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EFFECTIVE EMISSIVITY CHARACTERISATION AND CORRECTION FOR ACCURATE CONTROL OF AUTOMATED FIBRE PLACEMENT PROCESSES

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ABSTRACT

Material processing temperature can have a significant effect on Automated Fibre Placement (AFP) quality. Temperature is commonly measured using infrared cameras, which require an effective emissivity value for accurate measurement. A bespoke experimental setup was created to replicate AFP heating conditions and investigate the effect of external factors on effective emissivity for three separate processing materials. Effective emissivity was found to have a high variation at low temperatures and increase greatly with the presence of an AFP roller. For polyether ether ketone impregnated tapes, effective emissivity was shown to change behaviour at approximately 155°C, steadily increasing. These relationships can be used to improve temperature measurement and control for the AFP process.

1. INTRODUCTION

Automated Fibre Placement (AFP) is an additive layup technique in which a number of narrow composite tapes are combined within a deposition head and delivered onto a layup tool in a collimated band [1][2]. Deposition typically involves contact with a tool or substrate, applying heat with a machine or tool-mounted heat source and applying compaction with a roller [3]. AFP is highly automated and requires process control in order to produce components with consistent quality and dimensional conformance [2]. Processing temperature has been identified by a number of studies to have an important effect on preform quality and must be controlled throughout deposition [2].

Materials for AFP are mostly carbon-fibre based with either a thermoset matrix, high performance thermoplastic matrix, or held together with a binder [2]. Each of these matrix materials require a unique temperature range. Thermoset matrices (typically epoxy) are the most common and are deposited at temperatures between 20°C and 70°C to ensure each layer is adhered without degrading the resin [2]. Thermoplastic matrix and bindered dry fibre materials require much higher processing temperatures. Thermoplastic adhesion requires diffusion of polymers at the interface between layers [2][3]. For high performance thermoplastics, the matrix must therefore be at least at its melting point at the visible nip- point, i.e. the point between the roller and the substrate at which heat energy is typically delivered [2]. For example, Polyether Ether Ketone (PEEK) is a semi-crystalline thermoplastic polymer with a melting point around 343ºC [3], whereas binders for dry fibre AFP tapes are typically activated at 180 to 350ºC [2].

To achieve such temperatures while allowing the machine to maintain deposition speed and accuracy during layup, the heating method is often non-contact and machine-mounted [3][2]. Options include infra-red lamps for thermoset, and hot gas torches, infrared (IR) laser diodes, and Xenon flashlamps for thermoplastic materials [3][2]. For similar reasons, substrate temperature is usually measured via non-contact devices, such as long-wave infrared (LWIR) thermal cameras [1][3], which infer a surface temperature from emitted radiation. The temperature measurement data is then used to control heater power delivery via either an open-loop or closed-loop system. In each case, poor temperature control can lead to insufficient layer-to-layer adhesion or material degradation which can result in material and structural defects [4].

A key piece of information required by such a detector is the material emissivity; a radiative material property defined as ‘the ratio of energy radiated from a material’s surface to that radiated by a blackbody’. LWIR cameras measure radiation intensity, while the relationship between radiation whole-spectrum intensity (Q) and absolute temperature (T) is defined by the Stefan-Boltzmann law in *Equation 1*. ε represents material emissivity and σ is the Stefan-Boltzmann constant [5].

$$Q = \varepsilon \cdot \sigma \cdot T^4 \qquad \textbf{(1)}$$

As a result, inaccurate or incorrect capture of emissivity could lead to large errors in temperature reading, particularly high temperatures. For a sample at 1000°C with an emissivity of 0.9, an error of 0.1 in emissivity would lead to a temperature error of 35°C. The lower the material emissivity, the more amplified this effect will be [6]. Energy is not always emitted from a surface equally in all directions and emissivity can vary depending on the relevant wavelength band and detector angle with respect to the material surface [7].

