ADVANCED 3D FINITE ELEMENT SIMULATION OF THERMOPLASTIC CARBON FIBER COMPOSITE INDUCTION WELDING

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Abstract

The joining of carbon fiber reinforced thermoplastic (CFRTP) composites via induction welding is a complex multi-physics problem making the process very difficult to study by experiments alone. With the correct combination of experiments and simulations a more complete understanding of the process can be achieved together with an insight into which parameters need to be adjusted in order to optimize the process. In the present work, finite element analysis (FEA) methods have been used to simulate single and double plate static induction heating of carbon fiber based thermoplastic composite laminates of different thicknesses. The static plate heating tests are validated in LS-DYNA R7 by comparing point temperature measurements through the thickness of the specimens. Following on from this, a simulation test-bed has been created in order to study the continuous induction welding of two joining partners allowing the generation of 3D surface plots of temperatures through the thickness of the joint and most importantly at the joining interface.

1. Introduction

In 2014 the automotive industry has still only just begun to integrate fiber reinforce plastics (FRPs) into vehicles. It can be foreseen that in the future more and more individual parts will be designed and manufactured from FRPs. These parts will be expected to function synergistically with other materials such as advanced metals as has already occurred in the aerospace industry. With these developments in mind, mass production ready manufacturing techniques for FRPs will become of the utmost importance. One type of FRP showing the greatest potential for mass production are the continuous fiber reinforced semi-finished sheets or so called "organosheet" materials. These thermoplastic composites show processing potential similar to that of sheet metals. Shaping can be achieved via thermoforming and joining by fusion bonding (welding) using equipment close to that currently used for metals and making them a very attractive material addition for mass production.

Induction welding is one efficient means of joining such materials but involves many interacting parameters and is difficult to study let alone optimize by experiments alone. Many of the well-known general purpose finite element software codes are today becoming capable of multi-physics simulations and can help. The aim of this process modeling case is to be able to predict the optimal processing parameters of a continuous induction welding process. The input variables are the electromagnetic (EM) and thermal properties of both the material undergoing the heating and the induction coil which is part of the welding system. In addition, the electromagnetic and thermodynamic constraints of the surrounding environment (which is usually air) is also accounted for. The generator input parameters (e.g. frequency, coil current, coupling distance) are also required. Some of these parameters can be taken from the literature or databases, while others such as the generator input parameters can be measured directly from the induction heating equipment itself. One of the most critical set of input parameters is that of the laminate material itself. Here the parameters need to be measured using mechanical, thermal and electromagnetic material characterization experiments.

2. Induction welding simulation basics

Induction welding is a joining process that uses an oscillating electromagnetic field to generate a contact-free heating. The subsequent adhesion is supported by applying pressure and allowing enough time for fusion bonding to take place. During the process, an induction coil, connected to a high frequency oscillating current source (usually in the kHz – MHz range) creates an alternating current in the coil. This current in turn produces a time-variable magnetic field of the same frequency in the near surroundings of the coil as illustrated in Figure 1.

