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Publication date
2022

Document Version
Final published version

Published in
Proceedings of the 20th European Conference on Composite Materials: Composites Meet Sustainability

Citation (APA)
Liu, S., Sinke, J., & Dransfeld, C. A. (2022). Experimental and numerical validation of an inter-ply friction model for thermoset based fibre metal laminate under hot-pressing conditions. In A. P. Vassilopoulos , & V. Michaud (Eds.), *Proceedings of the 20th European Conference on Composite Materials: Composites Meet Sustainability: Vol 3 – Characterization* (pp. 374-381). EPFL Lausanne, Composite Construction Laboratory.

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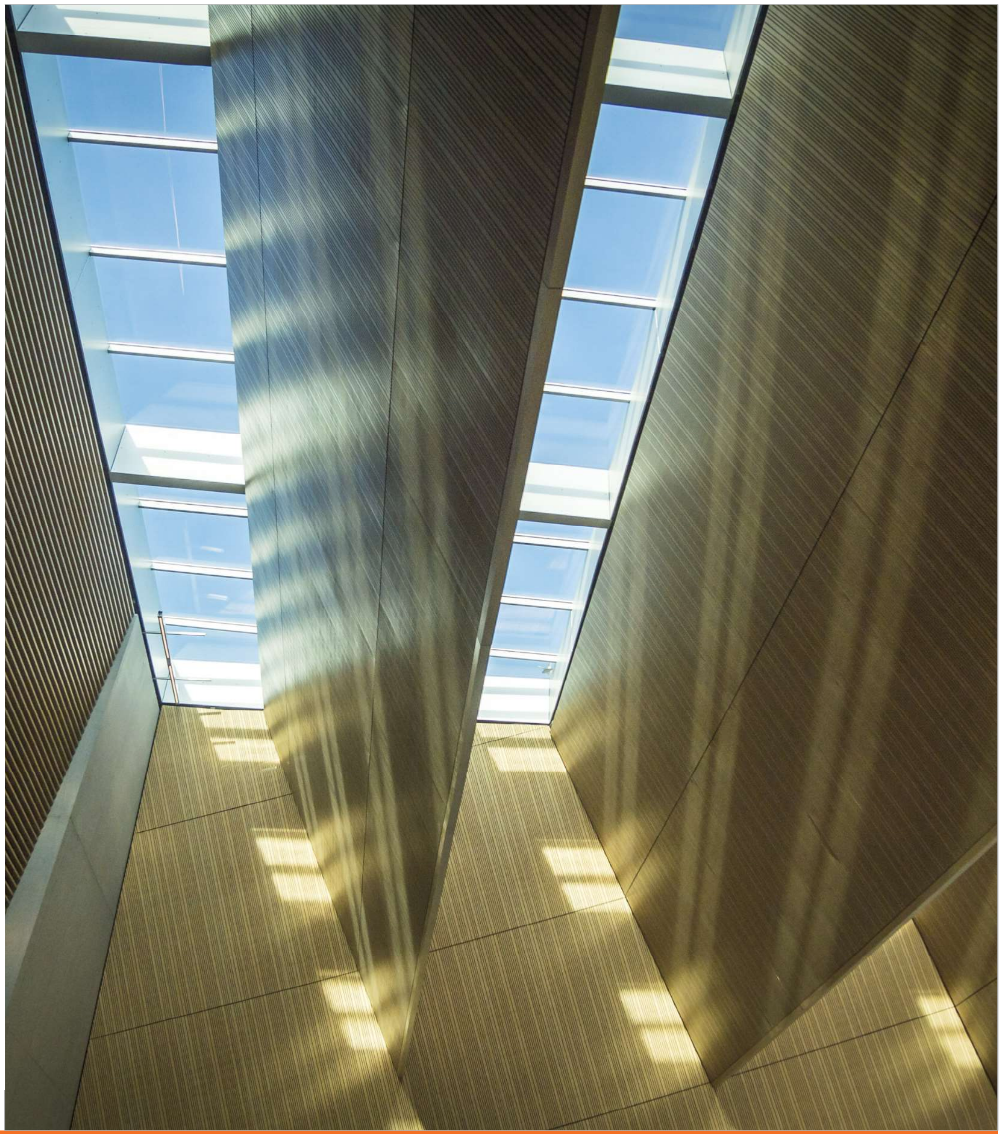