Effective emissivity is the representation of emissivity as seen by a detector and can differ from the material’s emissivity significantly. It is subject to external factors such as nearby emitters, material geometry and detector limitations [7]. Effective emissivity is required to correct temperature measurement in practical applications and this study shows how effective emissivity is affected by AFP process and setup aspects.

The emissivity of cured carbon fibre composites has previously been measured at 0.8 to 0.84 [8]. However, effective emissivity is not bound by the same rules as emissivity, with studies having measured an effective emissivity greater than 1 due to external influences [9]. As a result, emissivity must be characterised for each specific detector setup, spectral band and temperature window, in order to accurately measure substrate temperature. This study details an experimental setup designed to characterise the emissivity of three material types and use this information to improve temperature measurement accuracy.

2. EXPERIMENTATION

2.1 Experimental Setup

A bespoke experimental design similar to the work by Kok [9] and Theroux [10] was created to reproduce the conditions present during AFP and is shown in *Figures 1 and 2*. Temperature measurements from an infra-red camera were related to a precise local temperature measurement from a thermocouple and an effective emissivity was calculated. Two layers of the chosen AFP material were manually laid onto a flat metallic tooling plate to represent the deposition substrate during layup and an AFP roller was used to recreate the nip-point and layup conditions, as shown in *Figures 1 and 2.* Carbon fibre was also wrapped around the roller to simulate the tape feed from an AFP machine. A *Stuart UC150 Hot Stirrer* ceramic hotplate was used as the heat source, heating the tapes from below the tool surface.

In order to measure the material's true temperature, a 50μm K-type thermocouple, monitored by a *National Instruments* data-logger, was placed in the approximate centre of the nip-point region, on top of a tape in *ply 1* and between two tapes of *ply 2*. This maintains maximum thermal contact with the material and is illustrated in *Figure 1*. Data points were recorded at a rate of 1Hz.

Material surface temperature at the thermocouple location was measured using a *FLIR A325* LWIR camera installed on a mounting bracket with a position and orientation to replicate that of a similar camera used to monitor AFP deposition temperature at the National Composites Centre. *Figure 3* shows the x-y plane viewing angle, α, and x-z plane viewing angle, β, and standoff distance, x. The camera's IR detector has a resolution of 320 x 240 pixels (approx. 0.5 mm/pixel) and is calibrated in the 0– 700°C range to within ± 2 °C or ± 2 %, whichever is greater. Thermal data was recorded at 60 Hz.

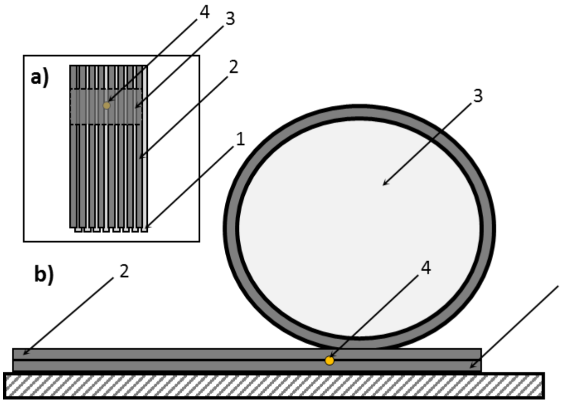

Figure 1; Test piece setup. a) side-view; b) plan view; 1. Carbon fibre first layer, 2. Carbon fibre staggered second layer, 3. AFP roller, 4. Thermocouple

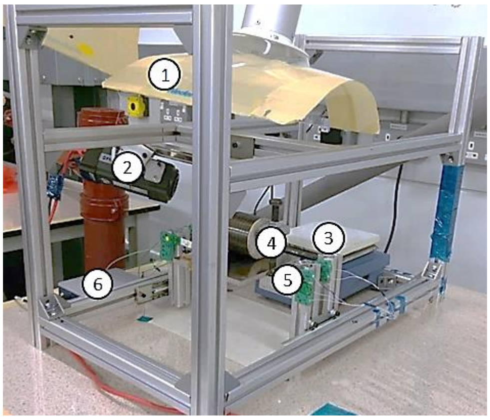

Figure 2: Emissivity measurement setup; 1. Fume extractor, 2. LWIR camera, 3. Hot plate, 4. AFP roller, 5. Thermocouples, 6. Data logger