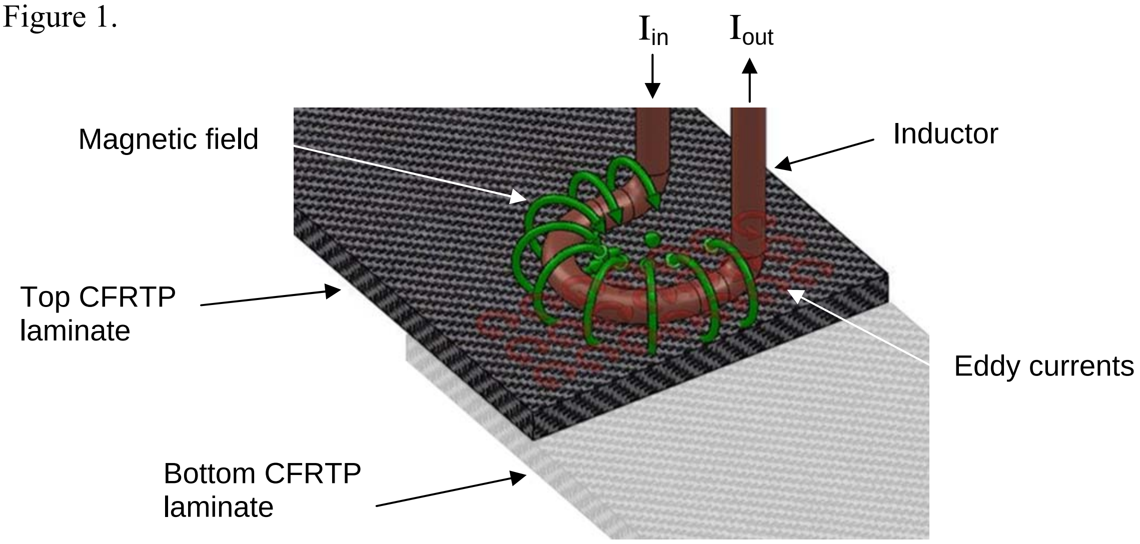

Figure 1. Working principle of induction heating in weave structured CFRTP sheet materials (image courtesy of Mrs. Mirja Didi IVW GmbH)

The alternating magnetic field induces oscillating eddy currents in a work piece when placed in close proximity to the coil. Heat energy is generated via the Joule effect as a result of the induced eddy currents flowing through the electrically conductive material [1, 2]. For composite materials containing glass fiber reinforcements, no Joule heating can occur and a susceptor material in the form of a steel mesh, for example, is required between the materials to be joined. Composites containing carbon fibers in certain configurations (weaves) however, do produce a Joule heating effect and can be utilized to create the heating effect necessary.

During a finite element simulation of the induction welding process, it is precisely this Joule heating phenomena which is of primary interest to be simulated. Moreover, knowledge about the heating, cooling, and pressure time history at the joint interface is exactly what is required in order to be able to predict the final joint strength. How these variables can be used to estimate the joint strength is a detailed topic in itself involving the theories of ‘intimate contact’ and ‘autohesion’ (or healing) as has been proposed by Loos et al. [3], Lee et al. [4] and later Yang and Pitchumani [5-7] and will not be covered here. It is safe to say, that only after the correct prediction of all the manufacturing phenomena which occur during induction welding is achieved does it make sense to proceed onwards in this direction.

3. Material properties

The most important inputs to any simulation are the material properties. To simulate induction welding a wide variety of material properties are required in order to capture all of the physics involved. Table 1 shows some of the typical mechanical, thermal and electromagnetic properties used, many of which (for example, the material stiffness, heat capacity, thermal conductivity, electrical conductivity and magnetic permeability) can be defined with a temperature dependency. In some cases the temperature dependence is not significant and can be ignored. This is the case, for example, with the thermal conductivity since its overall magnitude and resulting influence on the heating effect is very low. For other multi-physics parameters such as the material stiffness, heat capacity and the electrical conductivity, defining temperature dependent properties are crucial towards achieving the correct results.

Type of Physics	Material Property		Air	Coil (Copper)	Composite Plate (*CF-PPS)
Mech.	Stiffness, E (Pa)	E_1, ν_1	-	1.1×10^{11}, 0.34	6.0×10^{10}, 0.35 E, v vs. T curve
		E_2, ν_2	-		6.0×10^{10}, 0.35 E, v vs. T curve
		E_3, ν_3	-		4.0×10^{10}, 0.35 E, v vs. T curve
	Density, ρ (kg/m^3)		1.293	8960	1790
Therm.	Heat Capacity at (const. pressure), Cp (J/(kg*K)		1010	385	[6]1803 Cp vs. T curve
	Thermal Conductivity, k (W/m*K)	k_1	0.026	390	[7]2.50
		k_2	-	-	[7]2.50
		k_3	-	-	[7]0.32
EM	Electrical Conductivity, σ (S/m)	σ_1	1	5.998×10^7	[8]1.389×10^4 σ vs. T curve
		σ_2			[8]1.389×10^4 σ vs. T curve
		σ_3			[8]1.000×10^1 σ vs. T curve
	Relative Permittivity, ε_r		1	1	[9]3.7
	Relative Permeability, μ_r		1	1	1 B vs. H curve μ_r vs. T curve
	Surface Emissivity		-	0.5	0.95
	Skin Depth (mm) (automatically calculated)		-	~ 0.1	~ 3.5

[6,7,8,9] *Values taken from the measurements and data collected from the work of references [8, 9, 10].*
** Carbon fiber reinforced polyphenylene sulfide*

Table 1. Summary of typical material property parameters used in the LS-DYNA induction heating finite element models.