Proceedings of the 20th European Conference on Composite Materials

COMPOSITES MEET SUSTAINABILITY

Vol 3 – Characterization

Editors : Anastasios P. Vassilopoulos, Véronique Michaud

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ISBN: 978-2-9701614-0-0
DOI: http://dx.doi.org/10.5075/epfl-298799_978-2-9701614-0-0

Published by :

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Ecole Polytechnique Fédérale de Lausanne (EPFL)
BP 2225 (Bâtiment BP), Station 16
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EXPERIMENTAL AND NUMERICAL VALIDATION OF AN INTER-PLY FRICTION MODEL FOR THERMOSET BASED FIBRE METAL LAMINATE UNDER HOT-PRESSING CONDITIONS

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Abstract: *Hot-pressing can be an attractive fabrication method that enables the forming of hybrid materials like thermoset based fibre metal laminates. However, the process simulation on press forming requires accurate material characterization and boundary conditions to facilitate part design for a defect-free component. In order to improve the overall predictive simulation quality, the inter-ply sliding at metal-prepreg interfaces which is one of the critical deformation mechanisms is considered. An inter-ply friction model has been established using an experimental friction test apparatus and the effect of slip rate, normal force and temperature is taken into consideration. To validate the proposed friction model, a comparative study between results obtained from the numerical model and the experimental ones is carried out. The research demonstrates that the inter-ply friction model can be a valuable building block for the finite element simulation of the hot-pressing process for thermoset based fibre metal laminates.*

Keywords: Fibre metal laminates (FMLs); Inter-ply friction; Hot-pressing; Numerical simulation

1. Introduction

Fiber metal laminates are lightweight composites made by alternative layers of fibre reinforced materials and metal alloy sheets. The hybrid structures can be used for different properties using various constituents and the combination has superior performance over their individual layers [1,2]. Conventional approaches like lay-up techniques and autoclaves can only manufacture FML parts with a relatively simple shape, having large radiuses like aircraft fuselages. The main reason is that the deformability of the hybrid laminates is limited by the small failure strain of the fibres and the failure modes of the laminates [3]. Therefore, this research puts forward a methodology which combines hot-pressing and subsequent curing process in one cycle using the same mould to achieve better performance without the occurrence of fractures, wrinkles or other possible defects [4,5]. The proposed hot-pressing process is shown in Fig.1. Prior to the hot-pressing and curing steps, the uncured laminate is stacked and pre-heated which decreases the resin viscosity and eases the deformation of the prepreg, in particular inter-ply friction. However, temperature and time are two critical factors that need to be carefully controlled as the initiation of epoxy resin cure would increase the stiffness of the prepreg and constrain deformation. The process combines sheet metal forming and composite forming technologies for manufacturing the final product without losing much mechanical performance. Therefore, both the deformation modes of these two materials should be considered in order to improve the formability of the fibre metal laminates. The metal sheets are usually deformed into 3D shapes by bending and in-plane plastic deformation, while the deformation of fibre prepregs is achieved by allowing the individual layers to deform through intra-ply shear within the prepregs and inter-ply sliding in-between the metal sheets and prepregs.

