TOWARDS ROBUST, NON-APPLICATION SPECIFIC CONTINUOUS RESISTANCE WELDING

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ABSTRACT

The quality of high performance structural joints manufactured using resistance welding of thermoplastic composites is highly dependent on the temperature, pressure, and contact time at the weld interface. However, it is not possible to directly monitor the temperature along the weld line to provide high quality process feedback. To guarantee a process that is non-application specific (ie. independent from a specific structure), an approach is presented which uses process modeling and digital twinning to predict key parameters and process quality locally and actively intervenes to keep the process controlled within the pre-defined envelope. This paper describes the early stages of the collaboration between UBC, DLR, and NRC to apply process modeling to shorten the lead time for technology development of the continuous resistance welding process, and presents initial experimental and modelling results. The system and underlying physical phenomena are presented and then three critical stages of the systems approach to model-based control of continuous resistance welding are presented.

1 INTRODUCTION

Advanced thermoplastic composites are increasingly used in aerospace structures using matrices such as PEEK, PAEK, and PPS. Thermoplastic matrix components can have short processing times compared to thermosets and they can be re-melted and re-formed. Due to these characteristics, it is possible to harness techniques such as thermoplastic welding for assembly. When welding, the interface of the substrates or the parts to be joined are heated above the glass transition temperature (T_g) or the melting temperature (T_m) for amorphous and semi-crystalline materials, respectively [1]. This will cause softening or melting at the weld interface, allowing the movement of the polymeric chains. Pressure is applied to bring the adjacent substrates into intimate contact. After intimate contact has been achieved, the polymeric chains begin to inter-diffuse until attaining a fully joined structure. The performance of the weld is a function of temperature, contact time, and pressure [2, 3].

There are three main thermoplastic welding techniques which have been extensively investigated for aerospace applications: induction, ultrasonic, and resistance welding. Resistance welding, which is the topic of this research, uses a resistive implant at the joint interface to input heat into the system. The heating element is typically made from neat carbon fibre, composite prepreg, or a stainless steel metal mesh. When current is passed through the resistive element, heat is generated via the Joule effect, melting the surrounding thermoplastic polymer. When the joint is cooled, the polymer solidifies, resulting in a joined structure. Pressure must be controlled throughout the process, including the cool down. Since the volume of melted polymer extends only fractions of a millimetre into the laminate, the supporting fixturing which is used to precisely control the geometry can be vastly simplified when compared to traditional forming and compression moulding techniques. A coupon scale schematic of the static resistance welding process is shown in Figure 1a.

As advanced thermoplastic composite welding transitions from small, non-structural joints to high aspect ratio structural joints, the traditional static resistance welding process quickly becomes unfeasible and issues with process control arise. When this cannot be overcome by complex and costly fixturing, there is a need to adapt the joining methodology and continuous resistance welding (CRW) has been identified as a promising technique. CRW uses the same basic principle but replaces the static fixture with a moving end effector that applies pressure uniformly over a small sub-section of the joint and the electrode clamp connectors are discretized such that only a small area of the joint is heated at any given time, as shown in Figure 1b. This greatly reduces power supply and pressure requirements, simplifying process control.

Although the CRW process has been demonstrated on simple components, there exist several practical implementation challenges. For example, since the thermal heat flux on an aircraft structural joint varies over the weld length due to changing boundary conditions such as part thickness and stacking sequence, the ability to precisely control the weld process parameters in-line is a key enabler to assure adequate weld line properties.

In this collaboration project, The University of British Columbia (UBC) Composites Research Network (CRN), the German Aerospace Center (DLR), and the Canadian National Research Council (NRC) have joined forces to use process simulation to develop model-based process control of an automated CRW system. This approach offers, for example, the possibility to simulate the input power, thermal insulation, and heating time to attain a constant temperature along the weld interface, ensuring high quality welds. In this paper, a description of the CRW system and the underlying physics are provided. Next, preliminary welding test results using carbon fibre/PEEK laminates are presented along with the systems-based approach to adapt simulation into this process. In addition, the preliminary system diagram to adapt the process for automation is presented.

