Composites Part B 77 (2015) 494–501

Contents lists available at ScienceDirect

Composites Part B

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

Review on quality assurance along the CFRP value chain – Non-destructive testing of fabrics, preforms and CFRP by HF radio wave techniques

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A R T I C L E I N F O

Article history:
Received 17 October 2014
Received in revised form
2 February 2015
Accepted 4 March 2015
Available online 17 March 2015

Keywords:
CFRP
A. Carbon fibre
D. Non-destructive testing
High frequency eddy current
B: Electrical properties

A B S T R A C T

Eddy current testing is well established for non-destructive testing of electrical conductive materials [1]. The development of radio frequency (RF) eddy current technology with frequency ranges up to 100 MHz made it possible to extend the classical fields of application even towards less conductive materials like CFRP [2][3](Table 2). It turns out that RF eddy current technology on CFRP generates a growing number of valuable information for comprehensive material diagnostic. Both permittivity and conductivity of CFRP influence the complex impedance measured with RF eddy current devices. The electrical conductivity contains information about fiber texture like orientations, gaps or undulations in a multilayered material. The permittivity characterization influenced by dielectric properties allows the determination of local curing defects on CFRP e.g. hot spots, thermal impacts or polymer degradation. An explanation for that effect is seen in the measurement frequency range and the capacitive structure of the carbon rovings. Using radio wave frequencies for testing, the effect of displacement currents cannot be neglected anymore. The capacitive structures formed by the carbon rovings is supposed to further strengthen the dielectric influences on eddy current measurement signal [3]. This report gives an overview of several realized applications and should be understood as a general introduction of CFRP testing by HF Radio Wave techniques.

1. Introduction

Along the value chain of carbon fibre reinforced plastic (CFRP) different non-destructive testing (NDT) methods such as ultrasonic, thermography, X-rays or optical methods are successfully applied [7]. However, looking in more detail at the process chain, there is a gap where standard NDT methods cannot be used. For automated mass production facilities based on infusion processes (e.g. RTM – Resin Transfer Molding), it is important to acquire quality parameters prior to the resin infiltration step. This opens up the possibility of in-time process recalibration, for rework or repair of the fiber preform, if necessary. With knowledge of the incoming material characteristic at the textile- or preform stage, the following process steps can be adjusted in-time to reduce final part rejects resulting from defects in the pre-stage material. If problems like missing or misaligned fibre

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http://dx.doi.org/10.1016/j.compositesb.2015.03.022

bundles, waves or insertions are detected in time, the further processing can be stopped and readjusted resulting in less material waste. In addition, subsequent process steps can be controlled by utilizing the information on the incoming product quality e.g. gaps between fiber bundles which will influence the infiltration behavior. The current trend in aerospace industries is to evolve to more large primary aircraft structures in CFRP with high levels of function integration, resulting in more expensive parts and increasing the need for first-time-right products to avoid complex repairs. A critical defect originated in the lay-up phase, is Foreign Object Debris (FOD) introduced in the manual process steps. FOD prevention campaigns cannot reduce the occurrence to zero and therefore an inspection stage before subpart consolidation and -final cure can be economically interesting. Visual FOD inspection is no option for CFRP materials due to the lack of transparency. Also does classic ultrasonic inspection techniques require a couple medium (generally water) which should be avoided in contact with prepregs or dry fiber preforms. Thermography results in prepreg out-time reductions and processing is required to improve FOD contrast. RF radio wave technique is a promising alternative without couple medium and high sensitivity. This leads to an increasing demand for NDT methods that can be applied inline to dry multilayered carbon textiles as well as wet and consolidated materials. The application of ultrasound, thermography or shearographie requires solid state material for mechanical or thermal wave propagation or for deformation analyses respectively. Due to this limitation these standard NDT techniques cannot be applied to dry or wet pre stage components.

An ideal NDT method should be applicable along the whole CFRP value chain, from the fibre bundle over the fabric/prepreg and preform stage up to components and its life time. This paper provides an overview about a radio frequency technique that was emerged by an extension of state of the art eddy current techniques. Typical tasks of radio frequency techniques are the determination of fibre bundle orientation, misalignments, gap size distribution, local fibre areal weight/thickness and waviness. By measuring dielectric properties curing effects, hotspots, dry spots and polymer degradation can be analyzed, too. The RF technique shows a high potential to be used as an integrated inspection technique along the whole value chain and product life time by imaging the electrical and capacitive properties of CFRP nondestructively (Table 1).

2. Radio frequency inspection

Eddy current (EC) technology is a well-established nondestructive method for the characterization of surfaces or materials by analyzing conductivity and permeability variations [2]. A primary magnetic field is generated when an alternating current is applied to an induction coil. Eddy currents are generated in a conductive specimen when the coil is placed near that specimen (Fig. 1).