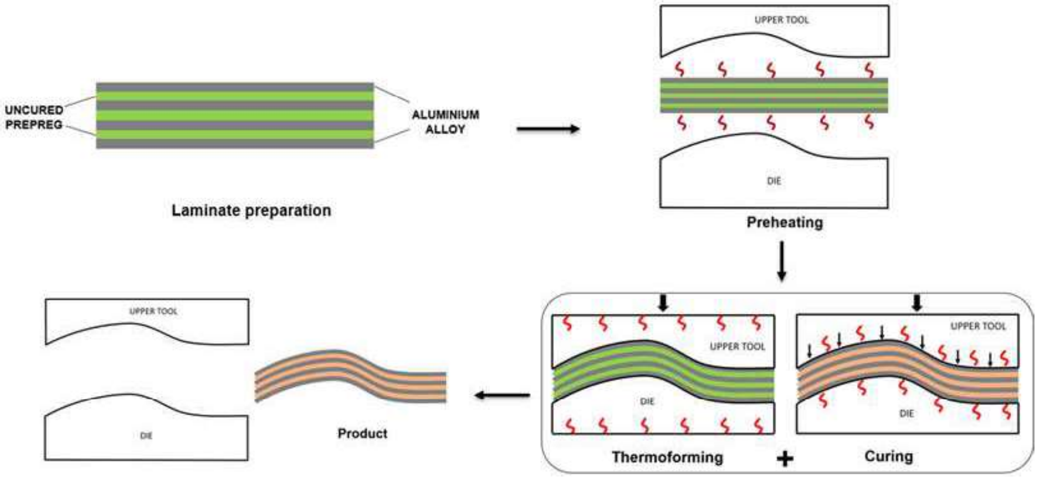


Figure 1. Proposed hot-pressing process of thermoset based fibre metal laminate manufacturing

The finite element modelling of fibre metal laminates can be approached mainly in three ways: micro-level, meso-level and macro-level. For the micro-level approach, individual materials are differentiated in the model consisting of fibres and matrix. This is the most complex but realistic approach as it requires partitioning the model into different pieces [6]. The meso-level approach regards the laminate as a system of independent layers with specific homogenized mechanical properties. This approach results in an effective modelling for all type of hybrid laminates as it requires relatively limited number of elements. Although there are some simplifications which skips the issue of layer boundary conditions, it would not affect the laminate performance unless delamination or other failure phenomena occur [7,8]. The macro-level approach describes the entire hybrid laminate as a homogenized material with anisotropic properties. This approach can be described as a simple generalization since only a few engineering constants are needed. The biggest problem for this method is to obtain the data of the homogenized material as the replacement for the hybrid laminate. One of the possible solutions is the application of Classical Laminate Theory which enables the description of their behaviour under external loads based on the engineering constants, representing membrane, bending and coupling behaviour, or by the uniaxial tensile test of the specimen in order to obtain the constant data in the theory [9,10]. Moreover, process simulation of the hot-pressing of fibre metal laminates requires an accurate mathematical description of the main deformation mechanisms such as intra-ply shear, inter-ply sliding as well as bending [11]. None of these mechanisms is negligible or dominant, as the laminate deformability is supposed to be a result of a delicate balance among them [12]. Therefore, more advanced material constitutive models and boundary conditions of each deformation mechanisms are required to improve the predictive quality for manufacturing.

This research aims to develop a homogenized meso-level model for inter-ply friction in the hot-pressing process and implement it into numerical software Abaqus for validation. The inter-ply friction mechanism at the metal-prepreg interfaces of glass fibre reinforced aluminium laminate (GLARE) is investigated experimentally. Then, the meso-level approach coupled with the friction contact model for numerical simulation is established. As the current frictional models neglect the effect of any transient which greatly influence the predictive quality [13,14], a static-kinetic exponential decay equation is used to model the transition from static to kinetic friction under different conditions such as temperature, sliding rate and normal force in order to include the initial transient response into the inter-ply friction model. The coefficients of static and kinetic friction are obtained by a novel experimental friction test as the values are key indicators of the initial and steady transient response. To validate the ability of the proposed friction models for replicating the response of the inter-ply friction test, numerical software ABAQUS which allows for the implementation of user-defined frictional behaviour via a subroutine is applied. Also, the results of the stress-displacement response are analysed and compared with the commonly used cohesive zone model and penalty friction model with steady response. The establishment of the inter-ply friction model provides deep insights into the underlying deformation mechanism of fibre metal laminate under various hot-pressing conditions.

2. Materials and methods

The hybrid material involved in this work was the aerospace graded fibre metal laminate named as GLARE-glass fibre reinforced aluminium laminate. The experimental sample presented in Fig.2 consists of three layers of 0.5-mm thick 2024-T3 aluminium sheets and two layers of glass fibre reinforced prepreg S2-glass/FM-94 epoxy. Each fibre layer included two unidirectional prepreg plies with a nominal thickness of 0.18 mm. The unidirectional fibre ply oriented at zero direction corresponded with the rolling direction of the aluminium sheet. Prior to assembling, aluminium surface was pre-treated with chromic acid anodizing and BR 127 primer for corrosion protection [15-17] since the surface treatment has a great influence on the friction studied in the research.

