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Meshfree Numerical Simulation of Hybrid Friction Stir Welding with Adhesive Bonding

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ABSTRACT

As interest for lightweight vehicles continues to increase, there has been significant progress in the development of hybrid joining approaches. A process that has been gaining interest is friction stir welding combined with adhesive bonding (FSW-AB). In the FSW-AB process, a lap joint is prepared with an uncured adhesive over the entire overlap region. Following the application of the adhesive, the FSW process is performed. Using this hybrid method can lead to improved joint strength as well as increased fatigue resistance. Furthermore, the adhesive acts as a sealant and protect the FSW joint from corrosion. Certainly the method is attractive; however, there are joint design aspects that must be considered such as the thermal degradation of the adhesive and the effect of the adhesive transport in the friction stir weld zone.

In this work, a meshfree coupled thermo-mechanical simulation of the FSW-AB process is performed using SPHriction-3D. The set of continuum mechanics equations describing the physics of the FSW-AB process are cast into an amenable set of algebraic equations using a weak-strong form approach called smoothed particle hydrodynamics (SPH). This approach uses a Lagrangian frame of reference, making it ideal for predicting the movement and thermal history of the adhesive layer during the FSW process. Experimental results along with adhesive degradation profiles and infrared spectroscopy are compared to the simulation results. The article will focus on details of the meshfree simulation method as well as comparison between the simulation and experimental results. We will show that the numerical model is able to predict the extent and location of the adhesive degradation. Ultimately, the developed simulation approach is a powerful design tool for advanced hybrid joining methods such as the FSW-AB process.

KEYWORDS

Friction stir welding, adhesive bonding, meshfree simulation, coupled thermo-mechanic, SPHriction-3D

INTRODUCTION

Friction stir welding (FSW), combined with adhesive bonding (AB) is an attractive hybrid joining method (FSW-AB). The approach could be very beneficial for various industries, especially industries concerned with vehicle light weighting. The combination of the two joining methods can result in superior static joint resistance, and significantly improved fatigue performance. Typically, a joint that is affixed using only an adhesive will have a very brittle failure, however, by combining FSW with AB, a high strength ductile failure can be achieved. Various authors [1-4] have investigated the FSW-AB process for various FSW parameters, alloys, as well as different types of adhesives. So far, the only application for FSW-AB has been with lap joints. The overlap region is required to apply the adhesive layer.

In order to obtain the benefit of adding an adhesive to the FSW process, the designer must take caution to use FSW operating parameters that do not lead to the thermal degradation of the adhesive. For this reason, prediction of the degradation of the adhesive is an important consideration. In this work, we propose a numerical simulation approach that is able to predict the extent of degradation in the adhesive layer. The model uses an advanced meshfree numerical method that is able to consider complex geometries, alloy combinations, and weld parameters. The code, called SPHriction-3D, is developed at the National Research council.

To date, there has not been any work to simulate the FSW-AB process. Never the less, numerical simulation of the FSW process has been successfully reported by many groups. Some early models use finite volume or element methods with an Eulerian fluid mechanics approach. Carlone *et al.* [5], performed CFD modeling using the commercial code ANSYS CFX to simulate butt joint FSW of AA2024-T3. They were able to predict results such as material flow, grain size, and micro-hardness profiles. One of the drawbacks of an Eulerian approach is that the material history is not taken into consideration. Furthermore, it is not easy to track the evolution of the free surface (defect prediction). On the other hand, evolving free surfaces can be tracked in the coupled Eulerian-Lagrangian (CEL) method. This method models the workpieces using the Eulerian description, whereas the tool is modelled with the Lagrangian approach. Hossfeld [6] used the CEL method to simulate the FSW process with a large level of detail. He notes that the CEL method (implemented within Abaqus) is very computationally heavy and leads to long calculation time.

Certainly the CEL approach has its interests and drawbacks, conversely, meshfree methods allow for a completely Lagrangian description of the entire FSW problem. One of the first authors to investigate the use of meshfree methods for FSW was Tartakovsky *et al.* [7]. They used the smoothed particle hydrodynamics (SPH) method with a fluid formulation of the continuum equations. Their early work was able to simulate simple geometries in two and three dimensions. Pan *et al.* [8] used the SPH method to predict the microstructure and texture evolution of magnesium alloys during the FSW process. More recently, Fraser *et al.* [9-11] have developed a robust and efficient implementation of the SPH method using a strength of materials approach. The code is able to predict defects, temperatures, residual stresses, and tool wear with excellent precision. They have also shown that the code can be used to optimize the FSW process parameters and determine the process operating window [12].

