APPLICATION OF JOULE HEATING IN AUTOMATED DRY FIBRE PLACEMENT (ADFP)

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ABSTRACT

Joule heating, also known as resistive or ohmic heating, is the phenomenon whereby the passage of electrical current through a conductive medium produces heat. It might be a good choice for automated dry fibre placement (ADFP) because it has a high heating rate as well as low energy consumption compared with commonly used heating sources. In this work, the feasibility of the application of joule heating in ADFP is assessed. The contact resistance between the tapes and cylinder electrodes are characterised. The influence of fibre tension, contact angle on the contact resistance is also investigated. The static joule heating testing is then conducted and an analytical model for the static joule heating testing is also built and validated experimentally. The model is used to investigate the influence of contact resistance on the efficiency of joule heating. In ADFP, the tape is cooled when travelling from the heating area to the nip point position. An experimentally validated analytical model is built to understand this cooling behaviour. The influence of the deposition speed and cooling region distance on the nip point temperature achieved by joule heating is investigated using the model. It is found that under a constant voltage input, decreasing contact resistance could increase power efficiency and heating temperature significantly. Sufficient fibre tension and contact angle could result in a low level of contact resistance. When applying a joule heating method in the ADFP hardware, it is recommended that the heating region should have sufficient length and be located close to the nip point. Power input can then be adjusted for different deposition speeds.

1 INTRODUCTION

Automated Dry Fibre Placement (ADFP) is a derivative of Automated Fibre Placement (AFP) where dry fibre tapes instead of prepregs are deposited and it has been used to manufacture large aerospace components [1]. Compared with the hand layup technique, ADFP shares many of the advantages of AFP. Furthermore, composite laminates manufactured using ADFP followed by vacuum resin infusion process show a 9% increase of fibre volume fraction and decreases of porosity and thickness variation than laminates manufactured by manual layup with vacuum resin infusion [2, 3]. Compared with AFP, the manufacturing costs of ADFP could be reduced because of the use of low-cost raw materials and out-of-autoclave process. Dry fibre reinforcement used in ADFP consists no matrix resin, which could result in a reduction in downtime events and repair times for the deposition hardware and an increase of laydown rates comparing with AFP [4].

In AFP, hot gas torches, infrared (IR) heaters, laser heaters and pulsed light heaters are commonly used heating sources [5]. Since there is little resin present in the tow in ADFP, joule heating could potentially be a suitable heating method especially for high speed deposition because it has high heating rates and fast response times [6]. In the ADFP head, cylinder or roller electrodes are suitable for joule heating to ensure smooth feeding for carbon fibre tapes. The contacts between cylinder electrodes and carbon fibre tapes are not perfect and the electrical contact resistance therefore exists. Contact resistance consumes energy locally and should be minimised to increase the efficiency of joule heating. Research in [7] characterised the contact resistance between carbon fibre tows and cylinder electrodes and it is found that the existence of contact resistance leads to the heating in the contact region and increasing fibre tension results in a decrease of contact resistance. However, the contact resistance between carbon fibre tapes used in ADFP and the cylinder electrodes has not been investigated. In this research the contact resistance between a commercial carbon fibre tape and copper cylinder electrodes is characterised under different contact angles and fibre tension levels. An analytical model is built using measured resistances to predict the heating temperature. The influence of contact resistance on the joule heating efficiency is also investigated.

Joule heating is a local heating method and only the tapes between the electrodes are heated. In ADFP, the tape is cooled when travelling from the joule heating area to the nip-point position due to convection, radiation and contact with cooler compaction roller. This cooling limits the deposition speed and brings difficulties for the nip point temperature control. In this research an analytical model is built and experimentally validated to understand this cooling behaviour. The influence of the deposition speed and cooling region distance on the nip point temperature achieved by joule heating is investigated using the model.

2 EXPERIMENTAL WORK

2.1 Materials

24 K TX1100 (Solvay) bindered carbon fibre tapes were used in this research. They are commonly used in ADFP process and have a width of 6.35 mm. Copper tubes were used as electrodes.