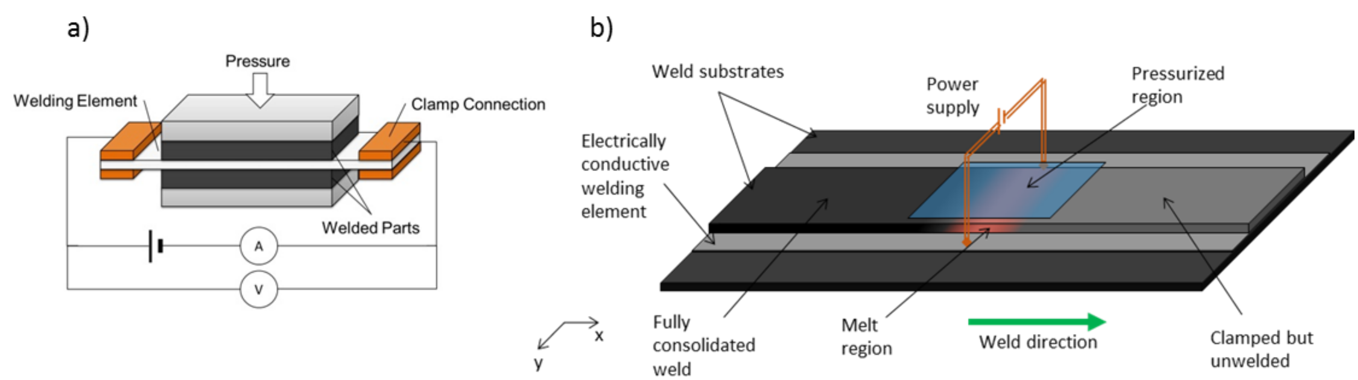

Figure 1: Schematic representation of a) static resisting welding (adapted from [4]) and b) continuous resistance welding setup.

2 DESCRIPTION OF THE CRW SYSTEM

2.1 Next Generation CRW Test Bench

A CRW end effector was designed to move in a continuous motion along the weld seam, pressurizing a sub-section of the weld length via a series of miniature compaction rollers. The power inlet is made from separate electrically insulated copper blocks along the edges of the weld (instead of a continuous copper block for static resistance welding). This method effectively enables the continuous repetition of the static resistance welding process, with a continuous resistive element along the entire weld length. The performance and the quality of the welded joint is related to the thermal history at the interface.

Figure 2 shows the design of the latest generation CRW end effector. The improved CRW end effector design features independent weld compaction and electrode compaction pressures, a caul plate/pressure pad to distribute the weld pressure and insulate the compaction assembly as well as accommodate for small variations in weld width, line of sight through the caul plate/pressure pad to the top surface of the top weld substrate to provide process feedback through IR sensors, and improved electrical feedback and control through an enhanced power controller.

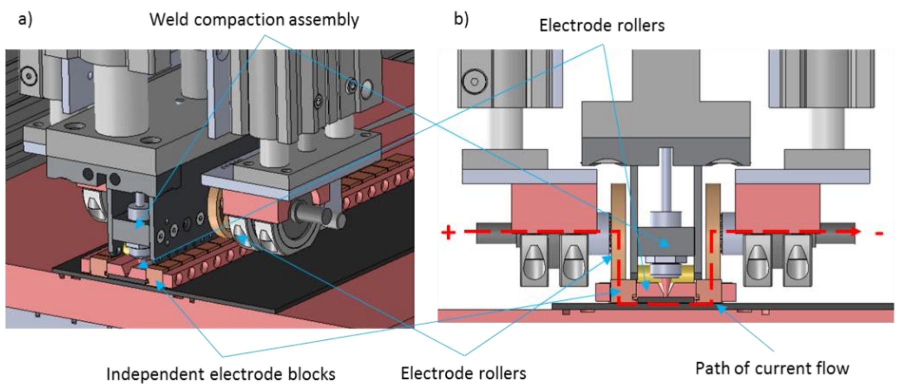

Figure 2: Schematic of the latest Continuous Resistance Welding end effector.

