Modeling of Curing Adhesives between Jointed Steel and Aluminum Plates using MAT_277 in LS-DYNA

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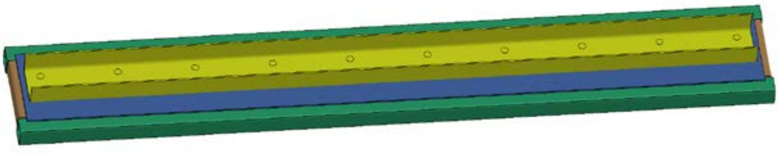
In this paper, a sandwich structure of two jointed plates with an adhesive layer in between is simulated. A top plate of aluminum, and bottom plate of steel are jointed with rivets. Then the plates go through the oven for paint baking, which lasts for approximately 60 minutes with oven temperature increasing in the beginning, then keeping constant, and decreasing towards the end. The difference in thermal properties between the aluminum and steel causes different expansion rates between the top and bottom plates, which leads to plastic deformation at, and around the mechanical fasteners. A layer of adhesives is therefore employed between the two plates, aiming to increase the bonding and also to reduce the plastic deformation. However, both the chemical and mechanical properties of the adhesives change nonlinearly with temperature. Therefore, it is critical to model the properties of the adhesives properly so that the deformation of the sandwich structure can be predicted, and the stress distribution can be analyzed. A new material card in LS-DYNA, Mat_277 is used in this project for the adhesives. This material card relates the chemical and mechanical properties of the adhesives not to temperature, but to an intermediate parameter named degree of cure. The degree of cure is decided by both the time and temperature of the baking process. The entire process is simulated using the LS-DYNA implicit solver. Instead of imposing the temperature at all nodes, a thermal-structure coupled analysis is conducted by way of using the *Boundary_convection card. This allows the different thermal conductivities of aluminum and steel to be taken into consideration. It was found that the adhesive strength prior to full cure is critical in preventing the plastic deformation at the joints. With certain levels of pre-cure strength, the adhesive layer can increase the bonding between the two plates without delaminating, which in turn could allow less mechanical fasteners to be employed. The relationship between the properties of the adhesives and the number of mechanical fasteners needed is therefore studied. Simulation results are validated qualitatively with experimental data and good correlation is found.

1 Introduction

In modern automotive vehicles, there often exist multi-material structures where dissimilar materials must be joined together. One example of such a multi-material joint is shown in Fig.1. The top plate is made of aluminium and joined to a base made of steel with self-piecing rivets (SPR). Ten pairs of SPR's are used with 100 mm spacing between each pair. This sandwich structure, together with the entire body to which it is connected, is put through a baking oven after its construction. The temperature profile of the oven is plotted in orange in Fig.2. The total baking process lasts approximately 60 minutes. The oven's temperature increases rapidly in the beginning of the baking process to around 180 ºC, holds steady for about one third of the baking time, and then decreases gradually to room temperature.



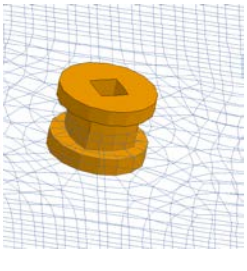


Fig.1: A sandwich structure of dissimilar materials: top aluminum plate in yellow, base steel plate in blue, joined with self-piercing rivets in orange.

