Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 62 (2017) 33 – 38

www.elsevier.com/locate/procedia

10th CIRP Conference on Intelligent Computation in Manufacturing Engineering - CIRP ICME '16

Use of thermography and ultrasound for the quality control of SMC lightweight material reinforced by carbon fiber tapes

Marielouise Zaiß[a]*, Merle-Hendrikje Jank[a], Udo Netzelmann[b], Thomas Waschkies[b], Ute Rabe[b], Hans-Georg Herrmann[b], Michael Thompson[c], Gisela Lanza[a]

[a]*wbk Institute of Production Science, Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany*
[b]*IZFP Fraunhofer Institute for Nondestructive Testing, 66123 Saarbrücken, Germany*
[c]*Department of Chemical Engineering, McMaster University, Hamilton, Ontario, Canada L8S 4L7*

* Corresponding author. Tel.: +49 721 608 44296; fax: +49 721 608 45005. *E-mail address:* marielouise.zaiss@kit.edu

---

Abstract

Growing requirements of Sheet Molding Compound (SMC) parts make new material combinations necessary. One strategy is to reinforce SMC with unidirectional carbon fiber tapes to improve its mechanical properties. As quality assessment of cured parts is necessary, examination of semi-finished materials would be favorable. Two types of nondestructive testing methods, Thermography and Ultrasound, are compared to determine the best control method. These methods are examined on cured plates and semi-finished material to identify defects like air inclusions, delamination, misaligned fibers and microstructural changes. The focus of this paper is an assessment of the testing methods for the manufacturing process.

Peer-review under responsibility of the scientific committee of the 10th CIRP Conference on Intelligent Computation in Manufacturing Engineering

Keywords: Quality assurance, SMC, Carbon Fiber Tape, Nondestructive Testing

---

1. Introduction

Transport accounts for one quarter of total CO_2 emissions in the European Union making it a crucial sector for potential greenhouse gas reduction [1]. One way to reduce CO_2 emissions for vehicles are technological advancements such as improved powertrain solutions and the use of lightweight materials [2]. The latter is important as it impacts energy efficiency, vehicle performance and cost. This especially accounts for carbon fiber or glass fiber polymer composites which combine excellent mechanical properties with weight savings.

Sheet Molding Compound (SMC) belongs to the group of long glass fiber reinforced thermosetting composites. It is widely used for automotive applications such as sunshades, spoilers, floor panels or decklids [3]. High productivity, cost effectiveness in production and a high degree of design freedom are advantages of SMC. However, the discontinuous fibrous reinforcement does not provide adequate strength and stiffness necessary for high-end structural parts.

To overcome this limitation, the material presented is composed of SMC and uni-directional (UD) carbon fiber tapes. Continuous carbon fibers provide the highest strength and stiffness relative to their weight as load-bearing components. However, continuous fiber tape is produced by compression molding and thus limited to simple geometries. To combine the benefits of both discontinuous and continuous reinforcement, a hybrid material of SMC and UD carbon fiber tapes was developed. This way, lightweight, formability, function integration and excellent load bearing properties are achieved making the hybrid suitable to a wide field of applications in diverse industries.

Since processing experience for new and customized materials is rare, proper quality control is crucial. Especially in the automotive industry, stable processes and flawless materials are essential for market penetration. For this purpose non-destructive testing (NDT) has been proven successfully

Peer-review under responsibility of the scientific committee of the 10th CIRP Conference on Intelligent Computation in Manufacturing Engineering
doi:10.1016/j.procir.2016.06.039

for composite materials [4–6]. The aim of this study is to compare NDT methods and identify best-practices for process quality control. Active thermography and three different ultrasonic methods are presented to analyze this new hybrid of SMC and carbon fiber tapes.

2. State of the art

A multitude of NDT methods are known which are applicable within the complete life cycle of a product, e.g. to test raw materials, monitor the production process, test components, as well as use for in-service inspection [7]. The use of NDT methods for the quality control of diverse composite materials has been investigated extensively [8]. However, until now very little research has been conducted on in-line quality control of the SMC production process and especially for the new production of a hybrid of SMC and carbon fiber tape. The detection of fiber distribution and defects like air entrapment had been demonstrated using optical systems and active thermography [9].

