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On the numerical prediction of radiative heat transfer for thermoset automated fiber placement

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ABSTRACT

During thermoset automated fiber placement the material temperature has to be adapted to the material being processed. The position and orientation of infrared emitters relative to the substrate influence the material temperature, as do power output and processing speed. The novelty of this paper resides in the numerical description of the radiative heat produced by an infrared emitter as a function of the position and orientation and power density of the emitter. The combination with a 2D thermal model allows the prediction of material temperatures during the process. The model was validated by comparing with experimental data. The change in material temperature depending on different positions and orientations of the infrared emitter was demonstrated. The model allows the optimization of processing speed and power output of the infrared emitter for different positions and orientations in order to obtain a constant laminate surface temperature.

1. Introduction

Thermoset (TS) AFP is a well-established technology for the automated manufacture of high-performance, near-net shape carbon-fiber-reinforced-plastic (CFRP) parts, especially in aviation [1]. Still, much work can be done on improving the process and the technology. A big challenge for AFP lies in the definition of reliable process windows. Commercially available software solutions allow the offline-programming of the AFP-equipment and the kinematic offline-simulation of the lay-up process. They do not support the user in defining optimum process settings, particularly with regard to the control of the material temperature T which influences the properties of the material, more precisely of the matrix component. The viscosity [2,3, page 348], the tack [4] and the degree of cure of the matrix vary and interact with each other depending on T. Improved temperature prediction is necessary to understand and control the interaction between compaction of the processed material and its temperature during the process. It enables optimized heating strategies which increase process productivity and later component quality. Laminates were manufactured by applying different material temperatures which are relevant for TS-AFP – 20–70 °C. Testing them showed the relevance of temperature control. Their mechanical performance changed significantly up to 50% for the interlaminar shear and compressive strength primarily due to reduction of interply voidage [1].

Extensive experimental investigations were carried-out in order to advance the AFP-process [5–7]. Alternatively, various thermal models were developed, firstly by Beyeler and Güçeri [8]. The heat transfer problem was investigated on different levels in literature. Tierney and Gillespie [9], Grouve [10] and Khan et al. [11] simplified the heat flux to occur through thickness of the laminate only. The heat flux in fiber direction was assumed to be minor compared to the mass flows during the process. 2D-analysis by neglecting the slit-tape's width is justified if the tape and the substrate are heated uniformly across their width [8,12–15]. According to Nejhad et al. a 2D analysis becomes sufficient as the laminate is defined to be long compared to the width of the local heat source [16]. Nejhad et al. [16], Kim et al. [17], Hassan et al. [18] and Chinesta et al. [19] analyzed the heat transfer problem in three dimensions. The heat transfer problems were either solved analytically [14] or numerically by using finite element method [10,15] or finite differences (FDs) [20]. Hot gas torches or laser systems were used as heat sources. Stokes-Griffin et al. for example modeled a near IR diode laser by simplifying a uniform heat flux over the illuminated regions [15]. Guan and Pitchumani [21] initiated to model the heat source, in their case a hot gas torch, additionally to the model of the laminate. They described the heat flow, varied process parameters and demonstrated the effect on laminate quality. Previous models resorted to experimentally measured temperature data at

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the substrate boundaries for specific placement head configurations [22]. Alternatively, nominal values for the heat flow on a region were used as a modeling parameter [14]. Grouve [10] considered effects of shadowing using 2D ray tracing calculations to predict the heat flow coming from a laser. Chinesta et al. [19] demonstrated the influence of imperfect thermal contact between different plies during the thermoplastic AFP (TP-AFP) process. Some models were validated against experimental data, e.g. [9,11,15,17,20]. Sonmez and Hahn [14] compared numerical with analytical approaches to evaluate the sensitivity of and relationships between process parameters on the TP-AFP. Pitchumani et al. [22], Schledjewski and Latrille [23] and Somnez and Akbulut [24] developed process parameter optimization schemes based on thermal models in combination with sub-models for determination of laminate quality. Chern et al. investigated radiative heating for the purpose of online-processing on hoop wound CFRP parts [25].

The majority of the thermal models were developed on TP-AFP. No models are reported in literature that describe the radiative heat transfer of an IR-emitter as a function of its position and orientation, for TS-AFP. These are necessary to be able to further define and optimize heating strategies for TS-AFP, but for example also to improve placement head design. The models for TP-AFP are applicable for TS-AFP taking two considerations into account apart from the thermal properties of the processed material.

