HEAT GENERATION ANALYSIS DURING THE ULTRASONIC WELDING PROCESS IN THERMOPLASTIC COMPOSITE JOINTS

Felipe B Savella[1], Genevieve Palardy[1]
1- Department of Mechanical and Industrial Engineering, Louisiana State University
Baton Rouge, LA 70803, United States

ABSTRACT

The investigation of joining methods for thermoplastic composite (TPC) structures holds significant importance, primarily for achieving reliable processes leading to structural strength. One such method involves ultrasonic welding, a process that applies high-frequency vibrations to components to be welded, resulting in rapid heat generation and fusion of both materials. However, there are knowledge gaps surrounding the various phases of this process, such as the effect of welding parameters and contact at the weld interface, which could generate different behaviors and results. This study focuses on the creation of single lap shear joints by welding glass fiber/polypropylene (GF/PP) adherends and multiphysics simulations to predict the heating process. Experiments were conducted to measure the temperature profile at different time steps using thermocouples and to observe corresponding fracture surfaces. Results were compared to simulations to validate and enhance the model created in COMSOL Multiphysics, and to analyze the effect of welding parameters and material properties on heat generation. More accurate simulations will improve prediction of the welding process behavior for diverse systems, with different materials, parameters, and joint designs, which can be applied in large-scale, continuous ultrasonic welding.

Keywords: Ultrasonic Welding, Heat Generation, Multiphysics Simulations
Corresponding author: Genevieve Palardy (gpalardy@lsu.edu)

1. INTRODUCTION

In the dynamic arena of materials engineering and manufacturing, thermoplastic composites (TPCs) have appeared as a promising class of materials thanks to their attributes, such as strength-to-weight ratio, impact resistance, and resistance to environmental factors [1],[2]. The diverse applications of TPC structures in sectors such as aerospace, automotive, energy, and construction highlight the importance of better understanding the methods used to join these structures, as it directly influences their mechanical properties, structural integrity, and overall functional capabilities. Among the techniques used to join TPC structures, ultrasonic welding (USW) has gained prominence as an efficient and versatile process [3],[4]. Therefore, exploration of the ultrasonic welding process and acceleration of its development through multiphysics modeling becomes viable to further push TPCs toward a wider range of applications and large-scale structures.

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USW involves the application of low amplitude vibrations at high frequency perpendicularly to components to be joined via a sonotrode (or "horn"). The majority of studies in the literature experimentally investigated the USW process for different materials [5],[6],[7], welding parameters [3],[5],[8], and joint designs [3],[9], including temperature measurements at the bond line [5]-[10]. Koutras et al. measured temperature at the interface for carbon fiber (CF)/polyphenylene sulfide (PPS) by embedding a Type K thermocouple within the energy directing film [6]. The maximum temperature reached values between 500°C and 600°C, well above the melting temperature of PPS (320°C [7]). During the cooling phase, temperature evolution was non-linear and cooling rates varied between 10°C/s and 41°C/s and decreased significantly over time, as low as 3.5°C/s. Similar measurements were acquired for USW of CF/polyaryletherketone adherends with different thicknesses [5]. Thermocouples were inserted in the adherends and placed at the interface below the energy director. Maximum temperatures varied between 600°C and 700°C, while the bottom adherend reached temperatures in the 300°C-520°C range. While the effect of thickness change on heat generation at the interface showed no specific trend, bulk heating of the top adherend was found to increase with its thickness. Infrared (IR) thermography was also employed to study the temperature distribution during welding by observing the lateral joint area for CF/polypropylene (PP) specimens [10]. It was found that a change of vibration amplitude (from 36 μm to 72 μm) led to faster heat generation, with a maximum temperature between 150°C and 200°C.

The USW process was modeled through various approaches and multiphysics software, including models tailored toward TPCs in a single lap configuration. Models taking into account surface friction and viscoelastic heating were developed to predict dissipated power [11],[12] or temperature distribution [13],[14] during the process. Comparison with experimental data showed similar trends with some reasonable agreement, but more accurate material parameters measurement (e.g., loss modulus at high frequency, friction at interface) could improve the simulations. Models solely implementing viscoelastic heat generation have demonstrated good agreement with experimental temperature profiles for USW and ultrasonic consolidation of dry fibers and thermoplastic fibers or films [15],[16],[17]. To further improve process simulations, analysis of parameters' influence on temperature generation is needed, but is limited in the literature. Therefore, in this work, an experimental analysis of heating behavior at different process times was first performed to better understand heat generation at the interface. Then, step-wise development of a multiphysics model for a single lap joint was initiated. In this paper, the first step is presented for a two-dimensional (2D) model, along with a parameters sensitivity analysis to assess their effect on heat generation and to identify areas of improvements for future development steps.