In this paper, details of the simulation approach used for the FSW-AB process will be introduced. Next, Fourier transform infrared spectroscopy is used to develop a degradation behaviour model of Henkel Teroson 5089 adhesive. Following that, a simulation model is created of an inner layer of adhesive (0.25 mm) that is sandwiched between two outer AA6061-T6 plates. The model is used to evaluate the degradation profile of the adhesive.

METHODOLOGY

Numerical simulation of the hybrid-FSW process requires the solution of a set of multi-physics equations. Conservation of mass, momentum, and energy can be written using a Lagrangian frame of reference as:

$$\frac{D\rho}{Dt} + \rho\nabla \cdot \bar{v} = 0 \qquad \text{(Eqn. 1)}$$

$$\frac{D\bar{v}}{Dt} = \frac{1}{\rho}\nabla \cdot \bar{\bar{\sigma}} \qquad \text{(Eqn. 2)}$$

$$\rho C_p \frac{DT}{Dt} = \nabla \cdot (k\nabla T) + \dot{q} \qquad \text{(Eqn. 3)}$$

where ρ is the density of the material, $\bar{v}$ is the material point velocity, $\bar{\bar{\sigma}}$ is the total stress tensor (Cauchy), C_p is the heat capacity, T is the temperature, k is the thermal conductivity, $\dot{q}$ is a heat generation term, and t is time. The set of transient and highly non-linear equations need to be solved numerically for any meaningful FSW geometries and parameters. Without a doubt, there are a large number of numerical methods that could be used. In this work, a meshfree method called smoothed particle hydrodynamics, SPH, is used [13-15]. This method is well suited to the large levels of plastic deformation and material mixing present in the FSW process. SPH is a material point collocation approach that is best explained by the image shown in Figure 1. The spatial integration is performed by collecting weighted values from the "j^{th}" neighboring material points of the "i^{th}" point of interest. The weighting is performed using a kernel function that has properties similar to a Gaussian bell shaped function. The kernel function used to perform the simulations in this work is the hyperbolic spline of Yang *et al.* [16].

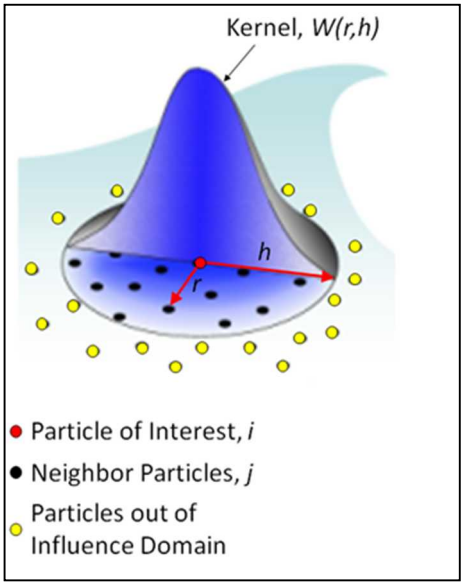

Figure 1 - Smoothed particle hydrodynamics method collocation (reproduced from [9])

Using the SPH discretization approach, the set of strong continuum equations are cast into a weak-like form that can be solved numerically. The equivalent SPH forms are:

$$\frac{d\rho_i}{dt} = \rho_i \sum_{j=1}^{N_i} \frac{m_j}{\rho_j}(v_i{}^{\beta} - v_j{}^{\beta})\frac{\partial W_{ij}}{\partial x_i{}^{\beta}} \qquad \text{(Eqn. 4)}$$

$$\frac{dv_i{}^{\alpha}}{dt} = -\sum_{j=1}^{N_i} m_j \left(\frac{p_i}{\rho_i{}^2} + \frac{p_j}{\rho_j{}^2}\right)\frac{\partial W_{ij}}{\partial x_i{}^{\beta}} \quad \text{(Eqn. 5)}$$

$$\frac{dT_i}{dt} = \frac{1}{\rho_i C_{p_i}}\left[\sum_{j=1}^{N_i} \frac{m_j}{\rho_j}\frac{4k_i k_j}{k_i + k_j}\frac{(T_i - T_j)}{|x_{ij}|^2} x_{ij}\frac{\partial W_{ij}}{\partial x_i{}^{\beta}} + \dot{q}_i\right] \quad \text{(Eqn. 6)}$$

In the SPH equations, subscripts are reserved to denote the interaction between material point pairs whereas the superscripts follow Einstein notation. Full details of the SPH formulation used for the FSW process can be found from the work of Fraser *et al.* [9-11, 17-19].