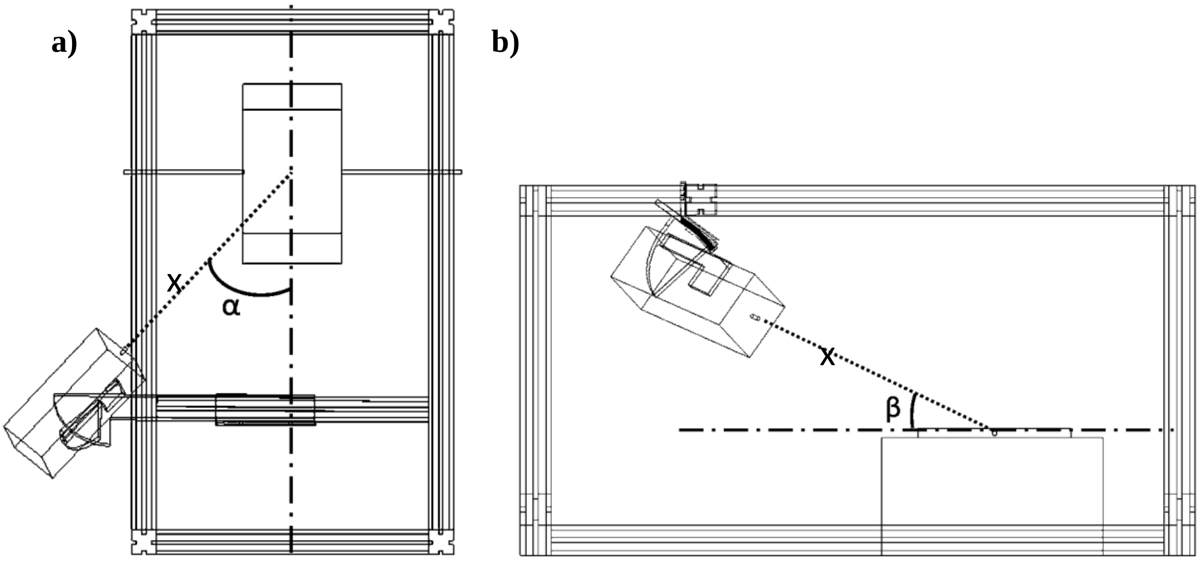

Figure 3: Camera angle notation. a) Plan view b) Side view

2.2 Emissivity Calculation

Emissivity was estimated using the method described in *ASTM E1933-14*. This is defined by *Equation 2* [11], where W_{tot} represents the total radiation received by the camera for a given object temperature (T_{obj}), object effective emissivity (ε_{obj}), object reflected temperature (T_{refl}), atmospheric temperature (T_{atm}), and atmospheric transmittance (τ_{atm}). As the object; a set of AFP tapes, is in a close proximity to the measurement device (300mm), τ_{atm} is assumed to be 1. Thus *Equation 2* can be simplified to *Equation 3.*

$$W_{tot} = \varepsilon_{obj} \cdot \tau_{atm} \cdot \sigma \cdot {T_{obj}}^4 + \left(1 - \varepsilon_{obj}\right) \cdot \tau_{atm} \cdot \sigma \cdot {T_{refl}}^4 + (1 - \tau_{atm}) \cdot \sigma \cdot {T_{atm}}^4 \qquad \textbf{(2)}$$

$$W_{tot} = \varepsilon_{obj} \cdot \sigma \cdot {T_{obj}}^4 + \left(1 - \varepsilon_{obj}\right) \cdot \sigma \cdot {T_{refl}}^4 \qquad \textbf{(3)}$$