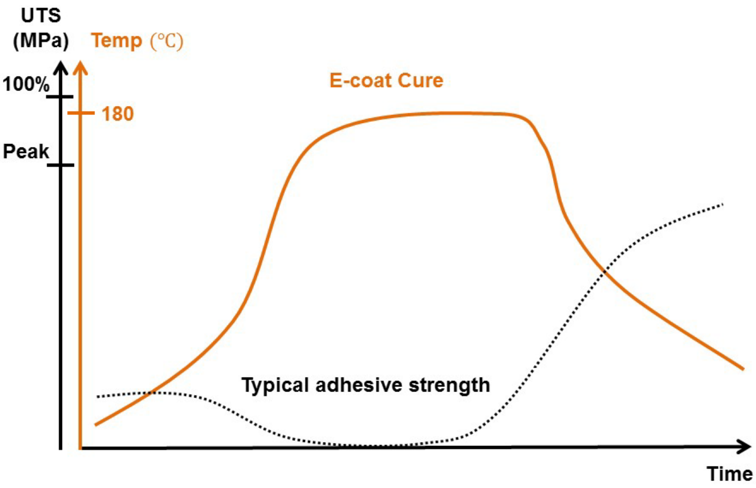


Fig.2: Temperature profile of the baking oven and the properties of the adhesives.

During the baking process, the top aluminium plate and the bottom steel plate deform at different rates and eventually have different maximum and residual deformations. Due to the different thermal expansion coefficients of aluminium and steel, the resultant discrepancy in thermal deformation between the two plates creates stress concentrations and eventually plastic deformation at the connecting rivets and in the plates around the rivets.

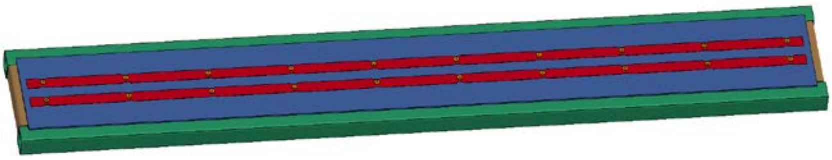


Fig.3: Adhesive layer placed between the top and base plates (in red).

One approach to reduce this effect is to employ an adhesive layer between the two parts in order to improve the bonding, and thus potentially reduce the number of rivets used. Adhesive, when applied at room temperature, behaves similarly to a liquid before it is fully cured. Together with the structure, the adhesive layer goes through the baking process for a full cycle of curing. The change of chemical and mechanical properties of the adhesives shown in Fig.3, together with the interaction of the curing adhesive layer with the rivets and plates, create challenges in modeling the sandwich structure as it goes through the baking process. This paper presents an innovative method in modeling such a structure during the baking process. The methodology is presented in section 2, with the simulation results shown in section 3, and a comparison between the simulation and test is discussed in section 4.

2 Methodology

The ultimate goal of this study is to build a CAE model that will capture the phenomenon depicted in the introduction. The challenge here is to relate the properties of the adhesives with the temperature. Common practice of modeling temperature dependent properties is to tabulate the properties with respect to temperature values. For example, *Mat_Elastic_Plastic_Thermal in LS-DYNA (Mat_004) provides temperature-dependent material properties including Young's modulus, Poisson's ratio, and thermal expansion coefficient among others. However, the relationship between temperature and properties for the adhesives is non-monotonical. This means for a certain temperature there should be two sets of corresponding properties: one during the temperature increase and one during the decrease. A new material card *Mat_Adhesive_Curing_Viscoelastic (Mat_277) in LS-DYNA has been developed for this type of problem.

Card 1	1	2	3	4	5	6	7	8
Variable	MID	RO	K1	K2	C1	C2	M	N
Type	A8	F	F	F	F	F	F	F

Card 2	1	2	3	4	5	6	7	8
Variable	CHEXP 1	CHEXP 2	CHEXP 3	LCCHE XP	LCTHEX P	R	LCTG	
Type	F	F	F	I	I	I	I	

Card 3	1	2	3	4	5	6	7	8
Variable	TREF	A	B	LCGINF	LCKINF			
Type	F	F	F	I	I			

Fig.4: Material card fro Mat_277 in LS-DYNA.

This material model is based on a theoretical model developed by Kamal (Kamal, 1974).

$$\frac{d\alpha}{dt} = (k_1 + k_2\alpha^m)(1-\alpha)^n$$

The model introduces an intermediate parameter α, which is named degree of cure. In the equation above, the relationship between degree of cure and time is defined. The material card is built upon the theoretical model and the parameters in card 1 correspond to the parameters in the model. Regardless of the temperature, a unique degree of cure is assigned to a time stamp. Card 2 is the card for the chemical properties of the adhesives that can be related to degree of cure, which can account for the chemical shrinkage of adhesives during curing. Card 3 assigns mechanical properties, i.e. shear and bulk moduli, to the degree of cure.

