CHARACTERISING METAL - CFRP HYBRID STRUCTURES BY NONDESTRUCTIVE TESTING METHODS

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ABSTRACT
In this work an aluminium - thermoplastic - CFRP (Carbon Fibre Reinforced Polymer) hybrid structure is characterised by the comparison of different nondestructive testing methods. Especially the interfaces and the CFRP itself are investigated. It is shown that with active thermography defects in the interface and in the CFRP itself can be detected and determined. The bonding of metal and thermoplastic can be characterised very well by ultrasonic testing with electromagnetic acoustic transducers (EMAT).

Keywords: Metal - CFRP hybrid, nondestructive testing, thermography, EMAT.

INTRODUCTION
To reach the permissive limits concerning CO2 emissions, it is necessary to optimise the weight of highly used means of transportation such as cars, trains or planes. Because of the fact that CFRP has a highly specific strength and stiffness while being very light at the same time, the use of this material increases. Nevertheless a complete substitution of metal by CFRP is economically not viable. Hence a new metal - CFRP hybrid is introduced in this work. To avoid corrosion and to reduce the gap of stiffness a thermoplastic polymer is inserted between the metal and the CFRP structure by injection moulding. This thermoplastic component also guarantees functional integration such as surface structuring (for further information see (Schwarz, 2015)). However, through this additional component two interfaces are created where defects likely occur (Casas-Rodriguez, 2008).

These defects occur either during the production process or under mechanical load. Therefore the interface between metal and thermoplastic is characterised by ultrasonic testing with EMAT, similar to (Castaings, 2014). The interface between the thermoplastic and CFRP as well as the CFRP itself are characterised by active thermography. To evaluate these testing methods, defects (e.g. delamination, pleat and 10° misalignment) are artificially implemented into the CFRP component. In previous works it was shown that these artificial defects can be characterised very well (Schwarz, 2016).

The hybrid structure shown in this work consists of three different materials. The CFRP component is an 3K plain weave with 30 vol% of carbon fibre embedded in an epoxy matrix and is made up of four layers [0°/90°, ±45°]s. The thermoplastic is a Polypropylene (PP) and the metal is an EN AW-6082 (AlSi1MgMn) aluminium.
THERMOGRAPHY

In general there are two different methods of measurement in thermography, passive and active thermography.

For active thermography an external excitation is needed to achieve a thermal contrast in the specimen. As excitation source ultrasonic, eddy current, laser, halogen lamps or flash generators can be used. In this work flash light is used, because it is a very fast and contactless method. Furthermore the measured data is captured as image and can be used for a qualitative assessment of inhomogeneities without an additional data or image processing.

After the specimen is excited an infrared camera with Stirling cooler captures the thermal radiation, as depicted in Fig. 1. The utilised infrared camera (Fig. 2) is a so-called Dualband camera which is able to capture the radiation of midwave (4.4 - 5.2 µm) and longwave (7.8 - 8.8 µm) infrared. The detector type of the camera is a FPA (focal plane array) QWIP (Quantum Well Infrared Photodetector) with a lateral resolution of 384x288 pixels. The temperature sensitivity is 25 mK and the pixel pitch is 40 µm. Furthermore the camera is able to record a frame rate of 300 Hz (Thermosensorik, 2009).

Fig. 1 - Measurement configuration of thermography testing

Fig. 2 - Infrared camera with device for flash excitation
The surface of objects whose temperature is above absolute zero radiates energy in form of infrared radiation (Meola, 2012). As the emitted radiation is a function of temperature, it can be concluded that with a higher temperature the radiant power increases.