2.2 Underlying Physics

2.2.1 Joule heating

In CRW, the energy required for joining the counterparts is provided by a heating element sandwiched between two layers of neat polymer film. According to Joule's first law, the input power is calculated by equation (1):

$$P = I^2 R \tag{1}$$

where P is the power (W), I is the electrical current (A) and R is the resistance of the heating element (Ω). Except for the electrical current, which is manually adjustable, resistance of the metallic heating element is influenced by the temperature and the clamping pressure. The electrical resistivity of a stainless steel metal mesh was studied by Stavrov et al. [4]. They revealed that just like a typical conductor, the resistance increases as the temperature increases. The pressure roller electrodes form an electrical circuit with the heating element through the block connectors, and thus clamping pressure also affects the contact resistance between the connectors and the heating element. According to Stavrov et al. [4], by increasing the clamping pressure, the contact resistance between the metal mesh and copper connector decreases until it reaches a plateau. The welding should ideally be performed in an electrode clamping pressure range that coincides with a plateau in contact resistance that is low in magnitude.

CRW follows the same basic principle, but due to the moving electrode roller the electrical current creates a temperature history which is significantly different than static resistance welding due to changes in boundary conditions around the weld zone.

2.2.2 Melt and crystallization

The degree of crystallinity is the factor which determines the physical and mechanical properties of thermoplastic polymers, e.g. stiffness, and barrier properties, just like degree of cure in thermosets. This parameter is significantly affected by heat-up, cool-down and the crystallization induction time during the process. Most of the crystallization kinetic models available in literature are applicable for constant temperature or constant cooling rates [5]. Gordnian [5] proposed an integrated melt and crystallization model for PEEK which features path dependency, crystallization induction time, effect of heat up rate on melt behavior and finally cold and hot crystallization.

2.2.3 Consolidation

In welding of two polymer substrates, when the polymer/polymer interface healing develops, consolidation happens. The term 'healing' describes the establishment of intimate contact and autohesion. The latter is a type of adhesion when the polymer chains from two identical surfaces diffuse to one another creating a strong bond. This can occur only when two surface have coalesced by applying pressure in elevated temperature. In other words, intimate contact is the pre-requirement of autohesion. Timewise, intimate contact develops slower than autohesion, so it is the determining parameter in any welding processes [6].

2.2.4 Degradation

Degradation is one of the phenomena that is completely influenced by the process cycle. In addition to excessive temperatures which degrades the polymer immediately, frequent or long periods of melting, quenching and recrystallization even in a manufacturer recommend process cycle can lead to degradation which adversely affects the mechanical properties of polymer [7]. It is critical to understand and model polymer degradation for a process involving rapid heating rates that can result in large thermal gradients if not controlled correctly.

3 SYSTEMS APPROACH TO CRW

Given the limited processing temperature range of PEEK [5], accurate prediction of the interface weld temperature is vital for creating a strong joint. However, measuring the temperature directly during a welding procedure is invasive and impacts weld quality. Therefore, process simulation is advantageous to effectively infer weld quality and develop an inline algorithm to control a robotic welding system. The three components of an automation-focused process simulation framework are sensing the physical system properties, simulating the system using mathematical models, and controlling the system through feedback provided by model predictions.

3.1 Physical System Feedback

Manufacturing process data feedback is critical not only to validate the model but also to enable active in-line control of the welding process. For CRW, speed of the end effector, temperature at the weld interface, and pressure over the weld area are critical. Speed and pressure can be continuously measured using typical methods (linear drive feedback for speed, pneumatic cylinder pressure and/or load cell for pressure); however, continuous measurement of the weld interface temperature is less obvious. Even, discrete measurement using thermocouples is not a reliable solution given the high temperatures and electrical current passing through the resistive implant. As a result, two methods of obtaining continuous process feedback data that can act as a proxy for weld interface temperature are investigated: temperature of the top surface of the upper substrate and resistance of the resistive implant.

Viability studies were performed using a static resistance welding setup similar to the one presented in [8] to study the effectiveness of the two proposed methods for process feedback. A modified pressure application approach was employed to provide line of sight to the top surface of the upper substrate, allowing for continuous temperature measurement using a FLIR SC8300HD infrared camera. Thermocouples at the weld interface were used to correlate top surface and weld interface temperatures. Figure 3 shows the results of one of the preliminary studies where weld interface temperature and top surface temperature are plotted against time during a series of static resistance welds to three target weld interface temperatures (300, 325, and 350 °C). The peak values for each curve correlate linearly (as shown in Figure 3 b). Furthermore, the calculated resistance of the electrical circuit for each of the three welds is plotted against time in Figure 4 a. As described in section 2.2.1, a number of factors can influence the resistance of the electric circuit, however, once the weld interface passes the glass transition temperature (occurs roughly between 20-30 seconds in Figure 4 a), the three curves display a roughly linear trend and the final resistance value can be correlated to the maximum weld temperature as measured by a thermocouple as shown in Figure 4 b.