Temperature was measured with the LWIR camera using *Equation 3* with an assumed $\varepsilon_{obj} = 1$, resulting in T_{meas}. Equating W_{tot} for both T_{meas} and true temperature, T_{obj}, gives *Equation 4,* which is used to estimate material effective emissivity. A similar result was found by Savage et al. [12].

$$\varepsilon_{obj} = \frac{{T_{meas}}^4 - {T_{refl}}^4}{{T_{obj}}^4 - {T_{refl}}^4} \qquad , T_{meas} = T_{obj\,(\varepsilon=1)} \qquad \textbf{(4)}$$

2.3 Experimental Method

Reflected temperature, T_{refl}, was measured prior to testing at the start of each test day using the method defined in *ASTM 1862-97*. A near-perfect reflector (aluminium foil) was temporarily placed at the measurement location and the temperature was measured using the thermal camera, with $\varepsilon_{obj} = 1$.

ThermaCAM Researcher Pro 2.10 software was used to capture T_{meas} continuously at the visible nip-point. Temperature was controlled using the hotplate; a set-point was selected (required T_{obj} + 50°C) and temperature was allowed to increase to this point. T_{obj} was measured constantly by the thermocouple shown in *Figure 1*. ε_{obj} was calculated for each measurement and plotted against T_{obj}. Values for camera angle (α, β) and standoff (x) are given in *Table 1* for each experiment.

2.4 Experimental Test Cases

2.4.1 Effective emissivity change with temperature

Effective emissivity was measured for three different materials using the method outlined in *Section 2.3* to determine the impact of material temperature. For each material, a temperature range was chosen based on typical processing values and a maximum temperature is indicated. The camera position was selected to replicate that used to monitor AFP deposition temperature at the National Composites Centre. Setup parameters are shown in *Table 1*.

Table 1: Experimental setup for emissivity vs temperature

Matrix Material	Maximum Temperature (°C)	α (°)	Β (°)	X (mm)
Epoxy Thermoset	90	54	27	300
Bindered dry fibre	275	54	27	300
PEEK Thermoplastic	350	54	27	300

2.4.2 Effect of roller presence

An experiment was performed to show the temperature-dependent impact of the presence of an AFP roller on emissivity. Two experiments were carried out; one with an AFP roller and one without, shown in *Figure 5*. All other processing parameters were the same. Bindered dry fibre material was used, with setup parameters as shown in *Table 1*.

3. RESULTS AND DISCUSSION

Figure 4 shows the average effective emissivity from three samples of epoxy thermoset tape, along with the coefficient of variation (CV). The effective emissivity increases from 0.59 to 0.81 at 33 °C followed by a gradual increase to 0.92 at 90°C. Below 45°C, the CV is very high; peaking at almost 80% but reducing to below 10% at 50°C. As Savage et al. described, if the surroundings are imperfect radiators with unknown temperature, as is the case here, then ε_{obj} can only be estimated with minimum error if $T_{obj} >> T_{refl}$ [12]. This is not the case in the region of interest, 30-70°C. Therefore, developing a function for effective emissivity is not likely to be useful in this range without repeat measurements with more precise measurement equipment, for example Fourier Transform-Infrared Spectroscopy (FTIR).

Figure 5 shows the temperature dependant effective emissivity for three samples of bindered dry fibre up to the region of binder activation, 180 - 350ºC. The effective emissivity remains constant at approximately 0.85, and the maximum CV is below 10%, far lower than was observed for the epoxy thermoset at low temperatures. This suggests that effective emissivity measurements are more consistent in the absence of resin, and that a constant value of emissivity of 0.85 would be an acceptable approximation with low uncertainty for a similar setup of bindered dry fibre.