2.2 Electrical resistance and contact resistance characterization

A procedure used in literature [7] is used to measure the contact resistance between carbon fibre tapes and copper electrodes. A joule heating test rig as shown in Figure 1 is used to measure the contact resistance. The rig consists of two electrode tubes and a guide tube. The distance between the two electrode tubes can be changed. A digital multimeter (KEITHLEY 2110) with a four-wire arrangement is used to measure the electrical resistance between the two tubes shown in Figure 1. The total electrical resistance measured by the multimeter is the sum of the contact resistance of the two contact regions, the carbon fibre tape resistance and copper electrodes resistance. Copper electrodes resistance is ignored. The total resistance is measured with four different tape lengths (50 mm, 100 mm, 150 mm and 200 mm) between the two electrodes. It is assumed that the electrical resistance of the carbon fibre tape increases linearly with the increase of tape length. When the total resistance values for four tape lengths are plotted, the data points are fitted linearly and the intercept in y axis of the fitted line is the contact resistance. The resistances of carbon fibre tapes at different length are obtained by the total resistance subtracting the contact resistance. The influence of fibre tension and contact angle on the contact resistance can also be investigated using this rig. Fibre tension is applied by hanging weight at the one end of the carbon fibre tape. The contact angle on the right electrode is a constant of 90° but the contact angle on the left electrode is changed by guiding fibre path using a copper tube and four contact angles (31.0°, 42.7°, 82.4° and 116.1°) can be obtained by install the guiding tube in different locations.

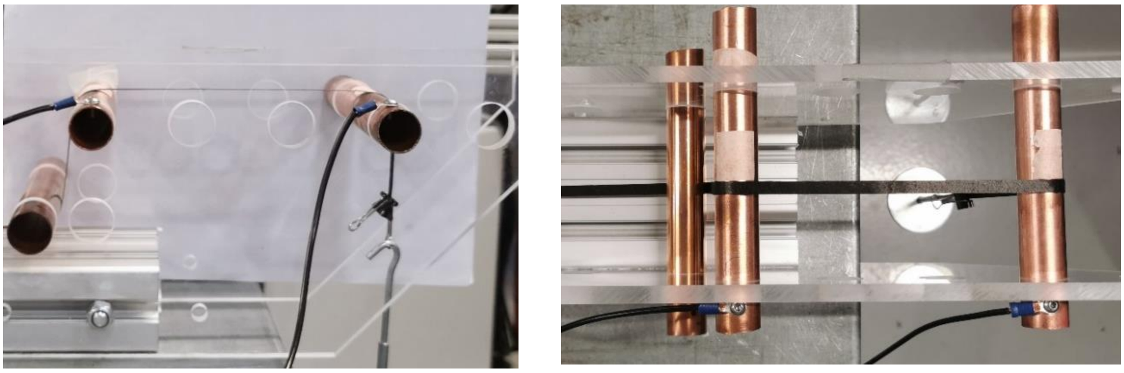


Figure 1 Joule heating rig: front view and top view

2.3 Static joule heating testing

Figure 2 shows the electric circuit for static joule heating testing. A power supply (Velleman LABPS3010SM) is used to provide constant voltage to the circuit. A shunt resistor (PCN RXM50) with an electrical resistance of 0.1 Ω is used for the current measurement. A Beckhoff EL3164 analogue input channel is used to measure the voltage across the shunt resistor. The current in the circuit is obtained from the Beckhoff channel voltage values divided by the electrical resistance 0.1 Ω. The digital multimeter is used to measure the voltage between the two wires of the joule heating rig. The total resistance between the two wires in the joule heating rig is then obtained from the multimeter voltage value divided by the circuit current value. The contact resistance is characterised using the same method as the electrical resistance measurement experiments. Fibre tension and contact angle are applied using the same method as the electrical resistance measurement experiments.