The eddy current within the specimen generates a secondary magnetic field opposed to the primary field. If the material properties are changed e.g. due to a deviation of current paths resulting from cracks or insertion in the sample, the secondary field also changes and causes an complex impedance shift in the pick-up coil. The measured values from the pick-up coil are evaluated on the complex impedance plane. An important parameter is the frequency of the excited alternating current. Due to the skin effect, the depth of excitation in the specimen decreases with increasing frequency. The point where the eddy current density has decreased to 1/e, or approximately 37% of the surface density, is called the standard depth of penetration δ [1]. The excitation depth into a material is affected by the frequency of the excitation current $\omega = 2\pi f$, the electrical conductivity σ, and magnetic permeability μ of the sample as given by:

$$\delta = \sqrt{2/\omega\sigma\mu} \tag{1}$$

This skin depth effect is the most important limitation for frequency selection during inspection. E.g. due to the good conductivity of Aluminum a frequency in the kHz range or lower has to be used to generate an acceptable probing volume for conventional crack detection in Aluminum structures. But beside the penetration problem frequency has a second important effect. By the use of higher frequencies, the penetration depth will be lost but increasing signal strength can be obtained. The density of the eddy current is influenced by the frequency itself. The Faraday's law of induction states that the induced voltage is proportional to the rate of change of the magnetic flux. In other words, since a frequency is an inverse of time, when the frequency of the flux increases the pick-up signal, which can equally be regarded as induced voltage (V), also increases. For CRFP a probate solution for determining the signal Voltage for CFRP is given in Ref. [5]. Higher frequencies therefore represent a good option through which the sensitivity of the Eddy current method can be increased for low conductive materials such as Carbon materials due to the extended tradeoff between penetration depths and signal amplitude.

Depending on conductivity and permeability of the material under test, an optimal frequency within the electromagnetic spectrum exists, exhibiting a suitable ration between penetration depth (equals to probing volume) and signal strength [6]. Table 2 gives an overview about the use of electromagnetic spectrum for NDT purposes. The HF range that is suitable for testing CFRP materials is located between the traditional medium frequency eddy current and the microwave and terahertz range.

3. Electrical properties of CFRP and measurement setup

Unidirectional single layered carbon fiber material has a conductivity up to $\sigma = 5*10^6$ S/m in longitudinal and $\sigma = 1*10^3$ S/m in the lateral direction. Through variation of fibre type, fibre orientation, stacking sequence, fibre/volume content, fibre density and compaction around the carbon rovings, these values differ. In

Table 1
Questions to be answered by NDT along the CFRP value chain.

	Process step	Question to be answered by NDT
1	Carbon rowing	Number of filaments? Type of filaments, cuts or damage?
2	Fabric	Number of layers and its orientation? Misalignments/waves/gaps? FOD insertions?
3	Preform	Right stack pre assembly? Waves or misalignments after draping
4	Component	Dry spots, curing process successful? Delamination?
5	Product life cycle	Degradation of fibres? Degradation of polymer? Re-qualification or recycling?

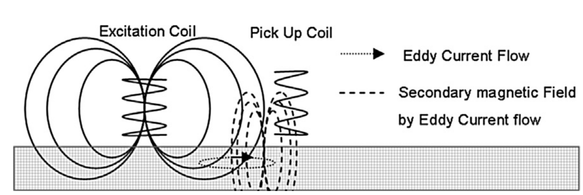


Fig. 1. Schematic diagram of probe and specimen configuration for eddy current testing.

Table 2
The electromagnetic spectrum [9,10] and its use for NDT purpose.

	Frequency nomenclature	NDT purpose
VLF	Very low frequency 3 kHz–30 kHz	Metal objects/high penetration depth *(e.g. Steel Plates/tubes with several cm penetration)*
LF	Low frequency 30 kHz–300 kHz	Metal objects/surface inspection *(e.g. Weld inspection, Surface Cracks)*
MF	Medium frequency 300 kHz–3 MHz	Thin metal objects with high resolution needs *(e.g. Crack detection in thin (mm) Aluminum sheets)*
HF	High Frequency 3 MHz–30 MHz	Weak Conductive Materials *(e.g. Thin Film Characterization, **CFRP Testing**)*
VHF	Very high frequency 30 MHz–300 MHz	Semiconductors, dielectric spectroscopy *(e.g. Solar Cell, Polymers, Curing)*
UHF	Ultra high frequency 300 MHz–3 GHz	Insulators, coatings, *(e.g. Ground Penetrating Radar GPR, Microwave Testing of GFRP)*
SHF	Super High Frequency 3 GHz–30 GHz	*(e.g. Radar, Microwave Testing of dielectric Material, Paint thickness measurement)*
EHF	Extremely High Frequency 30 GHz–300 GHz	*(e.g. Radar, "Terahertz" Testing, Security Application "naked scanner")*
THz	"Terahertz" 300 GHz–3 THz	*(e.g. "Terahertz" Testing, Spectroscopy)*

addition to the conductivity of the CFRP also its permittivity is important for RF testing. It generates a displacement current in the material, which influences the measurement signal as well as the eddy current [11,12]. In a dry carbon material, the permittivity is dominated by the fiber coating and the surrounding air. In a CFRP the air is substituted by a polymer resin, so that the permittivity is depending on type and processing quality of the resin [11]. Fig. 2 shows the main electrical effects of applying an alternating magnetic field to strongly anisotropic CFRP material that are influenced by three main parameters.