The effect of removing the AFP roller from the setup is also shown in *Figure 5*; with measurements *including an AFP roller* in red and *excluding an AFP roller* in blue. The presence of an AFP roller increases effective emissivity at the nip-point and this discrepancy increases with increasing temperature. A similar effect has been observed in aluminium rollers during plastic and paper processing. The contact point between rollers, analogous to the nip-point of an AFP roller, also increases the apparent temperature and hence effective emissivity[5]. Similarly for the current setup, effective emissivity is also increased due to reflections between the roller and substrate. As a result, machine setup and surroundings have a large influence on effective emissivity and should be considered during temperature measurement.

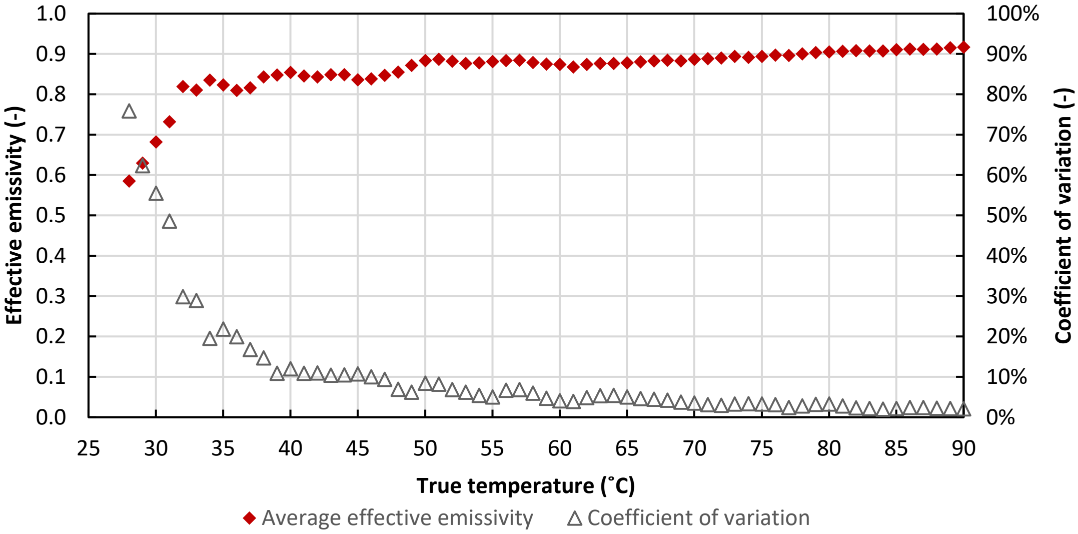

Figure 4: Effective emissivity vs material temperature for a thermoset material with an AFP roller, along with the coefficient of variation

