Advances in Simulating the Processing of Composite Materials by Electromagnetic Induction

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Abstract

In the previous installment of this work, a flat spiral "pancake" type coil geometry and two different plate material types with large differences in electrical and thermal conductivity (structural steel and carbon fiber reinforced polymer composite) were used to perform static plate induction heating characterization experiments for the purposes of characterizing the heating behavior of both materials in preparation for continuous induction welding simulations. The static plate heating tests were validated experimentally in two Finite Element Analysis (FEA) software codes including LSTC's LS-DYNA® 980 (R7) solver. Following on from this initial work, a simulation test-bed has been created in order to study the continuous induction welding of two joining partners. The simulation test-bed mimics an experimental setup developed at the Institut für Verbundwerkstoffe (IVW) GmbH which considers a two-dimensional joining setup (two flat overlapping plates) and allows a more complete investigation of the thermal behavior that occurs during a continuous induction welding process. 3D surface plots of the top surface temperatures which are generated across the entire width of the joint as well as along its length can be investigated for different welding speeds and induction welding processing parameters. More importantly, the same types of surface plots can also be generated at the joining interface providing a complete view of the temperature profile that occurs during the process at this important location. This information can be used to decide on the optimum processing parameters to ensure that the material anywhere at the joining interface always remains within its prescribed upper and lower processing temperature limits. With its three-way physics coupling, the simulation test-bed also allows the consideration of further processing parameters including the influence of roller contact and additional top surface cooling via a moving air-jet nozzle for different induction welding speeds.

1 Introduction

It will soon become obvious to automotive manufacturers and their material suppliers alike that thermoplastic based composites can help accommodate the requirements of lightweight vehicle design as well as provide the opportunity for the utilization of mass production techniques to rival and compliment that of metal parts production. The so called 'organic sheets' consisting of either glass or carbon fiber reinforced thermoplastics as manufactured by companies such as Tencate or Bond Laminates use fundamentally the same manufacturing technology needed for sheet metal stamping with the exception of additional heating requirements. Nevertheless heating even far beyond that required by the most advanced thermoplastic composites has in any case become a necessity for the stamp forming of more advanced aluminum alloys. The current state of the art in automotive manufacturing of composite parts consists mainly of thermoset composites (perhaps due to the cost) employing liquid composite molding (LCM) techniques such as wet pressing, resin transfer molding (RTM), and structural molding compound (SMC) pressing. The joining of such materials either to themselves or other metallic parts usually consists of adhesive technologies which is not always the ideal solution.

2 Induction welding basics

Induction welding is a joining process that uses an electromagnetic field for contact-free heating and subsequent adhesion via pressure. An induction coil which is connected to a high frequency alternating current source (usually in the kHz – MHz range) creates an alternating current in the inductor coil. The coil current in turn produces a time-variable magnetic field of the same frequency in its near surroundings as illustrated in Figure 1.

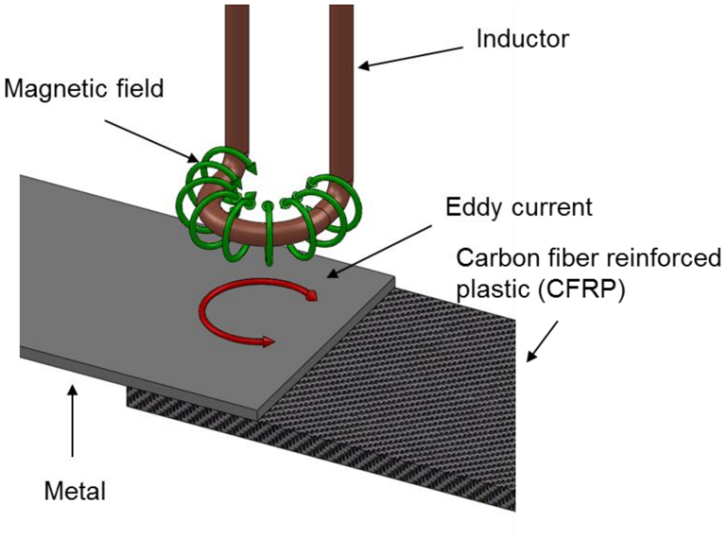

Fig. 1: Working principle of induction heating (image courtesy of Mrs. Mirja Didi IVW GmbH)

The alternating magnetic field then induces eddy currents in a workpiece when placed in close proximity to the coil. These currents have the same frequency as the coil current but flow in the opposite direction to that in 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]. In the case of a hybrid material joint, the metal part is heated and the thermoplastic matrix of the fiber reinforced polymer composite (FRPC) can be melted by conduction. If the joint desired is composite to composite, then a susceptor (an additional material with a suitably high electrical conductivity) may be required. 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 however, do produce a Joule heating effect and can again be utilized to create the heating effect necessary. Therefore, one main criteria for the induction heating of dissimilar materials is that at least one of the joining partners has an electrical conductivity of sufficient magnitude to allow a suitable Joule heating effect via induction to create the heat energy required for the joining procedure.

2.1 Continuous induction welding

The induction welding methods being investigated at Institut für Verbundwerkstoffe GmbH can generally be classified into continuous or discontinuous processes. Discontinuous induction welding closely resembles the spot welding procedure commonly used to join sheet metal in the automotive industry. Connections of a discontinuous nature can help relieve problems arising from large differences in thermal expansion behavior between the joining partners. For hybrid material joints, a special integrated temperature-pressure spot welding head that can then be mounted on an industrial robot has been developed. More details about the design of the hybrid material spot welding head and nature of this process can be found in the following references [3-6].