a) Fiber/Volume Ratio: The Fiber/Volume ratio determines the amount of conductive carbon fibres in a volume section and defines the average electrical conductivity of the material, which needs to take into account for general measurement parameterization (frequency, penetration depth).
b) Electrical connection between fiber bundles: Depending on the structure (woven, crimped, non-crimped etc.) chemical and structural conditions of the interfaces of filaments and the consolidation density due to mechanical pressing, the electrical contact between neighboring bundles can vary. Identical materials can provide different degrees of eddycurrent propagation due to the quality of internal electrical connections during consolidation. The horizontal electrical connection between fiber bundles (in plane, parallel to the surface) is direct influencing the contrast of the RF image. The vertical connection in depth direction is influencing the interlaminar interfaces [4] and thereby the penetration depth.
c) Capacitive effect and displacement current: In addition to the electrical connection of fiber bundles, the dielectric properties of the matrix material also influence the complex signal impedance.

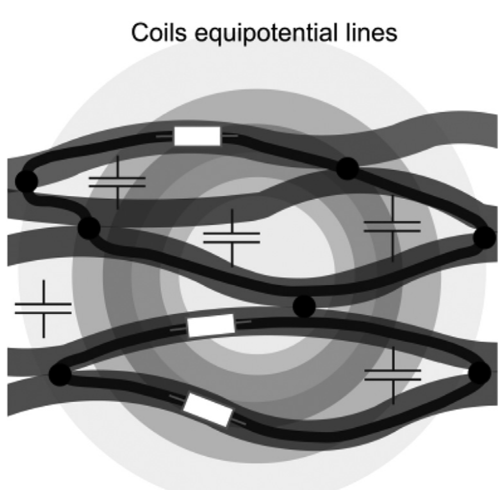


Fig. 2. Electric and dielectric behavior of carbon matrix composites [3].

This three parameters can be analyzed by RF EC instruments. Medium frequency eddy current (MF EC) inspection instruments are available in many configurations by different commercial suppliers. Typically, the instruments are designed for manual handling of a single coil sensor or array probe with wheel tracker. The frequency range and parameterization of such standard devices is optimized for conventional NDE task such as crack detection or material identification for metallic specimens. Also, mechanical manipulators like X-Y-Z axle scanners or robot based manipulators are in commercial use to scan an EC probe over a 3 dimensional surface (e.g. rotor blades). For low conductive carbon based materials, a contrast enhancement at frequency's up to 50 MHz, and in some special cases up to 80 MHz was observed. One reason is the increasing signal strength due to the Faraday law of induction, second the decrease impedance of the capacitive structure of CFRP at higher frequency [5]. This frequency range was usually observed only in laboratory based equipment [12]. Initiated by the increasing demand for HF eddy current measurements, instruments operating in the range of 100 kHz up to 100 MHz were developed. The results shown in the following chapters where acquired with EddyCus® instruments. Combined with a precision X-Y-Z manipulator with minimum 25 μm step width, high resolution HF EC images can be acquired. The sensors glide non-contact or lightly contacted over the surface. The used system can capture a maximum surface area of 300 mm by 300 mm with a maximum speed of 300 mm/s at a sampling rate of 3000 samples per second. In addition, the EddyCus® software provides a frequency sweep mode between 100 kHz–100 MHz with 256 steps or a sequential multi-frequency data acquisition with up to four frequencies. The instrument allows the acquisition of complex HF EC signals in amplitude and phase shift in the complex impedance plane and as a time plot by C-Scan [6].

To perform eddy current measurements in a frequency range above 1 MHz mechanical vibrations (lift off variations) and electromagnetic disturbance needs to be controlled precisely. Also, electrical conductive dust in carbon contaminated environments can deteriorate the measurement results. To solve this practical problem a robust setup needs to be used that is shielded against dust and has an EMS safe architecture (Fig. 3).

The used probes for CFRP inspection are based on copper wires winded on ferrite cores. The coil diameter differs between 2 and 7 mm in accordance to the requested spatial resolution and sensitivity. The following experimental results were obtained by half transmission probe configuration with two 5 mm coils. Due to the geometric distance between the sending and receiving coil (Fig. 1) the sensitive field of view of the probe is elliptical and the observed spatial resolution is higher than the core diameter. The parameterization of the frequency is done by a frequency sweeping at different points on the CFRP surface. The frequency's showing the best contrast for the specify inspection task are than used for scanning. The resulting frequency parameterization is a function of a) coil properties, b) material properties to be tested and c) the type of needed contrast mechanism inside CFRP. The determination of fiber

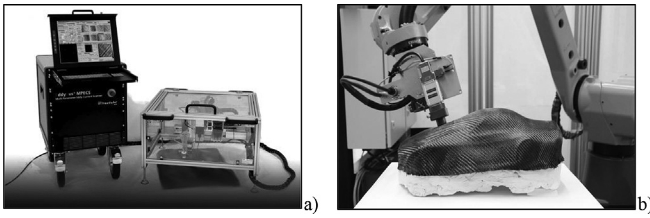


Fig. 3. EddyCus® systems a) Linear Axis system for flat and slightly curved structures and b) Robot based system 3d structures.[1]

texture requires contrast between fiber bundles (gaps) whereas the inspection of hot spots or polymer defects need contrast by dielectric properties of the specimen. The used optimal frequency is always a setup individual parameter and differs between different samples and inspection task. The frequency adjustment is typically done by 0.1 MHz steps for maximizing the image contrast.

