Chapter 12
Thermographic NDT for Through-Life Inspection of High Value Components

Sri Addepalli, Yifan Zhao and Lawrence Tinsley

Abstract Non-destructive testing (NDT) are techniques used to detect and characterise flaws that occur in materials from manufacture through to evaluating the health of the material without causing further damage to the component. With the development of cutting-edge technology over the last two decades, active thermographic NDT has grown considerably as a field. Access to lower cost, more portable hardware with higher performance has fuelled a major drive in research to develop analytical techniques and widen the applicability of thermography in order to exploit its advantages as a low-cost and non-contact inspection technique. While passive thermography is a heavily standardised process, active thermography is considerably lacking in industrial standards. Development of these standards represents an opportunity for research in the field of active thermography to be a part of that process. Recent industry pressure regarding research in NDT has developed a demand for NDT techniques to be quantifiable, and linked directly to material properties, thus allowing an estimation of remaining useful life (RUL) in order to maximise product value. There have been significant research developments in the field over recent years. Through developments in signal processing of thermography data, inspections would enable repeatable, quantifiable benchmarking of samples, which would allow automation of carefully controlled quality checks; and the measurement of thermal properties of the material, which would allow estimation of components' RUL. Addressing these challenges would increase the deployment of thermography in industry, enhance the toolset of through-life engineering, and significantly improve the competitiveness of industries which embrace these developments.

Keywords Pulsed thermography · Non-destructive testing · In-service damage · Automated NDT

S. Addepalli (✉) · Y. Zhao · L. Tinsley
EPSRC Centre for Through-Life Engineering Services, Cranfield University, Cranfield, UK
e-mail: p.n.addepalli@cranfield.ac.uk

L. Redding et al. (eds.), *Advances in Through-life Engineering Services*, Decision Engineering, DOI 10.1007/978-3-319-49938-3_12

12.1 Introduction

The 20th century has seen a rapid increase in the production of smart and innovative systems. Thanks to the developments in the area of applied computing which has revolutionised design of systems right at the component level. Age old techniques have now been replaced with a modern outlook to bring in the best performance that particular system can provide. With the introduction of such next generation parts comes the responsibility of maintaining them so that their life can be increased. This also means that, with the refinement in the design and manufacture of such complex engineered parts, traditional maintenance techniques need modification to help maintain the integrity of such systems thereby extending the life of the component and preventing any premature failure during service. However, with smart and advanced systems, implementing advanced maintenance techniques is the way forward.

Non-destructive testing or NDT has a major role to play in the maintenance activities of manufacturing and maintenance industries as they help assess the health of the component there by advising any additional repair that may be required by the component and or the system. Due to its nature of not altering the structural integrity of the component, and ability to determine the health of the component remotely using scientific methods, NDT has found its way into the industrial sector making huge maintenance savings. With the introduction of advanced innovative materials and products, it is a challenge for age old traditional NDT techniques to be able to provide concrete information about the health of the system. For example, detecting disbonds and monitoring their growth especially in graphite based composites might be a challenge for traditional NDT techniques where advanced techniques such as thermography and immersion pulse-echo ultrasonic technique might be the only way forward [1].

With the introduction of next generation systems that are far more advanced and superior than the existing counterparts, the industry is forced to look for supporting maintenance systems that could help cater the service needs those complex engineered systems might need in the future. With complete shift in service strategies where the service burden has fallen back to the manufacturers [2], high value manufacturing (HVM) industries are turning to cheaper and intelligent automated systems that could provide fast and reliable service critical decisions that reduces service lead times and improves confidence in understanding the health of the system during maintenance.

The current focus for HVM based industries is to develop smart and innovative maintenance solutions for their advanced parts that are currently in the research and development stage so that the maintenance technologies mature with time and are ready for use when such parts get into mainstream market. It should be understood that with the advent of advanced manufacturing systems such as additive layer manufacturing, there is a huge challenge to understand the behaviour of such parts in harsh environments and hence it is of utmost importance to have maintenance technologies in place that could investigate the health of parts during service.