While it is obvious that the materials thermal properties are and should be considered orthotropic, the question of whether or not orthotropic electrical conductivity should be considered arises. In the most complex case, a temperature dependent orthotropic material property input may be required. An attempt to answer this question is given in Section 4.2.

In addition to the material properties, boundary conditions such as the thermal contact heat transfer coefficient, contact resistivity, and temperature dependent convection coefficient on the exposed surfaces of the plates are important and all play a significant role.

4. Static plate heating simulations

4.1. Double plate heating models

The key elements of an induction welding simulation can be demonstrated using static double plate heating models. Comparisons can also be made with single plate heating simulations. Figures 2 a) and b) show example models and point temperature heating results of single and double (100 x 100 x 2 mm) CF-PPS static plate induction heating simulations compared to the corresponding experiments. Note that in the images the models have been cut in half in order to better visualize through the thickness temperatures.

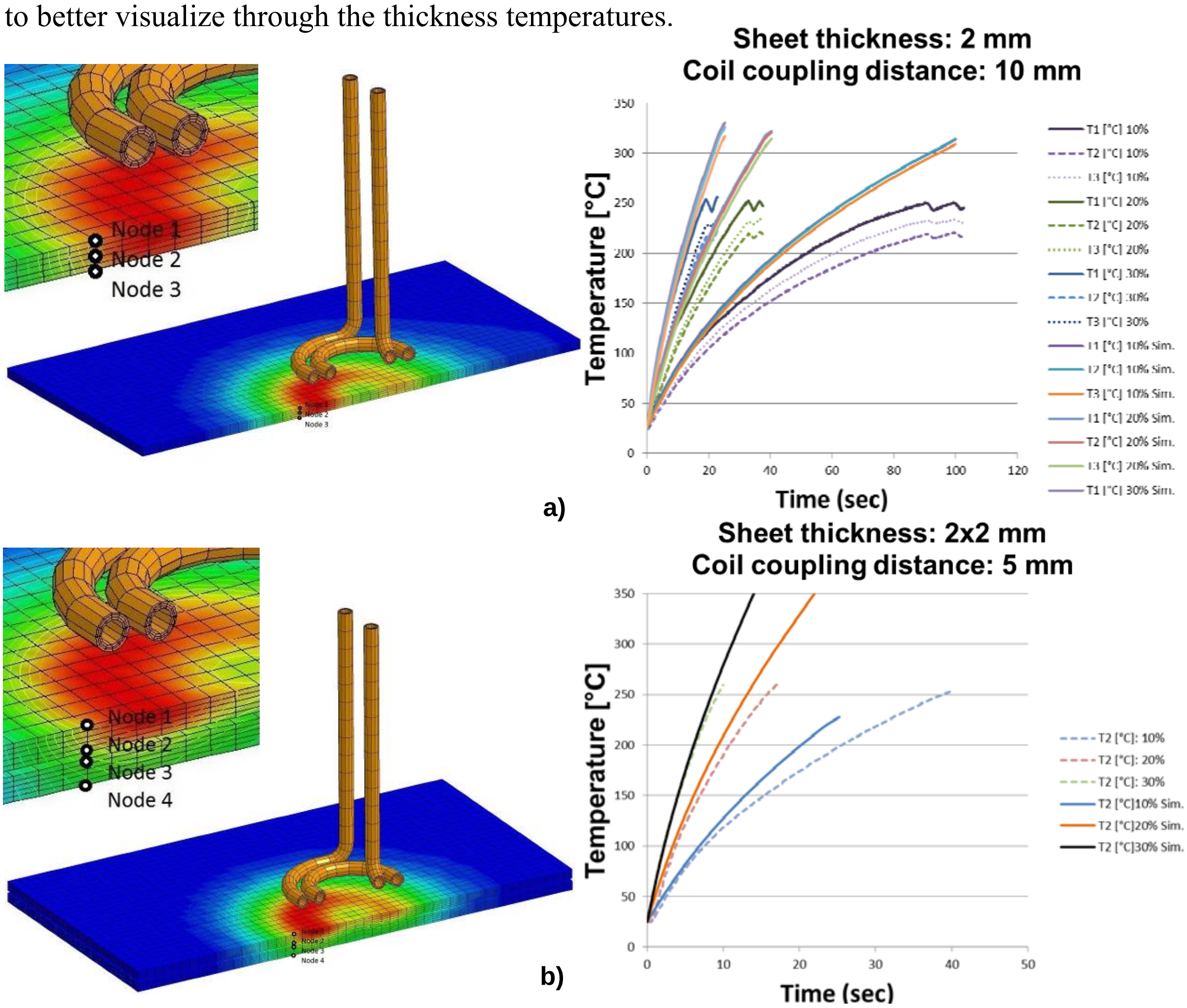

Figure 2. FEM/BEM simulation model set-up for a) single and b) double plate through the thickness temperature investigations and their corresponding point temperature comparisons between experiments and LS-DYNA simulation results at 10% (163 A), 20% (231 A) and 30% (283 A) power and a coil frequency of 540kHz.

The necessary geometry for both the coil and CFRTP plate are both meshed to a suitable resolution to allow for the correct electromagnetic and thermal behavior of the system to be calculated. In the present models both the coil and plate geometries are meshed using solid hexahedral elements. The electromagnetic calculation is performed using the boundary element method (BEM) which solves Maxwell's equations in the eddy current induction diffusion approximation. The elements required for the BEM calculations are automatically generated on the surfaces of the solid finite element mesh which itself considers the thermal and mechanical effects in the usual way. Both types of elements are strongly coupled meaning that there is transfer of information (e.g. temperature) between the solvers operating on each type of elements.

Note that the node locations shown in Figure 2 correspond to the location of thermocouples ($T_{1,2,3}$ on the graph legend) used in the physical experiments. The heating of two plates is of more interest than one but adds further complications as it involves an extra load contributor (i.e. an extra plate) in the electromagnetic circuit. The eddy currents developed in the top plate are now also affected by the presence of the bottom plate as well as the coil. In the double plate simulation case, nodes 2 and 3 are averaged to estimate the experimental temperature T_2 at the joining interface.