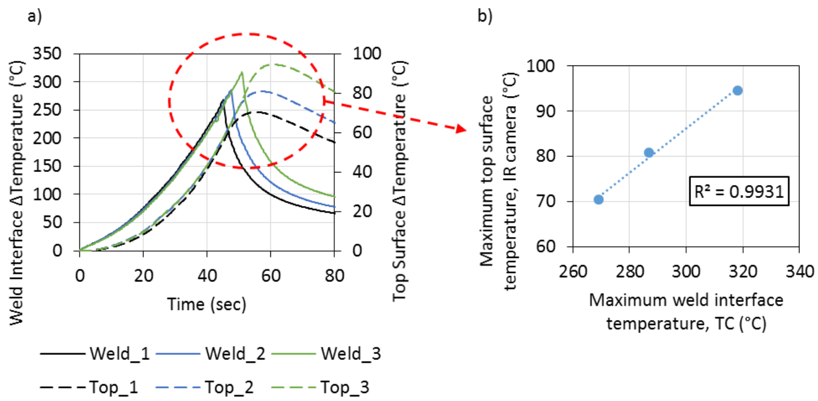

Figure 3: Results of the preliminary top surface temperature evaluation: a) evolution of weld interface and top surface temperatures with time for three target weld temperatures and b) maximum top surface temperature with maximum weld interface temperature.

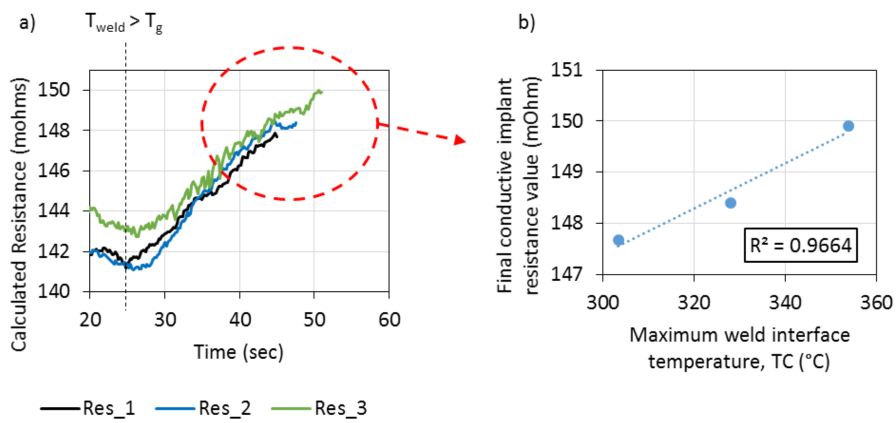

Figure 4: Results of the preliminary conductive implant resistance evaluation: a) evolution of the calculated conductive implant resistance with time for three target weld temperatures and b) final conductive implant resistance value with maximum weld interface temperature.

The two correlations shown in Figure 3 and Figure 4 relate the two values well, respectively; however, the data set and number of repetitions is very limited. Furthermore, transforming this methodology from a simple static welding setup to a complex continuously moving welding process is not a simple task. Given variability in material properties and initial conditions within a given weld and between welds, not to mention lag in the various physical phenomena (the weld will reach a maximum temperature prior to the top surface) it would not be possible to place a single IR sensor at a given location that will correspond to the maximum surface temperature throughout the process. There is not likely one process parameter that provides sufficient feedback to adequately control quality, but rather a combination of multiple streams of process feedback will be required to enhance simulation model predictions.

3.2 Process Simulation

Determining the weld interface quality though simulation relies on understanding how the system variables are affected by the three weld quality parameters: contact time (speed), contact pressure and temperature history. Previous work with static resistance welding and materials research are utilized to narrow the scope; however, the complex relationship between these parameters for continuous resistance welding is still largely unknown. A critical part of the system are the composite material properties which have been updated to develop a more accurate process simulation.