There are three possibilities for the radiant how to interact with an object: absorption, reflection and transmission (Mollmann, 2005). To describe these properties the following parameters are used: absorbance, reflectance and transmittance. These parameters are wavelength dependent and, as described in equation (1), the sum of them must be one at any wavelength (Maldague, 2001):

\[ \alpha + \rho + \tau = 1 \]  

Where \( \alpha \): absorbance, \( \rho \): reflectance, \( \tau \): transmittance

Materials with reflectance and transmittance equal to null are called blackbodies. In these materials all of the striking radiant energy is absorbed (\( \alpha = 1 \)). All of the energy absorbed must be radiated (emitted) again, so the emissivity has to be one. The emissivity of a surface is defined as (Maldague, 2001):

\[
\varepsilon(\lambda, T, \theta', \phi') = \frac{L'_{\lambda}(\lambda, T, \theta', \phi')}{L_{\lambda,b}(\lambda, T)}
\]  

With \( L'_{\lambda} \): spectral radiance of a surface, \( L_{\lambda,b} \): spectral radiance of the black body

As a result can be said that emissivity and absorbance of a blackbody has to be equal (Maldague, 2001), see Kirchhoff’s law in equation (3):

\[ \alpha = \varepsilon \]  

Where \( \alpha \): absorbance, \( \varepsilon \): emissivity

In (Usamentiaga, 2014) it is described how to get to the Stefan-Boltzmann formula (4). This formula gives the relation of temperature and radiant power for a blackbody:

\[ W = \sigma \cdot T^4 \]  

Where \( W \): radiant power [\( \frac{W}{m^2} \)], \( \sigma \): Boltzmann constant [\( \frac{W}{m^2 \cdot K^4} \)], \( T \): temperature [K]

To capture the radiation of a specimen by an infrared camera, it has to be guaranteed that the absorbance and thus the emissivity (cf. equation (3)) is high enough to get sufficient radiation. Since normal specimens do not act like blackbodies it could be necessary to colour the surface black to decrease reflection processes. Because of the natural black colour of CFRP a colouring is not necessary. While recording the radiation, defects act like thermal barriers and are depicted as bright areas in the infrared image.

In addition to the analysis of the radiation during the cooling process, the radiation can also be recorded through the lock-in method while the specimen is heated up. In this work the intensity of eddy current is modulated by a square signal while the infrared camera captures the radiation at the specimen’s surface. This method is called induction-lock-in thermography (ILT) and it is used because of its short inspection time and high proof sensitivity (Carl, 2005). From the measured image sequence an amplitude image and a phase image can...
be calculated through Fourier transform. In a phase image some disruptive effects that are caused by e.g. inhomogeneous excitation are decreased. To vary the thermal penetration in the material, the modulation frequency can be changed (cf. equation (5)).

$$\mu = \sqrt{\frac{\alpha}{\pi f}}$$  (5)

Where $\mu$: thermal penetration $[\text{m}]$, $\alpha$: thermal diffusivity $[\text{m}^2\text{s}^{-1}]$ and $f$: modulation frequency $[\text{s}^{-1}]$.

In contrast to active thermography techniques, passive thermography does not need any external excitation methods. As deformation processes and friction cause internal heat dissipation within the material, passive thermography can be applied for \textit{in situ} damage monitoring. Temperature variations caused by internal heat dissipation can be described as a superposition of thermoelastic temperature variation $\Delta T_{\text{el}}$, heat dissipation $\Delta T_{\text{diss}}$ and heat exchange with the environment $\Delta T_{\text{loss}}$, see equation (6) (Rösner, 2004):

$$\Delta T(t) = T(t) - T_0 = \Delta T_{\text{el}}(t) + \Delta T_{\text{diss}}(t) + \Delta T_{\text{loss}}(t)$$  (6)

Where $\Delta T$: total temperature change, $T_0$: absolute reference temperature at $t=0$.

Commonly applied methods are MIDA (mechanical induced dissipated heat analysis) or TSA (thermal stress analysis), which enable the identification of weak spots or defects by local temperature hot spots during mechanical testing.

By using thermography as nondestructive testing method there is the possibility to detect defects in the CFRP-structure and at the interface of the hybrid. Furthermore the sample can be characterised before, after and during mechanical testing by active and passive thermography, respectively. Finally, there is the possibility to compare the different thermography methods to achieve the best characterisation of defects.