2. EXPERIMENTATION

2.1 Materials and sample preparation

Ultrasonic welding utilized adherends composed of glass fiber and polypropylene (GF/PP), sourced from Avient (formerly PolyOne, Englewood, CO, USA) and specifically made of GF/PP IE 6030 unitape Polystrand™ [18] prepregs. These prepregs featured a fiber volume fraction of 60%, an areal density of 461 g/m^2, and a tape thickness of 0.33 mm. Substrates were produced using compression molding on a laboratory press (Dake, Grand Haven, MI, USA). A total of eight unidirectional (UD) prepreg layers, each measuring 254 mm x 254 mm, were arranged in a $[0]_8$ sequence between steel plates, and then positioned between the heated platens of the press. The consolidation of the laminate occurred under 1 MPa at a temperature of 180ºC for approximately 15 minutes. Throughout the compression molding process, a thermocouple was positioned at one edge of the laminate to monitor the temperature between the plies. Following demolding, a laminate with a final average thickness of 1.8 mm was obtained. The laminate was cut into rectangular specimens (101.6 mm x 25.4 mm) using a water-cooled diamond saw PICO 155 from Pace Technologies. To promote heat generation between adherends, energy directors (EDs), made from pure polyropylene films, were positioned at the interface (Figure 1). The films were created using PP granules obtained from Goodfellow Corp. The fabrication process involved compression molding conducted with the same heated laboratory press from Dake, then cut into samples measuring 25.4 mm x 12.7 mm with an average thickness of 0.5 mm.

2.2 Ultrasonic welding process

GF/PP adherends were subjected to ultrasonic welding in a single lap configuration, featuring an overlap area measuring 25.4 mm x 12.7 mm (Figure 1). The welding process utilized a Dynamic 3000 ultrasonic welder from Rinco Ultrasonics (Danbury, CT, USA), with a maximum power of 3000 W and consistently operating at a frequency of 20 kHz. A 40 mm diameter titanium sonotrode was employed in the process. Both adherends were securely clamped using aluminum bars and M8 socket head screws on a baseplate, as depicted in Figure 1. A 0.5 mm-thick PP film was placed between the adherends to promote heat generation at the interface. To capture the changes at the interface during the process and acquire temperature profiles, the welding process was controlled through welding duration (time). Samples were welded at four different process times (75 ms, 150 ms, 225 ms, 300 ms), and three replicates of each time were made to confirm values. These times were selected based on previous research where 300 ms corresponded to a uniformly melted interface [19]. A welding force of 1000 N was applied with an amplitude of 38.1 µm during the process. Once the prescribed time was reached, applied force and amplitude were removed, the sonotrode was lifted up from the specimen, and the latter was retrieved for further analysis.

2.3 Temperature measurements and mechanical testing

During the process, to measure temperature in the middle of the overlap, a Type K thermocouple was inserted at the interface, on top of the PP film (Figure 1). Temperature data was acquired with a DATAQ DI-2008, which featured multiple analog input channels with a temperature measurement resolution of 0.096°C on Type K thermocouples and a range from -180°C to 1360°C [20].

After the welding process, the joints were broken using a 50 kN tensile machine (TestResources 313, TestResources Inc., Shakopee, MN, USA) following the ASTM D1002 standard, where the samples were secured between hydraulic grips positioned 60 mm apart. The alignment of both grips was adjusted to ensure that the load direction was parallel to the overlap direction.

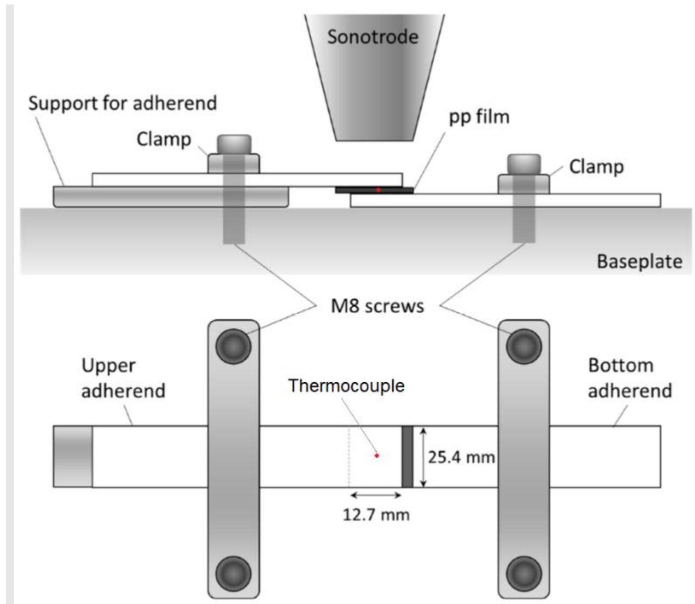


Figure 1. Ultrasonic welding setup for single lap joints. Dimensions are not to scale. Adapted from [19].

