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Publication date
2024

Document Version
Final published version

Published in
Proceedings of the 21st European Conference on Composite Materials

Hot-pressing of uncured metal-composite laminates: A numerical study on simultaneous deformation

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Keywords: Metal-composite laminates, Simultaneous deformation, Metal cracking, Prepreg buckling, Finite element modelling

Abstract

The research focuses on the simultaneous deformation of uncured metal-composite laminates under the press forming process of a double-curved dome part. The study is designed to evaluate the influence of material type, inter-ply friction and clamping force by the use of a finite element modelling method. The result shows that the main failure mode for aluminium-based hybrid materials is metal cracking while prepreg buckling dominates the failure of stainless steel-based hybrid materials. The increase of clamping force contributes to the deformation of fibre reinforced prepreg layer and decrease the risk of prepreg buckling, but the simultaneous increase of plastic deformation tends to induce the failure of metal cracking. The variation of friction coefficient at the metal-prepreg interface affects the inter-ply sliding displacement during the forming process. This work provides a numerical method on the material selection and process parameter optimisation where compatible deformation of the individual layers can be achieved through its own mechanisms.

1. Introduction

The Metal-composite laminates, which are also known as fibre metal laminates (FMLs), are one of those lightweight composite materials made by alternating thin sheets of metal alloys and layers of fibre reinforced polymers [1,2]. This hybrid combination creates a material which has excellent specific strength, higher stiffness, and superior fatigue resistance than the monolithic metal sheets as well as better impact strength and damage tolerance compared with full composites [3,4]. Traditional method for the manufacturing of metal-composite laminates is through layup techniques followed by autoclave curing, which is applicable for the product with a relatively simple shape, having large radiuses like aircraft fuselages [5]. As for the forming of small and medium sized part with relatively small radii and complex shapes, the concept of press forming is proposed where the hybrid laminates are pressed using a die and shaped by the deforming force [6]. However, there are some limitations for the press forming of hybrid laminates especially for the epoxy-based hybrid materials because of the needs for various forming and curing stages as well as for the complex deformation mechanisms. Therefore, this study puts forward a hot-pressing cycle involving a laminate preparing and preheating stage, forming of uncured laminate, consolidation or (partial) curing in a same mould as well as the cooling and removal of the component as shown in **Fig.1**. This approach contributes to a better formability of metal-composite laminates based on the understanding of different deformation mechanisms for both layers as well as the optimisation of processing parameters in the hot-pressing cycle.

The forming of metal sheet into the desired shape involves the elastic-plastic deformation of the material by bending, stretching and drawing. Typically, the deformation induces in-plane strain ratios from pure shear to biaxial stretch and the failure strain for the metal alloy materials is in the range of 10% to 50% [7,8]. Therefore, the deformability of the metal sheet is mainly determined by the metal

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constituent and the failure mode is dominated by the metal cracking in the forming process [9]. The wrinkling may occur for metal sheet which caused by the increase of compressive stress, but the increasing thickness and clamping force contribute to the delay of such phenomenon [10]. For the deformability of composites, fibre reinforcements and prepregs are particularly prone to wrinkling due to the fibre composition and the possible slippage in-between the fibre tows [11,12]. The wrinkling of woven fabrics is related to intra-ply shear in studies based on the "shear locking angle", which is the maximum angle between warp and weft yarns [13]. Besides, the wrinkling of unidirectional (UD) fibres occurs due to the large differences in rigidity between the fibre orientation and its transverse direction. Therefore, the wrinkles are related to the bridging of the rigid ply and the ply-ply friction during forming [14]. Larberg [15] found that the stacking sequence of UD-prepreg laminates have a significant effect on wrinkle development when forming a spar geometry. He explained this effect as that the combination of 0° and 45° layers may reduce the material deformability through shearing. Akermo et.al [16] further discovered that the inter-ply friction improves the forming behaviour of cross-plied UD prepregs by serving as a connection between the plies, but also introduce wrinkles if not properly controlled.

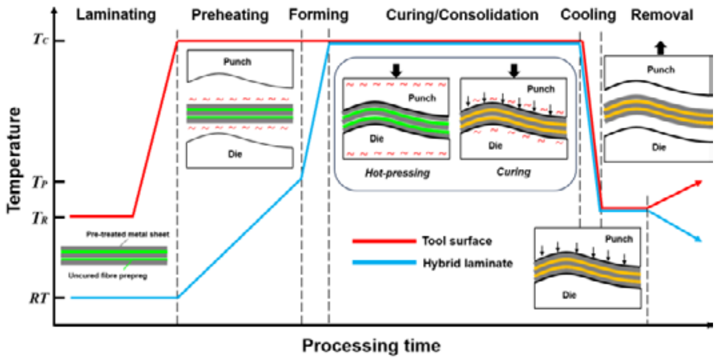


Fig.1: Processing temperature-time profile of the tool surface and hybrid laminates

The numerical modelling of metal-composite laminates can be approached mainly in three ways: micro-level, meso-level and macro-level. As 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 [17]. The meso-level method 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 [18,19]. 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 according to 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 [20,21]. Moreover, process simulation of the hot-pressing of fibre metal laminates requires an accurate mathematical description of the main deformation mechanisms like intra-ply shear, inter-ply sliding as well as bending [22]. None of these mechanisms is negligible or dominant, as the laminate deformability is supposed to be a result of a delicate balance among them [23,24]. Therefore, more advanced material constitutive models and boundary conditions of each deformation mechanisms are required to improve the predictive quality for manufacturing.