Furthermore, it is key to retain that tacit knowledge and convert the maintenance activities into an intelligent decision making system whereby repair strategy decisions could be automated through the access of knowledge based database systems, thus performing the entire maintenance activity autonomously with a high level of reliability. This chapter mainly presents an alternate automated inspection approach where the entire activity right from inspection to analysis is fully automated.

12.2 Automation Approach

Within the area of material degradation assessment, there has been constant development in automating the data capture with evidence especially in the HVM context. Literature does show the use of advanced signal and image processing techniques and key challenges to integrate technologies that use temperature measurements and relate them with material properties [1, 3, 4]. There are many advantages in the use of pulsed thermography, an active thermography technique, where a surface temperature decay curve response due to flash heating brings in sub-surface anomalies as surface temperature colour maps there by providing enhanced structural information of the part being inspected in a non-destructive manner [3–7]. Together with automation, this NDT tool provides a much faster, repeatable and reliable inspection process leading to reduction in repair and other maintenance strategies for such HVM parts.

Figure 12.1 below is a process flow diagram explaining the automation approach that has been successfully implemented as part of the research in the area of HVM component degradation analysis. The automated inspection process which starts with the operator starting an industrial robotic arm to pick the part; in this case the robot follows a pre-defined tool path. Once the part is picked up, the robot arm presents it to the pulsed active thermography system ready for inspection. As soon as the part arrives to the predefined inspection position, the inspection system triggers an optical pulse flash followed by the infrared camera (part of the inspection system) capturing the surface temperature decay profile of the part. The surface temperature data now goes through a post-processing stage, where it gets reconstructed using the thermographic signal reconstruction or TSR method [8–10]. The data then gets transferred and saved on to the cloud. The in-house analysis

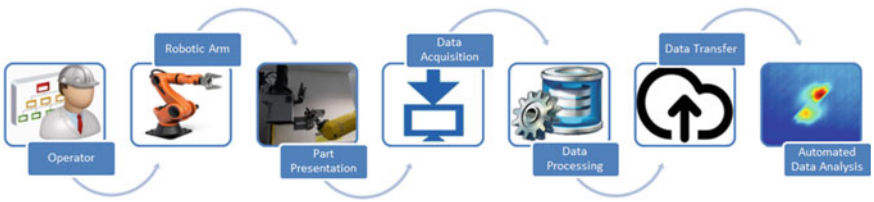

Fig. 12.1 An automated pulsed thermography inspection system

software, then retrieves the post-processed data from the cloud, and sifts through the data and presents it in the form of infrared images or thermograms and temperature time plots. Thus the entire system in effect becomes a one click system where the entire process right from part presentation to the inspection system through to the final analysis is fully automated. The main highlight of the system is its ability to autonomously perform the inspection to a user defined process, where the sentencing of the part can be achieved by easily providing a temperature threshold which increases the signal-to-noise ratio or SNR of the system which then clearly identifies the damage area. This technique benefits from not just the multiple visualisation techniques employed to represent the acquired data, but also the adaptability of the inspection system to be mounted on to the robotic arm thereby building the systems capability to inspect large components. Another additional feature of this method is the ability to present a complex geometry part in pre-defined multiple angles maintaining repeatability of part presentation and to cover maximum surface area especially around curvatures.

12.3 Multiple Data Visualisation Techniques

For demonstrating the strength of the inspection technique and its ability to be represented in multiple visualisation techniques, carbon fibre reinforced polymers or CFRP laminates having varying levels of controlled impact damage was chosen. The following sub-sections describe the laminate, the impact test and the pulsed thermography inspection results.

12.3.1 The Impact Test

CFRP laminates made of unidirectional fibres with Hexcel M21 resin were made through autoclave process and were cut to samples of 150 × 100 × 4 mm. These laminates were then subjected to a drop test using the instron drop test machine for pre-defined drop energy levels between 5 and 30 J. The drop hammer had a hemispherical indentor of 16 mm diameter and weighed 2.281 kg. Energy levels were calculated based on the drop height where the energy equivalent (E) can be calculated using the equation;

$$E = m \times g \times h \tag{12.1}$$

where, m—mass of the indentor = 2.281 kg; g—acceleration due to gravity = 9.81 m/s^2 and h—the drop height in meters.