4. Experimental results

4.1. Inspection of texture and waviness

As shown in Refs. [12,13] the HF eddy current technique can be applied to dry, wet and consolidated carbon based materials. One major task of HF EC is the characterization of waves inside carbon fibre preforms or consolidated materials. The image of Fig. 4 shows in-plane and out-of plane waves perpendicular to each other. The In-plane wave can be seen directly due to the typical not straight forward orientation of the fibre bundle. A out-of- plane wave shows a modulation of the signal amplitude as gray value contrast.

Due to local changing of fiber volume content the signal amplitude changes depending on the out-of-plane wave position. In Fig. 4 the out-of-plane waves are indicated by black contrast change compared to the typical undulation of in-plane waves. Due to this different contrast mechanism it follows that in-plane waves and out of plane waves require a different algorithm for evaluation. For industrial application of HF EC imaging techniques, the textural information like roving orientation, gap sizes or waviness needs to be extracted by image processing. Especially for multi axial materials, a two dimensional fast Fourier transformation (2D-FFT) shows high potential for automated fiber texture analyses [13]. In textured materials the image frequency is correlated with the periodic structure. In relation to the texture of CFRP fabrics, the image frequency correlates with gap size and fiber bundle size whereas the rotation of the image frequency maxima represents a layer orientation. The Fig. 5a) shows a HF EC Image of a 3 axial non-crimp fabric with two horizontal layers on the back side. The corresponding 2D-FFT of Fig. 5b shows the 3 characteristic lines indicating the 45°, 0° and −45° layer.

Inside the 2D FFT data in Fig. 5 b each point bar contains information for one specific CFRP orientation. By setting a filter that is suppressing all points except the point bar from the layer and performing an inverse 2D-FFT the textural image of one individual layer can be reconstructed. The procedure is descript in Ref. [13]. The Fig. 6 shows such a reconstruction of one layer of Fig. 4 with significant in-plane undulations [13].

4.2. Characterization of defects according to their depth

The modulation of the signal amplitude as a function of the depth of an out-of-plane wave can be explained by formula (1) and (2). The eddy current density decays exponentially with increasing depth. For an isotropy material with good conductivity, the current density can be calculated by:

$$J(d) = J_s e^{-d\delta} \tag{2}$$

where J_s is the Current density at the surface, d is the depth of object and δ the penetration depth shown in (2), [8]. But due to the strong anisotropy of CFRPs, this relation can be used only as rough estimation. To validate the in-depth resolution for a specific CFRP material, a reference sample with insertions in different depth has to be used. Fig. 7 shows a HF EC Image of CFRP plate with 14th layers of GV 300 U TFX (12 k) non crimped fabrics with a grammage of 317 g/m^2 for each layer and fiber volume content of 67%. During the laydown process, pieces of copper foil where inserted between different layers. The shape of the copper foil was used to identify the insertion depth by reference after curing.

With increasing depth the signal amplitude and the phase angle where the maximum amplitude occurs is changing. In the following diagram Fig. 8, the signal amplitude over the number of CFRP layers covering the copper foil is shown. An exponential decay of amplitude such as expected by formula (2) was found. In this special case the copper insertion was seen until the 12th layer. The phase angle where the amplitude reaches a maximum shows a linear dependency until the 7th layer from the surface. For the deeper regions between 7th and 14th layer the phased angle seems to be constant or is slightly decreasing. This behavior was not investigated yet but was be reproduced in additional experiments.

It turns out that not only insertions of higher conductive materials like copper, but also lower or non-conductive materials could be found. A rectangular sandwich panel measuring 300 × 210 mm with FOD inclusions was made consisting of an Ω stiffener of Rohacell 110 WF-HT covered with 8 CFRP fabric layers

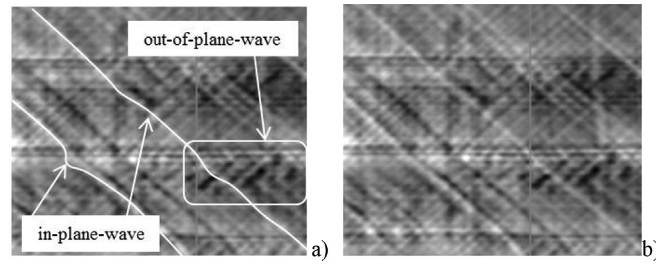


Fig. 4. HF EC Images of CFRP plates with in-plane and out-off-plane waves. (Size 150 × 150 mm x 5 mm). a) indication of wave position, b) raw data image.