The body of this project's work can be broken down into the tasks shown in Fig.5.

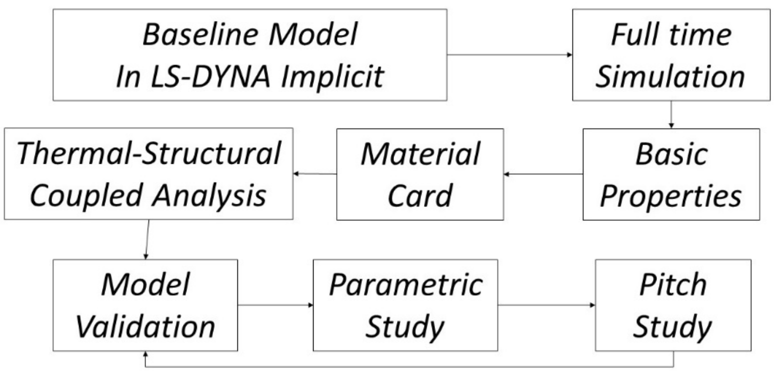


Fig.5: Schematics of the thermomechanical analysis.

The baseline model was built in LS-DYNA using an implicit solver due to the quasi-static nature of this problem. Initially, the entire process was shortened in the simulation from 60 minutes to 80 seconds in order to reduce computing resources. However, since an implicit solver can adjust the time-step according to the number of iterations needed to find equilibrium, the process was finally simulated for the full 60 minutes, which in fact does not cost extra computing time.

The basic properties of the adhesive were measured using lap shear tests, resulting in relative displacements versus forces. At different degrees of cure, the adhesive exhibits different elastic and bulk moduli, which are essential inputs for the material model used to represent curing adhesives in the simulation. A simple model is set up in LS-DYNA to simulate the coupon tests, as shown in Fig.6. A layer of adhesive is applied at the overlapping ends of two plates to join them together. The blue plate is fixed at the one end while the green plate is pulled at the other end. For adhesives with different degrees of cure, different sets of moduli are used in the material model. Corresponding displacement-force curves from the simulation are then compared to the curves measured from the tests. The moduli are then adjusted so that the simulated and measured curves reach a best match. This set of moduli is then considered as those for the adhesive at that degree of cure.

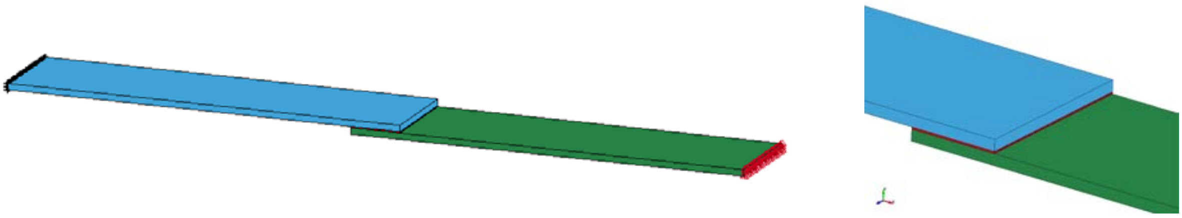
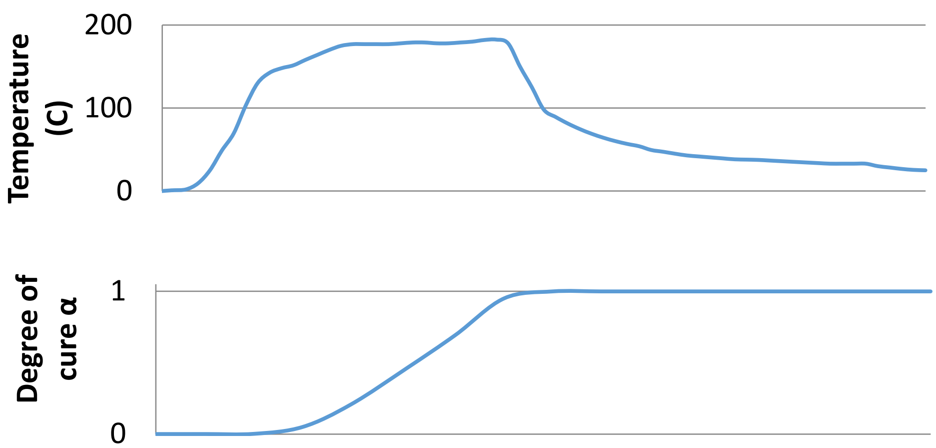