For the purpose of this study only three energy levels, 10, 20 and 30 J were selected to present the results. The full detailed information of the work and the complete set of results can be found from Zhao et al.'s paper on coefficient clustering analysis for composite laminate impact damage assessment [11].

12.3.2 Pulsed Thermography Results

The drop test machine produced visible damage on the laminates as seen in Fig. 12.2 below. It was noticed that the 10 J impact did not show any direct surface breaking damage other than a physical deformation, however the 20 and 30 J laminates showed associated surface cracking which is dependent on the drop test energy level. To understand if the damage could be detected in the first place, the laminate was subject to pulsed thermography inspection. It should be noted that the inspection was performed from the back surface and not the impact side. The pulsed thermography system comprised of 2 xenon flash lamps enclosed in a reflective hood and powered by a capacitor bank system, a computer control unit and a FLIR SC7600 indium antimonide (InSb) sensor based infrared radiometer operating at wavelengths 3–5.1 μm.

Pulsed thermography could be described as the technique that observes the surface temperature decay profile when excited with an instantaneous heat pulse. It has been demonstrated that when a homogeneous material cools, the heat diffusion through the material which is dependent on its thermal conductivity is constant and thus the surface cools evenly. As soon as a discontinuity occurs along the heat diffusion path, there is localised change in diffusion which appears as either a hot or a cold spot on the surface temperature. Thus the surface temperature at a time (T(t)) can be determined using the following equation [12];

$$T(t) = \frac{Q}{\sqrt{\pi \rho c k t}} \left[1 + 2 \sum_{n=1}^{\infty} R^n \exp\left(-\frac{n^2 L^2}{\alpha t} \right) \right] \quad (2)$$

where Q—heat pulse energy, ρ—material density, c—materials specific heat capacity, k—thermal conductivity of the material, L—defect depth, α—thermal diffusivity and R—the air gap interface's coefficient of thermal reflection. This equation describes the heat flow through a semi-infinite homogeneous plate where the heat decay characteristics are governed by the plate's material property. It has also been established that when a time temperature plot is produced in the logarithmic domain, the slope for a standard area occurs with a slope of −0.5 and for that of the damage will deviate from the this value [13].

The result obtained from a 30J impact sample (see Fig. 12.3) shows that the damage created due to the drop test is clearly visible with the highest damage being represented by the red area in the image. As mentioned above, the curve representing the sound area has a steady cooling characteristic over time with damage

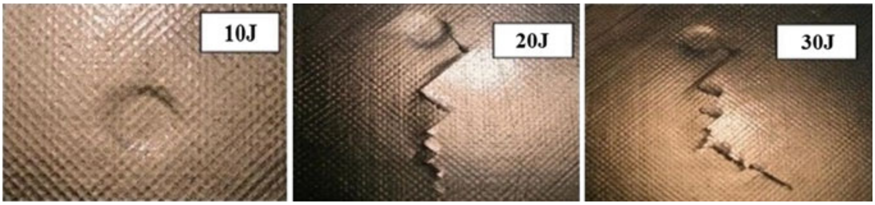

Fig. 12.2 Individual laminates showing the impact area (adapted from [11])

