Composites: Part B 59 (2014) 67–73

Contents lists available at ScienceDirect

Composites: Part B

journal homepage: www.elsevier.com/locate/compositesb

A compact thermosonic inspection system for the inspection of composites ☆

U. Polimeno, D.P. Almond *, B. Weekes, E.W.J. Chen

UK Research Centre in NDE, Department of Mechanical Engineering, University of Bath, Bath BA2 7AY, UK

ARTICLE INFO

Article history:
Received 9 December 2010
Received in revised form 13 November 2013
Accepted 17 November 2013
Available online 23 November 2013

Keywords:
D. Non-destructive testing
B. Defects
B. Delamination
B. Impact behaviour

ABSTRACT

A portable thermosonic inspection system has been developed incorporating a miniature microbolometer array camera. The vibrations excited during a test are monitored using a high frequency microphone and assessed automatically to validate the test. An investigation of the correlation between thermosonic heating and vibration excitation energy in composites is presented. The system has been trialled on aerospace components containing impact damage.

1. Introduction

The thermosonic technique (also known as ultrasonically stimulated thermography, vibro-thermography and sonic IR) [1–6] is currently gaining considerable interest worldwide as an alternative means of nondestructive evaluation (NDE) that has many potential applications. Thermosonic inspection involves the generation of large amplitude vibrations in a test piece to cause frictional heating at crack surfaces that can be imaged by an infrared camera. Typically, these vibrations are produced by an ultrasonic plastic welding horn being pressed against a surface on the part under inspection. Operating frequencies range from 15 to 40 kHz. The technique has the attractions: of being very rapid; of large area coverage and of providing a simple direct image of detected defects. It has been demonstrated to have great potential for the detection of cracks, as small as 1 mm in length, in gas turbine engine parts [7,8] and for the detection of impact damage, of area as small as 3 cm^2, in composites [9]. Thermosonics has also been shown to be more reliable than the established pulsed and lock-in thermographic NDE techniques [10–13] at detecting impact damage in composites [9,14]. In a survey [9] of 88 examples of impact damage in CFRP test pieces 19 were not detected by the latter techniques. These techniques depend on there being a significant air gap between delaminated surfaces to block the flow of heat from the surface into the bulk. Where delaminated surfaces are separated by a very small gap or are in contact, these techniques fail to detect the defect whilst such conditions are ideal for detection by thermosonics.

Thermographic NDE techniques of all types compete with ultrasonic imaging which may be regarded as the “gold standard” for composite inspection. Their attractiveness is that they are rapid large area imaging techniques that do not involve water immersion and that are little affected by component geometry. However, they often provide an inaccurate indication of defect size and may have the role of providing a means of rapidly screening components for defects which, if found, would be sized by more accurate but slower ultrasonic techniques. Examples of the differences in impact damage size indicated by ultrasonic and conventional thermographic NDE are given in [15]. The sizes of impact damage found in this work using the above two techniques and thermosonics are shown in Table 1. These thick laminates have impact damage delaminations throughout their thicknesses growing in size towards the back faces of the test pieces. All of these delaminations affect ultrasonic C-scan imaging whilst the thermographic techniques, applied to the front (impact) face, are dominated by the delaminations within the first ~2 mm of the surface. The table includes three examples, samples 1, 2 and 3 of impact damage that was not detectable by established optical flash excitation thermographic NDE but which were readily detected by thermosonics. Indeed, all of the examples of impact damage that were not detected by conventional thermographic NDE [9] that have been tested by thermosonics have been successfully imaged by this technique.

The above mentioned potential applications of thermosonics differ in one significant way: for the first, the comparatively small

---

☆ This is an open-access article distributed under the terms of the Creative Commons Attribution-NonCommercial-No Derivative Works License, which permits non-commercial use, distribution, and reproduction in any medium, provided the original author and source are credited.

* Corresponding author. Tel.: +44 1225 386708.
E-mail address: D.P.Almond@bath.ac.uk (D.P. Almond).

1359-8368/$ - see front matter © 2013 The Authors. Published by Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.compositesb.2013.11.019

Table 1
Areas of barely visible impact damage in 8 CFRP samples indicated by: ultrasonic C-scan, flash thermography and thermosonics.

Sample	Ultrasonic C-scan area (cm^2)	Thermography area (cm^2)	Thermosonics area (cm^2)	Sample thickness (mm)
1	2.9	0	2.3	4
2	6.7	0	4.0	4
3	7.0	0	3.9	4
4	7.3	8.1	5.2	4
5	25.6	19.9	4.2	8
6	27.6	17.3	9.4	8
7	69.9	7.9	6.7	8
8	79.6	11.8	7.5	8

gas turbine engine parts can be brought to an inspection station whereas for the second, the composite parts are often large and it will be necessary for the inspection system to be portable and taken to the parts requiring inspection, the composite wing of an aircraft for example. This paper outlines the design and construction of a compact portable thermosonic inspection system developed for the inspection of composite components.