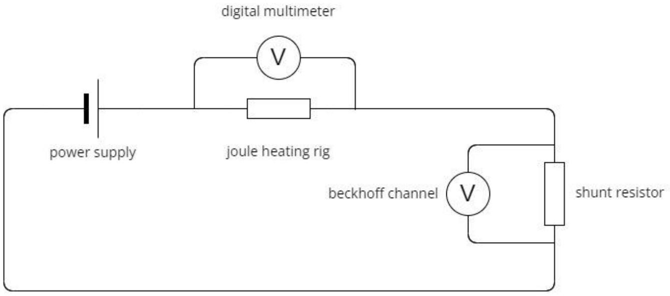


Figure 2 Electric circuit for static joule heating testing

In the static joule heating process, the carbon fibre tapes are heated up to a steady-state temperature in a few seconds. When the steady state is achieved, the circuit current and multimeter voltage value are recorded. A thermal camera is then used to measure the temperature of the carbon fibre tape. The average temperature along the length of the tape is recorded.

2.4 Dynamic joule heating testing in ADFP deposition head

The dynamic joule heating test was conducted using a lab scale ADFP deposition head [6] shown in Figure 3. The carbon fibre tapes are heated between the two electrodes and then feed to the nip point. To simplify the experiment, the deposition head is stationary but feeding the carbon fibre tape under different speeds with joule heating. For the joule heating setup in the head, a constant voltage is generated from a power supply and a duty cycle method is used for the control of power input [6]. A shunt resistor is also connected for the current measurement. A thermal camera is used to measure the temperature of carbon fibre tape at the nip-point. Figure 4 shows the thermal camera measurement.

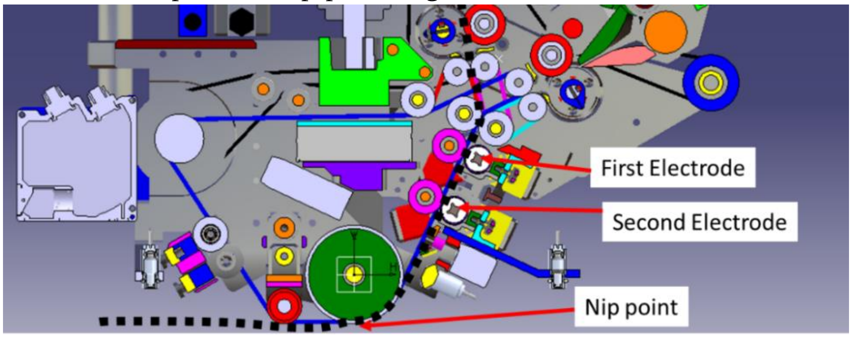


Figure 3 Joule heating setup in the ADFP deposition head

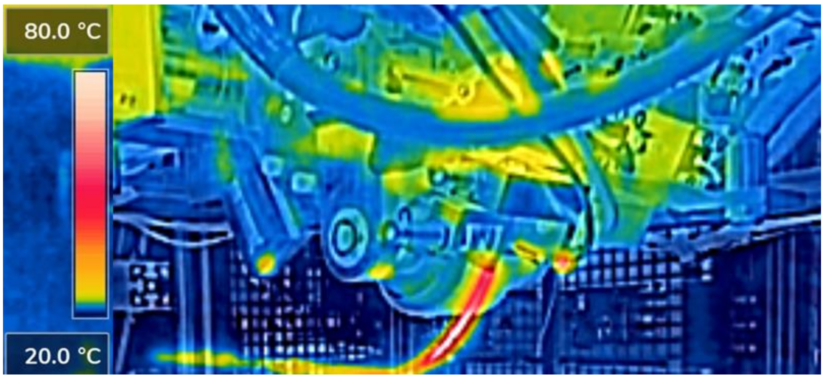


Figure 4 Thermal camera temperature measurement for dynamic joule heating test in the ADFP head