2.1. Thermography

Transient and pulse thermography was used to examine carbon fiber and glass fiber reinforced composites in several studies, which mutually agreed that thermography was a well suited NDT method for detecting defects such as impact damage or fiber breakouts [10–16]. Other studies have focused on impact damage that can occur during the production process, with the in-line applicability of thermographic inspection being proven for glass fiber composites [17]. In general, thermographic methods are limited to near-surface defects of lateral dimensions between 2-3 mm. Through transmission mode is considered superior to reflection mode in terms of detecting deeper flaws [18].

2.2. Ultrasonic testing via immersion (UT-Immersion)

Ultrasonic testing (UT) is a widely used technique for defect detection in composite materials. Water is often used as a coupling medium between the sample and the ultrasonic transducer/receiver. The liquid can be locally spilled around the transducer in close surface contact [19] or in a water jet (squirter technique). A very common method is immersion, where the sample is entirely submerged in a water tank. Often the pulse-echo setup is used for industrial applications. Depending on the transducer frequency and step width of the scanning unit, the technique is capable of detecting defects, inclusions and air entrapment with high precision [5].

2.3. Ultrasonic testing with air coupling (UT-AC)

Due to a high impedance mismatch between the transducer, air and the test specimen, air coupled ultrasound requires special technology which deals with the high amount of reflection at each interface. UT-AC is a contact-free technique well suited for the quality control of thin plate-like components like composites. [20–22]. As one-sided measurements are difficult due to the strong reflection at the sample surface, transmission through the sample is the preferred method for the ultrasonic signal.

2.4. Ultrasonic spectroscopy (US-S)

Ultrasonic spectroscopy based on guided Lamb waves is used to evaluate the alignment of carbon fibers in the tape. Due to the anisotropic and attenuative characteristics of composites the interpretation of the propagation of these waves is highly complex. For UD and cross-ply carbon fiber composites, ref [23] successfully related energy and velocity to fiber orientation. Detecting variation in the fiber angle was determined to correlate to resonances in the frequency range of 50-250 kHz. Ref [24] proves how the change in orientation between a delamination and probes cause a shift in amplitudes.

The defect detection capabilities for the discussed methods are summarized in Table 1.

3. Material

The material samples consist of a total of 10 plates having the dimensions of 800×250 mm², whereby half are reinforced with UD carbon fiber tapes. Table 2 provides an overview of the tested material. The specimens vary in terms of thickness, carbon fiber orientation and mold coverage. Due to the continuous reinforcement half of material is cured by compression molding whereby the pure SMC plates are manufactured using flow forming.

The SMC material consists of vinyl ester resin (DSM) and has a glass fiber volume fraction of 23 %. For the UD carbon fiber tape the hybrid resin Daron 41 (DSM) is used and reinforced by a 50 % fiber volume fraction.

Table 1: Capability of thermography, UT-Immersion and UT-AC for typical defects within SMC and carbon fiber tape production.

	Delamination	Inclusion	Porosity	Fiber/ matrix distribution	Fiber orientation	Degree of curing	References
Thermography	10	7	6	5	5	0	[5], [19]
UT-Immersion	10	9	8	5	3	0	[5], [19]
UT-AC	10	9	9	0	0	1	[22]
US-S	6	0	0	0	7	0	[23–25]

10-8 *high applicability*; 7-5 *good applicability*; 4-1 *low applicability*; 0 - *no data*

Table 2: Overview about testing material.

Specimen no.	Reinforced by 0.3 mm thick UD tape	No. of SMC prepreg layers	Surface mold coverage [%]	Thickness [mm]
1, 4, 5	yes	2	100	2.4-2.6
2, 3	yes	4	100	4.5-4.7
6, 7, 8	no	4	50	2.4-2.7
9, 10	no	6	50	3.8-4.0

Fig. 1 depicts the production process of the SMC material. First, the paste is mixed and applied to an upper and lower carrier foil. Thereafter, chopped 4800 tex glass fibers (by Johns Manville GmbH) are sandwiched between two layers of paste. After passing a calendaring unit the pre-impregnated SMC material is stored in a maturation unit for 4 weeks at 30 °C and 30 % relative humidity. The prepreg SMC weights 1-2 kg/m². Detailed information about SMC manufacturing can be found in [26].