The continuous induction welding process on the other hand applies relative movement between the heating/consolidation unit and the workpiece, producing the weld. Figure 2 a) shows a schematic of a two-dimensional experimental test-bed setup consisting of a fixed coil, consolidation roller and moving platform. For a fully automated implementation of this process, a welding head consisting of the coil and consolidation roller can be mounted on an industrial robot as shown in Figure 3. In either case, 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 can be seen in Figure 2 b) [7].

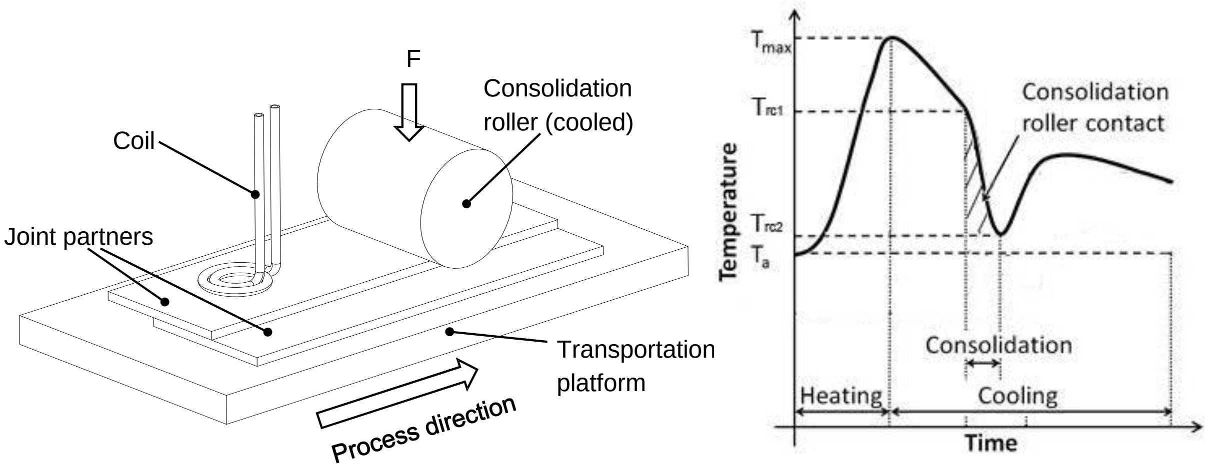

Fig. 2: a) Experimental test-bed setup for the continuous induction welding of two material partners and b) corresponding example thermal profile on the top surface of the joint

The nature of the graph in Figure 2 b) can be described as follows. As the material passes below the coil, its temperature rises until it reaches T_{max} signifying the end of the heating phase of the process. The temperature then drops slightly due to heat transferred to the jig and surroundings via free convection and conduction until the roller first contacts the measurement point at 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 inertia resulting from the intrinsic induction heating then causes a rise in the temperature, well below melt temperature, after which the material then slowly cools to the starting temperature T_a.

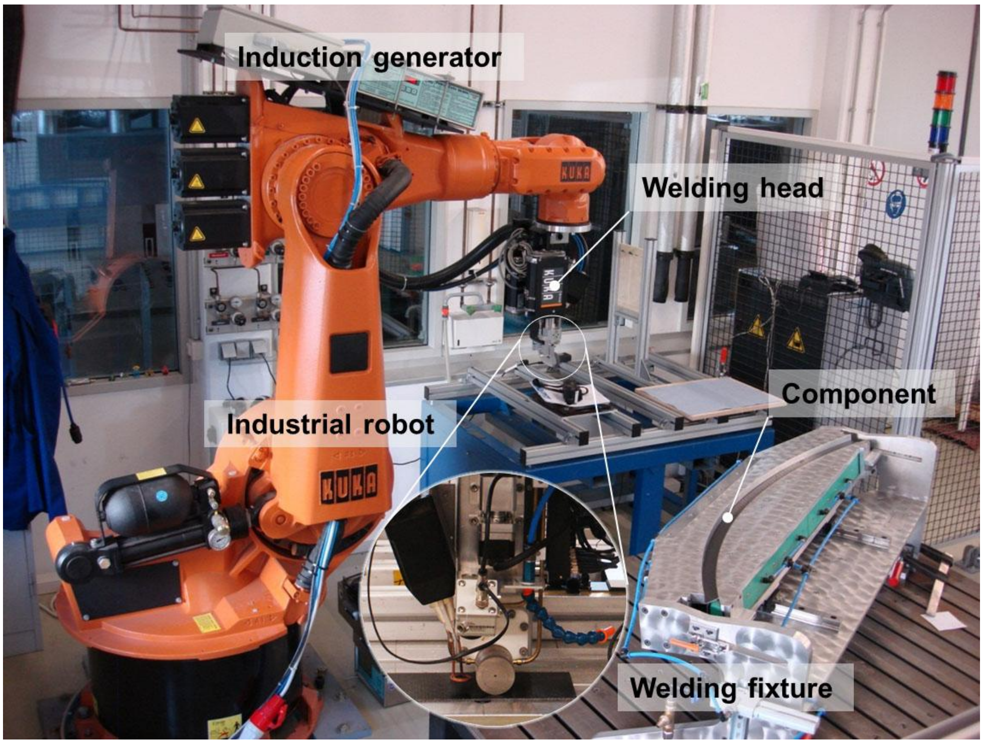

Fig. 3: Industrial continuous induction welding setup using a KUKA robot at the Institute für Verbunwerkstoffe GmbH

Knowledge and an understanding of the thermal profile at every single point across the width of the desired weld area with respect to time are of the utmost importance. This is true not only for the top surface of the laminate stack but even more so for the bond line surface. In the case of the top surface, temperatures below melting point of the polymer are desired in order to avoid deconsolidation of the laminate. Degradation of the top surface due to a combination of overheating and excessive application of consolidation pressure can also be a problem. The through thickness temperature profile is another very important feature of the process to know and understand. Methods which focus heat energy directly at the bond line such as top surface cooling as investigated and patented by Moser et al. [8, 9] as well as the use of additional or integrated susceptor materials can influence this behavior significantly. Experimental measurement of temperatures in the bond line becomes very difficult as the available thermal sensors (both fiber optic and metallic sensors alike) are affected by the magnetic field.