4.2. Influence non-linear electrical conductivity and orthotropic material input

In general, using a constant value of electrical conductivity over-predicts the heating effect over a wider temperature range as can be seen in Figure 2. By defining a non-linear electrical conductivity dependent on temperature, both the temperature spread through the thickness and the predictions over a large temperature range can be improved. This improvement however, comes at the expense of computing time as the electromagnetic fields must be recalculated enough times to capture the non-linearity.

Simulations performed to assess the significance of orthotropic electrical conductivity tend to suggest no difference in the heating behavior when the material is considered electrically orthotropic as opposed to isotropic. In an isotropic case, the material is assumed to have an electrical conductivity equivalent in all directions to that measured in the in-plane directions. It can only be presumed that the large order of magnitude difference (~1000) between the in-plane and through the thickness electrical conductivity, combined with the large skin depth (almost the entire thickness of the laminate stack) results in an insensitivity to the through thickness value of electrical conductivity. This means that a simpler (isotropic) electromagnetic material model can in this case be applied.

5. Understanding continuous induction welding

Figure 3 a) shows a schematic of a two-dimensional experimental test-bed setup consisting of a fixed coil, consolidation roller and a moving platform. The corresponding typical temperature versus time graph of a single point within the heating zone measured on the top surface of the material stack during the joining process is shown in Figure 3 b).

The nature of the graph can be described as follows: As the material passes below the coil, its temperature rises until it reaches T_{max}. This signifies the end of the heating after which the temperature drops slightly due to heat transferred to the jig and surroundings via free convection and conduction. The point at which the consolidation roller first contacts the measurement point is indicated by T_{rc1}. Here the consolidation phase begins and the temperature drops steeply as the roller applies pressure and cools the material to T_{rc2}. Heat flowing from the inner to the outer top surface of the laminate stack then causes a small rise in the temperature and the material then slowly cools back to its starting temperature T_a.