In this work, an inter-ply friction test was chosen as the experimental procedure. It was designed by modifying the ASTM D3528 standard which is used to determine the shear strengths of adhesives for bonded metals [18]. The schematic diagram and dimension for the test sample is presented in Fig.2 and the normal force is applied on top and bottom layers by a clamping loadcell. Besides, the preheat temperature inside the chamber and the sliding rate for pull-out can be set through manual input. The friction test apparatus which allows for testing at various conditions, was designed for the measurement of inter-ply friction coefficient at metal-prepreg interface. Instead of bonding and curing through standard autoclave cycle, the uncured prepreg layer could slide along the pre-treated aluminium sheet under specific normal loads. The heated resin was not only the matrix material of the resulting prepreg but also acted as a lubricant when the prepreg slides between two metal plates. To investigate the effects of different parameters on the friction coefficient at the metal-prepreg interface, a set of values were chosen in Table 1. Experiments were conducted varying two parameters at a time while keeping the other at their baseline values.

Table 1: Test parameters used for inter-ply friction tests .

Parameter	Baseline value	Additional values investigated
Normal force (N)	500	100,200,300,600,1000
Sliding rate (mm/min)	10	5,15,20,30,40
Temperature (℃)	23	40,60,80,100,120

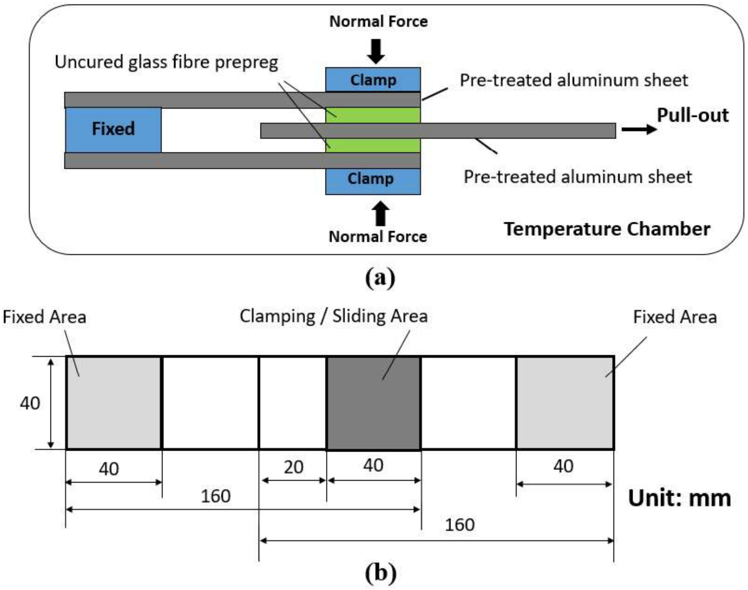


Figure 2. Schematic diagram (a) and dimension (b) for the designed inter-ply friction test

For the numerical verification, a finite element model of the experimental friction setup was done with Abaqus. The finite element model shown in Fig.3 includes two outer aluminium sheets fixed at one end and a middle aluminium sheet pulled out from the other end, together with two alternating glass fibre prepreg layers. A normal force was applied on the outer aluminium surfaces and the sizes as well as thicknesses were the same as the experimental setups. To simplify the setup and reduce computation time, the two material constituents were modelled as deformable bodies with four-node bilinear plane stress quadrilateral elements (CPS4R) and with a mesh size of 1 mm. Such laminate model was represented in the composite layup module where all layers and material parameters like orientation, thickness, property and relative location was defined. The inter-ply friction model used a static-kinetic exponential decay equation to simulate surface to surface contact instead of constant friction coefficient value. Values of static and kinetic friction coefficient were obtained by an experimental friction test and the decay constant was calculated to best fit the experimental data points [19]. A cohesive zone model with contact elements was compared for validation. The interface properties of the cohesive layers were gathered from literatures and the interfacial delamination can be modelled based on cohesive law by adopting a softening relationship between traction and separation [20].

