclusion

Porosity estimation of composites using acoustic attenuation method was discussed and Hilbert transform and spectral-filter were introduced to process the ultrasonic RF signals. Metalloscope were used to calibrate the relational model. The results indicate that the porosity values estimated by the calibrated formula are in good agreement with the values determined by metalloscope.

Acknowledgement: The work was supported by college project (Grant no.XK-2015-22) and the collaborative innovation center of high-end manufacturing, Zhuhai (Grant no.ZX-2015-063).

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