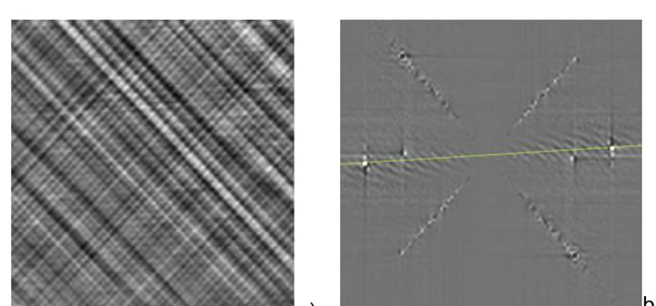


Fig. 5. Analyzing the image frequencies of a 5 layer CFRP (30 × 30 cm) with two horizontal layers that differ by 2°. a) shows the raw HF EC, b) corresponding 2D FFT (rotated by 90°), The green line indicated the misaligned horizontal layer. (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of this article.)

[1] http://www.youtube.com/watch?v=wNng6ClM1CM.

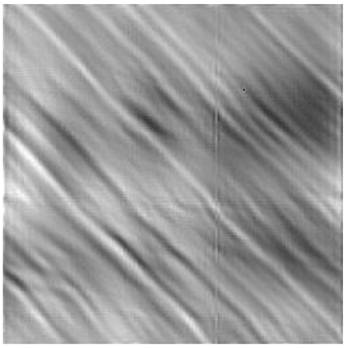


Fig. 6. Analysis In-Plane waviness of Sample in Fig. 4 by Filtering in the Fourier Space and following inverse FFT.

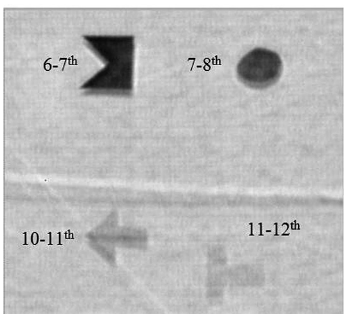


Fig. 7. HF EC Image at 8.12 MHz (phase 50,5°) of CFRP with inserted Copper foils in different depths.

(977-2A-37%-3kHTA-5H-280-1200) and 4 additional UD layers (977-2-34-12KHTS-196-T1-150) at the Ω top. Four types of FOD inclusions are inserted at different depths, all measuring 10 × 10 mm: 1. copper mesh (M21/67%/ECF73 + V12/900 mm), 2. Flashbreaker® tape 0.18 mm thick, 3. UD-backing paper (0.1 mm thick, ±130 g/m^2) and a 0.13 mm thick Polyethylene prepreg release foil. In Fig. 9 the position of the insertion an the Ω is illustrated.

The copper mesh was included as a reference and is still detected under 8 layers of CFRP fabric and 4 UD layers (in total 12 layers). The detection depth of the tape, polyethylene foil and paper are 6 fabric layers and 3 UD layers respectively. On top of the Ω structure, this is increased to 7 CFRP fabric and 3 UD layers respectively. The increased detection depth is probably due a

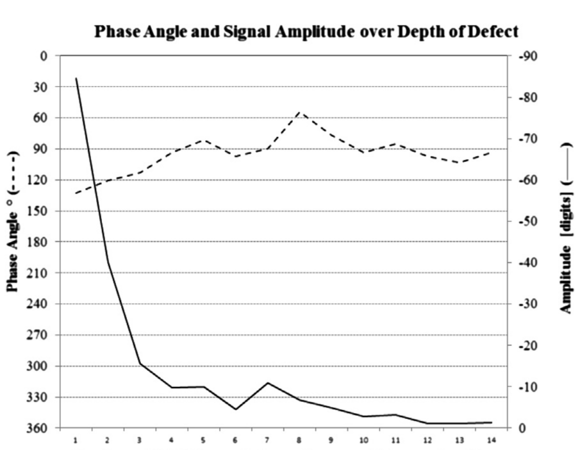


Fig. 8. Decay of signal amplitude with increasing depth of the inserted copper foil.

reduced amount of air inclusions on the Ω-top. In another experiment a CFRP plate with cut out wedges was produced. In Fig. 10a) the position of the cut outs are shown, in Fig. 10b the corresponding HF EC image is shown respectively.

In the area of the cut out, the fiber orientation is disturbed but shaped CRFP parts often require a termination of hidden layers inside a multilayer stack.

Shaped CRFP parts often require a termination of layers inside a multilayer stack (so called "ply drops"). For quality assurance the number of the terminating layers must be determined. As shown in Fig. 11, the area around ply drops has a characteristic electrical behavior that allows an imaging of the terminating zone by a signal strength variation.