It has taken 15 years to achieve the knowledge to be able to produce high quality continuously welded joints of either composite to composite (e.g. Carbon fiber-reinforced polyetheretherketone (CF/PEEK), Carbon fiber-reinforced polyamide 66 (CF/PA66)) or composite to metal (e.g. Aluminium alloys such as AlMg3 to CF/PEEK or CF/PA66) joints using the induction welding process. Nevertheless the welding speeds possible are still only in the range of 3-5 mm/sec. For all these reasons, a finite element induction welding simulation test-bed considering all the possible physics of the process has been developed and built in the finite element software LS-DYNA® (R7) [10-12].

3 Induction welding finite element simulation test-bed

The simulation test-bed considers all thermal, mechanical and electromagnetic interactions for the case of a two-dimensional induction welding situation as was described in Figures 2 a) and b). The only physics missing from the different solvers available is fluid dynamics, which is demonstrated for the case of induction coil cooling in the paper by Caldichoury et al. [13]. Relative movement between the laminate stack and coil, roller and nozzle has been modeled as in the case of an induction robot welding head performing the operation. Here the coil, consolidation roller and air-jet nozzle are assembled as a unit and are all moved by a robot at constant welding velocities. This is contrary to the simplified laboratory setup where the coil, roller and nozzle remain static and a transport platform moves the laminate stack however, both arrangements give the same results. Details of all the material properties, thermal and electromagnetic, used in the model can be found in the earlier paper by Duhovic et al. [14].

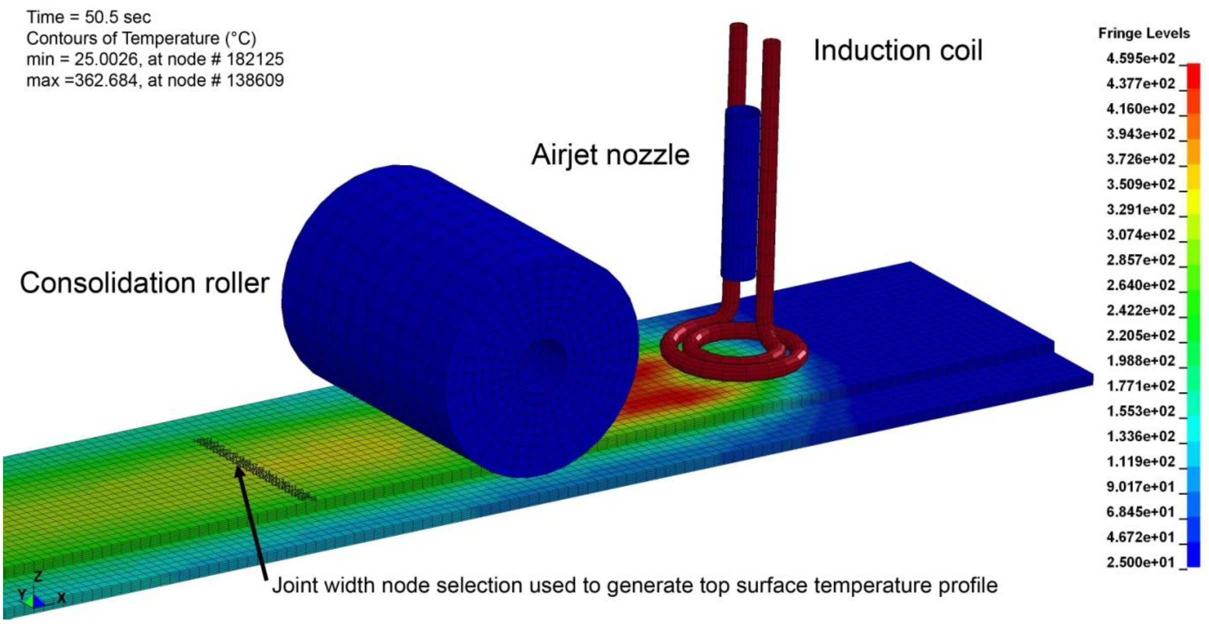

Fig. 4: Induction welding simulation test-bed developed using LS-DYNA® (R7) and the wealth of knowledge accumulated at the Institut für Verbundwerkstoffe GmbH over the last 15 years

Mechanical interactions between the consolidation roller plus air-jet pressure and the laminate stack have also been included in the model. This is important since it is a combination of temperature, pressure and time in the correct amounts which in the end determines the quality and strength of the joint. The necessary degrees of freedom have been applied to the roller and a surface to surface contact between the roller and laminate stack which includes static and dynamic friction coefficients enables the rolling contact motion. In an actual welding process, induction heating starts together with top surface cooling and when the correct temperature is reached, the roller contacts the laminate stack with the applied consolidation pressure and the welding procedure begins. Figure 5 shows a plot of the z – direction force in Newtons (N) between the rigid body master (the roller) and the top laminate part. In this case, a normal force of 300 N, as commonly used in practice, has been applied as the roller traverses the laminate stack. The image inside the plot shows the contours of pressure resulting from roller contact and the air-jet. It can been seen that pressures in the order of 1 MPa are generated as a result of roller contact while those from the air-jet are in reality considerably lower and have been scaled in Figure 5 so that they appear in the plot. In reality, unless very special air-jet nozzles are used, the pressures generated from the air-jet can be ignored.