Fig.6: Simulation of the lap shear test in LS-DYNA.

The essence of this project is to find and use the right material model for simulating the entire baking process. Such a material model must account for the non-linear relationship between temperature and the adhesive's properties. At room temperature, the adhesive material has some strength due to its viscosity. This is referred to as the adhesive's residual strength in this paper. This residual strength decreases to virtually zero when temperature increases as the baking process initiates. From a manufacturing point of view, it could be beneficial to avoid the residual strength dropping to zero such that some strength remains at the lowest point. This strength is referred to as pre-cure in this paper. As the baking continues, the adhesive begins to cure and the strength continues to increase until the adhesive material reaches the fully cured state. The challenge is how to relate the adhesive's properties to the temperature.

The degree of cure in the Kamal model is time-dependent and monotonously increasing from 0 (fully uncured) to 1 (fully cured) over the duration of the baking process. As shown in Fig.7, a unique degree of cure is related to each time stamp, while a temperature is assigned to each degree of cure.



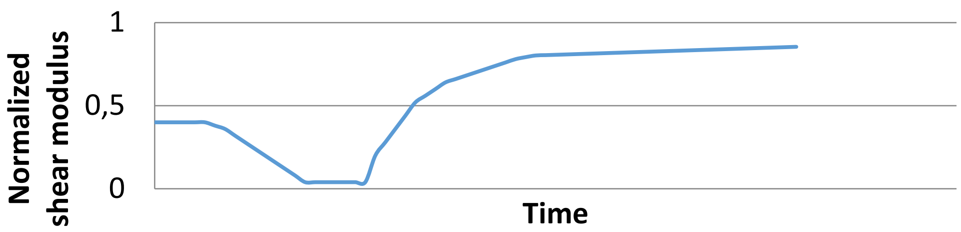


Fig.7: Time-dependent degree of cure defined to correlate adhesive properties with temperature.

In the baseline model, the change in temperature was imposed to all nodes and the sandwich structure reacted to this delta. This approach is commonly seen in thermal analysis using a structural solver. However, in this work, there is a difference between the thermal properties of aluminium and steel (such as the thermal expansion coefficient and thermal conductivity). This causes not only the aluminium top plate and steel bottom plate to deform at different rates, but also the temperatures of the plates to rise at different paces. Therefore, it is more accurate to simulate the heat transmitted to surfaces of the structure from the ambient rather than imposing the temperature at all of the nodes. This is often referred to as a thermal-structural coupled analysis. In LS-DYNA, *Boundary_convection can be used to address this issue. Four nodes can be defined in Card 1 to help defining a segment where the heat is convected and the convection is defined in Card 2.

Card 1	1	2	3	4	5	6	7	8
Variable	N1	N2	N3	N4				
Type	I	I	I	I				
Default	none	none	none	none				

Card 2	1	2	3	4	5	6	7	8
Variable	HLCID	HMULT	TLCID	TMULT	LOC			
Type	I	F	I	F	I			
Default	none	0.	none	0.	0			

*Fig.8: *Boundary_Convection cards in LS-DYNA.*

A top view of the temperature contour of the structure is shown in Fig.9, in which the aluminium plate has slight higher temperature than the base plate of steel.