Due to the extreme level of plastic deformation encountered within the FSW process, an appropriate material model is required that will not over predict the flow stress with increasing values of plastic strain. Here, we have used the FKS material law that is described by a multiplicative relationship of the form [9]:

$$\sigma_y(\varepsilon^p, \dot{\varepsilon}, T^*) = H(\varepsilon^p)\Lambda(\dot{\varepsilon}, T^*)\Theta(T^*) \quad \text{(Eqn. 7)}$$

$$H(\varepsilon^p) = a_1 + a_2 tan^{-1}(a_3\varepsilon^p) \quad \text{(Eqn. 8)}$$

$$\Lambda(\dot{\varepsilon}, T^*) = 1 + \left[b_1 T^{*b_2}\right]\left[b_3 ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right] \quad \text{(Eqn. 9)}$$

$$\Theta(T^*) = 1 - \frac{1}{(1 + e^{-c_1 T^*})^{\frac{1}{c_2}}} \quad \text{(Eqn. 10)}$$

$$T^* = \frac{T - T_{room}}{T_{melt} - T_{room}} \quad \text{(Eqn. 11)}$$

The FKS model provides a description of the material flow stress as a function of strain hardening, thermal softening, as well as strain rate.

Contact between the tool, backing, and the workpieces is considered according to the hybrid thermo-mechanic contact algorithm of Fraser *et al.* [17]. Due to the Lagrangian framework of the method, an adaptive algorithm is needed to apply the thermal boundary conditions [20].

ADHESIVE DEGRADATION MODEL

To be able to predict the degradation of the adhesive in the FSW-AB joint, a model of its behaviour as a function of temperature is needed. We have performed a Fourier transport infrared spectroscopy (FTIR) analysis of the Teroson 5089 epoxy based adhesive at different temperatures. The equipment used was a Nicolet 6700 spectrometer from Thermo Scientific equipped with a MCT-A detector. The adhesive samples were subjected to a heat pulse akin to that found in the FSW process. An example of such a heat pulse (210°C case) is shown in Figure 2.

Eight different temperatures were used to evaluate the degradation of the T5089 adhesive: Room temperature, 50°C, 75°C, 100°C, 135°C, 150°C, 175°C, and 210°C. From the spectroscopy results, the level of degradation of the epoxy is evaluated by the relative strength of the absorption of two compound groups, namely, a hydroxyl group, and C-H groups. The results from the FTIR analysis are shown in Figure 3. The telltale sign of the presence of the

O-H and C-H groups are absent to an increasing degree starting at 75°C. At 150°C, the C-H fingerprint is entirely non present, as such the adhesive is considered to be fully degraded at that temperature.