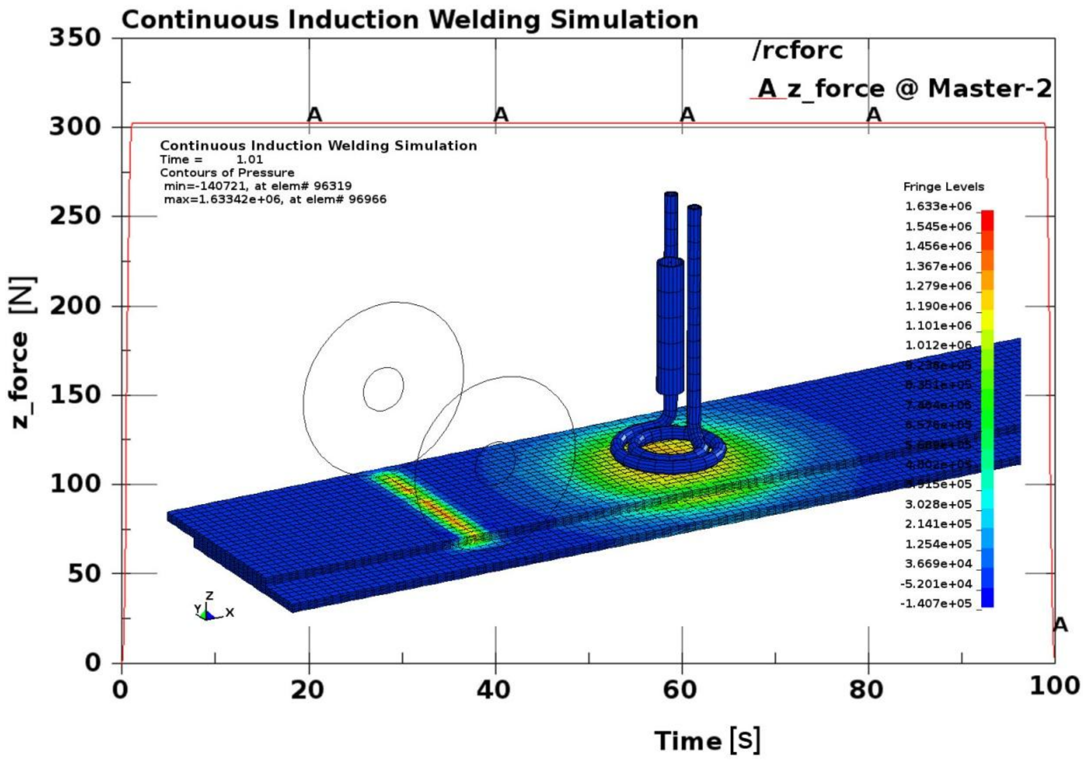

Fig. 5: Induction welding simulation test-bed showing the overall roller contact force together with contours of pressure in the laminate generated as a result of roller contact and air-jet pressure

Top surface laminate cooling resulting from the air-jet nozzle blowing air through the center of the pancake coil has been modeled using a “moving heat flux” boundary condition setup via the *DEFINE_FUNCTION card. An average moving heat flux of 440 W/m2.K is used which corresponds to a volume flow of an impinging air-jet of 304 liters/min as calculated in the dissertation of Moser [8] using theory derived from the VDI-Wärmeatlas [15]. The moving convection as a function of position is centered on the air-jet nozzle which moves together with the coil and roller and has been assigned an effective cooling area of 80 mm diameter [8]. Roller to laminate contact has been assigned a typical metal to polymer contact heat transfer conductance value of 300 W/m.K. A good overview of what this value should be for different polymers types can be found in the works of Marotta and Fletcher [16]. Although the mechanical interactions are important for calculating overall bond strength (which will be covered in a future publication) they are also required for obtaining the correct thermal behavior. Heat transfer via convection to the surrounding air and holding fixtures as well as conduction from the laminate stack to the consolidation roller play an important role in determining the overall temperature profile developed in the laminate stack and most importantly at the bond line surface. The subsequent contents of this paper will focus on temperature developed at various locations of the laminate stack with respect to time using the simulation test-bed developed.

As mentioned before, excellent welded joints for materials such as CF/PEEK and CF/PPS thermoplastic laminates when joining to themselves have been achieved at welding speeds between 3 – 5 mm/min [8]. The problem of top surface degradation has also been eliminated using air-jet cooling which has been shown to work extremely well at these speeds [8]. The initial test-bed simulations therefore focus on reproducing this set of processing parameters and examining the temperature profiles that are generated as a result. Figure 6 shows the top surface temperature plot for the top laminate using nodes selected across the entire width of the weld.