2.4 Simulation approach

COMSOL Multiphysics 5.3 was used to simulate the heating phase of the USW process. Ultrasonic welding was modeled using the energy conservation equation (Eq. 1), combined with equations that account for the heat generated by ultrasonic waves (Q) and the heat absorbed in the melting of the thermoplastic ($\dot{H}_m$):

$$\rho C_p \frac{\partial T}{\partial t} = k_x \frac{\partial^2 T}{\partial x^2} + k_y \frac{\partial^2 T}{\partial y^2} + Q - \rho \dot{H}_m \tag{1}$$

where ρ (kg/m³) is the density, C_p (J/kg/K) the specific heat capacity, and k (W/mK) the thermal conductivity. The main properties of the materials used in the simulation are listed in Figure 1 [16],[17].

Table 1. Material properties used in the USW process simulation [16],[17].

	GF/PP laminate (IE-6030)	E. Director (PP Film)	Sonotrode (Titanium)	Platform (Steel)
Density (ρ) (kg/m^3)	1436	1270	4507	7860
Thermal conductivity (k) (W/(mK))	$k_x = 0.55$, $k_y = 0.3$, $k_z = 0.3$	0.25	18	15
Heat capacity (C_p) (J/kgK)	1541	2000	544	502

The generation of heat produced by viscoelastic heating when the material undergoes sinusoidal deformation at high frequency releases a fraction of energy in the form of heat due to intermolecular friction. It is represented by Q, which is dependent on the applied ultrasonic frequency (f), the deformation amplitude (ε_0) from the ultrasonic vibration, and the loss modulus ($E"$) of the material, according to Eq. 2:

$$Q = \frac{\omega \varepsilon_0^2 E"}{2} \tag{2}$$

where $\omega = 2\pi f$, with ultrasonic frequency (f) at 20 kHz. $E"$ is the loss modulus, a measure of the energy dissipated through intermolecular friction. Based on the amplitude applied by the welder, a value of $\varepsilon_0 = 0.0127$ was estimated, according to the ratios of moduli and thicknesses for the adherends and PP film [16]. A constant loss modulus ($E"$) value for PP equal to 0.32 GPa at 20 kHz was assumed, based on the literature [4],[16]. A sensitivity analysis for ε_0 and $E"$ was performed to assess their effect on heat generation at the weld interface as they were determined through the assumptions mentioned above and could introduce uncertainty. At this point, the model presented in this work neglects surface friction, taking place at the beginning of the welding process. In the literature, however, it was shown that solely considering viscoelastic heat generation produced reasonably accurate results to predict temperature profiles and was therefore selected as a starting point for this model [16],[17].

The term $\dot{H}_m$ represents the power necessary to promote the fusion of the sample and was expressed as a function of the degree of fusion X_m (Eq. 3), where H_T was a reference value (0.0184 J), which was assumed to be the total heat absorbed in the fusion process [16].

$$\dot{H}_m = H_T \frac{dX_m}{dt} \tag{3}$$

The degree of melting X_m was defined as Eq. 4, where $H(T)$ is the enthalpy absorbed from the start of melting to temperature T:

$$X_m(T) = \frac{H(T)}{H_T} \tag{4}$$

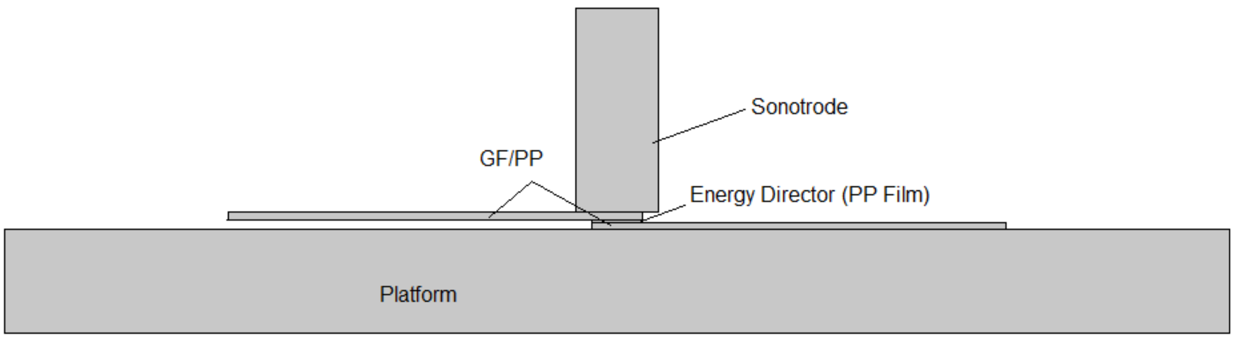
The degree of fusion X_m was expressed by the statistical approach of Greco and Maffezzoli [22], where T_c is the peak temperature of the differential scanning calorimetry (DSC) signal, which was considered as the melting temperature of the samples (165°C). k_{mb} is an intensity factor related to the sharpness of the distribution (0.6566), and d is the shape factor (9.428), as expressed in Eq. 5:

$$X_m(T) = \{1 + (d-1)\exp[k_{mb}(T - T_c)]\}^{\frac{1}{1-d}} \tag{5}$$

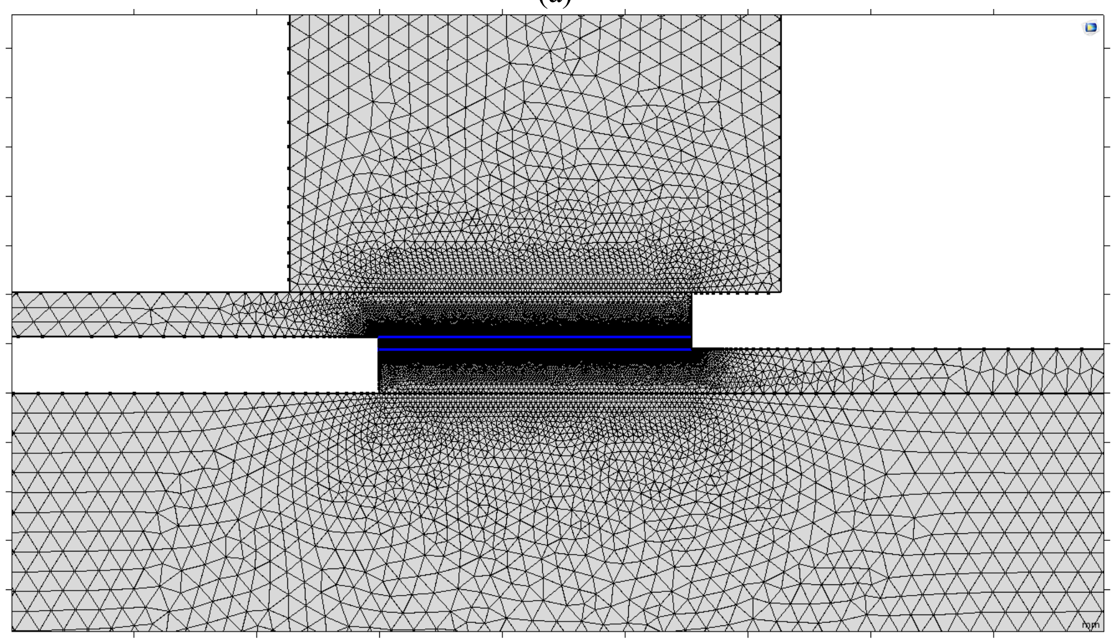
Those values were obtained from the literature for GF/PP rovings [16] and compared with DSC curves on the GF/PP material used in this study.

A 2-dimentional (2D) model was implemented in COMSOL as shown in Figure 2a. For an analysis of the thermal behavior between the materials, a refined 500-point tetrahedral mesh was applied to the energy director (highlighted in blue), as presented in Figure 2b. The heat generation ($Q -$

$\rho\dot{H}_m$) was applied to the ED as a heat source. Faces in contact with air were assigned a free convection boundary condition (BC) with a convection coefficient, h, equal to 5 W/mK (at $T\infty$ = 20ºC). For the initial temperature of the simulation, 20ºC was defined as the room temperature.



(a)



(b)

Figure 2. (a) Full model for single lap joint configuration and (b) Model's Mesh refinement at the interface.

3. RESULTS

To understand the behavior of the welding process, the results of the experiments were first analyzed, then compared with those of the simulation model.

3.1 Fracture surfaces to assess the extent of heat generation

To assess heat generation during the welding process, the samples were first separated to analyze how the PP film actually fused with the GF/PP samples over time. Three replicates were created to confirm the results obtained, and the samples with the best visibility were selected for comparing results. Figure 3a-c shows that in shorter welding times (75 ms, 150 ms, and 225 ms), where uniform temperature was not achieved over the interface, there are larger unmelted areas (delineated in red), meaning the PP film did not bond with the adherends. At 75 ms, there is almost no visible melting of the energy director, generally indicating there were no particular initiation sites at the edges. From 150 ms to 300 ms (Figure 3b-d), the areas where no melting is visible (in red) significantly decrease, suggesting an increase of temperature with process duration and heat transfer throughout the interface. The ED then eventually fully melts, as well as the upper layers of the adherends. The fracture surfaces show that heat generation did not occur evenly at the overlap, which could be caused by misaligned adherends or surface asperities locally increasing contact in specific areas.