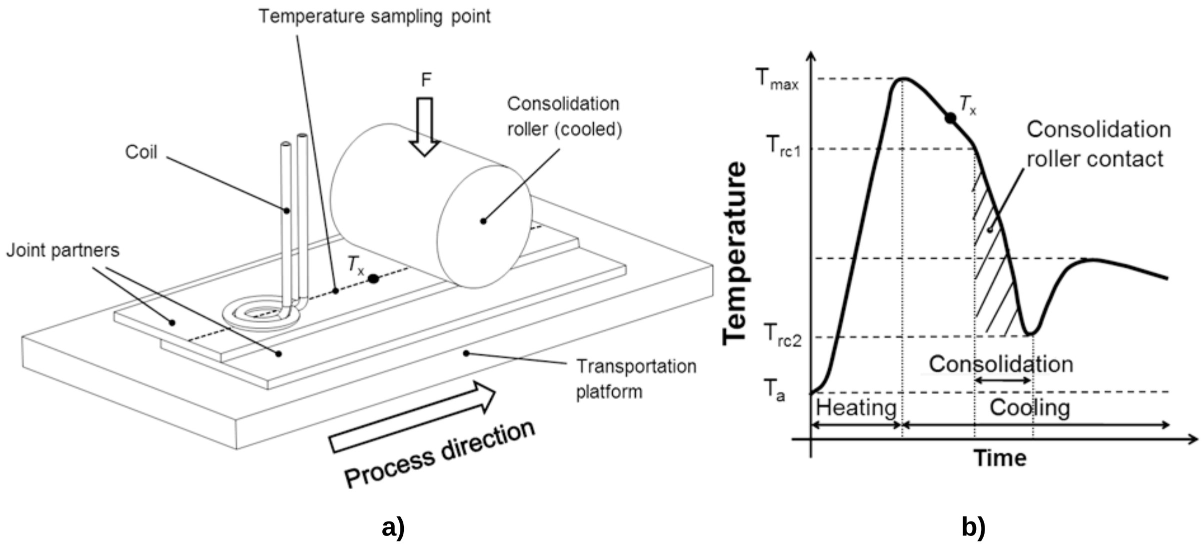

Figure 3. a) Experimental test-bed setup for the continuous induction welding of two material joining partners and b) corresponding example thermal profile on the top surface of the joint.

The most important part of the curve is represented by the temperature drop achieved between T_{rc1} and T_{rc2}. At the joining interface there should also ideally be a temperature rise and drop starting from above the melt temperature of the polymer, T_m, to just below the glass transition temperature, T_g, within the time that the consolidation roller applies pressure. In this way, the material has the time it needs to create the bond. For slow welding speeds in the order of 1-3 mm/sec this is easy to achieve. For processing speeds of up to 100-300 mm/sec (which would be deemed acceptable for mass production scenarios) difficulties arise. One of the goals of the test-bed simulation is to therefore analyze the possibilities of such welding speeds and to assess if and how they could possibly be achieved.

6. Simulating continuous induction welding

Figure 4 shows a snap shot of the induction welding simulation test-bed during a welding simulation.