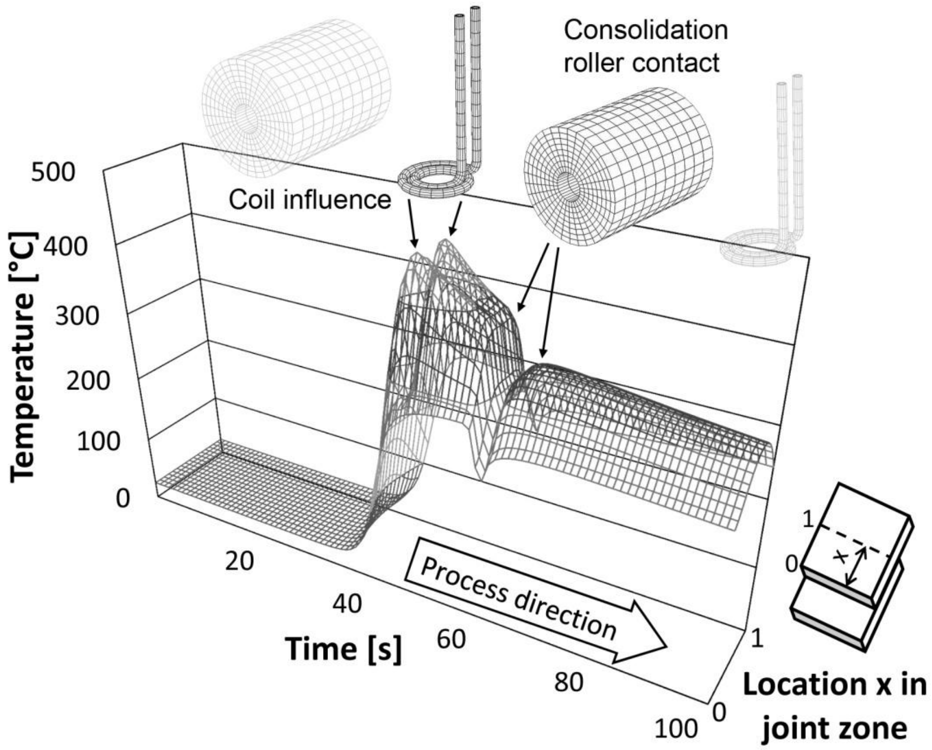

Fig. 6: Top surface temperature plot for the top laminate using nodes selected across the entire width of the weld, welding speed 3 mm/sec, fixed coil coupling distance and coil to roller offset without air-jet cooling (CF/PEEK to CF/PEEK)

The characteristic features of the surface plot are analogous to that explained in Figure 2 b) except that now the entire weld width is represented. All temperatures that are felt with respect to time during the welding procedure can therefore be visualized and one can take the into account the processing window of the material when choosing the processing parameters such as coil type, current, coupling distance and coil to consolidation roller offset distance. These values are deliberately not mentioned explicitly here, but remain the same (except of course for the coil current) in the subsequent temperature surface plots that are shown.

Figure 7 shows the effect of top surface cooling using an air-jet of 304 liters/min (5 mm nozzle diameter) at the same welding speed and processing parameters used in Figure 6. It can be seen that the max temperature has been lowered by almost 200 °C meaning that for a material such as CF/PEEK, the material on the top surface of the laminate stack closest to the induction coil can remain in a completely solid state.

What is of more interest is to examine what is happening at the bond line surface in the cases of top surface cooling and no top surface cooling. The temperature profiles here depend also very much on the in-plane and through thickness thermal conductivity of the material. Figures 8 and 9 show the corresponding surface plots.

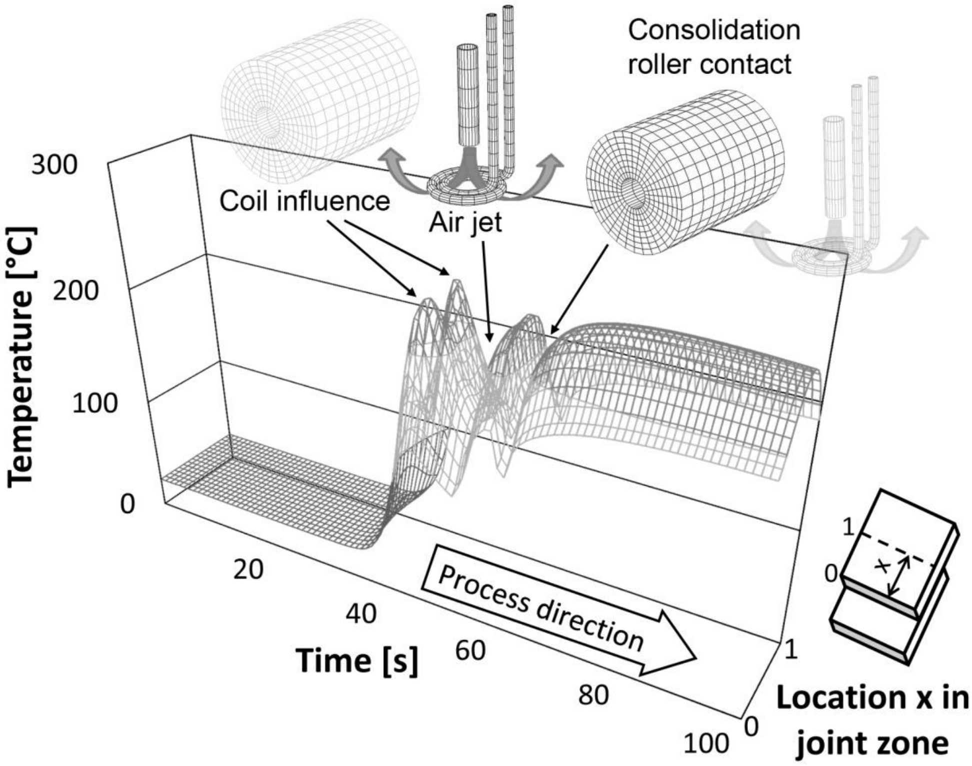

Fig. 7: Top surface temperature plot for the top laminate using nodes selected across the entire width of the weld, welding speed 3 mm/sec, fixed coil coupling distance and coil to roller offset with air-jet cooling (304 litres/min) (CF/PEEK to CF/PEEK)