3 ANALYTICAL MODELS

3.1 Analytical model for static joule heating

Efficiency of joule heating: The two contact resistances and the fibre resistance are connected in serial. The current passing through them is the same and represented as I. The power used on heating contact area P_c and carbon fibre tapes P_f can be calculated from equation (1-2) based on Joule's law. R_c and R_f is the total contact resistance and fibre tape resistance and their values are measured experimentally. The power efficiency of joule heating E is then calculated by equation (3).

$$P_c = I^2 R_c \tag{1}$$

$$P_f = I^2 R_f \tag{2}$$

$$E = \frac{P_f}{P_f + P_c} = \frac{I^2 R_f}{I^2 R_c + I^2 R_f} = \frac{R_f}{R_f + R_c} \tag{3}$$

Steady state heating temperature: When a steady state is achieved, the power from joule heating is equal to the power of radiation and convection cooling. This can be expressed in equation (4) according to heat transfer theory [8] and the steady state heating temperature T_s is then obtained.

$$I^2 R_f = hA(T_s - T_r) + \sigma\varepsilon A({T_s}^4 - {T_r}^4) \tag{4}$$

Where h is the convection coefficient of air. A is the surface area of the carbon fibre tape which depends on the length of the carbon fibre tape in the heating area. T_r is the room temperature. σ is the Stefan-Boltzmann constant. ε is the emissivity of the carbon fibre tape. I is the current in the electric circuit and it is measured from the static joule heating testing.

3.2 Analytical model for dynamic joule heating in ADFP deposition head

During ADFP deposition process, fibre tapes are heated between two electrodes before moving to the nip point with certain deposition speed. To predict the nip-point temperature, a one-dimensional transient heat transfer model considering the effect of deposition speed has been built. The model has a total length of 145 mm consisting of 40 mm-length joule heating region and 105 mm-length cooling region according to the dimension of the lab-scale ADFP machine. In this model, the heat transfer between the fibre tapes and the compaction roller is not considered. The one-dimensional transient heat equation with joule heating, conduction, convection and radiation can be expressed by equation (5).

$$\frac{\rho c_p}{k}\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial x^2} + \frac{\dot{q}_{jh}}{k} - \frac{\dot{q}_{con}}{k} - \frac{\dot{q}_{rad}}{k} \tag{5}$$

Where T is the temperature of the carbon fire tape. ρ is the density of the carbon fibre tape. c_p is the specific heat capacity of the carbon fibre tape. k is the thermal conductivity along the fibre direction of the carbon fibre tape. $\dot{q}_{jh}$, $\dot{q}_{con}$ and $\dot{q}_{rad}$ are the volumetric heat generation or dissipation by joule heating, convection and radiation respectively and they can be calculated by following equations.

$$\dot{q}_{jh} = \frac{I^2 R_f}{V} \tag{6}$$

$$\dot{q}_{con} = \frac{hA(T - T_r)}{V} \tag{7}$$

$$\dot{q}_{rad} = \frac{\sigma\varepsilon A(T^4 - {T_r}^4)}{V} \tag{8}$$

Where I is the current in the electric circuit and it is measured from the dynamic joule heating testing. V is the volume of the carbon fibre tapes.

A finite-difference method is used for equation (5). The discretisation of time is shown in following equations.

$$t = p\Delta t \tag{9}$$

$$\frac{\partial T}{\partial t}\Big|_i = \frac{T_i^{p+1} - T_i^p}{\Delta t} \tag{10}$$

Where t is the time. Δt is the time interval. p is the integer to denote the time dependence of T. i is the integer to designate the location of discrete nodal points. For the discretisation of the conduction heat transfer term, an explicit method with a forward-difference approximation is used and shown in equation (11).

$$\frac{\partial^2 T}{\partial x^2} = \frac{T_{i+1}^p + T_{i-1}^p - 2T_i^p}{(\Delta x)^2} \tag{11}$$

Where Δx is the length interval. Substituting equations (6-8) (10-11) into equation (5), equation (12) is then obtained. It is used for the joule heating region while for the cooling region the joule heating term is removed and the other terms are the same.