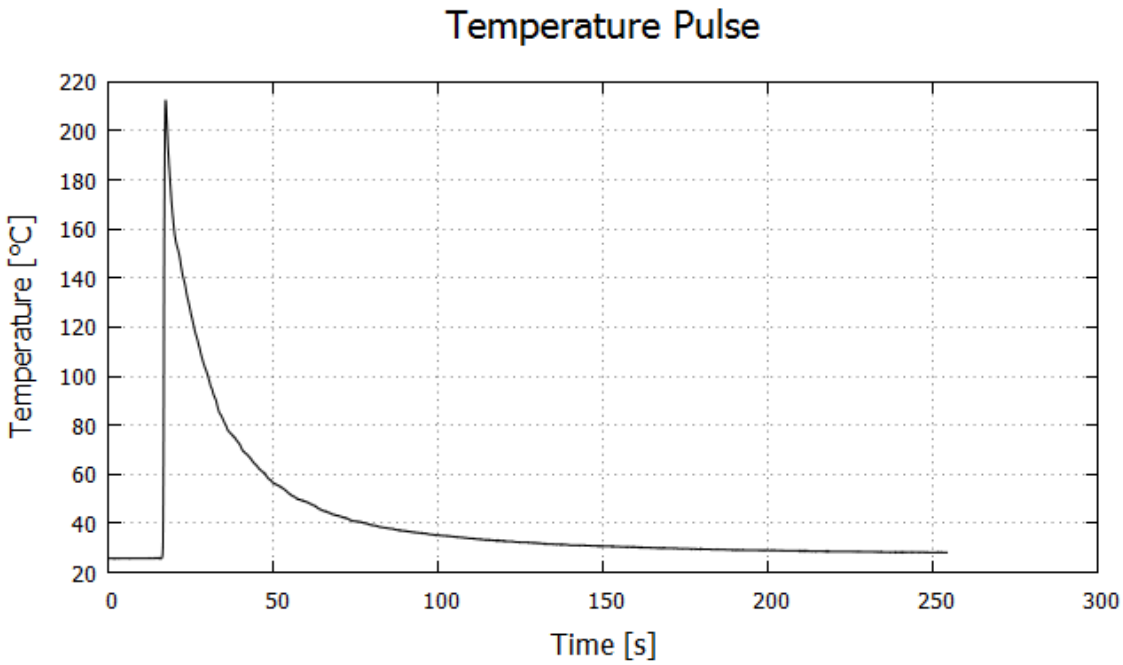

Figure 2 – 210°C Heat pulse

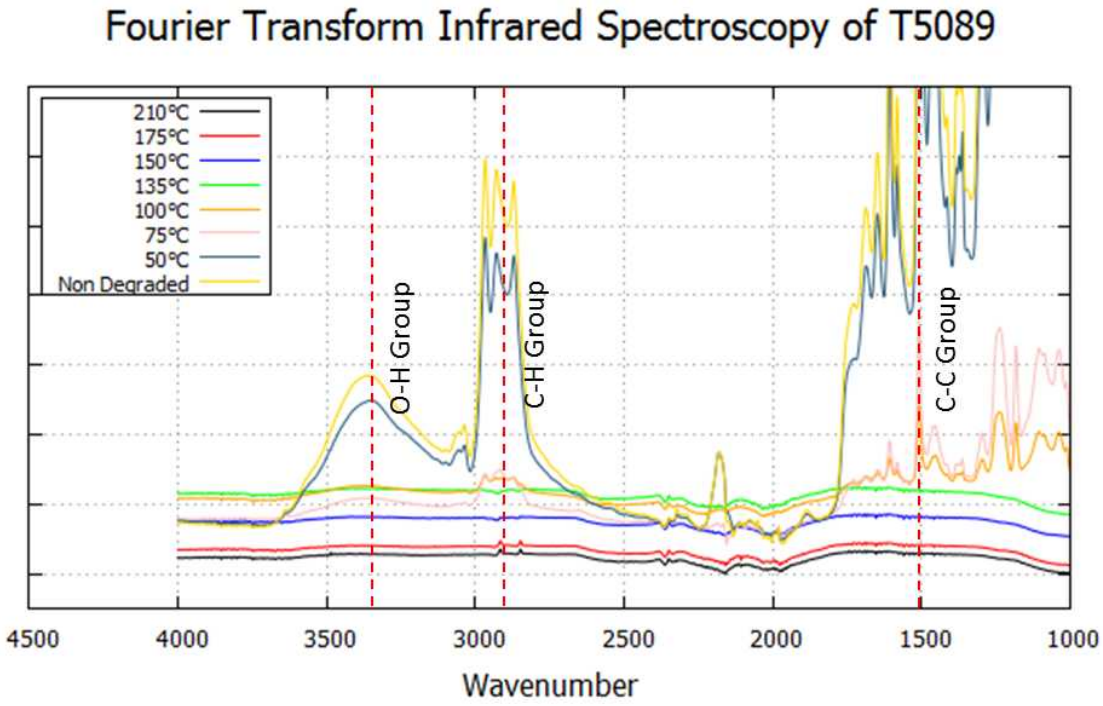

Figure 3 – FTIR results of the adhesive in the hybrid bond

From the FTIR results, a degradation model of the T5089 is developed by associating a relative strength percentage of the O-H and C-H groups at the various temperatures. The resulting degradation model is described by:

$$D_{T5089}(T_{max}) = \begin{cases} 0, & Room\ Temperature \leq T_{max} < 75°C \\ \frac{1}{75}T_{max} - 1.0, & 75°C \leq T_{max} < 150°C \\ 1, & T_{max} \geq 150°C \end{cases} \quad \text{(Eqn. 12)}$$

The model can be interpreted as follows: Below 75°C, the O-H (oxirane) and C-H (aliphatic) groups are fully present. Starting at 75°C, evidence of these groups decreases. Finally, above 150°C, The oxirane and aliphatic groups no longer register a perceivable signature in the spectrometry results. Once the value of D_{T5089} is equal to 1.0, the adhesive is fully degraded. At this point the strength of the T5089 adhesive is considered to be null.

SIMULATION MODEL

The simulation model of the FSW-AB process as well as its discretization is shown in Figure 4 and Figure 5. The simulation model is setup to closely resemble the experimental arrangement. The aluminum workpieces are both 2 mm thick AA6061-T6 plates. Between the two plates is a 0.25 mm layer of Henkel Teroson 5089 epoxy adhesive. The weld is carried out close to the edge of the sandwich setup in order to better evaluate the adhesive degradation over a large lateral distance from the weld line. The work pieces and adhesive layer are discretized with SPH elements. Material point spacing of 0.25 mm is used in the weld region and 0.5 mm outside of this region. The tool is an MX Tri-Flute design with a 11 mm shoulder diameter. The shoulder has a convexity of 0.22 mm. The pin diameter is 5.0 mm. The tool is meshed with triangular rigid finite element plates with a characteristic element size of 0.25 mm. The overall dimensions of the model are selected to provide enough lateral material to evaluate the adhesive degradation and enough material along the welding direction to obtain a quasi-steady result during the tool advance.