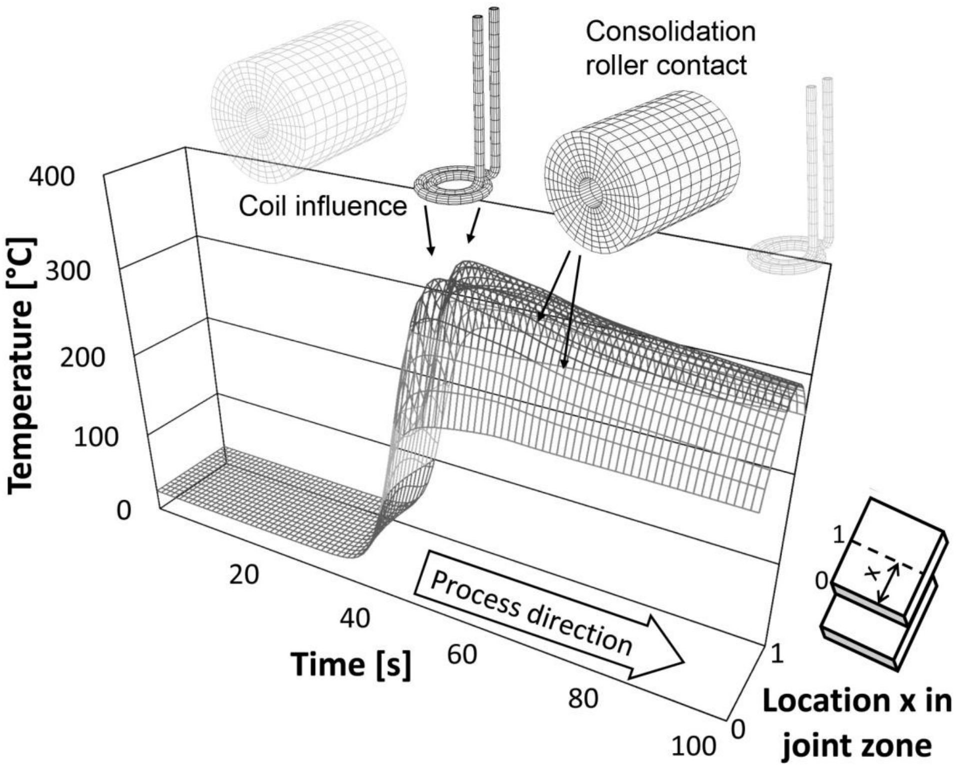

Fig. 8: Bond line surface temperature plot using nodes selected across the entire width of the weld, welding speed 3 mm/sec, fixed coil coupling distance and coil to roller offset without air-jet cooling (CF/PEEK to CF/PEEK)

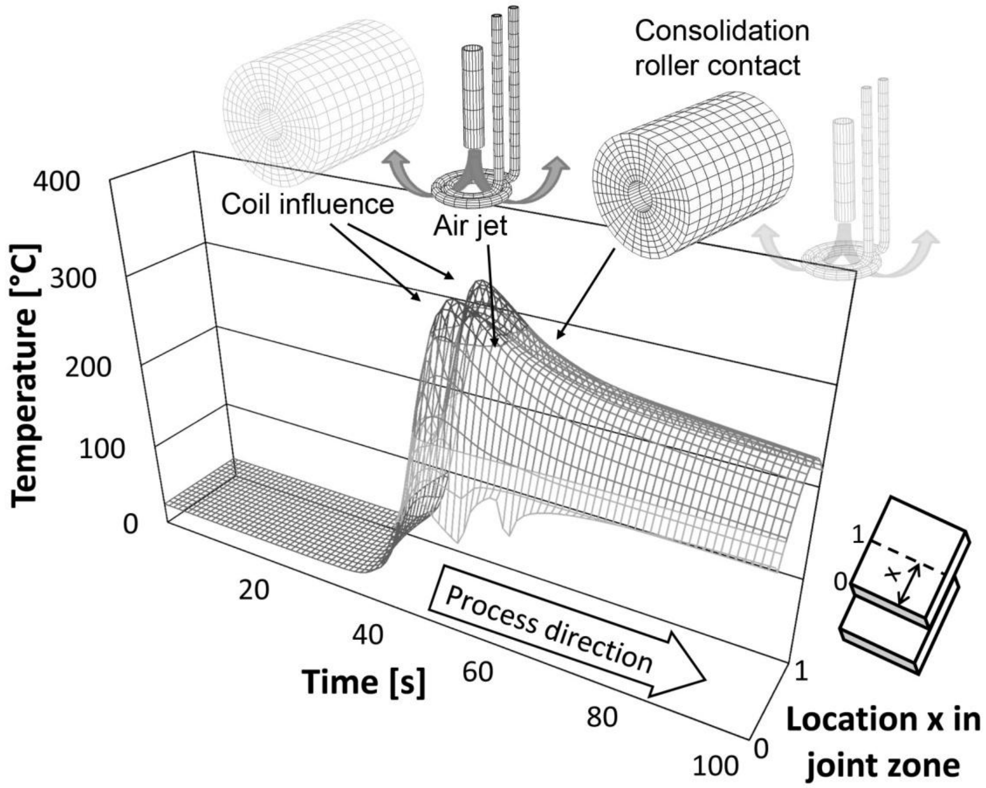

Fig. 9: Bond line surface temperature plot using nodes selected across the entire width of the weld, welding speed 3 mm/sec, fixed coil coupling distance and coil to roller offset with air-jet cooling (304 litres/min) (CF/PEEK to CF/PEEK)

Both the graphs in Figures 8 and 9 show the characteristic drop in temperature which is required for consolidation to take place at this welding speed even though the coil current chosen in this case is not quite high enough for proper consolidation to take place with CF/PEEK. Remember that without the top surface cooling, the temperature on the top surface of the top laminate in some areas reaches above 400 °C with the given parameters for the pancake type coil as was shown in Figure 6. This means that if we were to increase the coil current to achieve the correct range of bond line temperatures, then the top surface of the top laminate would surely burn as has been observed many times in practice. The simulation therefore justifies the use of top surface cooling for the low welding speed of 3 mm/sec.