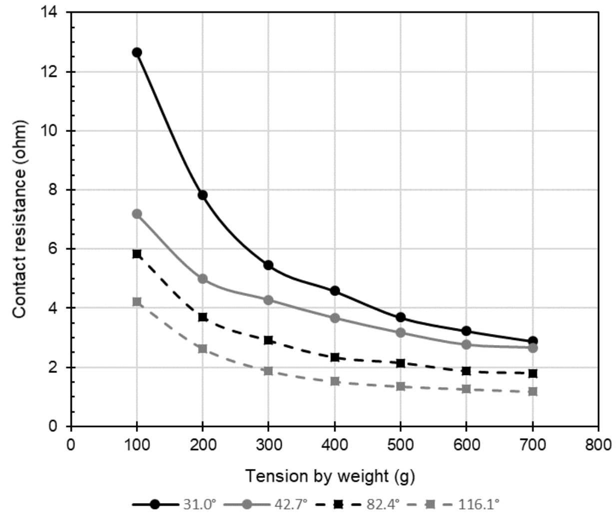
$$\frac{\rho c_p}{k}\frac{T_i^{p+1} - T_i^p}{\Delta t} = \frac{T_{i+1}^p + T_{i-1}^p - 2T_i^p}{(\Delta x)^2} + \frac{I^2 R_f}{kV} - \frac{hA(T_i^p - T_r)}{kV} - \frac{\sigma\varepsilon A({T_i^p}^4 - {T_r}^4)}{kV} \tag{12}$$

To simulate the movement of carbon fibre tapes, at the start of each time interval, the temperature distribution moves a certain distance along the discrete nodal points based on the deposition speed and the room temperature is assigned to the nodal points of the certain distance in the initial location of the model. Then the equation (12) is used to calculate the temperature of each nodal point.

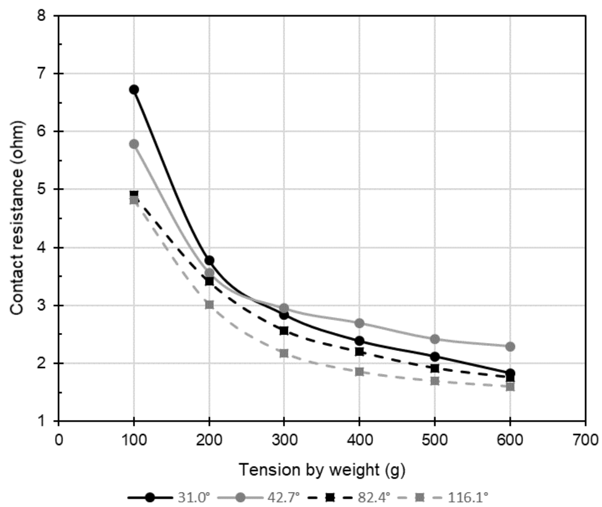
4 RESULTS AND DISCUSSION

4.1 Contact resistance

Figure 5 shows the contact resistance results from electrical resistance measurement without current and static joule heating testing. It is found that for all contact angles, when increasing the tension, the contact resistance drops significantly at low level of tensions and gradually reaches a plateau at high level of tension. Increasing contact angle can also lead to a decrease of contact resistance especially at low tension level. However, the contact angle is limited by the deposition hardware therefore in practical situations, increasing the tape tension is a more feasibly way to reduce the contact resistance. It is also found that the contact resistance measurement results from current passing in the circuit are smaller than that from no current passing. It is assumed that this reduction is due to the heating of tapes by the current. The temperature effects on the contact resistance will be determined in the future.