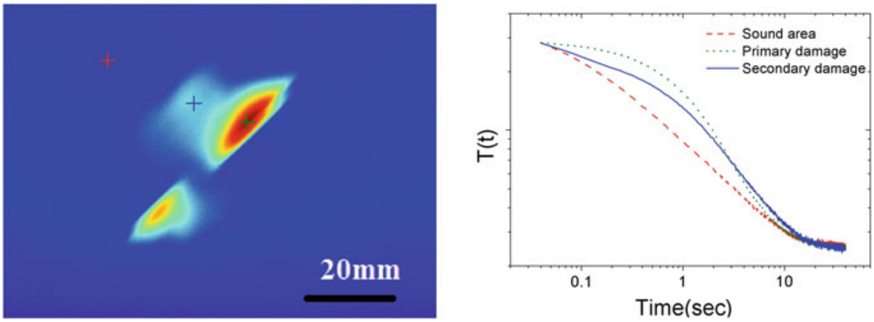

Fig. 12.3 RAW Thermal data from 30 J impact sample with the thermogram on the *left* and a representative temperature time plot on the *right* (The *coloured curves* in the plot are data points obtained from pixel locations represented by *colour markers* from the image on the *left*) (adapted from [11])

areas showing distinct deviation from the curve obtained from the sound area as established in the literature [14–16]. It was also noticed that the maximum damage in this case was around the impact area and not directly at the indentor contact point as seen from the visual image above (see Fig. 12.2).

12.3.3 Damage Area Measurement

One of the key areas of algorithm development was to present the ability of measuring the damage area where visualisation in the binary form is used to measure the damage shape. The following visualisation was created from laminates that have undergone varying energy impact test.

From the binary maps (see Fig. 12.4) the damage area was estimated to be 154.92, 648.84 and 1283.04 mm^2 for the 10, 20 and 30 J laminates respectively. Further, reconstructed visualisation produced the images showing varying damage levels created during impact (see Fig. 12.5).

Fig. 12.4 Binary visualisation for impact tested laminates

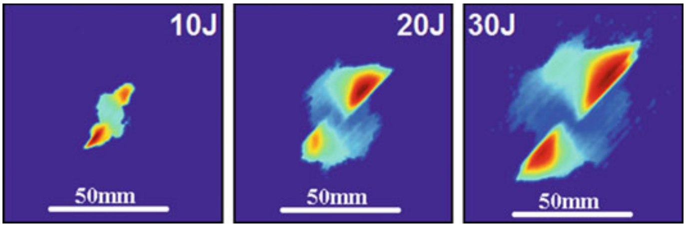

Fig. 12.5 Damage visualisation of the reconstructed data from the coefficient clustering analysis (CCA) method

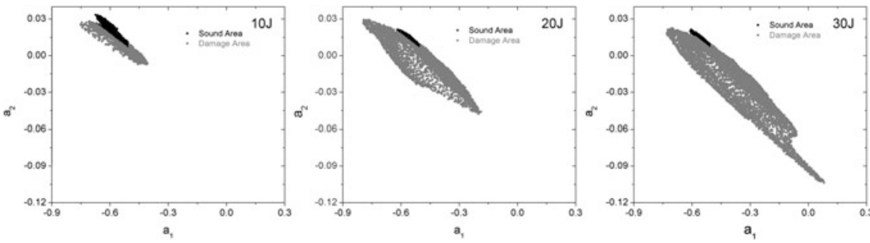

Fig. 12.6 Scatter plot obtained from the first and second order coefficients for all impacted laminates

12.3.4 *Coefficient Cluster Analysis (CCA)*

The following is the data obtained from the coefficient cluster analysis or CCA method where the scatter below is obtained from selecting the regions around the impact area for a size of 200 × 200 pixels.

The principle of the CCA method is to use a low order polynomial model to fit the raw temperature decay curve initially, and then a clustering method is applied into the scatter between the identified parameters to classify the pixels from sound and damage areas. As shown in Fig. 12.6, the x and y axes denote the coefficients of the first and second order terms. The grey dots are classified as the pixels from the damage area and the black points are the pixels from the sound area.

The results from the clustering can then be reversed back to the space domain as demonstrated in Fig. 12.4.

The results presented in this section are from a case-study where CFRP laminates were subjected to impact damage and inspected using pulsed thermography. It was found that the information obtained from the inspection could be presented in the form of thermograms and temperature time plots for selected pixels, which has been well established by various studies [8, 10, 16]. In addition to the established techniques, this paper presents additional visualisation techniques where damage in a localised area could be plotted as against single pixel information [11]. Further the reconstructed data showed the overall damage area and provided a much better differentiation between primary and secondary damage when compared with the data representing sound area. It was also established that in this case, the damage area continued to grow with increasing impact energy. This was also visualised from the scatter plot (see Fig. 12.6) where the scatter for the damage area continued to increase with impact energy.