**SHEAR HORIZONTAL GUIDED WAVES (SH-WAVES)**

In addition to thermographic methods, there is the opportunity to use shear horizontal guided waves (SH-waves) to characterise the hybrid structure. SH-waves are a special form of ultrasonic waves propagating in plates. They are characterised by an oscillation of the lattice atoms in the plane parallel to the surface and perpendicular to the direction of propagation. Provided that the oscillation is in the same dimension as the ultrasonic wavelength, oscillation occurs in the entire thickness of the plate. This vibration spreads along the whole plate until it is reflected at sharp edges, i.e. at the end of the plate.

SH-waves are used to investigate metallic structures (Petcher, 2014) but they are also proved to be promising for the application on adhesive bonded samples consisting of two metallic plates (Arun, 2011), (Castaings, 2014) as well as polymer/composit parts (LeCrom, 2010), (Pérès, 2011).

In this work SH-waves will be excited with electromagnetic acoustic transducers (EMAT). The advantage of EMAT in comparison to the normally used piezoelectric transducers is that no couplant medium is needed (Salzburger, 2012). Furthermore it is a contactless method. As this method is used to characterise, inter alia, adhesive bonded samples (Castaings, 2014)
further advantages arise. Due to the fact that the waves propagate along the whole surface and because of their long-range capability, it is possible to excite waves apart of the join. At the same time inaccessible locations can be reached (Figure 3).

This fact creates further advantages like fast and cheap testing. However, the sample either has to be conductive or ferromagnetic. Because of that fact the suitability of CFRP is limited. The ultrasonic testing with electromagnetic acoustic transducers is excited either by the Lorentz force or by magnetostriction (Neumann, 1995). By using surface acoustic waves with this kind of ultrasonic testing the interface between the metal and the polymer in the hybrid structure can be investigated. Especially the quality of the connection between the two components and also defects can be characterised.

**MECHANICAL TESTING**

After the characterisation with active thermography, the hybrid-joints with different artificially implemented defects as well as defect-free ones were subjected to mechanical testing.

In previous investigations on the influence of implemented defects on mechanical properties of CFRP it is shown that significant attenuations were caused by 10° misalignment, pleat and delamination (Summa, 2016). The tensile strength and the stiffness strongly decreased whereas fatigue failure emerged up to two decades earlier than for defect-free specimens. Moreover passive thermography revealed that the evolution of a dominant hot spot was promoted in the presence of aforementioned defects, which indicated interlaminar failure.

For mechanical investigations the hybrid-joints were mounted on an Instron 8500 with a 100 kN load cell with action side grips and 25 mm clamping length from both sides. Fig. 4 shows the experimental setup. According to DIN EN ISO 527-4, quasi-static tensile tests were driven displacement controlled with 2 mm/min cross-head speed.
In situ damage monitoring by passive thermography was carried out with an InfraTec VarioCAM® HD head bolometer camera with a resolution of 1024x768 pixels. The camera's interval of spectral sensitivity ranges from 7.5 to 14 μm and its temperature resolution is beneath 0.05 K (at T = 303.15 K).

This technique makes it possible to reveal weak points and damage propagation due to local temperature changes. However, tensile loading has been applied to the insert, which was accompanied by growing mode-I separation of the CFRP-laminate until the force resistance vanished.

RESULTS

To validate nondestructive testing methods, measurements on CFRP-samples with artificial defects were performed in previous works (Schwarz, 2016). For example, it was shown that gapping or pleat defects can be characterised very well by active flash thermography. In this work, samples are measured with flash and inductive thermography.

In Fig. 5 two pictures of hybrid samples are depicted. In both figures, the metal-thermoplastic insert with its fir tree structure can be seen very well. The sample in the left image has a pleat defect in the first (top) CFRP layer which is already visible to the naked eye. Contrary to this, the sample in the right picture has a pleat in the second layer of the CFRP. This pleat cannot be seen at the surface.

Fig. 5 - Pictures of hybrid samples with pleat in first (left) and second (right) layer

In contrast to the pictures in Figure 4 the infrared pictures appear very similar. In the left picture of Figure 6 the infrared image of the sample with the pleat in the first layer is shown.