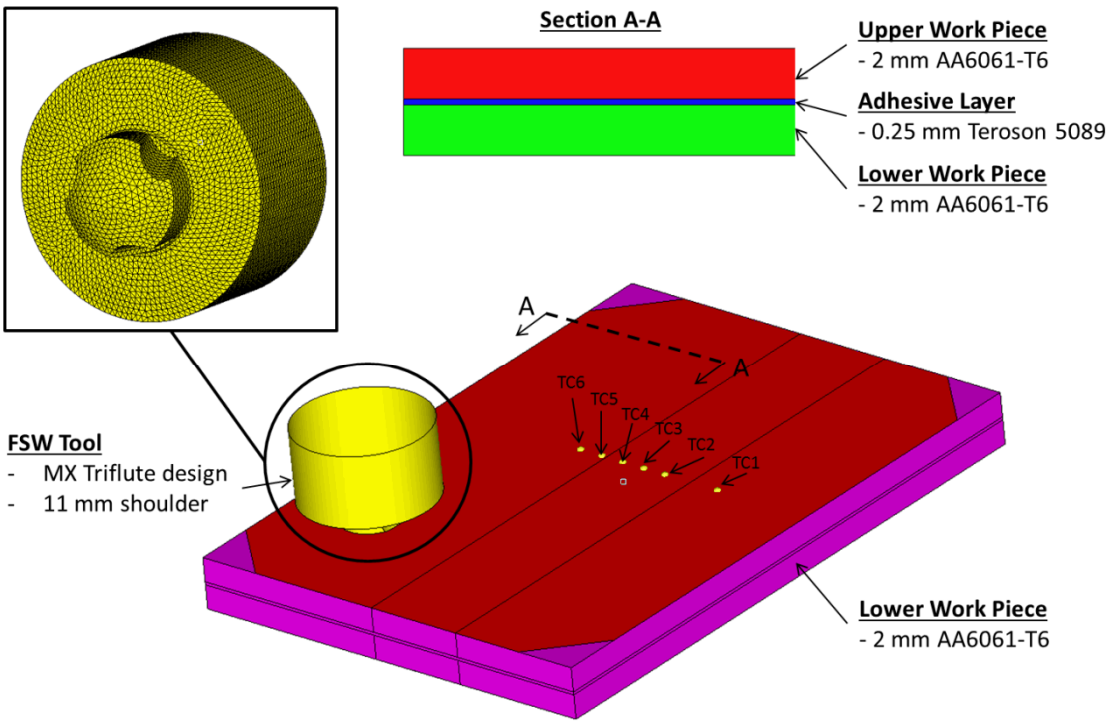

Figure 4 – FSW-AB Simulation model

A series of six thermocouples are placed in the simulation model to keep track of the thermal history at those points (as shown in Figure 4). The thermocouples are located half way along the axial direction of the weld. TC6 is laterally located on the edge of the weld (5.5 mm from

the axis of the tool). The lateral spacing between TC1 and TC2 is 5 mm. Elsewhere the spacing is 2 mm apart between subsequent thermocouples. The support base and clamps are meshed with triangular rigid finite element plates with a characteristic element size of 0.5 mm. Interaction of the tool and the base/support with the work pieces/adhesive is considered using a hybrid thermo-mechanical contact algorithm.

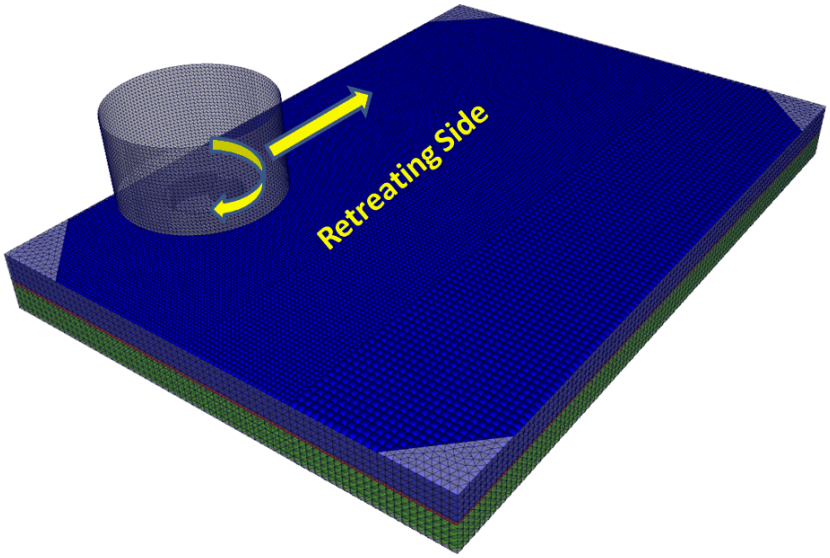

Figure 5 – Discretized model

The material model for the workpieces takes into account both elastic and plastic strains by using a strength of material approach. The FKS flow stress model was used and can be seen in Figure 6 (see [12] for material parameters for AA6061-T6). A special characteristic of this model is that the flow stress saturates above a critical plastic strain level. This ensures that the flow stress will not be over predicted at the large strain levels present in the FSW process.