3.2.1 Updated melt/crystallization model for PEEK

The Gordnian melt/crystallization model for PEEK [5] has been updated with a new set of temperature-dependent inert thermal property models, as the original model set employed a set of temperature-independent material properties. Through a comprehensive literature review on available inert thermal properties for PEEK in open literature, it appears that many references are in turn reporting results from other 'root' references. The best root references were used to update the material model set.

Blundell et al. [9] reported the density, enthalpy and transverse thermal conductivity of APC-2 as a function of temperature in 1986. Holmes et al [10] derived the specific heat of APC-2 using the measured enthalpy. Grove et al. reported longitudinal thermal conductivity [11]. These were employed to update the material model set. To verify the reported values for the specific heat capacity, a set of MDSC experiments were conducted on Toray TC1200 PEEK/AS4 prepreg. The results of this work revealed that specific heat calculated by Holmes et al. [10] using enthalpy values reported by Blundell et al. [9] are well in line with the new measurements.

The updated PEEK melt/crystallization model was compared with the original in a three-dimensional transient heat transfer simulation of resistance welding as performed in [12]. Figure 5 shows the boundary conditions applied on the geometry in this simulation.

The results from [12] were replicated and the crystallization history at the center of the weld (defined path) was captured by ANSYS with the COMPRO™ plugin using the melt/crystallization model [5] updated with the new temperature-dependent inert thermal property models. Element type Solid278 was used. The mesh size for both the heating element and polymer films was 4.072×10^{-4} mm; a coarser mesh was used for other less critical components. The 3-D simulations were conducted with convection, conduction and radiation heat transfer modes included, and power was applied to the heating element with a constant density equal to 2 GW/m^3. The heat-up step was 61 seconds long, then the heat generation stopped, and the system cooled for 50 seconds under ambient conditions.

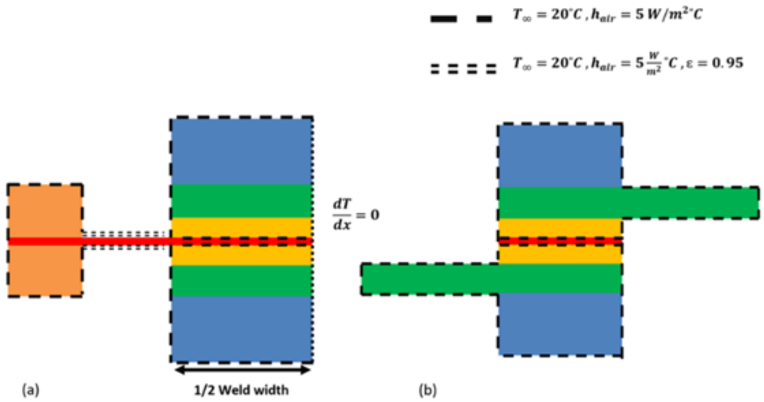

Figure 5: Schematic of boundary conditions in three-dimensional thermal model: (a) side view, (b) front view.

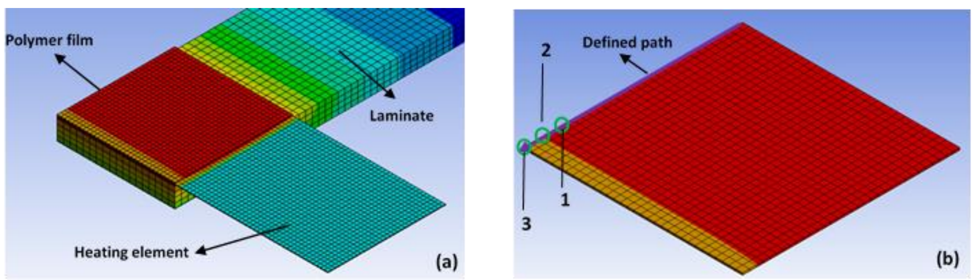

Figure 6: (a) Finite element representation of half of the weld stack (b) Nodes for which crystallinity history is presented in Figure 7.