Firstly, common heat sources for TS-AFP are hot gas torches and more dominantly IR-emitters. The intensity of the resulting radiative heat transfer from the IR-emitter is not uniformly distributed in lay-up direction depending on the position and orientation towards the substrate. Within the work presented here the heat flux was described depending on the geometry and the power density of the IR-emitter and on the so-called view factor which allows the determination of the radiative heat transfer between two surfaces in relative orientation to each other [26]. It was not xperimentally measured or nominally defined on a specific area as stated by Guan and Pitchumani [21]. Secondly, for TS-AFP the system boundary has to be expanded to a larger area as the radiative heat transfer occurs on a defined area – radiation cone [27] – not directly at the nip-point but in front of it into the substrate. The material is cooled inside the placement head to reduce tack and is then placed onto the heated substrate to guarantee adhesion between both layers. During TP-AFP by contrast, the incoming tape and the substrate are equally heated to melt them directly at the nip-point to achieve fusion bonding. Equivalent models investigated very locally only small lengths in front of the nip-point [10]. It was the objective of the work presented here to model the radiative heat transfer and then investigate the influence of the position and orientation of the IR-emitter on the material temperature. A 2D thermal model was implemented in *MATLAB®* to describe the heat transfer inside the laminate. 2D models do not describe heat conduction and convection realistically as one dimension is neglected which provides an extra heat release path throughout the width of the slit-tape and the tool. Therefore, an assumption was made to compensate the missing dimension by assuming the convection to be forced on the laminate surface. The thermal contact between plies was assumed to be ideal. The transient heat transfer problem was solved using FDs. The model was validated by comparing experimental data in three different cases by variation of the relative position of the IR-emitter. The model was further validated by investigating the influence of the thermal properties of the uncured pre-impregnated TS carbon-fiber material (prepreg) on the simulation results. Thermal properties were obtained from literature [28–31]. The validated model allowed the control and optimization of the TS-AFP process based on process window predictions.

2. Theoretical model

Different heat transfer mechanisms occur during TS-AFP – see Fig. 1. The global systems contained a laminate consisting of n plies, the aluminum tool (tool) and the surrounding medium receiving thermal energy mainly via radiation.

The global system loses thermal energy via conduction and convection. The thermal energy stored in the control volume was described by the following energy rate balance:

$$q_{RA} - q_{CV} - q_{CD} = \rho \cdot V \cdot c_p \frac{dT}{dt} \tag{1}$$

The radiative heat flow q_{RA} between two surfaces was defined as [26]:

$$q_{RA} = \frac{\sigma_B \cdot (T_{A_1}^4 - T_{A_2}^4)}{\frac{1-\varepsilon_1}{\varepsilon_1 \cdot A_1} + \frac{1}{A_1 \cdot F_{12}} + \frac{1-\varepsilon_2}{\varepsilon_2 \cdot A_2}} = \frac{\eta \frac{q''_{IR,max}}{P_{EL,max}} P_{EL} - \sigma_B \cdot T_{A_2}^4}{\frac{1-\varepsilon_1}{\varepsilon_1 \cdot A_1} + \frac{1}{A_1 \cdot F_{12}} + \frac{1-\varepsilon_2}{\varepsilon_2 \cdot A_2}} \tag{2}$$

The emitting surface A_1 – IR-emitter – has to be in visual contact with the mostly absorbing surface A_2 – tool or ply – to transfer heat. The view factor F_{12} is defined as the fraction of the radiation that leaves A_1 and intercepts A_2 [26]:

$$F_{12} = \frac{1}{\pi \cdot A_1} \int_{A_1} \int_{A_2} \frac{\cos(\Phi_1) \cdot \cos(\Phi_2)}{r^2} \, dA_1 \, dA_2 \tag{3}$$

F_{12} and q_{RA} sensitively depend on the relative orientation of the surfaces in visual contact, defined by the angles Φ_1 and Φ_2. They also vary inversely with r^2. σ_B is the Stephan–Boltzmann constant. All surfaces were defined as diffuse gray bodies. According to Kirchhoff's law, the emissivity ε and absorptivity α of both surfaces do not depend on their wavelength spectrum and therefore are equal. The heat flux q''_{IR} of the IR-emitter was assumed to change linearly with the power P_{EL}. The factor η was defined as the effectiveness of the conversion of electrical power into radiative power from the IR-emitter – see Table 1. The ply was defined as a solid. Its enthalpy does not change by variation of the pressure. The volume of the ply V, its density ρ were assumed to remain constant. c_p was defined as the specific heat capacity. For thermally anisotropic material conductivity k depends on the orientation of the solid towards the thermal heat flux q''_{CD}:

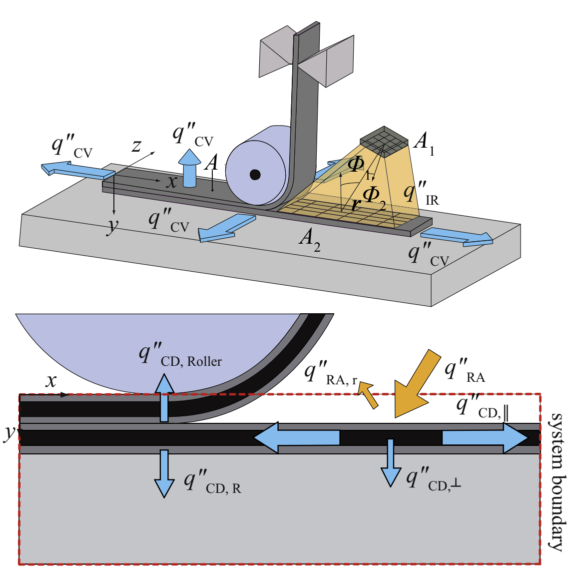

Fig. 1. Schematic illustration of the heat transfer mechanisms radiation – orange cone –, convection (top) and conduction (bottom) – blue arrows – occurring during thermoset automated fiber placement. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)