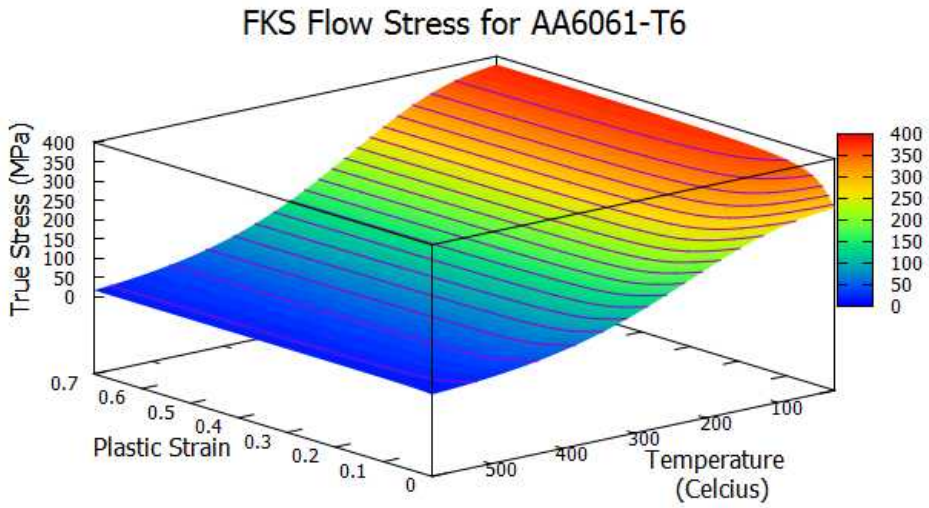

Figure 6 – FKS flow stress model for AA6061-T6

RESULTS

The simulation model was run in SPHriction-3D with three distinct phases: plunge, advance, and cooling. The RPM of the tool was held constant at 2000 throughout the plunge and

advance phases. The tool plunge speed is 50 mm/min, and the advance speed is 2000 mm/min (leading to a rev. pitch of 1.0). The same parameter set was performed in the lab with thermocouples welded to the top surface of the plate at TC3-TC5 locations.

A comparison between the temperature history predicted from the simulation (solid colored lines) and that of experiment (points) is shown in Figure 7. Excellent agreement between the simulation and experiment is obtained. It is critical to be able to precisely predict the temperature during the FSW-AB process. This is because the degradation model is directly dependant on the temperature history in the adhesive layer.