(a)



(b)

Figure 5 Total contact resistance results (a) without current (b) with current passing in the circuit

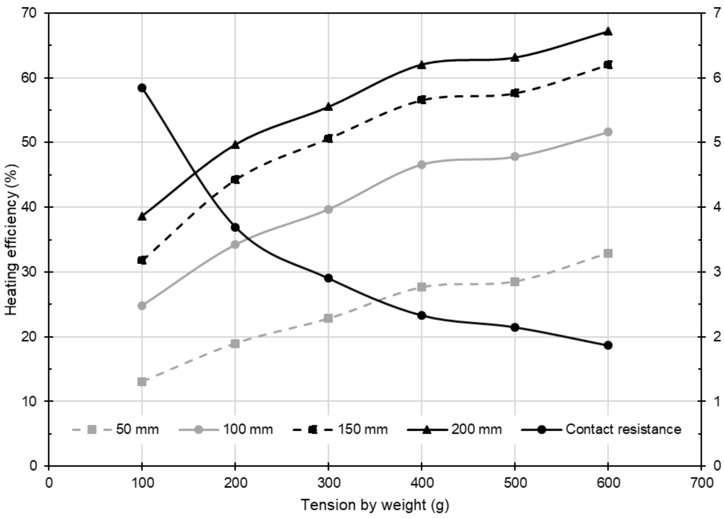


Figure 6 Joule heating efficiency results at contact angle of 82.4°

Figure 6 shows the joule heating efficiency results calculated by equation (3) using the experimental contact resistance results. At fibre tension of 100 N, the tape resistance is smaller than the contact resistance. Therefore, the heating efficiencies are lower than 50 %. When fibre tension increases to 600 N, the heating efficiencies for the four length doubles approximately. It is also found that longer heating length, due to their higher resistance, leads to higher efficiency. It is recommended to increase the length of heating region in the deposition head design to reduce the energy waste at the contact region.

4.2 Static joule heating

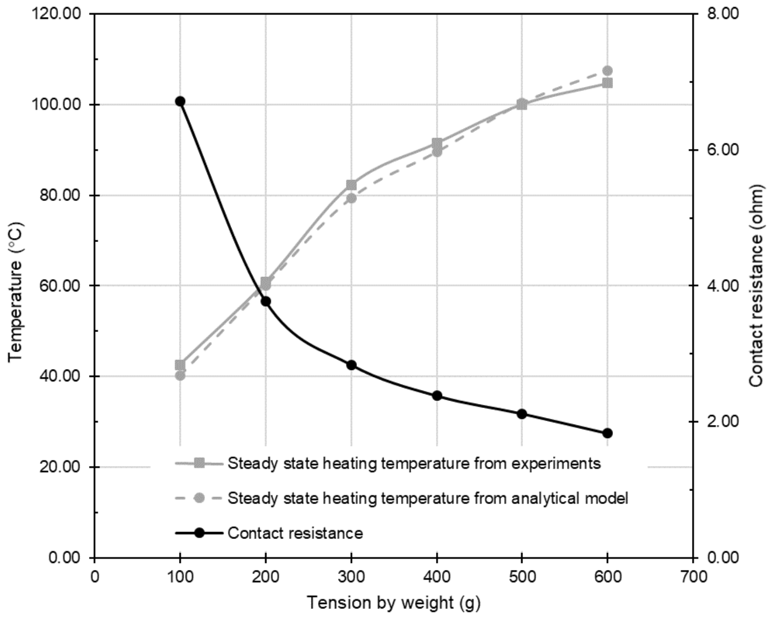


Figure 7 Static joule heating results for 50 mm length with 31.0° contact angle under a constant voltage supply

Figure 7 shows the steady state heating temperature results from experiments and static analytical model from equation (4). It is found that reducing contact resistance results in a significant increase of heating temperature with a constant voltage supply. The results from the static analytical model show good agreement with the experimental data. The analytical model is then used to investigate the influence of contact resistance and heating region length on the steady state heating temperature. Figure 8 shows the benefits of reducing contact resistance by fibre tension. Decreasing contact resistance could increase heating temperature significantly. In the case of 50 mm heating length, the steady state heating temperature at tension of 600 N is more than three times of that at tension of 100 N. With a constant voltage supply, shorter heating length leads to higher heating temperature due to the lower resistance. If the power supply is limited, the heating length should be short enough to achieve enough heating temperature. However, if the power supply is sufficient, long heating length is recommended because it has higher heating efficiency and in real ADFP head, the tape has more heating time.