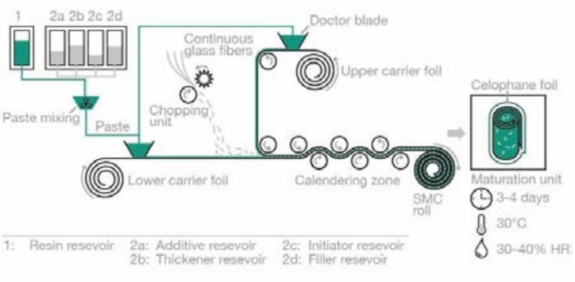

Fig. 1: SMC manufacturing process.

Independently of this process, the UD carbon fiber tapes are manufactured on a laboratory prepreging line as shown in Fig. 2. A pad of dry, continuous, aligned carbon fibers is joined to a lower carrier foil brushed with the hybrid resin. An upper carrier foil then covers the fibers. Calendaring rolls ensure proper material impregnation.

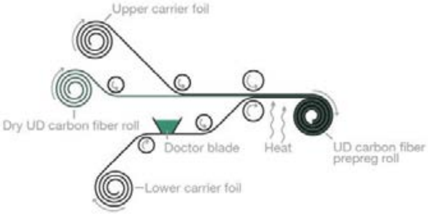

Fig. 2: UD carbon fiber tape manufacturing process.

After maturation of both components the hybridization takes place. The material is cut in the desired shape, stacked and put in a DYL630/500 press (by Dieffenbacher). Both compression molding and flow forming take place at 100 bar for 90 seconds in a 150 °C pre-heated mold. The cavity has the lateral dimensions of 800×250 mm².

4. Test execution

For NDT each sample listed in Table 2 was cut into two pieces of 400×250 mm² size, where "u" and "o" denominate the upper and lower part of the original plate.

4.1. Thermography

All 20 cured specimens were tested using an infrared (IR) camera of the type Flir SC5200 and a pulse-echo setup. The distance between the camera and the sample was 60 cm. Each of the two flash lamps emits a light pulse from a discharge of an electrical energy of 6.4 kJ within 10 ms onto the specimens' surface. Data was collected at a frame rate of 5 Hz and 400 thermograms were recorded in total. 4 measurements were taken to depict the entire plate. Data evaluation is done by means of the software Thermolab by Fraunhofer IZFP. Based on the 400 frames a pulse-phase analysis was done.

One sample was also tested using the QWIP 384 Dual-Band IR camera (by Thermosensorik) to check the IR permeability of the material. The setup was similar to the one described previously with one ring flash lamp emitting 3.2 kJ flash energy in 5 ms. Uncured, pure prepreg SMC was also measured with this setup.

4.2. Ultrasonic-testing via immersion

The plates no. 1u, 2, 3, 4o, 6u, 7u, 8u and 9u were placed in a water tank and tested with ultrasound by pulse-echo mode. Three ultrasonic probes with different nominal resonant frequencies, TS 6 WB 2-7 (by Karl Deutsch), H5M (by GE) and IAP 15.6.2 (by GE) were used for imaging. The specimens were scanned in lateral steps of 2 mm. The acoustic transmitter was facing the side of the plate opposite of the tape reinforcement. In addition, selected sample areas and prepreg SMC were scanned with smaller step size. Data was acquired using special software (US-Lab) programmed in LabVIEW by Fraunhofer IZFP.

4.3. Ultrasonic-testing with air coupling

All 20 plates were examined with air coupled ultrasound in transmission mode. Two ultrasonic probes were used with an operating frequency of 580 kHz and a focal spot of 1.4 mm. A 2-axes manipulator scanned with the probes which were mounted vis-à-vis. The sample was fixed between the probes such that the transmitter was on the tape side. A PCM ultrasonic system (by Inoson) was used and in addition, a preamplifier for the received signal. Data acquisition and evaluation are performed with the software US-Lab by Fraunhofer IZFP.