This paper aims to develop a homogenised meso-level model for simultaneous deformation in a hot-pressing process and implement it into numerical software Abaqus for analysis. A set of forming tools for the forming of double-curved hemisphere part are designed and the meso-level approach coupled with the friction contact model for finite element simulation is established. The novelty of the research is to study the "harmony" deform of the individual layers with its own deformation mechanisms when applying the initial circle and square shapes for metal sheet and uncured fibre prepreg, respectively. The simulations are conducted with various material constituents, as well as the clamping forces and inter-ply friction coefficients to evaluate what combinations would be good for a maximum deformability. Then, the numerical model is capable of predicting the local strain distributions and the maximum draw depths for the uncured hybrid materials.

2. Materials and methods

2.1. Materials

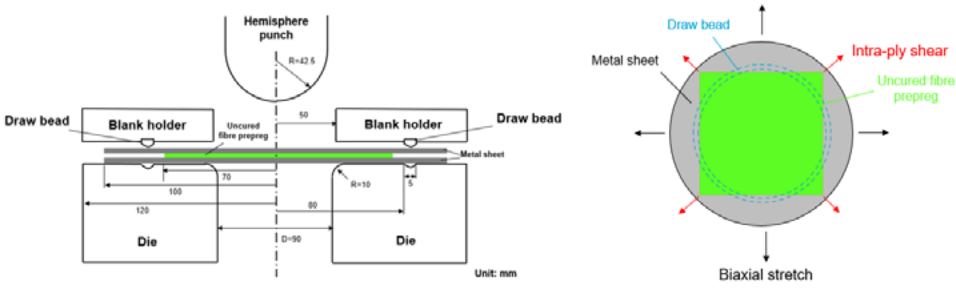
The hybrid laminates involved in the research are the metal sheets of aluminium alloy 2024-T3 (Al) and stainless steel 304L (Ss), as well as the fibre reinforced prepregs of S2-glass/FM-94 (GFRP) and T300-carbon/MTC510 (CFRP). The metal-composite materials consist of two layers of 0.5-mm thick metal sheet and one layer of fibre prepregs which are known as a 2/1 layup. Each fibre layer includes two cross-plied unidirectional (UD) prepregs with a total thickness of 0.3mm. The UD fibre ply oriented at 0° corresponds with the rolling direction of metal sheet. The mechanical properties of the material constituents in hybrid laminates are shown in **Table 1** and the behaviour of the metal sheet cannot be affected under the studied temperature ranges. Two parameters of elastic modulus and ultimate strength for the UD reinforced fibre prepregs represent the properties in the fibre orientation of 0° and 90°, respectively.

Table 1 Mechanical properties of the material constituents in hybrid laminates [25,26]

	Density (g/cm^3)	Elastic modulus (GPa)	Poisson's ratio	Shear modulus (GPa)	Yield strength (MPa)	Ultimate strength (MPa)	Shear strength (MPa)	Elongation at break (%)
Aluminium alloy 2023-T3	2.7	71	0.33	28	320	480	283	16.2
Stainless steel 304L	8.0	200	0.30	77	210	574	378	45.6
UD glass fibre prepreg-FM94	2.6	54.0/9.4	0.33	5.5/2.6	-	1870/50	38.5	3.8
UD carbon fibre prepreg-MTC510	1.5	119.3/8.2	0.34	3.6/2.0	-	2282/54	99	1.3

2.2. Concept design

The concept of simultaneous deformation of uncured metal-composite laminates came from the design of an integral forming and curing cycle in the proposed hot-pressing process as exhibited in **Fig.1**. In order to investigate the three-dimensional (3D) deformations of the individual layers and the metal-prepreg interfaces, a double-curved hemisphere forming tool concept with draw bead is designed as the schematic graph shown in **Fig.2(a)**. The hybrid laminate with a circle shape of 70mm radius for metal sheet layer and a square shape of 100×100mm for fibre prepreg layer is placed symmetrically on the die surface and clamped by blank holder. As the schematic graph presented in **Fig.2(b)**, the metal sheet and fibre prepreg deforms independently through bias-stretch and intra-ply shear, and the different shape design contribute to the study of "harmony" deform for the individual layers. Furthermore, the concept of draw bead with the depth of 1mm and length of 5mm is proposed to constrain the material flow as well as to achieve a part without cracks and wrinkles. The hemisphere punch with a radius of 42.5mm moves vertically down the centreline of the laminate to a special displacement. In addition to the different material constituents studied in the research, the effects of clamping force and intra-ply friction are compared as well. **Table 2** presents the test parameters used for the forming simulation and the model is conducted varying one parameter at a time while keeping the other parameters at the baseline value. To simplify the hot-pressing temperature condition, the friction coefficient (μ) of 1 is regarded as the forming condition of room temperature (RT). Then, the frictional contacts where μ= ∞(Tie), 0.5, 0.2 are created as the state of full-cured, medium-friction as well as low-friction, respectively.