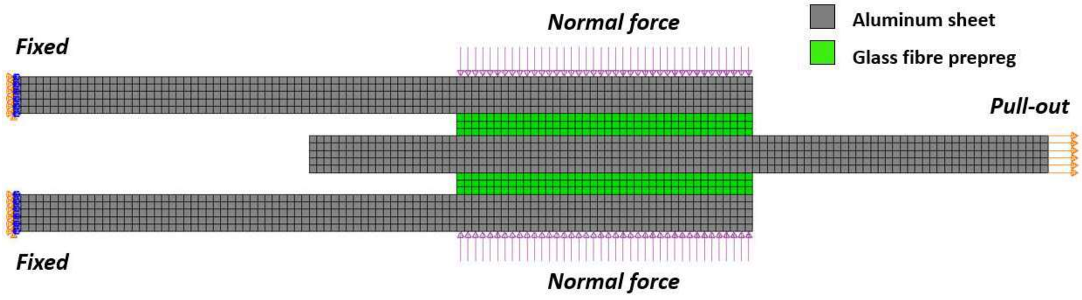


Figure 3. Finite element model for the inter-ply friction test of fibre metal laminates

3. Results and discussion

3.1 Numerical implementation of experimental results

For the inter-ply friction behaviour, the graph of Fig.4 validated that the numerical model can capture a peak state as it was associated with the static friction and a steady sliding state for the kinetic friction. Both results revealed that friction coefficient increases with the increasing sliding rate and this relationship suggested that the friction was characterised by the Newtonian shearing of the epoxy matrix where shear stresses increase with the increasing shear rate. In contrast, the friction decreases with the increasing normal force and explanation can be that at low normal forces, interface between the fibre reinforced prepreg and aluminium sheet has a relatively rough surface contact with high asperities. While higher normal force can result in the resin percolation as well as a better film of slippage, and thus decrease the friction coefficients. Fig.4(b) revealed that the static and kinetic friction coefficients decrease as the test temperature increases from the temperature of 40℃ to 120℃. The reason for that is mainly due to the lower viscosity and increased lubrication as resin squeezing out when the temperature increases. More details can be found in reference [19]. The Fig.4 also showed that static friction coefficient and onset sliding displacement obtained from the model does not correspond exactly to the experimental data, and the model observed a steady kinetic friction at the early stage of displacement while the experimental coefficient of friction continues to drop slightly. This small difference can be ignored due to the inevitable experimental errors and the numerical model can thus be regarded as a good solution to predict the inter-ply friction accounting for the variations in sliding rate, normal force and temperature of the preformed fibre metal laminates.

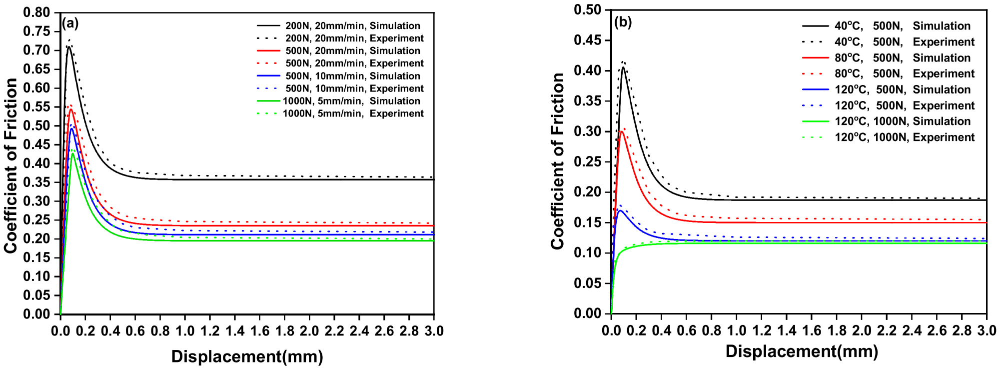


Figure 4. Comparison between numerical and experimental results for inter-ply friction of fibre metal laminates: (a) At room temperature 23 ℃; (b) At sliding rate 10 mm/min