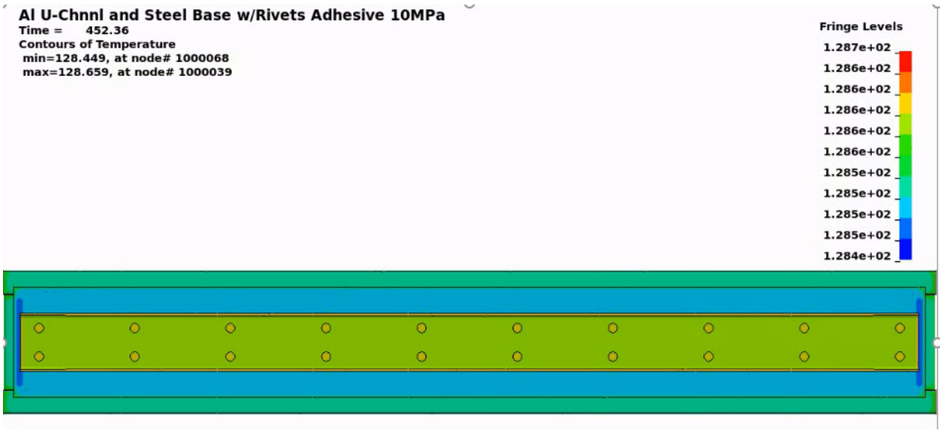


Fig.9: Temperature contour of the sandwich structure using a thermal-structural coupled analysis.

Simulation results of the sandwich structure with and without adhesive layers were compared with experimental measurements to validate the model using indexes such as the plastic deformation, the degree of bow in the structure, etc.

3 Computational results

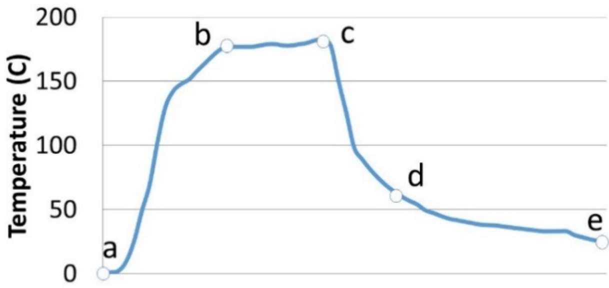


Fig.10: Five time stamps in the temperature profile.

Both structures with and without an adhesive layer are modeled going through the baking process with the same temperature profile. As shown in Fig.10, five discrete points on the curve are picked at which the state of deformation is plotted to depict the change of the structure during the baking. Figure 11 shows the five states of the structure with rivets at two ends (900 mm pitch), but without an adhesive layer. When the temperature increases from a to b, the aluminium plate expands to a greater degree than the base steel plates. The restriction from the base plate creates an up-bowing in the aluminium plate. This bow remains approximately the same amount from b to c, then decreases from c to d, and to e. Due to the plastic deformation created at and around the rivets during the process, there exists a residual bow in the end, as shown in Fig.11 (e).

(d)

(e)

Fig.11: Deformation of plates with no adhesives during the baking.

When an adhesive layer is applied, the bow of the aluminium plate from a to b is not as apparent due to the fact that the adhesive layer bonds the two plates and forces them to deform together. It should be noted that in all five plots of Fig.12, the displacement has been magnified 10 times to show the effects. From b to c, the temperature remains virtually constant, and the bow settles slightly as the adhesive cures. From c to d, the adhesive layer finishes curing and gains stiffness. As the temperature cools down, the aluminium plate contracts more than the steel and pushes down the base plate, as shown in plot (d) and (e).

(a)

(b)

(c)

(d)

(e)

Fig.12: Deformation of plates with adhesive during the baking process.