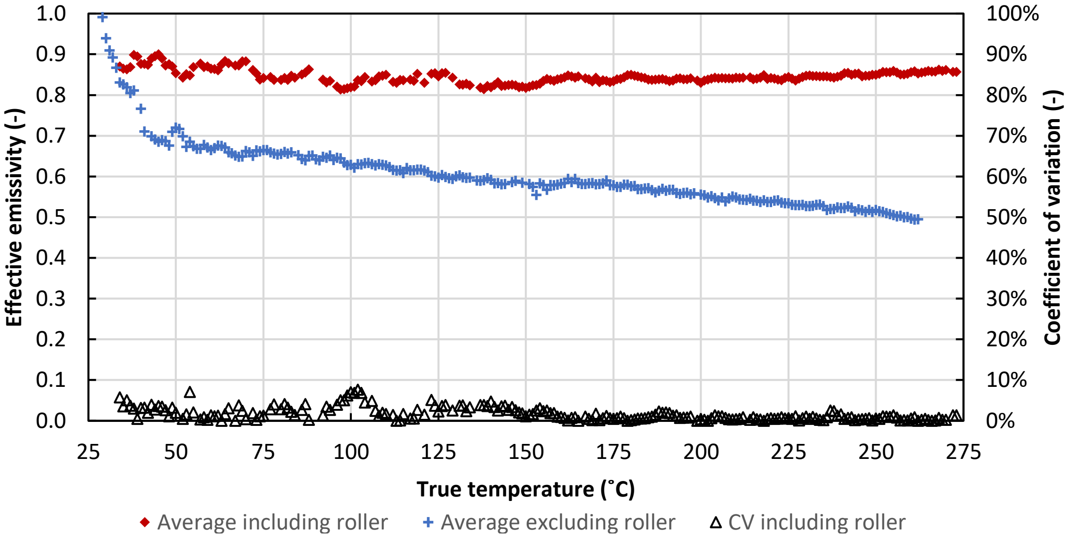

Figure 5: Effective emissivity vs material temperature for bindered dry fibre and CV with an AFP roller, and without an AFP roller

Figure 6 shows the temperature-dependent effective emissivity of carbon-fibre reinforced PEEK between 30°C and 350°C. From 50°C to 150°C, the effective emissivity does not deviate significantly from dry fibre at approximately 0.85. At roughly 155°C, the behaviour changes and effective emissivity increases to just above 0.9 at the material's melting temperature, T_m, at approximately 343 °C.

This point of inflection follows the material's glass transition, T_g, at approximately 143 °C. Le Louët et al. conducted an experiment on PEEK using Fourier-transform infrared spectroscopy (FTIR), capturing the reflectivity of PEEK-impregnated carbon fibre. A slight but steady decrease in reflectivity was observed between T_g and T_m [3]. By Kirchhoff's law, as reflectivity decreases, an increase in emissivity is expected, and this increase was observed in *Figure 6*.

A combination of this study and the work by Le Louët et al. [3] would suggest that a phase change in the resin has an effect on the emissivity of the composite, and assumption of a single emissivity value for the region of interest will lead to errors in measurement. This is particularly relevant for thermoplastic materials as this region involves temperatures close to T_m. To mitigate these errors, a variable effective emissivity could be used to capture the variation, using a function based on *Figure 6*. Le Louët's work also shows a sharp increase in reflectivity above T_m, and a sharp decrease in emissivity would be expected as a result [3]. Below 50°C, measurement uncertainty is likely to be higher and repeat measurements would be required to draw conclusions in this region.

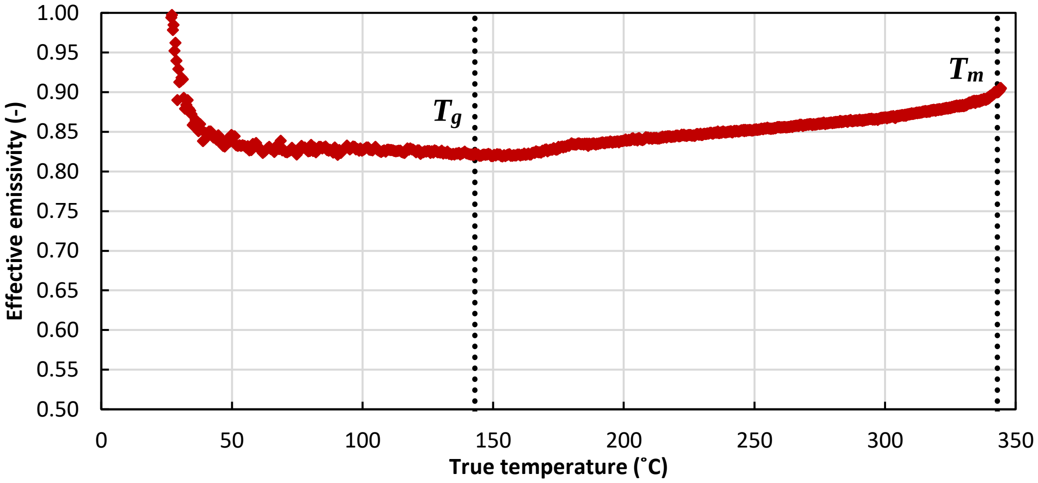

Figure 6: Effective emissivity vs material temperature for carbon fibre-reinforced PEEK with an AFP roller. Approximate glass transition and melting temperatures are marked

4. CONCLUSIONS AND FURTHER WORK

An experimental setup was designed to determine the temperature-dependent effective emissivity of three different composite materials in an AFP setup. These findings can be used as a guide to improve temperature measurement for AFP, particularly in temperature-sensitive applications such as the development of temperature processing guidelines and power laws.