A factor of particular importance for the thermosonic technique is the monitoring of the excitation created by the ultrasonic horn in the part under inspection. It is clear that a threshold excitation energy must be exceeded for defects to generate sufficient heat to be detected by an infrared camera. Whilst procedures have been developed to monitor the ultrasonic excitations and to determine threshold excitation levels for cracks in metallic parts [16–18], no work of this type has been completed for defects in composites. For this reason, the first part of this paper will present the results of an investigation of the ultrasonic excitations achieved in composite parts and the corresponding thermosonic images of impact damage defects. An ultrasonic excitation monitoring system is an essential and integral part of the compact portable thermosonic inspection system.

2. Ultrasonic excitation level monitoring

It is now well known that the ultrasonic excitation produced in parts by the application of high power ultrasonic horns takes the form of a complicated set of vibrations that vary in both frequency and amplitude during the period of excitation. In addition, the excitation process is not reproducible; very different spectra of vibrations being generated from one horn-part contact to another. It has been found advantageous [19] to couple a horn to a part via a layer of compliant material, such as duct tape. The result is that the horn is loosely coupled and acts as an ultrasonic hammer that chatters against the part surface. This becomes a complex nonlinear vibration excitation process that produces a large number of harmonics and sub-harmonics and it has been suggested [19,20] that a condition of "acoustic chaos" can be reached that is particularly favourable to crack heating. The non-repeatability is thought to result from the inherent nonlinearity of the excitation process.

The acknowledged non-repeatability of the ultrasonic excitation process introduces the danger of the excitation energy, at a particular horn-part contact, being lower than is necessary to produce sufficient frictional heating at a defect for its detection by thermal imaging. To guard against this possibility it is necessary to make an assessment of vibrational excitation energy achieved in each test. This assessment involves making a measurement of the amplitude and frequency characteristics of the vibrations excited in a part during the excitation process and computing a parameter that estimates the heating potential of these vibrations at a defect. This parameter has been called the "heating index" [18].

2.1. Review of the heating index characterisation of excitation energy

Previous [16] thermosonic studies of fatigue cracks in steel beams established a relationship between the frictional heating observed at a crack and the acoustic damping caused by the crack to mechanical vibrations excited in a beam. In this work, the beams were excited by a ~0.6 s burst of ultrasonic horn excitation. The vibrations in the beams were monitored by strain gauges and the resulting vibration spectra were analysed throughout the ~0.6 s burst of excitation. The vibration spectra were found to be rich in harmonics that varied in amplitude throughout the period of the excitation pulse. In addition, these characteristics were found to lack reproducibility, in agreement with the findings of others, mentioned above. A relationship was demonstrated between the frictional heating energy at a crack and the damping of beam vibrations caused by the presence of the crack. This necessitated the quantification of the damping of all the vibrational modes recorded during the excitation pulses.

The assumption was made that the temperature rise produced at a crack is related directly to the power (P) dissipated at the crack during vibration. The power dissipated at a crack is given by [17]:

$$P = 2\pi\eta_{crack} fV \tag{1}$$

where η_{crack} is the crack loss factor, f is the mode vibration frequency and V is the mode strain energy. Since V is proportional to vibration amplitude A squared,

$$P \propto fA^2 \tag{2}$$

This parameter has been termed by Morbidini and Cawley [18] "the energy index", EI, of a vibration. In thermosonic tests numerous vibrational modes are excited and EI may be computed using:

$$\mathrm{EI} = \sum_n W_n A_n^2 \tag{3}$$

In which the sum is taken over the n excited modes and the weight $W_n = f_n/f_0$ is the "weight" of the nth frequency component and is computed as the ratio of the frequency, f_n, to a reference frequency which was chosen as the centre frequency of the exciter, f_0 (=35 kHz or 40 kHz here). As the amplitudes of the excited modes are found to vary throughout the duration of an excitation pulse, the value of EI given by Eq. (3) must be regarded as an instantaneous value. The heating observed at an instant of time, τ, at the surface around a crack will be the sum of the heating generated at the surface by the crack, at that instant of time and at earlier times, and the heating generated at earlier times by the crack below the surface that has diffused to the surface to contribute to the total heating at time τ. It has been suggested by Morbidini and Cawley [18] that a measure of the total heating, termed the "heating index", HI, can be obtained from the energy index by:

$$HI(\tau) = \int_0^{\tau} e^{k(t-\tau)} EI(t)dt \tag{4}$$

where t is the time integration variable and k is a decay constant which can be estimated from the temporal decay of heating when the excitation is switched off. It was found experimentally that there was a good correlation between the temperature dependence of the heating index and the temperature rise at a crack, observed