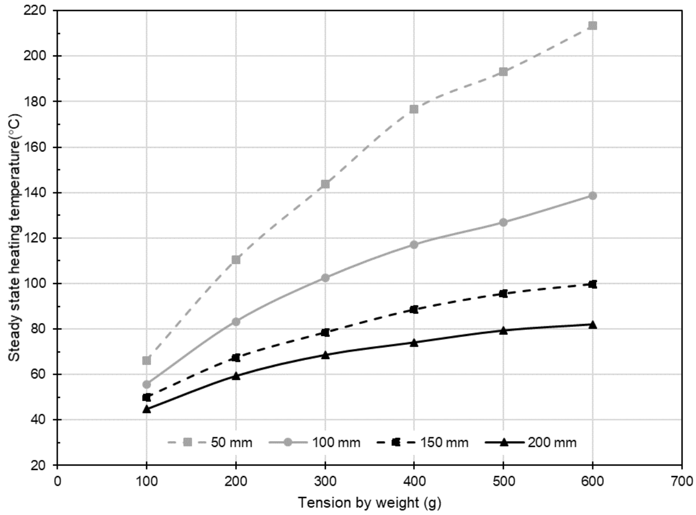


Figure 8 Analytical results of steady state heating temperature for 31.0° contact angle with a constant voltage of 5 V

4.3 Dynamic joule heating

To validate the dynamic analytical model, a simple joule heating testing with a step current input was conducted using the joule heating rig shown in Figure 1 and Figure 2. A thermocouple was attached to the surface of the tape to measure the temperature continuously. The measured current values from the shunt resistor are used as the input of the dynamic analytical model to generate the heating and cooling curve. The temperature calculated by the model agrees with the experimental data as shown in Figure 9. The equation (12) used in the model and the finite-difference method are then validated.

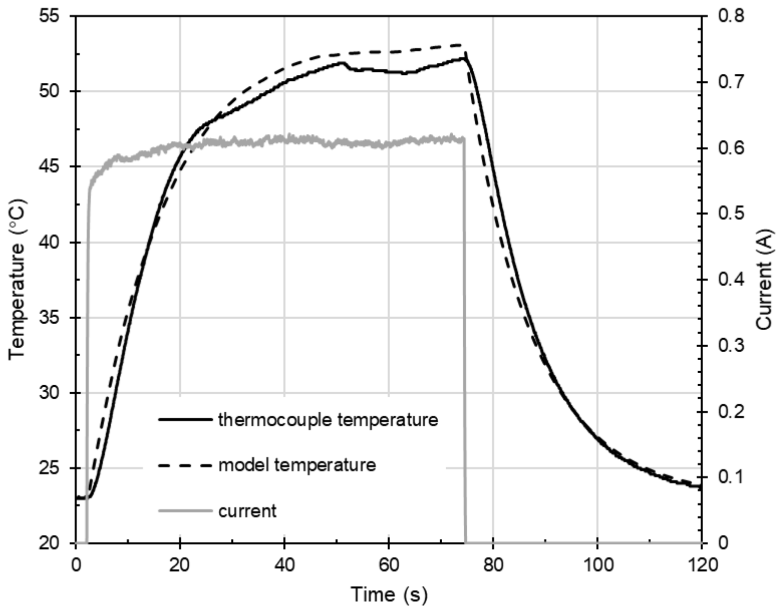


Figure 9 Heating and cooling curve of carbon fibre tape under a step current input

Figure 10 shows the nip point temperature from dynamic joule heating with fibre feeding in the ADFP head. It is found that the nip point heating temperature increases approximately linearly with the increase of duty cycle. The model prediction agrees with the experimental data. The dynamic joule heating model is then validated. The model can be used to obtain the relationship between feeding speed, power input and the nip point temperature.