Fig. 6 - Infrared pictures of hybrid samples with pleat in first (left) and second (right) layer
Besides the metal-thermoplastic insert that can be detected on first sight there is a pleat which is easily visible in the middle. In the right picture the infrared picture of the sample in the second layer is shown. As in the left picture the insert is easily detectable. Although the pleat is not visible at the surface (see Figure 5) it is detectable with thermography. In addition to the pleat in the middle of the image there is a fibre irregularity in the right corner. Furthermore there are three bright areas at the end of the “arms” of the fir tree structure. These areas are inhomogeneities at the surface of the sample.

Besides flash thermography inductive thermography is also used as testing method. In Fig. 7 the effect of the coil position is depicted in phase images with a frequency of \( f = 0.28 \) Hz. In the left picture the coil is placed between the specimen and the infrared camera. In the right picture it is behind the specimen. The position of the coil makes no difference for the signal contrast, but the position in front of the specimen blocks the view on the same. In the middle of both images there is an area which is undefined. In this part no current flows through the material.

By using inductive thermography the fibre orientation can be detected very well. In Fig. 7 the contrast of the fibres give a quadratic structure. This effect is caused by the coil behind or in front of the specimen and occurs because of the better conduction of the fibre in comparison to the matrix material.

![Fig. 7 - Infrared images of hybrid samples with pleat and coil in front of (left) and behind the sample (right)](image)

The comparison of the flash and the inductive image shows that the contrast in the flash image displays the pleat better. But in return the induction thermography is better suited to characterise the fibre orientation, at least in the upper layer.

Additionally to the characterised hybrid samples in Fig. 6 and Fig. 7, active thermography can be applied after mechanical testing. In Fig. 8 a hybrid sample with delamination is shown after mechanical testing. In contrast to Fig. 6 the intensity does not evenly distribute. Around the insert- which can be easily seen- a bright area develops. This bright area indicates a delamination of the CFRP component from the thermoplastic, due to the mechanical testing. Furthermore two bright areas between the upper and the second “arm” of the fir tree structure can be recognised. These bright areas are artificially induced delaminations between the first and second layer of the CFRP. It can therefore be stated that delaminations which are either induced artificially during the production process or in a natural way by mechanical load, can be characterised very well by using active thermography.
In addition to thermography also ultrasonic testing is used to characterise the hybrid-joint. In cases of plate-like specimens the propagation of ultrasonic pulses occurs as shown in Fig. 9. The first signal is the direct signal between the transmitter and the receiver. The second and third signals are the reflection at the near or far end of the plate, respectively. By moving the transmitter and the receiver it shall be ensured that the signals do not overlap.

However, in Fig. 10 only the first signal is easily visible and the other signals overlap so that they cannot be clearly identified. Nevertheless statements about the condition of the metallic insert can be made. In the figure the signal of a metallic insert with thermoplastic (red line) is compared to the signal of a metallic insert without thermoplastic (grey line). The signal of the metallic insert with thermoplastic is significantly reduced. This indicates that the bonding to a thermoplastic causes an attenuation of the ultrasonic signal.
CONCLUSION AND OUTLOOK

In this paper it is shown that active thermography can be used to characterise different artificially induced defects in a metal-CFRP hybrid structure. A pleat can be detected very well by flash thermography no matter if it is in the upper or in a deeper layer of the CFRP component. Additionally a sample after mechanical testing can be identified without problems. By using induction thermography the fibre orientation of the CFRP component can be determined better than with flash thermography. Furthermore it is shown that the coil can be positioned behind the sample to not block the view. Besides thermography, SH waves are used to characterise the bonding between the metallic insert and the thermoplastic.

In further works it shall be examined which defects are identified the best by which testing method. An optimisation of induction thermography shall improve the detectable defect depth. Moreover a further comparison of the artificially induced and mechanically induced defects shall be performed.

Ultrasonic testing with SH-waves on hybrid joints shall be improved in future works. Also mechanically tested hybrid joints shall be characterised by SH-waves. A further method to monitor the condition of the hybrid joint is to establish ultrasonic testing with SH-waves in situ during mechanical testing, as reported in (Murayama, 2011).

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