Effective emissivity of the thermoset material increased from below 0.59 to 0.88 at temperatures below 50°C, with variation high in this region. Variation reduces with increasing temperature, reflecting the limitations of a LWIR camera measuring near-ambient temperatures. Above 50°C, the CV is low and a constant value of approximately 0.9 can be used for effective emissivity with minimal errors.

In the case of bindered dry fibre, emissivity remained at 0.81 – 0.86 throughout the region of interest, suggesting that selecting a single emissivity value will lead to small errors. This has shown to be setup dependent; removing the AFP roller changed the behaviour dramatically, showing that a representative setup is necessary to avoid significant measurement error.

The effective emissivity of PEEK thermoplastic tapes remained constant until approximately 155°C when the emissivity gradually increased. Because the region of interest is above this temperature, a single value of emissivity is not sufficient for minimum uncertainty. The figures contained herein can be used as a guide; to relate the measured temperature with an effective emissivity value with which to calculate the true temperature. Further work is required in the form of repeat experiments to confirm this relationship and the point of inflection.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

[1] Lukaszewicz DHJA, Ward C, Potter KD. The engineering aspects of automated prepreg layup: History, present and future. Composites Part B Engineering. 43 (2012) 997–1009.

[2] Di Francesco M, Veldenz L, Dell'Anno G, Potter K. Heater power control for multi-material, variable speed Automated Fibre Placement. Composites Part A. 101 (2017) 408–21.

[3] Le Louët V, Rousseau B, Le Corre S, Boyard N, Tardif X, Delmas J, et al. Study of the reflective behaviour of carbon fibres reinforced polymer composite up to 450°C. AIP Conference Procedings. (2017) 1896.

[4] Kahn MA, Mitschang P, Schledjewski R. Identification of Some Optimal Parameters to Achieve Higher Laminate Quality through Tape Placement Process. Adv. Polym. Technol. 29 (2010) 29:98–111.

[5] Terry Clausing L. Emissivity: Understanding the difference between apparent and actual infrared temperatures. Fluke Corporation, Everett, WA USA 2007.

[6] Zhang F, Yu K, Zhang K, Liu Y, Xu K, Liu Y. An emissivity measurement apparatus for near infrared spectrum. Infrared. Phys. Technol. 73 (2015) 275–80.

[7] Honner M, Honnerová P. Survey of emissivity measurement by radiometric methods. Appl. Opt. 54 (2015) 669.

[8] Li X, Strieder W. Emissivity of high-temperature fiber composites. Ind. Eng. Chem. Res. 48 (2009) 2236–44.

[9] Kok T. On the consolidation quality in laser assisted fiber placement: The role of the heating phase, PhD thesis. University of Twente, 2018.

[10] Théroux L-D, Dumoulin J, Manceau JL. Dynamic heating control by infrared thermography of prepreg thermoplastic CFRP designed for reinforced concrete strengthening, 12th International Conference on Quantitative InfraRed Thermography (2014).

[11] Usamentiaga R, Venegas P, Guerediaga J, Vega L, Molleda J, Bulnes FG. Infrared thermography for temperature measurement and non-destructive testing. Sensors (Switzerland). 14 (2014) 12305–48.

[12] Savage MJ, Heilman JL. Infrared calibration of net radiometers and infrared thermometers. Agric For Meteorol. 149 (2009) 1279–93.