4.4. Ultrasonic spectroscopy

Several sensor layouts and frequency spectrums were tested to find the most suitable one for the hybrid testing material. Finally, the transducer C604 (Olympus) was placed on the tape side as a transmitter and the F30alpha

(Physical Acoustics) sensor on the opposite side and at a distance of 20 mm using coupling gel. A combination of sinusoidal S_0 and A_0 Lamb waves in the frequency range of 100-900 kHz were stepwise induced to the specimen using a waveform generator (Agilent 33210A). The signal was pre-amplified by 60 dB and data was acquired with software programmed in LabVIEW. The area of identified resonant frequency regions was calculated by fitting a Gaussian distribution using the software Fityk [27].

5. Results

The results are presented for specimen *4o* as representative for the overall findings of this study. A photograph taken of the tape side of this sample is shown in Fig. 3.

Fig. 3: Photograph of the tape reinforced side of specimen 4o.

5.1. Thermography

Within the series of thermograms recorded both the glass fiber distribution as well as single carbon fiber rovings were depicted clearly though not in the same thermogram. This effect is based on the difference in optical absorption and thermal conductivity of the components.

Images at defined IR frequency were obtained by applying a Fourier transform. Fig.4 shows a phase image at 0.025 Hz which provides insights to deeper defects. Thermography is capable of detecting air bubbles that were underneath the tape as having a diameter of 4 mm.

The tests using the dual-band camera for inspection of the cured plates and the SF material showed that the IR permeability for the hybrid material is approximately the same for the long- and mid-wave spectrum.

Also, the dual-band camera was used for thermographic inspection on the semi-finished (SF) SMC material at a higher frame rate of 145 Hz. The 1.1 mm thick prepreg was heated homogeneously and the glass fibers were depicted clearly so that the fiber distribution became visible too, see Fig. 5. Air entrapment in the prepreg was not visible.

5.2. Ultrasonic-testing via immersion

Fig. 6 shows the C-Scan (2D presentation of echoes in a top view on the test surface) of the volume of the sample 4o scanned with the probe TS 6 WB 2-7 (2 MHz frequency). As the plates were slightly bulged after manufacturing, they were clamped at four points, which are visible black spots at the upper and lower ends of the sample. The darker contrast at the right and left border of the sample is probably also due to the remaining curvature. The probe was placed on the opposite side of the tape. Since the tape thickness (0.3 mm) is much lower than the plate thickness, the tape becomes only slightly visible in this image. A multitude of pores is indicated as yellow and red spots in the middle of the plate. Depth analysis clearly showed that the pores were located in the SMC and not at the interface between tape and SMC. Due to the low frequency of 2 MHz and the relatively large step size of 2 mm it is impossible to see single fibers in the image.

The SF material was tested with a transducer with higher center frequency (15 MHz) and lower step size of 0.5 mm (Fig. 7). Here, the fibers become clearly visible, which illustrates the potential of high frequency ultrasonic. Areas with low fiber content show blue contrast.

5.3. Ultrasonic-testing with air coupling

Fig. 8 shows the air-coupled ultrasonic C-Scan. The contrast is inverted compared to the reflection mode image in Fig. 6, i.e. defect tree areas are red as they transmit much energy, while pores appear blue as they block the transmission of the ultrasonic pulse. The tape is slightly visible and the average porosity varies in width direction being at maximum in the middle of the plate.

Due to the high amount of porosity, the SF SMC is almost opaque to air ultrasound, in some areas (especially lower right corner, red spots), the pores merged to continuous gaps in the surface, and the ultrasonic pulse was transmitted unobstructed to the receiver (Fig. 9).

5.4. Ultrasonic spectroscopy

Spectroscopic analysis succeeded in determining the dominant resonant frequency for SMC at around 300 kHz whereas the stiffer UD carbon fibers can be detected at ca. 600 kHz; the resonances at 600 kHz disappeared when no UD carbon fibers were present. The area of a fitted distribution to the frequencies near 600 kHz was compared to the carbon fiber orientation. Fig. 10 shows the variation of the area and thus the material's frequency response as the carbon fiber orientation changes relatively to the sensors. The largest area is obtained when the fibers are aligned to the probes. As fibers move from 0 ° towards 90 ° the curve area for the high-frequency mode decreases and activity shifts towards lower frequencies. The low values for the 165 °- 240 ° orientation is caused by air entrapment.