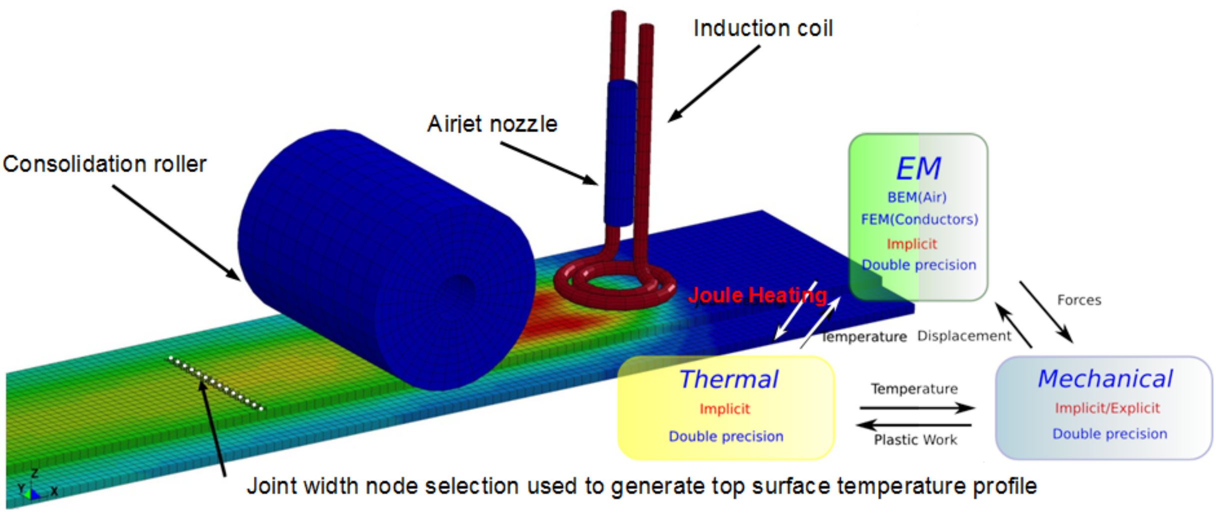

Figure 4. Experimental test-bed setup for the continuous induction welding of two material partners and corresponding physics interactions.

Contrary to Figure 2 a) the laminate stack now remains static while the induction coil and consolidation roller move as if configured onto a welding head mounted on the end of an industrial welding robot. All of the necessary physics has been defined, including the joule heating resulting from the induction coil interacting with the two CFRTP plates. A vertical consolidation roller contact force has been applied and together with a friction coefficient and a horizontal velocity boundary condition (which defines the processing speed) the correct rolling motion is enabled. Heat transfer via convection to the surrounding air as well as conduction to the consolidation roller is also considered. Finally, the heat transfer and pressure resulting from an air-jet is simulated via a moving heat flux and moving pressure boundary conditions respectively. Further details about the model can be found in the previous works of Duhovic et al. [9, 10].

6.1. Influence of top surface cooling

In Figures 5 a) and b), the simulation test-bed is used to investigate the influence of top surface cooling on the temperature development of the top surface laminate during induction welding of CFRTP (CF-PPS) organosheet for fixed power and frequency settings of 240 A and 400kHz respectively. It can be seen that the effect of the top surface cooling reduces the maximum temperature developed in the top plate by almost 200°C thereby avoiding any thermal damage on the plate surface closest to the induction coil.