Figure 7 illustrates the crystallinity histories of defined nodes on the polymer film, where heating is applied from time 0 to 61 s. As can be seen, the use of temperature dependent thermal properties results in delayed predictions of melting and recrystallization of the material, with the change in timing of the order of a few seconds. Although small in absolute terms, these changes can be significant for a continuous resistance welding process.

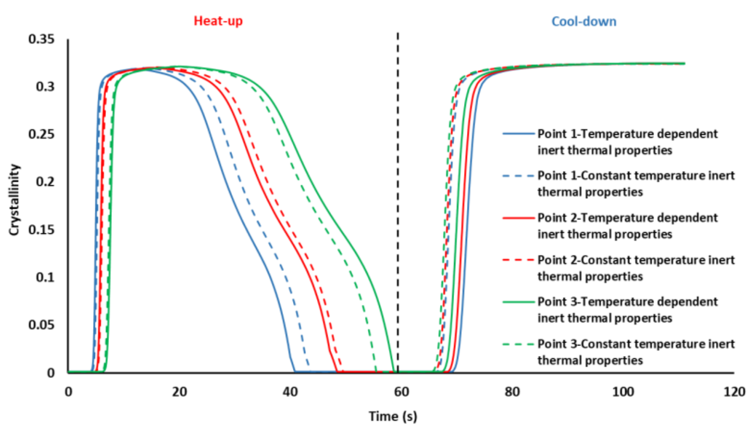

Figure 7: The crystallinity history at the defined nodes at the weld center, where heating stops at 61 seconds.

3.2.2 Simulation Framework

A simulation framework is crucial to define the important attributes of the CRW system. The framework will also be used to simplify the model for effective use in an inline control scheme as a fully-detailed finite element model would be too slow for real-time adjustments. The process to reduce model complexity will involve performing sensitivity analyses to determine aspects of the system which can be neglected without detriment to weld predictions. The simulation for this step will be completed using a transient coupled thermal-electrical model in Abaqus with the COMPRO^{TM} plugin for composite material models. Prior to analysis, the extraneous physical attributes of the new welding setup need to be removed while still maintaining all the 3D system attributes. This initial reduction in complexity is based on attributes of resistance welding investigated in previous studies, [4, 12-15]. To facilitate the simulation framework, the system has been separated into four main objects which contain all the relevant variables for weld state prediction:

- **End effector:** Compaction, Electrical Inputs**,** Feed movement speed
- **Part:** Substrate material properties, Interface properties (temperature, intimate contact)
- **Tooling:** Supporting material properties, Part shape
- **Boundary Conditions:** Convective heat transfer**,** Ambient temperature, Applied pressure

Based on this system definition, a proposed modeling approach (Figure 8) has been developed to systematically reduce complexity while determining the critical variables useful for controlling the process. Since the new setup will weld in a stepwise heating pattern, rather than fully continuous, a potential simplification will be to determine if a static model can be used. With this approach, transient heat transfer analysis will still be performed; however, after a prescribed weld time is reached, the model will reset. A potential complication with this approach is ensuring characteristics from the process history, such as residual heating out of the weld zone, are still being considered. Further simplifications, which will be investigated in parallel to the feed movement attributes, include reducing the cross-section complexity by removing unnecessary objects and merging material properties.

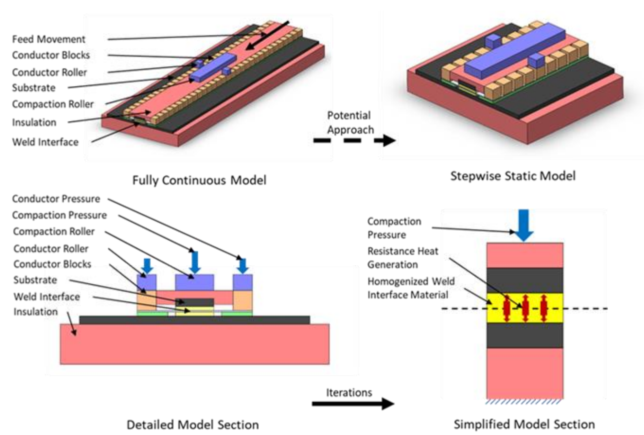

Figure 8: Diagram outlining the proposed modelling approach for the CRW system.