4 Comparison between simulation and experiments (at different pitches)

<u>900 mm pitch with no adhesives</u>

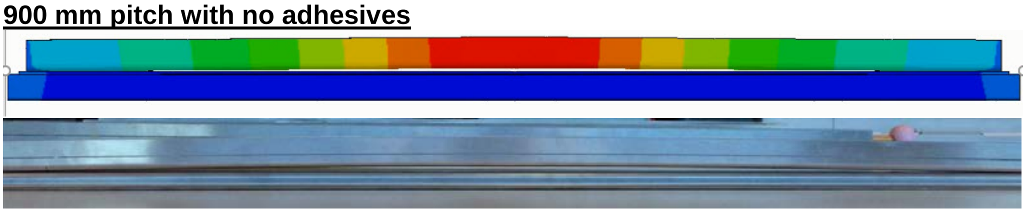


Fig.13: Comparison of simulation and test: final shape of the plates with no adhesive layer.

As described in the previous section, when there is no adhesive between the two plates, the difference between the thermal properties causes plastic strain to develop around the joints at two ends. This leads to the upward bow in the middle of the aluminum plate. The simulation successfully predicted the bowing, and it quantitatively matches the bow displacement measured after completion of the baking process. The colors denote the displacement in the vertical direction. Red represent the maximum positive displacement (upward bow), while blue represents the maximum negative displacement (downward bow).

900 mm pitch with nominally pre-cured adhesive

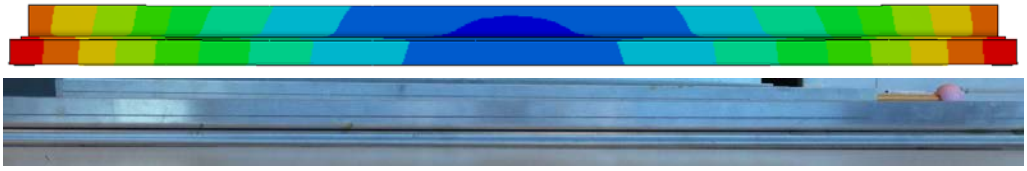


Fig.14: Comparison of simulation and test: final shape of the plates (900 mm pitch) with a nominally pre-cured adhesive layer.

When a nominally pre-cured adhesive layer is applied between the two plates, the upward bowing is eliminated. The final state even has a slight downward bow due to the properties of the adhesives. The adhesive stretches naturally during the baking when it is still curing and becomes hardened after it is fully or close to fully cured. Therefore, when the temperature drops and the plates contract, the top aluminum plates contracts faster than the bottom steel plate. This pushes down the cured adhesives and ultimately the bottom plate. As a result, the final shape of the plates has a downward bowing in this case.

100 mm pitch with nominally pre-cured adhesive

Fig.15: Comparison of simulation and test: final shape of the plates (100 mm pitch) with a pre-cured adhesive layer.

When the rivet pitch decreases (increasing the number of mechanical fasteners between the two plates), this together with the adhesive layer also eliminates the upward bowing. The residual bow is upwards rather than downwards. The reason for this difference is that the additional rivets shared the plastic deformation that would have taken place on the end rivets and also restrain the amount of stretch that the adhesive layer endured.

5 Concluding remarks

Modeling a structure of dissimilar materials joined with adhesive during a paint baking process can be quite challenging when the curing of the adhesive during this process is considered. This study provides a methodology to model curing adhesives whose properties are in a non-linear and non-monotonical relationship with temperature. By introducing an intermediate parameter, the time-dependent degree of cure, this complex relationship can be accurately predicted in LS-DYNA. The model is able to simulate the entire baking process and take into consideration the different thermal properties of aluminium and steel. Using this modeling methodology, the final shape of the plates from the simulation show a close qualitative match to the tested specimens. A study on the pre-cure showed that by adding an amount of pre-cure, a significant reduction in residual stress and strain can be achieved both in the adhesive layer and in the aluminium plate.

6 Acknowledgements

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7 References

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