6. Comparison and estimation

In Table 3 a comparison between the methods can be found. For the cured plates thermography is capable of detecting delaminations, air entrapment, fiber orientation and fiber distribution. It is a quick and contactless method providing imaging results within short cycle times. However, the method's capability to inspect the quality of the SF SMC is rather poor. The fiber distribution can be detected properly

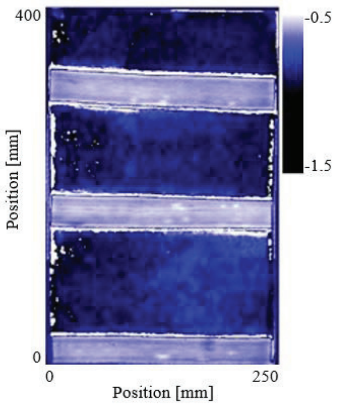

Fig. 4: Sample 4o, active thermography phase image at a frequency of 0.025 Hz.

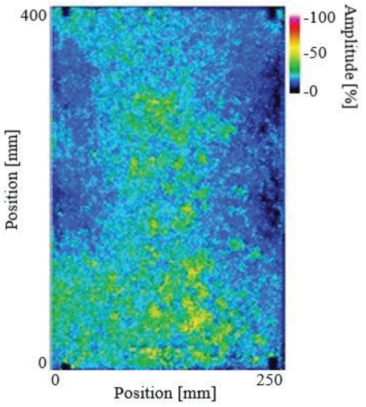

Fig. 6: Sample 4o, UT-Immersion C-Scan, 2 MHz frequency, 30 dB amplification, 2 mm measurement steps.

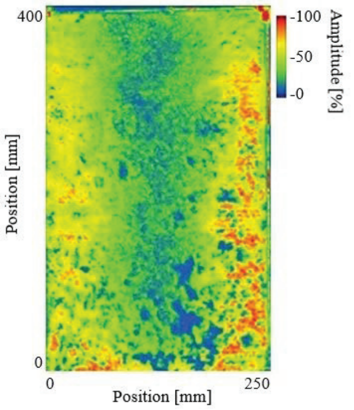

Fig. 8: Sample 4o, UT-AC C-Scan, 580 kHz frequency, 71 dB amplification, 1 mm measurement steps.

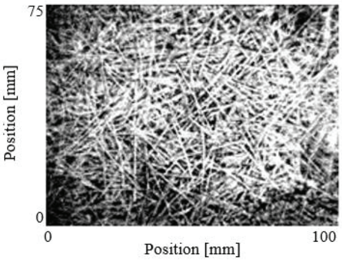

Fig. 5: Semi-finished SMC; 145 fps; test area is 100×75 mm²; long wave IR frequency spectrum.

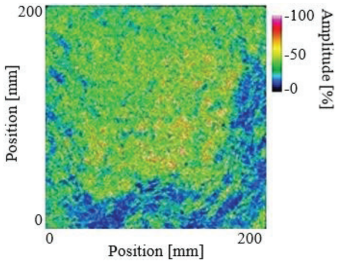

Fig. 7: UT-Immersion of semi-finished SMC; 15 MHz frequency, 26 dB amplification, 10 dB attenuation, 0.5 mm measurement steps.

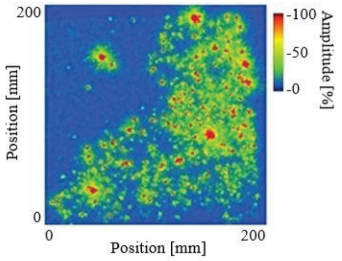

Fig. 9: UT-AC C-Scan of semi-finished SMC; 580 kHz, 55 dB amplification, 1 mm measurement steps.