For CF/PEEK, the ideal temperature drop for bonding to take place is from 380 °C to 280 °C, where the polymer reaches its recrystallization temperature. If this drop in temperature does not take place within the timeframe in which the consolidation roller is present to apply pressure to the laminate stack, then good bonding will not occur. It is interesting to also look at what happens when a welding speed of 300 mm/sec, for example is simulated, the speed at which the process would become interesting for mass production implementation. The coil current in this case model is increased by a factor of 10 so that temperatures close to melting can be achieved and a cooling flow rate of 304 litres/min is still used. It can be seen from Figures 10 and 11 that regardless of the top surface cooling, the temperature plots of the top surface and in the bond line surface both show no drop in temperature, which means that no bonding can occur.

In other words, due to the poor thermal conductivity of the laminate, the heat input cannot escape fast enough to create the conditions required for bonding to take place within the given timeframe. There are several ways to address this problem, they are discussed briefly in the following section and provide the basis for future investigations.

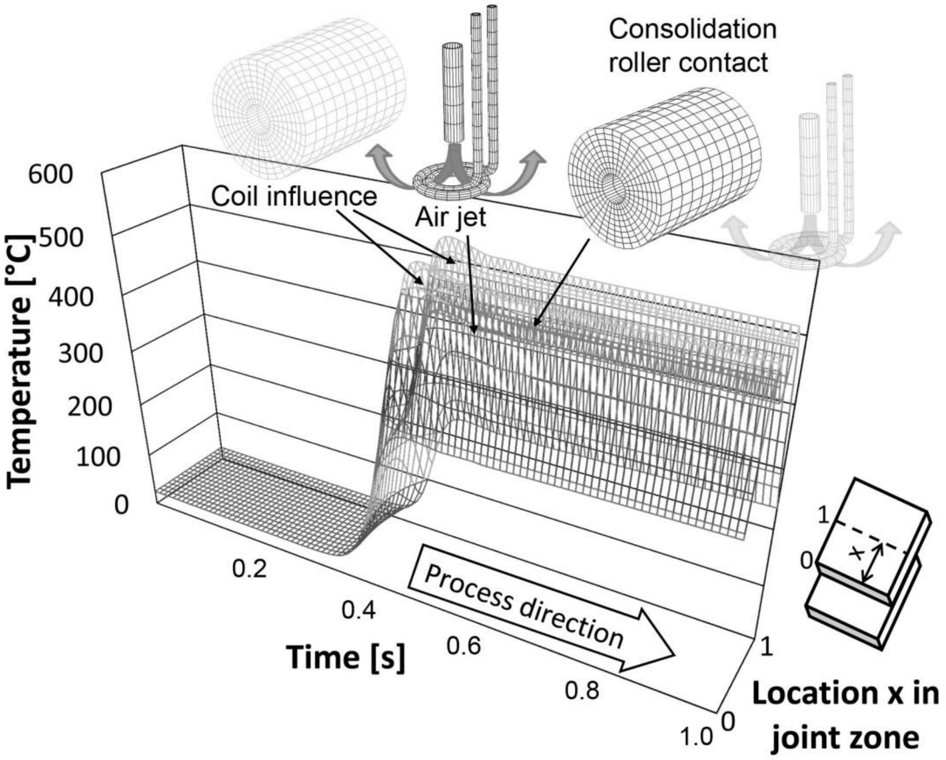

Fig. 10: Top surface temperature plot for the top laminate using nodes selected across the entire width of the weld, welding speed 300 mm/sec, fixed coil coupling distance and coil to roller offset with air-jet cooling (304 litres/min) (CF/PEEK to CF/PEEK)

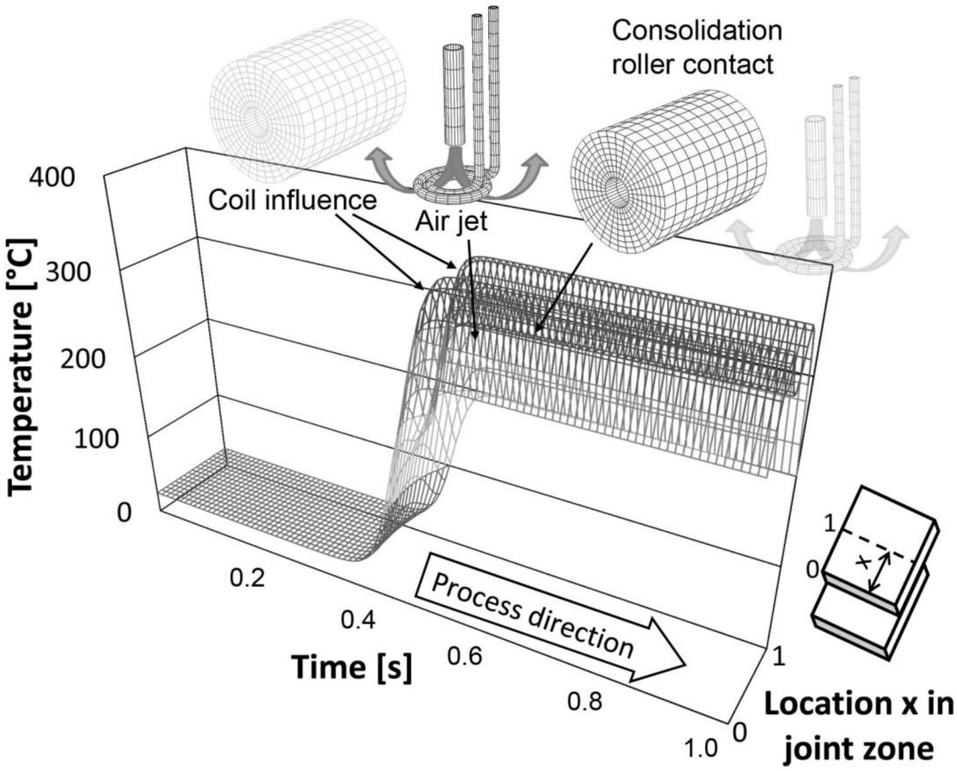

Fig. 11: Bond line surface temperature plot using nodes selected across the entire width of the weld, welding speed 300 mm/sec, fixed coil coupling distance and coil to roller offset with air-jet cooling (304 litres/min) (CF/PEEK to CF/PEEK)