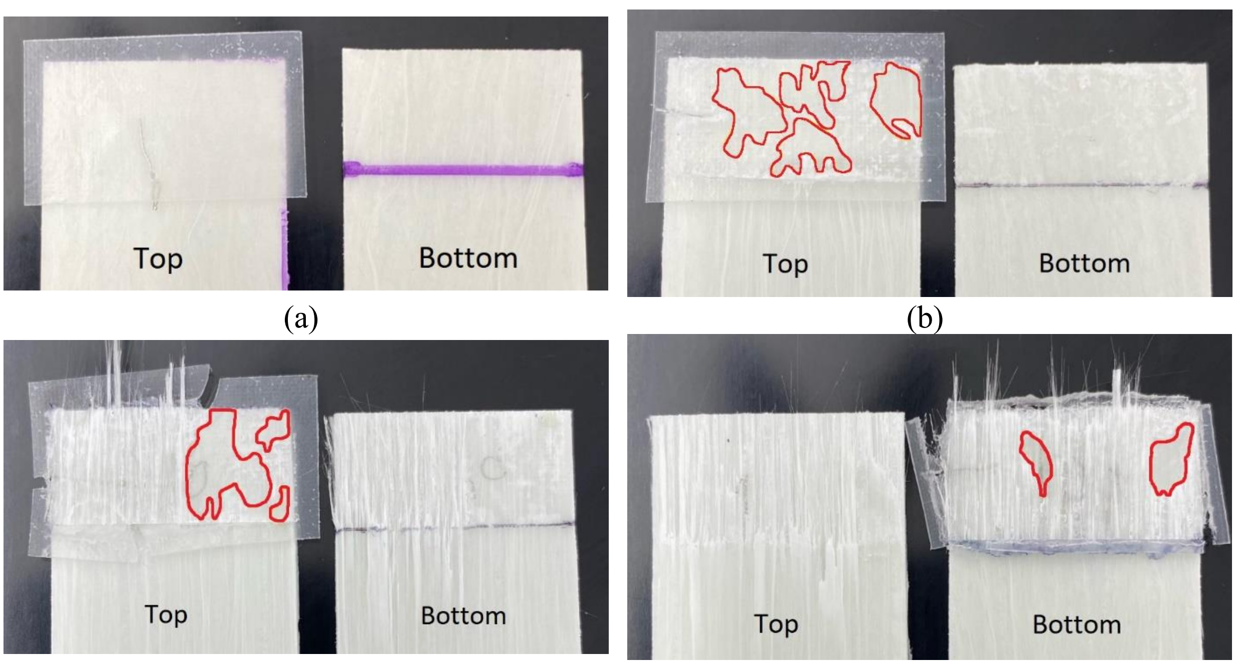


Figure 3. Fracture surfaces of welded samples at (a) 75 ms (b) 150 ms (c) 225 ms, and (d) 300 ms. The red, delineated areas indicate intact interface where the ED (PP film) did not melt.

3.2 Heat generation results

Figure 4 summarizes the predicted temperature at the weld interface according to the COMSOL simulation. The simulation was stopped at 300 ms to obtain temperature curves for comparison with experimental data. 2D temperature maps are shown in inset at process times of 75, 150, 225, and 300 ms, respectively. The maps suggest that the heat-affected zone extends into the adherends as time increases, similarly to what was observed in Figure 3. Figure 5 displays representative, experimental temperature curves at all four process times, indicating that the peak temperature increased with time (from 143.1ºC to 328.2ºC). It is noted that past 75 ms, the interface exceeded the melting temperature of PP (165ºC), which corresponds to Figure 3b-c where some areas at the interface started melting. In the literature, similar temperature profiles were experimentally obtained for USW of oriented polypropylene with thermocouples [20] , while IR temperature measurements showed lower values, up to 200ºC [10]. As the latter was obtained at the edge of the weld interface, it is expected this could affect the temperature profile, compared to measurements obtained directly from the weld line. Nonetheless, for the USW process, thermocouples can lead to large variations as the mechanical vibrations may affect localized heat generation at the tip.