4.3. Determination of local areal weight and carbon fiber volume content

Besides analyzing the texture, another quantitative parameter, the local areal weight, can be determined by HF EC. Particularly, for non-woven fabrics such as fleece or recycled short fibers, this parameter is more of interest for quality assurance. Basis weight is defined by weight per area square typically given in g/m^2 or gsm. The realized prototype system is able to non-destructively measure the basis weight within a 25 mm diameter spot size. In comparison to sensors used for textural analysis, the sensors for basis weight determination are using a comparably larger measurement spot, which allows quantitative measurement at a reasonably sized area. The advantage of using eddy current measurement is its ability for inline integration (no contact, no radiation) and the potential for comprehensive data analyses. In order to determine properties of an unknown specimen the system will be calibrated with known reference samples first [16,17].

The base weight data can be displayed as single value or, when captured as an EC-scan, as a homogeneity image. Such an EC-scan is depicted in Fig. 12, showing the uniformity of the sample. When using a narrow tolerance or a filtering of the scale, minor inhomogeneities are revealed (Fig. 13).

As shown in Fig. 12 five A4-sized dry carbon fiber fleece samples were measured in the center. The darker the image appears the higher the carbon fiber content within the measurement spot is. The fleece uniformity can be visualized by enhancing the contrast of a narrow EC value range (Fig. 13).

For fast inline applications a prototype of a multiple sensor systems for base weight monitoring was realized (Fig. 14).

The system has been evaluated for grammages of 30 gsm up to 2500 gsm. The achievable accuracy is better than +/5%. In addition the method can be used to determine the carbon fiber volume content of composites. Particularly, for chopped fibers in SMC or thermoset composites, the uniformity mapping shows areas of large accumulation of fibers or areas of low fiber density. In addition, the general fibre alignment can be investigated too. Sensor with oval shaped measurement spots are very sensitive to fibres aligned in the same direction. This focus of the sensor can be utilized to obtain more information on the dominant fiber orientation within the sensors.

4.4. Characterization of infiltration and curing

As explained in chapter 2, not only the conductive carbon fibres but also the permittivity of the matrix material influences the eddy current measurement signal. This effect can be used for quality control of processes, where the complex permittivity of the composite changes [11]. So, potential applications could range from cure monitoring (*e.g.* resin flow front detection, determining the degree of polymerization) to the testing of consolidated CFRP with

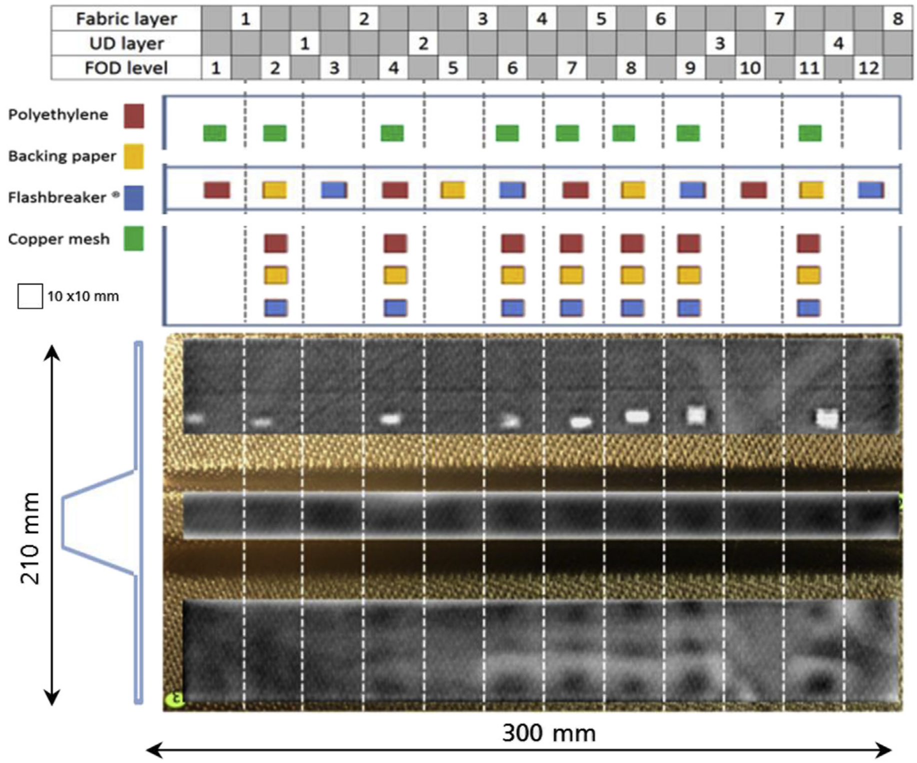


Fig. 9. Schematic image FOD sample shows the type and position of different insertions with the corresponding RF EC image.