The potential control variables must be considered at every step within the proposed model framework. Based on preliminary results, a few properties hypothesized as potential control variables, which will form the basis for further investigation, include weld stack thickness, heating element electrical resistance, and top substrate surface temperature. The motivation for selecting these variables includes practicality of measurement, ease of implementation, and potential sensitivity for welding control. The thickness variation change is a result of both expansion during heating and the consolidation as the neat film resin flows into the metal mesh heating element. The same effects change the heating element electrical resistance which may be a more practical parameter to measure. Lastly, the top surface temperature is directly related to the interface temperature through conductive heat transfer and can potentially by used as a state control variable depending on sensitivity to boundary effects and measurement complexity.

3.3 Control Automation

The proposed simulation model provides the basis for the development of an automated solution for the CRW process. A first system for CRW was presented based on a gantry system with a linear axis [16]. For basic investigations, a gantry system offers the advantage that it is relatively stiff and thus inaccuracies in positioning and path deviations can be ignored. Only in the next step, when these influences are quantified and well understood, it is recommended to transfer to a robotic system.

At the beginning of the design of the automated CRW system, relevant process feedback values need to be specified for both process control and an accompanying inline quality control. For this purpose, experience from continuous ultrasonic welding could be used in the development. In recent years, the German Aerospace Center (DLR) has successfully implemented a robotic ultrasonic end-effector that allows the welding of components with arbitrary lengths and curved geometries. The data collected during the process is used to predict the strength of the welded joints with the help of neural networks [17, 18].

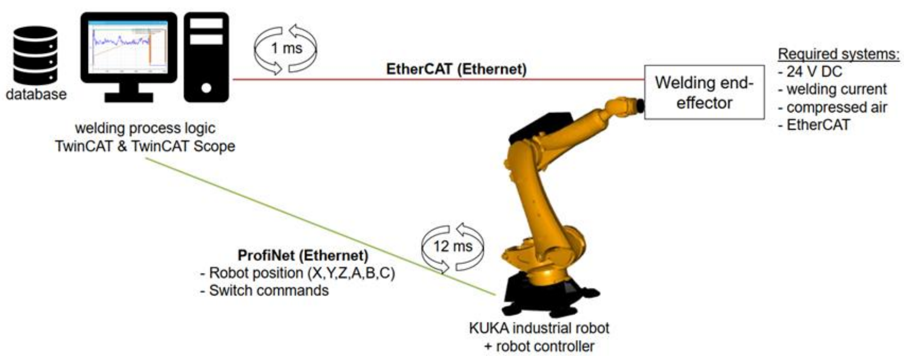

Figure 9: System architecture for data exchange between the systems involved.

Figure 9 shows the system architecture of the continuous ultrasonic welding system that can be transferred to the CRW system. The core of the system is a master computer, which runs TwinCAT and TwinCAT Scope. The master is responsible for both the process control and the recording of the process data. This computer communicates via ProfiNet with a KUKA robot and the associated PC-based KRC4 controller. Via this interface, data can be sent to the robot and back at 12 ms intervals. Switching commands are sent from the computer to the robot in order to start the welding process and change parameters. During the actual welding process, data from the robot, such as its velocity, the torques of the axes and other data, are then sent to the host computer and stored in a database. A second network card in the master computer communicates via EtherCAT with the end effector in both directions to set the welding parameters and to record the process parameters such as contact pressure and amplitude, which are synchronized with the robot data and stored in the database. Since the robot position is exchanged with the host computer every 12 ms during the welding process, all process data can be correlated exactly with the position in the weld specimen and evaluated accordingly. Later, after preparing specimens for tensile tests, the process data can be correlated and can be fed back into the simulation.

4 Summary and Next Steps

This paper presented a high-level description of the CRW system and the underlying physics as well as provided insights into the three key elements of this collaborative work between UBC, DLR, and NRC: physical process feedback, process simulation, and control automation. A critical next step is to develop a process simulation framework for the CRW system to determine appropriate control variables. The updated material models for PEEK will provide the basis for new generation of models; however, other effects still need to be investigated. Importantly, parameter sensitivity analysis needs to be performed to simplify the model for use in a real-time robotic control scheme. The improved continuous resistance welding test bench will be online in the coming months, providing critical process data to the feed the simulation efforts.

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