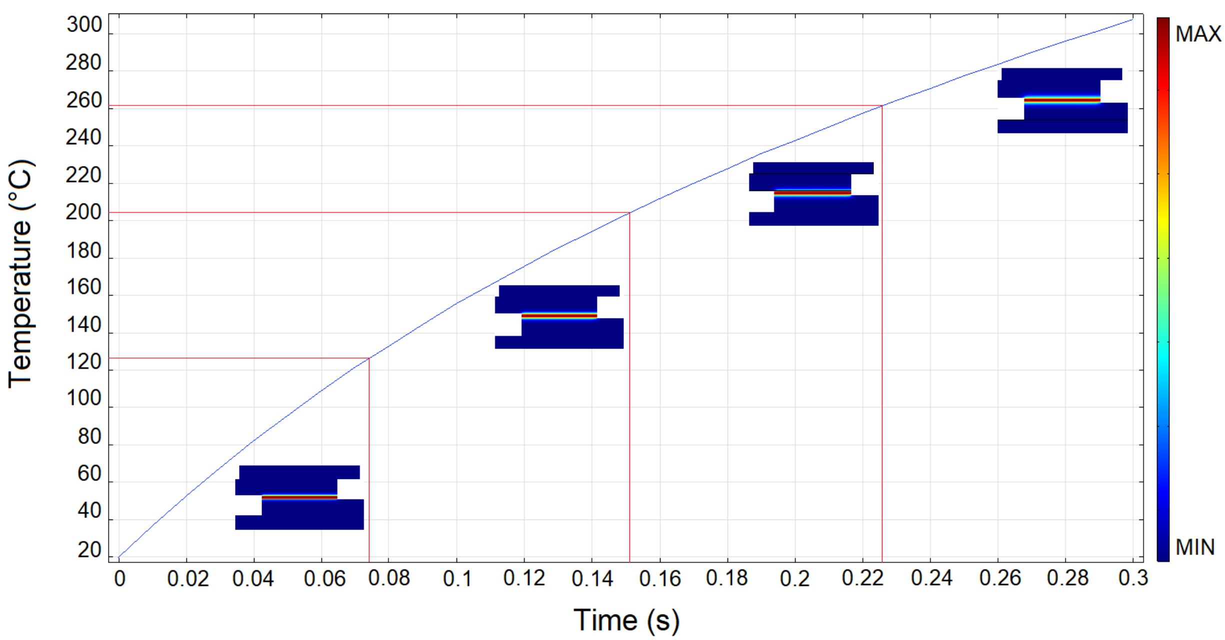


Figure 4. Predicted temperature at the middle of the interface and corresponding 2D temperature cross-sections during the USW process.