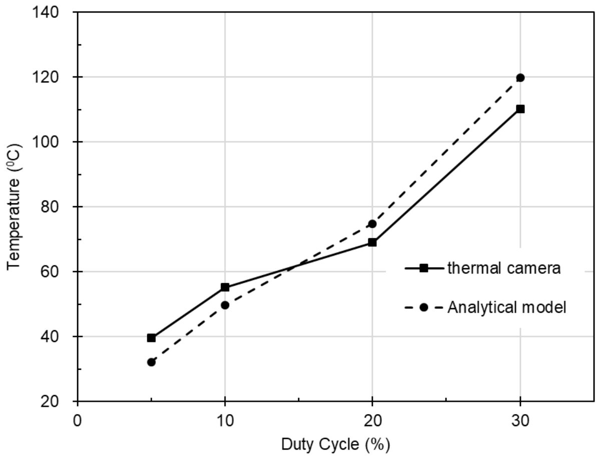


Figure 10 Nip point temperature from dynamic joule heating with 100 mm/s feeding velocity

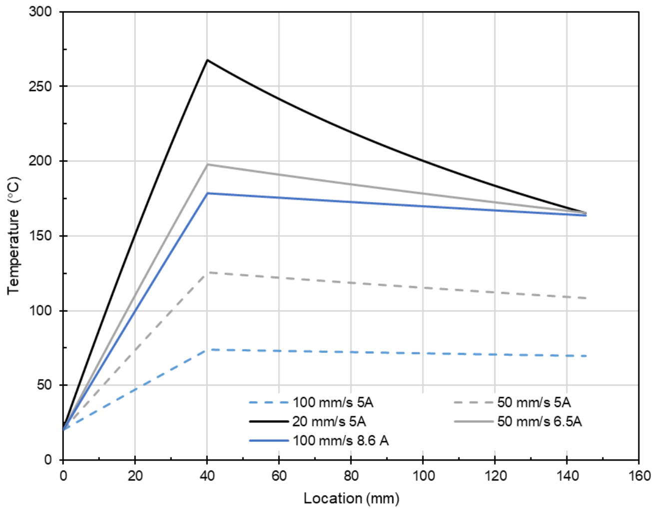


Figure 11 Model calculated temperature distribution in the ADFP head from heating region to the nip point (the right end is the nip point)

Figure 11 shows the model predicted temperature distribution in the ADFP head from heating region to the nip point under different feeding velocity and current input. With same current supply, lower feeding speed leads to higher nip point temperature because the tape has more heating time. The power supply should be adjusted for different feeding velocity to achieve the same nip point temperature and this model can provide guidance as shown in the solid lines in Figure 11. The lower feeding speed also leads to more cooling time. The black curve in the Figure 11 shows a near 100 °C temperature drop in the cooling area. In this situation, although the nip point temperature achieves the required temperature, the tape is overheated in the heating region which could degrade or even burn the binder in the carbon tape. It is recommended that the distance between the end point of the heating region and the nip point should be minimised.

5 CONCLUSIONS

In this paper, the contact resistance between a commercial ADFP tape and cylindrical electrodes is characterised under a variety of process conditions. The influence of contact resistance on joule heating efficiency is investigated. Joule heating while fibre feeding test is conducted using a lab scale ADFP head. Following conclusions are obtained.

The contact resistance between the commercial carbon fibre tape between cylinder copper electrodes is comparable or even higher compared with the tape resistance at low level of fibre tension. This results in low heating efficiency and heating temperature. Increasing fibre tension and contact angle can decrease the contact resistance and the joule heating efficiency is then significantly increased. It is found that reducing contact resistance by increasing fibre tension can triple the heating temperature under same voltage supply.

When applying joule heating in the ADFP hardware, the cooling of tapes when travelling from the end of heating region to the nip point is significant especially at low deposition speed, therefore the cooling distance should be reduced. The length of heating region should also be large enough because the carbon fibre tapes have more heating time and the energy wasted at the contact area is reduced. The power input should be adjusted based on the deposition speed and the dynamic model built in this research could provide guidance.

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