3.2 Comparison with other numerical models

To further validate the accurate response of the applied static-kinetic friction model, two other numerical models for simulating the inter-ply contact behaviour were compared. The stress and displacement curves for the three models under specific conditions are presented in Fig.5. The penalty friction model was set at a steady friction coefficient value of 0.2 and a normal force of 500N, while the cohesive zone model was performed with the shear stiffness of 10^5 MPa/mm, maximum shear strength of 50 MPa and fracture toughness of 0.2 N/mm. It was obviously seen from the figure that the value of stress for the cohesive zone model during the sliding period is not in the same order of magnitude as the other two friction models, and the maximum stress is reached at a smaller displacement. This is because the cohesive zone model is essentially equivalent to tie constraint where the initial slide of aluminium sheet causes the layer separation or even fracture with extremely high shear stress. Fig.6(a) shows the delamination at the metal-prepreg interfaces when the cohesive zone model was applied. This failure mode may limit the deformability of fibre metal laminate as it was more like a cured sample. Therefore, the cohesive zone model was not suitable to simulate the inter-ply contact at various hot-pressing conditions. As for the penalty friction model, there is no difference in the steady sliding state compared with the static-kinetic friction model even though stress concentration occurs in the initial sliding area (Fig.6(b)). However, the initial transient response behaved differently where no obvious static state was found. This was more likely to occur at higher temperature with lower resin viscosity shown in the inter-ply friction tests. Therefore, the penalty friction model was inappropriate for simulating the inter-ply sliding behaviour under all the hot-pressing conditions. After comparing with the two numerical models, the static-kinetic friction model was proved to be the best-fit to accurately model the inter-ply friction of fibre metal laminate in actual hot-pressing process.

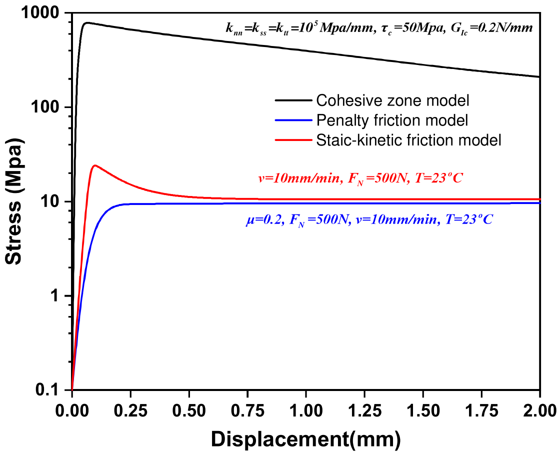
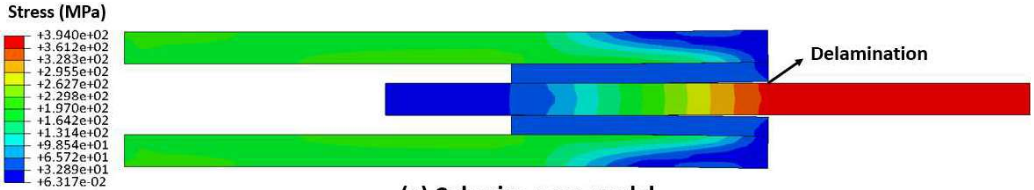
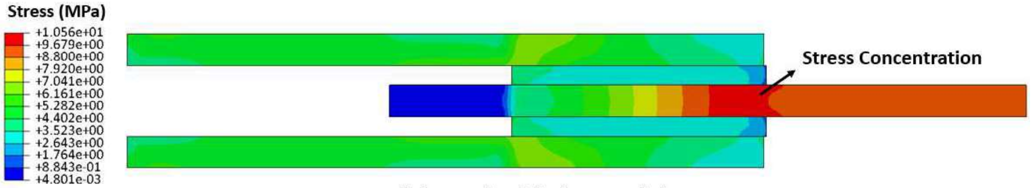


Figure 5. Comparison of three numerical models at the metal-prepreg interface



(a) Cohesive zone model



(b) Penalty friction model

Figure 6. Numerical results of two different contact models at the displacement of 1 mm

4. Conclusion

In the present work, the friction coefficient at metal-prepreg interfaces for fibre metal laminate under various hot-pressing conditions was measured using a novel friction-test apparatus. A static-kinetic friction model for the prediction of the inter-ply friction behaviour of fibre metal laminate was established and validated. The proposed model was able to predict initial transient response and transition from static to kinetic friction under different parameters such as sliding rate, temperature and normal force. The friction coefficient-displacement trends predicted by the numerical model correlated well to those determined through experimental test. Moreover, two other numerical models for simulating the inter-ply contact of fibre metal laminates were proposed. The cohesive zone model was proved to be insufficient as the shear stress was too high and delamination was prone to occur. The penalty friction model can model the kinetic friction during the steady sliding state, while the initial transient response was neglected thus cannot be applied under all hot-pressing conditions. As a result, the inter-ply friction model can be a valuable building block for the finite element simulation of the hot-pressing process for thermoset based fibre metal laminates.

Acknowledgements

The presenting author would like to thank the financial supports of China Scholarship Council (No.201906040174).

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