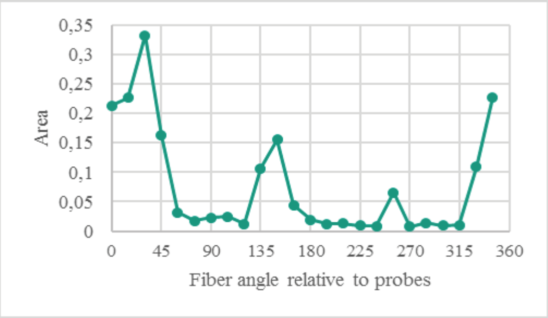

Fig. 10: Sample 4o: Calculated area underneath the high-frequency response curve angular profile.

but air entrapment is not visible, since the 1 mm thick material heats up quickly and homogeneously. Also, the flaw detection capability decreases overly with thickness.

UT-Immersion is a method capable of detecting common material flaws. The depths of the flaws can be detected easily. The possibility to focus on a specific depth enables detailed monitoring of the specimen structure. A drawback of this method is the contamination of the material with water, which can affect the properties of the SF material and, thus, the manufacturing of final parts. Also, the production time increases, as the material requires drying.

UT-AC is a contact-free method to detect material flaws, but without depth resolution. Also, the specimen needs to be assessed from two sides, which is difficult to realize in many industry applications. Immersion US and air-coupled US are both scanning techniques requiring a compromise between speed and resolution. Different types of ultrasonic arrays are available for immersion allowing fast inspection.

The carbon fiber orientation can be detected using US-S. The fact that the method needs a coupling, which is hard to remove, is disadvantageous for industrial applications.

Thus, no method can solely cover the entire spectrum of process control for the 20 plates tested but rather a combination of methods builds a reliable control system.

7. Conclusion and outlook

The newly invested hybrid material composed of SMC and UD carbon fiber tapes combines the benefits of both continuous and discontinuous reinforced composite materials and thus has a strong potential for use within the automotive industry. In this study the NDT methods thermography, air and water coupled ultrasound as well as ultrasonic spectroscopy are examined on the hybrid material at hand. This studies’ aim is to provide a recommendation for an in-line process control for this new material.

All 4 NDT methods are tested on both the SF SMC and cured hybrid plates. It is shown that none of the methods is capable of detecting all common defects and providing an excellent in-line application. However, thermography is identified as the fastest, most efficient contact-less method to detect flaws within the production process. Also, as the IR permeability of the material does not differ between long- and mid-wave radiations cheaper long-wave IR cameras can be applied. However, for the SF SMC, thermography is not able to properly detect porosity but UT-AC provides promising results. Future studies will examine additional NDT methods and a sensor combination to improve quality.

Acknowledgements

The research documented in this paper has been initiated by the German-Canadian research group "Integrated engineering of continuous-discontinuous long fiber reinforced polymer structures". The support of the group by the German Research Foundation (DFG) is gratefully acknowledged.

Table 3: Comparison of NDT methods used in this study; ++ very high capability, + high capability, o good capability, - low capability.

	Capability of flaw detection						In-line process capability				
	Delami-nation	Inclusion	Porosity	Fiber/ matrix distribution	Fiber orientation	Degree of curing	Contact-less	Complex/ thick shapes	Cycle time	Imaging	SF material
Thermography	++	+	o	+	++	-	++	-	++	++	o
UT-Immersion	+	+	++	-	-	-	-	+	+	++	-
UT-AC	++	++	++	-	-	-	++	+	+/o	++	o
US-S	o	-	-	-	+	-	-	o	-	-	-

References

[1] European Union (2014) EU transport in figures. Publications Office of the European Union, Luxembourg.

[2] González Palencia JC, Furubayashi T, Nakata T (2012) Energy use and CO2 emissions reduction potential in passenger car fleet using zero emission vehicles and lightweight materials. Energy 48(1):548–65.

[3] McConnell VP (2007) SMC has plenty of road to run in automotive applications. Reinforced Plastics 51(1):20–5.

[4] Adams RD, Cawley P (1988) A review of defect types and nondestructive testing techniques for composites and bonded joints. NDT International 21(4):208–22.

[5] Vaara P, Leinonen J (2012) Technology Survey on NDT of Carbon-fiber Composites, Publication, Kemi, Kemi- Tornio Universtiy of Applied Sciences.

[6] Meyendorf N, Nagy PB, Rokhlin SI (2004) Nondestructive materials characterization: With applications to aerospace materials. Springer-Verlag, Berlin, New York.

[7] Hellier C (2013) Handbook of nondestructive evaluation. 2nd ed. McGraw-Hill, New York.