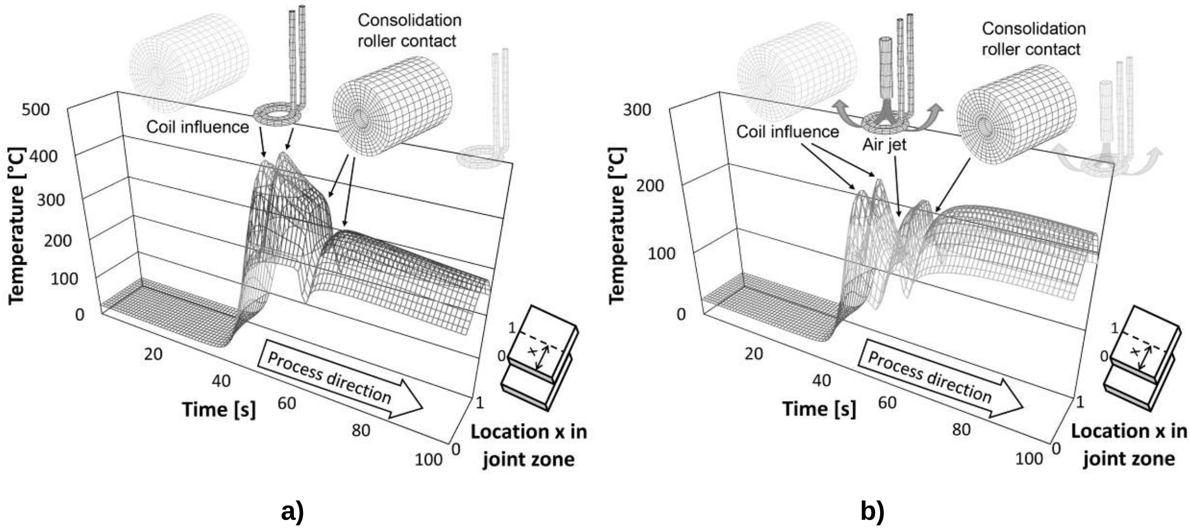

Figure 5. Top surface temperature plots for the top laminate using nodes selected across the entire width of the weld as shown in Figure 4, welding speed 3 mm/sec, fixed coil coupling distance 2 mm and coil to roller offset distance 60 mm; a) without and b) with air-jet cooling (304 liters/min).

An equally favorable effect of the surface cooling on the bond-line surface temperature can be seen in Figures 6 a) and b). The surface plots here show that a larger drop in temperature is achieved over a shorter period of time as a result of the surface cooling, suggesting that better consolidation of the laminates should take place. In an ideal joining case, the goal would be that the temperatures across the width of the surface plot must all fall within the processing temperature window of the thermoplastic polymer material used, if complete adhesion of the overlapping area is desired. It can now be seen that this is characteristic is strongly dependent on the nature of the heating pattern generated by the coil or in other words, the coil geometry. To achieve faster welding speeds the heating non-uniformity of the coil across the width of the joint must therefore be kept to a minimum.

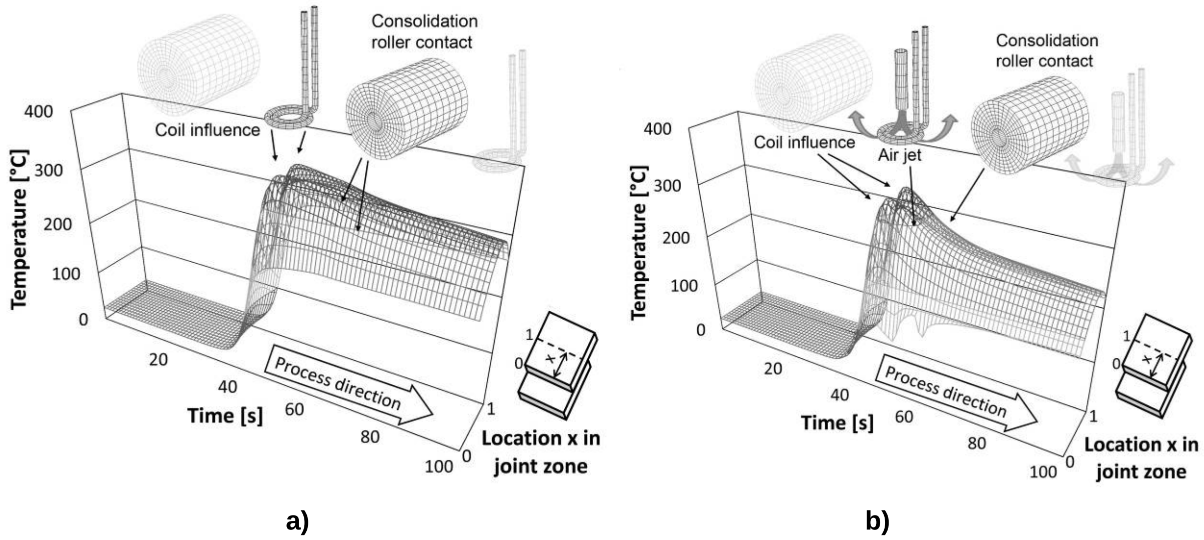

Figure 6. Bond-line surface temperature plot using nodes selected across the entire width of the weld as shown in Figure 4, welding speed 3 mm/sec, fixed coil coupling distance 2 mm and coil to roller offset distance 60 mm; a) without and b) with air-jet cooling (304 liters/min).

7. Conclusions

The present work has demonstrated some of the advanced 3D modelling techniques which can be used to help optimize the induction welding process of CFRTP materials. Further work continues to see what can be done in order to achieve the processing speeds necessary for mass production.

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