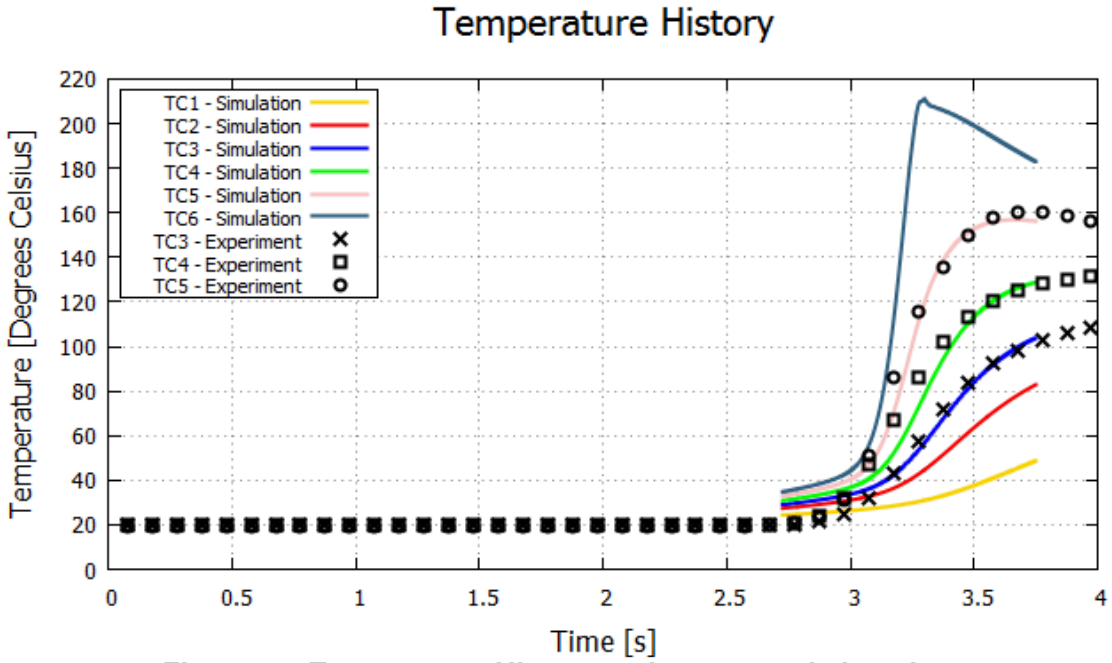

Figure 7 – Temperature History at thermocouple locations

Temperature contour results for the entire model are shown at the end of the plunge phase (top left), mid advance (top right) and end advance (bottom left) in Figure 8. The simulation code is able to predict the excess material that flows past the side of the tool (flash) as can be seen at the start of the simulated weld. For comparison an image of the start of the weld performed in the lab is provided in the lower right corner of Figure 8. This type of flash formation is common at the plunge site of the weld. Once the tool plunges into the work piece, a ring of material rises. Then as the tool starts to advance, it pushes through this ring, leaving a “U” shaped flash profile. We can also see that the simulation model predicts a slight defect on the advancing side of the weld. This case is at the higher end of the operating window in terms of RPM, thus leading to slight defects. The same type of defects was also found experimentally. Notice that the temperature profile under the tool shows that the hottest zone is along the trailing edge of the tool, and shifted slightly towards the retreating side. This is a telltale sign that the FSW parameters are at the onset of defect formation. Typically, a sound weld will have the maximum temperature along the trailing edge, but shifted towards the advancing side. Information about the location of the maximum temperature can be used to predict the onset of defect formation.