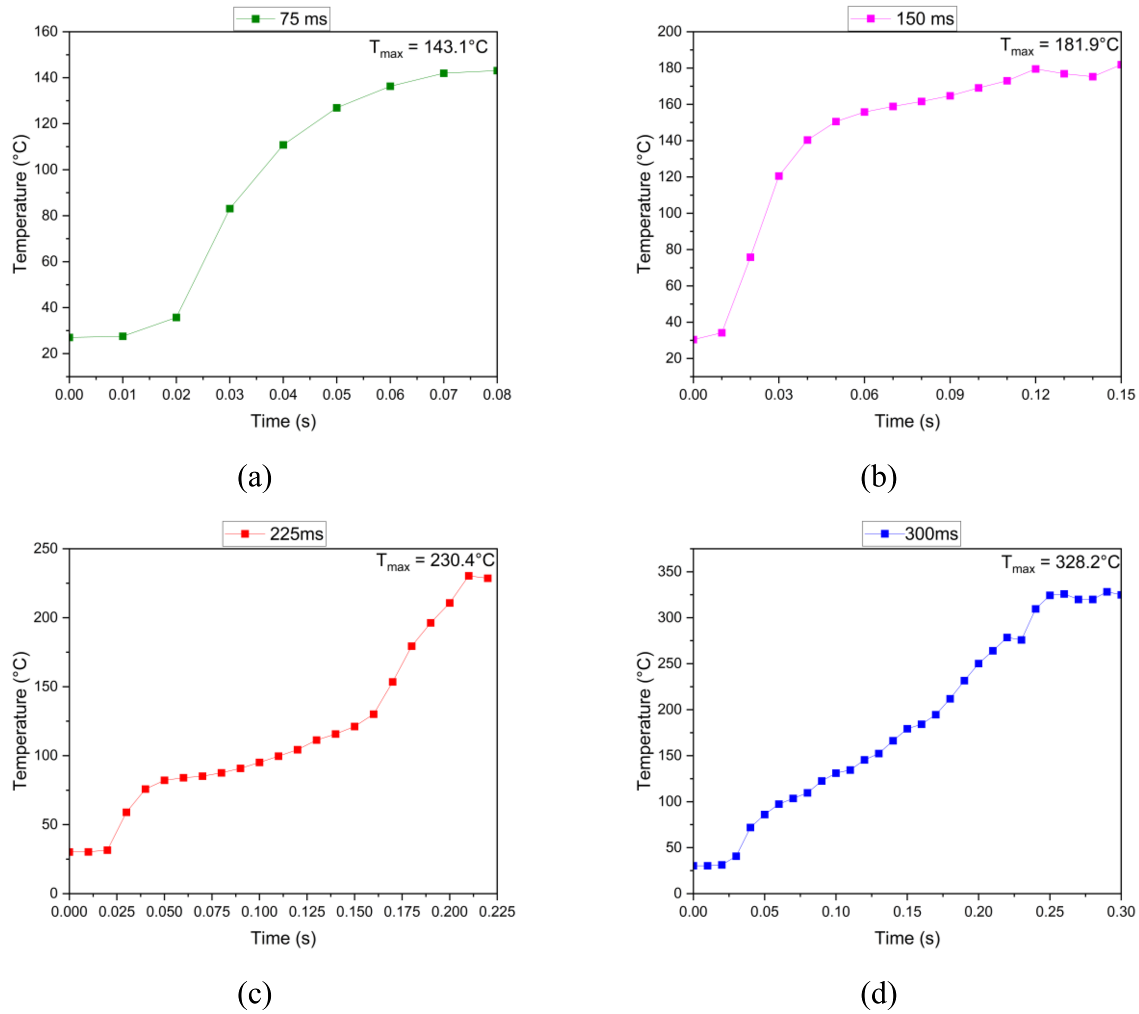


Figure 5. Experimental temperature curves at the GF/PP weld interface at (a) 75 ms (b) 150 ms (c) 225 ms, and (d) 300 ms.

3.3 Comparison and discussion: simulation and experiments

Comparing the predicted temperature profile from the model with the experiments (Figure 6), the behavior follows a similar trend, with reasonably good agreement regarding maximum temperature. The largest deviation between simulations and experiments is found at 150 ms (42°C) and 225 ms (58°C), especially when comparing peak temperatures.

The superposition of the experimental profiles highlights the differences between repeated experiments at increasing process times. These differences could be explained by several reasons. First, the position of the thermocouple wires may not have been consistent for all welded specimens. Second, localized friction between the wires could affect heat generation and temperature measurements. Last, imperfections/misalignment of the samples could potentially initiate heat generation in specific areas, instead of uniformly over the interface overlap [23]. Regardless of those differences, the model can provide a processing time window within which melting temperature is reached for a given material (at least 90 ms for PP), reducing the number of experiments required to optimize process parameters. Regarding sources of errors in the model, neglecting surface friction at the beginning of the process and assuming even contact at the interface may contribute to deviations with experiments. In addition, applied strain (ε_0) and loss modulus (E") in Eq. (2) possess uncertainty in their quantification [24]. Simulations were carried out while varying those two parameters (by up to 8%), as shown in Figure 7. A change of 8% in ε_0 or E" led to a difference from 40ºC to 18ºC in maximum temperature at the middle of the interface. This indicates the importance of accurately estimating and measuring those specific parameters, as they affect the temperature profiles, which could reduce the error between simulations and experiments. For instance, it has been discussed in the literature that hammering, the loss of contact between the sonotrode and the upper adherend, could change the actual mechanical vibration amplitude applied at the joint, thereby influencing heat generation [11],[12]. In addition to improving parameters estimation, future iterations of the model will consider surface friction at the beginning of the USW process and 3D representation to capture differences in localized heat generation at the interface, as observed in Figure 3.

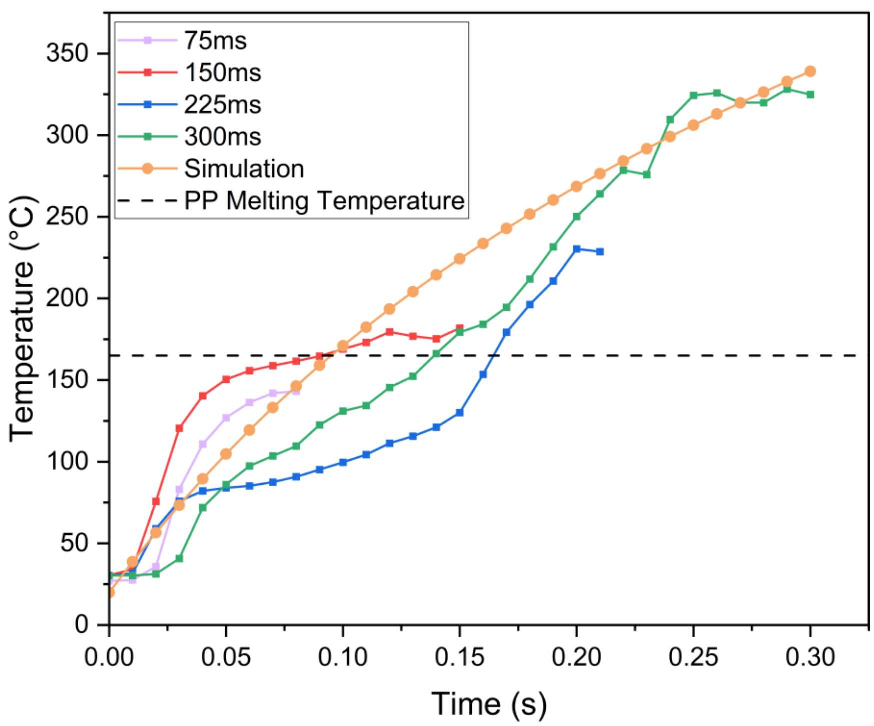
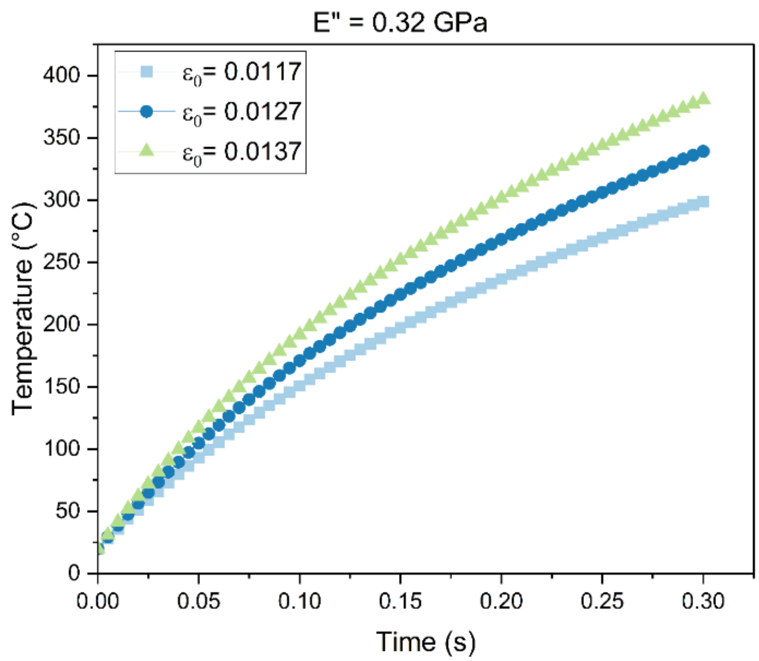