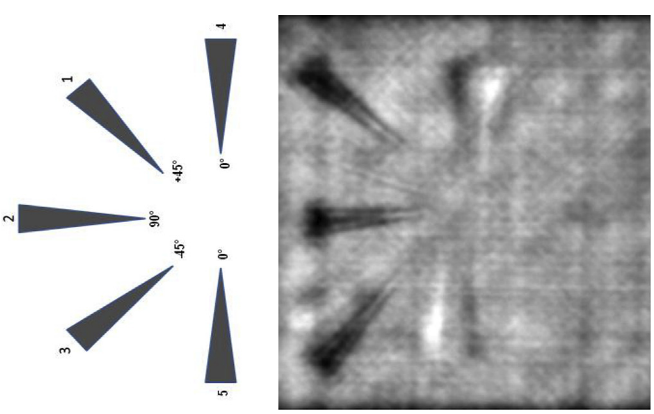


Fig. 10. HF EC Image of dry NCF plate with 5 UD Layers with cut out wedges in several depth. Sample Size 300 × 300 mm.

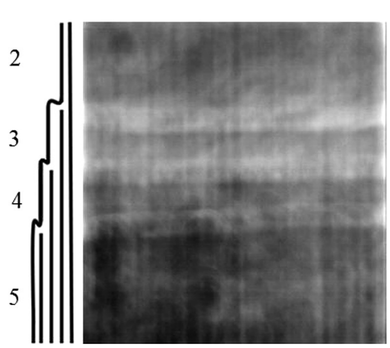


Fig. 11. HF EC Image from backside of NCF sample with 5 layers of which 3 are terminating. Sample Size 300 × 300 mm).

focus on infiltration or curing defects. A typical infiltration defect is the occurrence of unimpregnated dry spots [14,15]. That means that there is not enough resin reaching a certain area of the CFRP part. Consequently, matrix material is lacking locally. Which result in a deviation of local permittivity and local conductivity, especially at the contact points between roving's. Consequently, this defect can be identified using eddy current, even when it occurs within the non-visible layers. The dry spot sample in Fig. 15 was measured at 13, 22 MHz and shows the transition zone between infiltrated and no filtrated areas as black contrast.

In addition to the ‘dry spots’ also ‘hot spots’ within a CFRP component can be identified using eddy current technology (Fig. 16). Those defects can occur when component structure doesn't allow an appropriate heat distribution, while dissipating the thermal energy that is generated during the curing reaction. If the temperature of the spot stays bellow the glass transition temperature of the resin (at that specific state of cure) the curing process gets faster. If temperature climbs above that temperature, thermal damage of the matrix material is the consequence [11].

Even in complex CFRP structures the ‘hot spot’ within the matrix can be well separated from fiber related effects. The change of the complex eddy current signal due to conductivity variations (e.g. varying number of layers) has a different direction compared to the change resulting from permittivity variations (Fig. 17). The differentiation towards edge and lift-off effects is more challenging and requires further research work to be conducted.

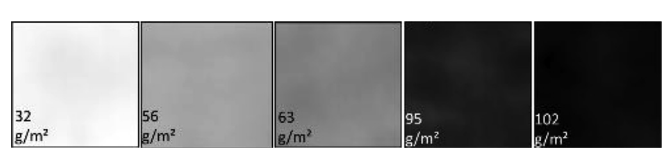
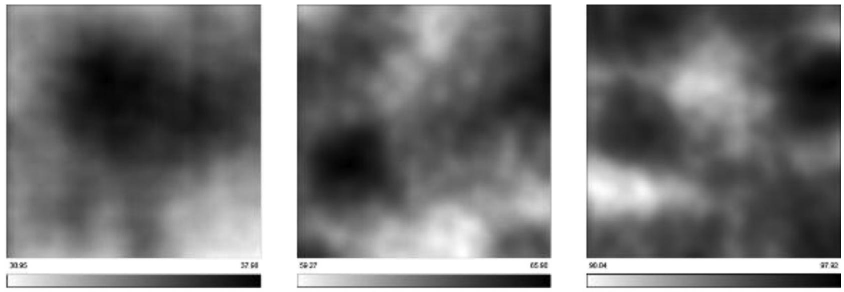


Fig. 12. EC contrast function for Carbon fleece with different weight per area (100 × 100 mm).



g/m²	Left	Center	Right
Target	32	63	95
Min	30.5	58.3	89.2
Av	34	62.4	93.7
Max	39	66.4	98.1

Fig. 13. Visualization of Uniformity of fleece (100 × 100 mm) by image contrast enhancement (adaption of histogram).

5. Conclusion

In the decision matrix of NDT methods for CFRPs, the HF EC method can provide unique information when compared to other NDE methods. CFRPs exhibit an electrical conductivity enabling the use of electromagnetic testing techniques. In recent years, high resolution eddy current imaging technology has been substantially developed further. HF EC Imaging is a potential technology for inspection of raw carbon fiber fabrics, infiltrated wet prepregs and consolidated CFRPs. HFEC based methods are interesting due to the simplicity of machinery integration, allowing HF EC sensors to be directly integrated into the process chain without affecting the material properties and quality. Textural analyses and fault testing can be performed with an image quality up to 500 μm resolution. Analyzing the quality of semi-finished products such as reinforcement fabrics very early in the value chain can help to increase the yield of the production process and the safety of the final product.