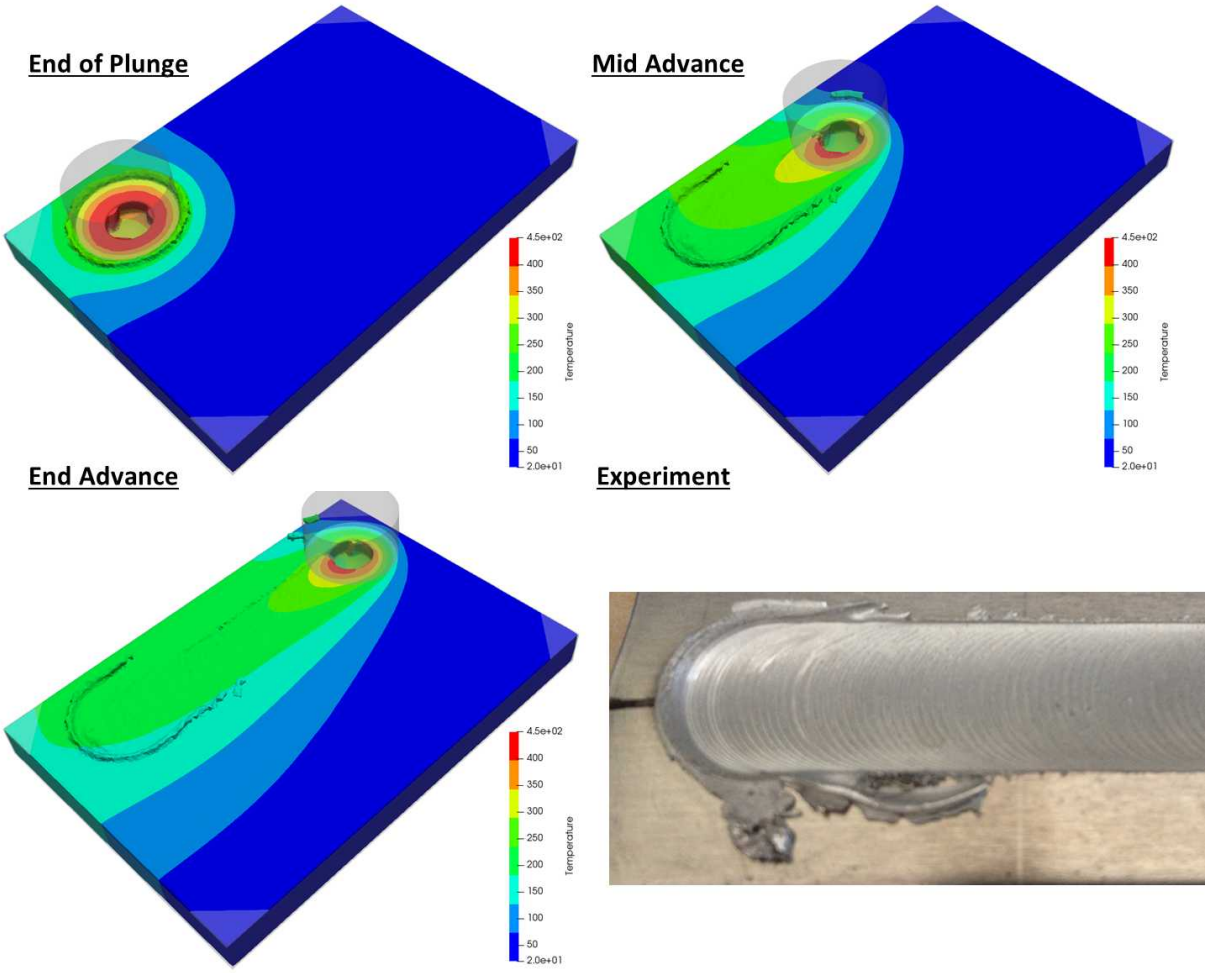

Figure 8 – Temperature and adhesive degradation results

Finally, the model can be used to evaluate the degradation of the adhesive. A comparison of the predicted and experimentally measured degradation during the FSW-AB process is shown in Figure 9 (left). The degradation is measured along a lateral line from the edge of the weld zone.

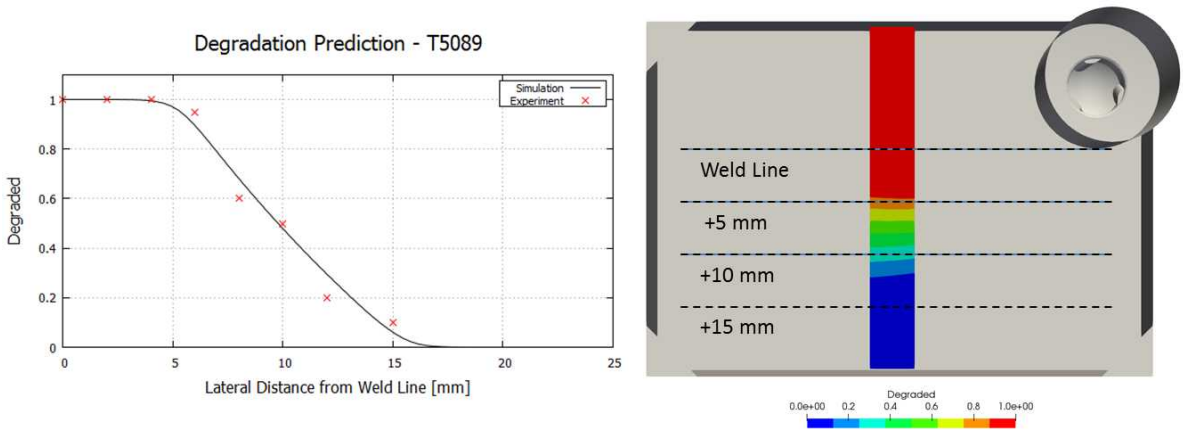

Figure 9 – Predicted and measured degradation

The simulation model obtains good correlation with experimental results. On the right side of Figure 9 is a contour plot of the predicted degradation of a strip of adhesive. This strip is

considered to be within the “quasi-steady” region of the advance phase. The results show that the simulation model predicts that the first ~5 mm outside of the weld zone are fully degraded. Then between 5 mm and 15 mm, the O-H and C-H groups are affected. Outside of the 15 mm region the adhesive is considered to be unaffected by the thermal cycle of the welding process (for these specific process parameters). Knowing that the adhesive is completely degraded in a 5 mm region outside of the weld zone is important for the weld design engineer. Armed with this knowledge, the engineer may opt to increase or decrease the overlap dimensions in the joint to maximize the cost effectiveness of the FSW-AB joint design.

CONCLUSION AND DISCUSSION

This work has presented the first use of a numerical simulation approach to predict the degradation of an FSW-AB joint. The model was validated for temperature history, defects, and degradation profile. The numerical simulation framework can be used to determine the process parameters and the joint design that will lead to a minimum of adhesive degradation. The meshfree method provides a robust and efficient means to determine critical design parameters within a reasonable time frame.

Looking towards the next steps, we plan to perform subsequent experimental work to develop a more comprehensive degradation model that takes into account the diffusion of different chemical species as a function of temperature. To this end, we would be able to have a transport/evaporation model that can predict the degradation of different types of adhesives based on the presence of specific chemical groups. This approach would require the solution of a Fickian diffusion problem for the adhesive layer as well as the work pieces.

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