Figure 6. Comparison between experiments and simulation for GF/PP adherends assembled via USW, with reference to PP melting temperature at 165ºC (dashed line).



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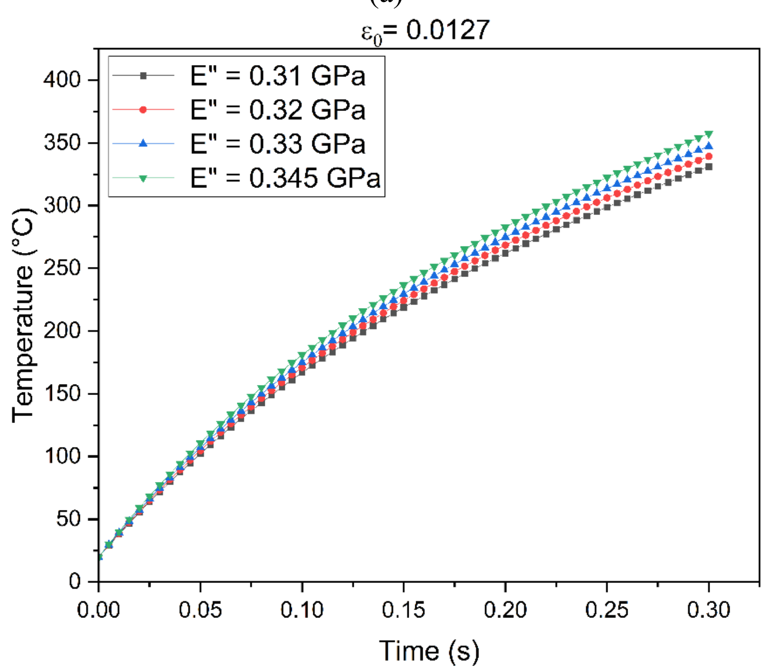

(b)

Figure 7. Sensitivity analysis for different values of (a) ε_0 (with E'' = 0.32 GPa) and (b) E'' (with $\varepsilon_0 = 0.0127$).

4. CONCLUSIONS

In summary, the model's predicted temperature profiles align well with experimental data, particularly in maximum temperature, with discrepancies noted at specific time points, where variations in thermocouple wire positioning, localized friction, and specimen imperfections may contribute to these deviations. Despite these differences, the model effectively estimates a processing time window for material melting. The model itself also introduce deviations by neglecting surface friction, assuming perfect contact at the interface, and estimating vibration amplitude and loss modulus. Future model iterations will address these issues, incorporating improved parameter estimation, considering surface friction at the process initiation, and introducing a 3D representation to capture localized heat generation differences and bonding evolution. Experimentally, next steps include temperature measurements at additional points through the welded interface and combining thermocouple measurements with IR imaging. This research provides a foundation for enhancing the model's accuracy and optimizing the ultrasonic welding process for various materials toward large-scale applications.

5. ACKNOWLEDGEMENTS

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