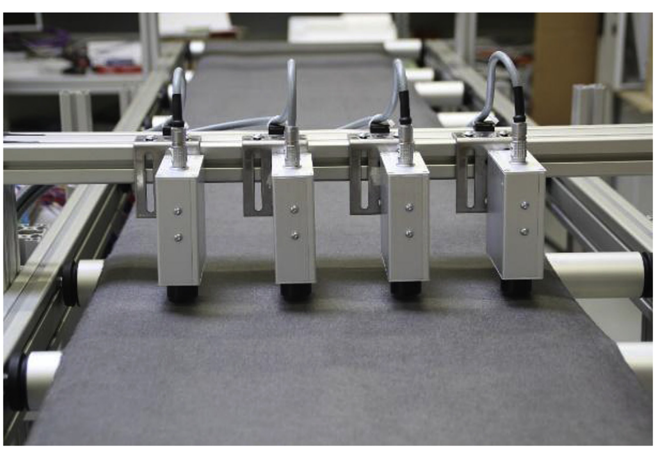


Fig. 14. Prototype EddyCus® Inline for Inline gramature determination by RF EC.

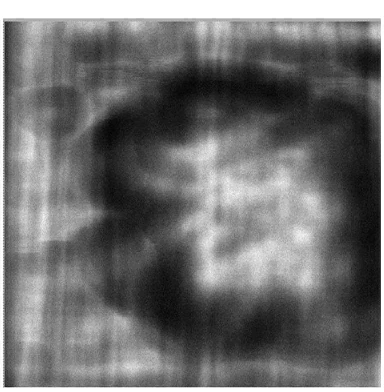


Fig. 15. Eddy current Image of CFRP sample with a 'dry spot' (Image Size 150 × 150 mm).

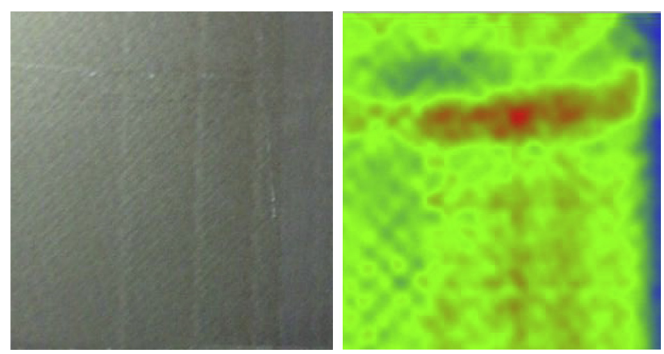


Fig. 16. Photography and Eddy Current Image of 10 × 10 cm CFRP sample with a 'hot spot'.

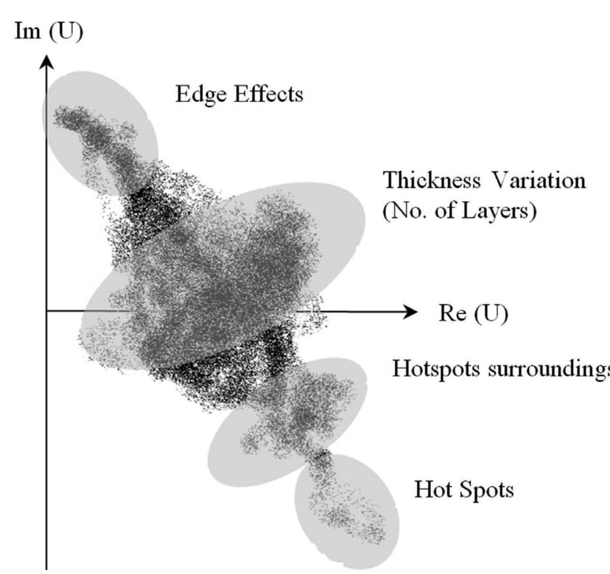


Fig. 17. eData of 10 × 10 cm CFRP sample with a 'hot spot' displayed in the complex plane.

The initial trials of FOD detection of a Ω stiffener in the prepreg stage proved to be successful up to 4 CFRP fabric layers deep in this configuration. This opens up the potential of two inspection intervals per stiffener in serial production. Small scale trials with manually operated probes are required to validate shop floor use and quantify real life inspection speeds. The potential to inspect terminating layers offers the possibility to integrate HF EC technique into a fully automated system for research on the production of airplane parts e.g. frames in the fuselage, produced in a RTM process at the DLR in Stade, Germany. The characterization of permittivity changes allows at the characterization of the curing process. In a long term vision the possibility of a non-destructive characterization of CFRPs textural properties may open the way for more accurate structural design and more consequent light weight design. Experiments currently conducted have to show if HF EC can be used to monitor CFRP ageing by observing deviation of dielectrical properties of the polymer matrix due to matrix degradation.

Acknowledgment

Parts of this work were supported by ERDF through the Free State of Saxony, Germany, as well as by the German Ministry of Education and Research. Further we would like to thank Prof. Johann Hinken and Reinhold Oster for fruitful discussions.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.compositesb.2015.03.022.

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