[8] Oster R (2013) Herausforderungen an die ZfP bei Ihrer Anwendung an Faserverbundbauteile. Deutsche Gesellschaft Für Zerstörungsfreie Prüfung e.V., München.

[9] Kraemer A, Lin S, Brabandt D, Böhlke T, Lanza G (2014) Quality Control in the Production Process of SMC Lightweight Material. Procedia CIRP 17:772–7.

[10] Meola C, Carlomagno GM (2014) Infrared thermography to evaluate impact damage in glass/epoxy with manufacturing defects. International Journal of Impact Engineering 67:1–11.

[11] Ghadermazi K, Khozeimeh MA, Taheri-Behrooz F, Safizadeh MS (2015) Delamination detection in glass–epoxy composites using step-phase thermography (SPT). Infrared Physics & Technology 72:204–9.

[12] Zheng K, Chang Y, Wang K, Yao Y (2015) Improved non-destructive testing of carbon fiber reinforced polymer (CFRP) composites using pulsed thermograph. Polymer Testing 46:26–32.

[13] Avdelidis NP, Hawtin BC, Almond DP (2003) Transient thermography in the assessment of defects of aircraft composites. NDT & E International 36(6):433–9.

[14] Avdelidis NP, Almond DP, Dobbinson A, Hawtin BC, Ibarra-Castanedo C, Maldague X (2004) Aircraft composites assessment by means of transient thermal NDT. Progress in Aerospace Sciences 40(3):143–62.

[15] Shepard S, Frendberg M (July) Thermographic Detection and Characterization of Flaws in Composite Materials. Materials Evaluation, July:928–37.

[16] Katunin A, Dragan K, Dziendzikowski M (2015) Damage identification in aircraft composite structures: A case study using various non-destructive testing techniques. Composite Structures 127:1–9.

[17] Sackewitz M, (Ed.) (2011) Leitfaden zur Wärmefluss-Thermographie: Zerstörungsfreie Prüfung mit Bildverarbeitung. Fraunhofer-Verl., Stuttgart.

[18] Lizaranzu M, Lario A, Chiminelli A, Amenabar I (2015) Non-destructive testing of composite materials by means of active thermography-based tools. Infrared Physics & Technology 71:113–20.

[19] Kochan A (2012) Untersuchungen zur zerstörungsfreien Prüfung von CFK-Bauteilen für die fertigungsbegleitende Qualitätssicherung im Automobilbau. Shaker, Aachen.

[20] Dong Z, Jun ZR, Ma YZ, An XN (2012) The Present Development Situation of Air-Coupled Ultrasonic Non-Destructive Testing Technology. AMR 532-533:178–82.

[21] Ambrozinski L, Piwakowski B, Stepinksi T, Uhl T (2012) Application of Air-Coupled Ultrasonic Transducers for Damage Assessment of Composite Panels. Presented at 6th European Workshop on Strucutural Health Monitoring, Dresden.

[22] Waschkies T, Licht R, Pudovikov S, Valeske B, Walte F (2013) Bildgebende Verfahren für die Ultraschallprüfung: Seminar des FA Ultraschallprüfung, 11. - 12. November 2013, Berlin. Vortrag 3: Innovative abbildende Ultraschallverfahren in der Forschung und Applikation. DGZfP, Berlin.

[23] Putkis O, Dalton RP, Croxford AJ (2016) The anisotropic propagation of ultrasonic guided waves in composite materials and implications for practical applications. Ultrasonics 65:390–9.

[24] Ng C, Veidt M (2011) Scattering of the fundamental anti-symmetric Lamb wave at delaminations in composite laminates. J. Acoust. Soc. Am. 129(3):1288.

[25] Ng CT, Veidt M (2009) A Lamb-wave-based technique for damage detection in composite laminates. Smart Mater. Struct. 18(7):74006.

[26] Orgéas L, Dumont PJJ (2011) Sheet Molding Compounds. in Nicolais L, (Ed.). Wiley Encyclopedia of Composites. John Wiley & Sons, Inc. Hoboken, NJ, USA.

[27] M. Wojdyr, J. Appl. Cryst. 43,1126-1128, 2010