4 Future analyses with LS-DYNA®

Many further simulation scenarios are possible using the simulation test-bed which has been developed here. Models where layers of susceptor materials are placed at the bond line surface and whose electrical conductivity is higher than that of the composite material itself can be examined. Just as importantly, susceptor materials whose thermal conductivity is suitably high can also be investigated. The properties of the susceptor (layer/film) material, i.e. its electrical and thermal conductivity and well as its appropriate thickness to allow a certain welding speed can in effect all be designed using the simulation test-bed. The influence of coil geometry can also be examined in addition to other forms of through thickness temperature control besides air-jet cooling. By examining the models available via the test-bed simulation, the optimum parameters can then be chosen for the induction welding equipment in practice.

Calculation of joint strength is another goal as mentioned earlier. With information about pressure, temperature and time, theory of polymer bonding models as found in the dissertation of Khan [17] and more specifically [18-21] can be applied by setting up the appropriate theoretical equations in LS-PrePost® and processing the data which is readily available from the simulation. Finally, more complex welding scenarios whereby three-dimension coil movements are required can be simulated. Figure 12 shows a large demonstration model of the welding of an automotive bumper beam as performed by the KUKA induction welding robot installation at the Institut für Verbundwerkstoffe GmbH.

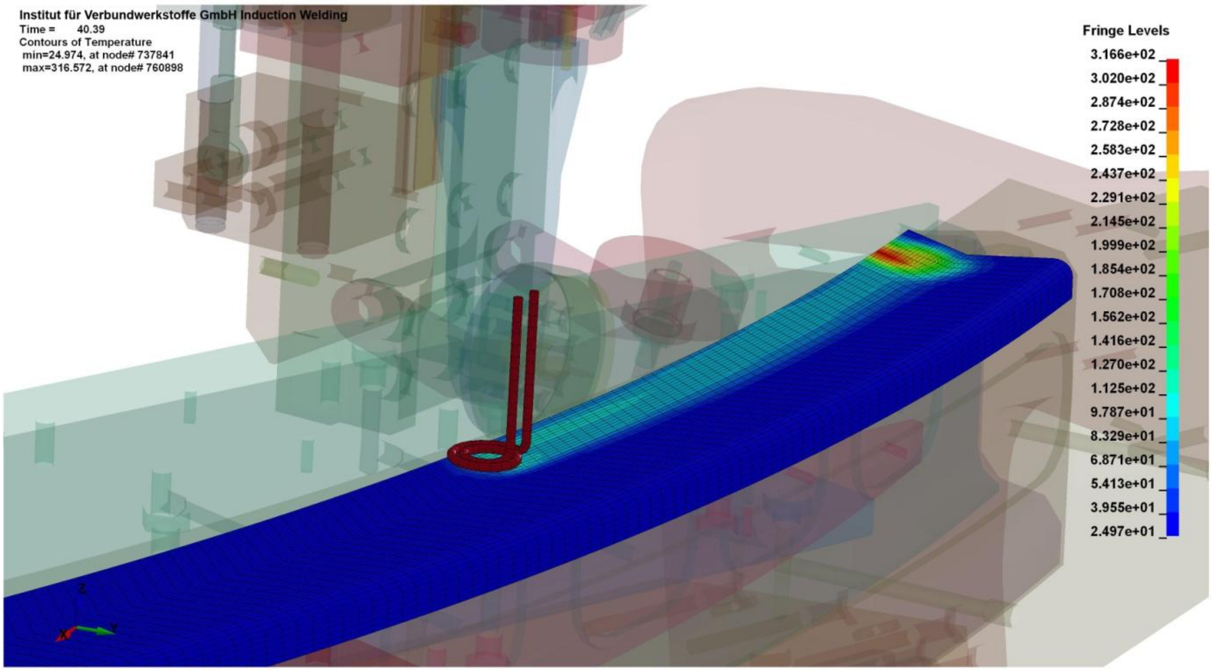

Fig. 12: Large demonstration model of the KUKA robot at the Institut für Verbundwerkstoffe GmbH performing an induction welding procedure on an automotive component

5 Summary

The following work has demonstrated an advanced application of the new induction heating solver available in the multiphysics release of LS-DYNA® (R7). A simulation test-bed investigating a two-dimensional induction welding procedure has been developed which considers all three types of physics (structural mechanics, heat transfer and electromagnetism) occurring in the real process. The model considers an induction heating coil, consolidation roller and cooling air-jet nozzle which traverse a total distance of 300 mm and create the conditions necessary for the fusion bonding of two composite (CF/PEEK) laminate materials. The structural mechanics includes roller contact and a moving radial pressure which has also been included to account for the force generated by a cooling air-jet. The models have been used to investigate welding temperature processing windows and potential optimization strategies that can help this method reach the process speeds necessary for it to be implemented in mass production scenarios.

6 Acknowledgments

The authors would like to thank Mr. Arthur Shapiro for the keyword function code which defines the cooling air-jet moving convection boundary condition used in these models.

7 Literature

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