12.4 Summary

This chapter presents the developments in the area of automated thermographic detection by providing an overview of the entire automation process right from picking the part all the way to the post analysis and the associated tool sets that will help the operator make those critical decisions as part of the inspection process. It has been demonstrated that, in addition to the strength of the inspection technique, there is continuous development of tool sets that help visualise data in a way that can be easily interpreted. All the visualisation tool sets were developed in-house and the results were compared with standard commercial systems that can validate the original inspection data. It is the aim that these developments will enhance not just the decision making capabilities but also provide a higher confidence level when it comes to sentencing the part especially during maintenance through automation.

Acknowledgements The authors would like to thank Professor Peter Foote from Cranfield University for providing the CFRP specimens. This work was supported by the EPSRC Centre for Innovative Manufacturing in Through-life Engineering Services (Grant number EP/I033246/1).

References

1. Genest M, Martinez M, Mrad N, Renaud G, Fahr A (2009) Pulsed thermography for non-destructive evaluation and damage growth monitoring of bonded repairs. Compos Struct 88(1):112–120
2. Meier H, Volker O, Funke B (2011) Industrial Product-Service Systems (IPS^2)—paradigm shift by mutually determined products and services. Int J Adv Manuf Technol 52:1175–1191

3. Mehnen J, Tinsley L, Roy R (2014) Automated in-service damage identification. CIRP Ann Manuf Technol 1
4. Addepalli S, Tinsley L (2015) Active thermography in through-life engineering. In: Redding L, Roy R (eds) Through-life engineering services, decision engineering. Springer International Publishing, pp 117–127
5. Maldague X (1999) Infrared thermography and nondestructive evaluation, May 1999 [Online]. http://www.ndt.net/article/v04n05/irtnde/irtnde1.htm. Accessed 26 Jan 2014
6. Ibarra-Castanedo C, Piau J, Guilbert S, Avdelidis N, Genest M, Bendada A, Maldague XPV (2009) Comparative study of active thermography techniques for the nondestructive evaluation of honeycomb structures. Res Nondestr Eval 20(1):1–31
7. Maldague XPV (2002) Introduction to NDT by active infrared thermography. Mater Eval 60(9):1060–1073
8. Shepard SM (2007) Flash thermography of aerospace composites. In: IV Conferencia Panamericana de END, Buenos Aires
9. Balageas DL, Roche J-M, Leroy F-H, Liu W-M, Gorbach AM (2015) The thermographic signal reconstruction method: a powerful tool for the enhancement of transient thermographic images. Biocybern Biomed Eng 35(1):1–9
10. Shepard SM (2003) Temporal noise reduction, compression and analysis of thermographic image data sequences. United States of America Patent US Patent 6516084 B2
11. Zhao Y, Tinsley L, Addepalli S, Mehnen J, Roy R (2016) A coefficient clustering analysis for damage assessment of composites based on pulsed thermographic inspection. NDT&E Int 83:59–67
12. Lau S, Almond D, Milne J (1991) A quantitative analysis of pulsed video thermography. NDT&E Int 24(4):195–202
13. Shepard SM, Hou J, Lhota JR, Golden JM (2007) Automated processing of thermographic derivatives for quality assurance. Opt Eng 46(5):051008
14. Shepard SM (2011) Advances in pulsed thermography. Proc SPIE 4360:511–515
15. Vavilov V, Maldague X, Dufort B, Robitaille F, Picard J (1993) Thermal nondestructive testing of carbon epoxy composites: detailed analysis and data processing. NDT&E Int 26(2):85–95
16. Ball R, Almond D (1998) The detection and measurement of impact damage in thick carbon fiber reinforced laminates by transient thermography. NDT&E Int 31(3):165–173