(a) **(b)**

Fig.2: (a) Schematic graph of the double-curved dome forming tool design and dimension; (b) Deformation mechanisms and initial shapes of the individual metal sheet and fibre prepreg

Table 2 Test parameters used for the hybrid laminate hot-pressing concept

Test parameter	Baseline value	Additional values investigated
Clamping force (kN)	0	0.1, 1, 2
Inter-ply friction (μ)	1 (RT)	∞(Tie), 0.5, 0.2

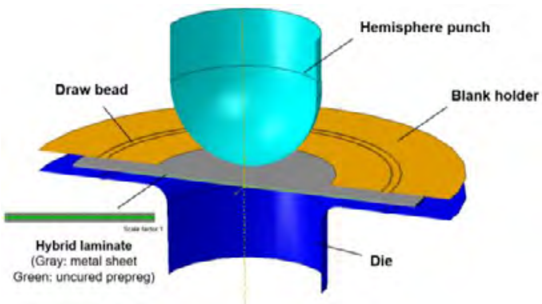


Fig.3: Finite element model of the hot-pressing process for uncured hybrid laminates

2.3. Finite element model

The application of finite element model (FEM) made it efficient to analyse the simultaneous deformation of uncured hybrid laminates and provide guidance for actual experimental testing. In the research, finite element analysis software Abaqus is used to simulate the forming process of the uncured laminates by using the stress-strain distributions of the metal sheet and the unique anisotropic properties of the fibre reinforced prepreg. **Fig.3** exhibits the simulation model established for the study and all the materials as well as tool geometries followed by the concept design. The elastic-plastic properties of the metal sheets and the elastic constants for the uncured prepreg lamina as shown in **Table 1** are imported into the material property module in Abaqus. In the finite element model, all tools including the hemisphere punch, die and blank holder are modelled as discrete rigid shell elements with a mesh size of 2 mm. Metal sheets and the uncured fibre prepreg are created as four-node doubly curved conventional shell element with reduced integration (S4R) in the same mesh size. The laminate structure in the simulation model is represented in the composite layup module where all layers and their parameters such as orientation, thickness, property and relative location are defined and assembled into the forming simulation. As for the interactions and boundary conditions in the model, the value of clamping force and punch displacement can be set, and the contacts between the fixed tools and the uncured laminates are set as penalty friction in a constant value of 0.15. The interaction at the metal-prepreg interfaces is also defined as friction contact as shown in **Table 2**.

3. Results and discussion

3.1. Effect of material composition

During the laminate press forming process, the metal and composite type both play a significant role in the deformability and failure modes of the hybrid materials. **Fig.4** shows the numerical results of the vertical displacement (U3) before failure for Al/GFRP laminate at room temperature and zero clamping force. The metal cracking which dealt by element deletion when the element exceeds the forming limits is the main failure mode as shown in the figure. It is observed that the lower aluminium sheet cracks first at the displacement of 25.08mm and the failure occurs at the centre regions of the metal material. The GFRP material, which is not shown in the figure, stays in contact with the outer metal layers and has no failure at such displacement. Also, the type of fibre prepreg has limited effect on the metal cracking and maximum depth for the aluminium-based hybrid laminates as the prepreg changes from GFRP to CFRP. The reason is due to the fact that the aluminium alloy has lower failure strain than the stainless steel while the fibre prepreg in the middle has not experienced large intra-ply shear strains nor failure at the same depth. When replacing the metal type from aluminium alloy to stainless steel, the failure mode for hybrid materials is totally different. The CFRP and GFRP material in the stainless steel-based hybrid laminate undergo prepreg buckling while the outer metal layers have no failure of metal cracking as exhibited in **Fig.5**. In this case, the numerical result on the vertical displacement (U3) before failure under room temperature and zero clamping force condition for the Ss/CFRP and Ss/GFRP laminates are 39.81mm and 44.64mm, respectively. The prepreg buckling is caused by the layer overlaps due to the increase of intra-ply shear strain which exceeds the locking angle. The locking strain for the GFRP is higher than the CFRP under the same condition which results in a larger failure depth during the forming process.

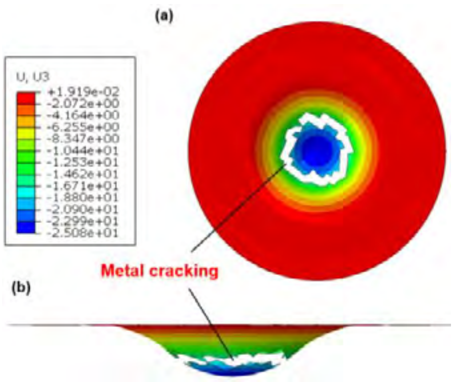


Fig.4: Numerical simulation on vertical displacement (U3) at the maximum value at room temperature and zero clamping force for Al/GFRP laminates: (a) XY plane-Al; (b) XZ plane-Al

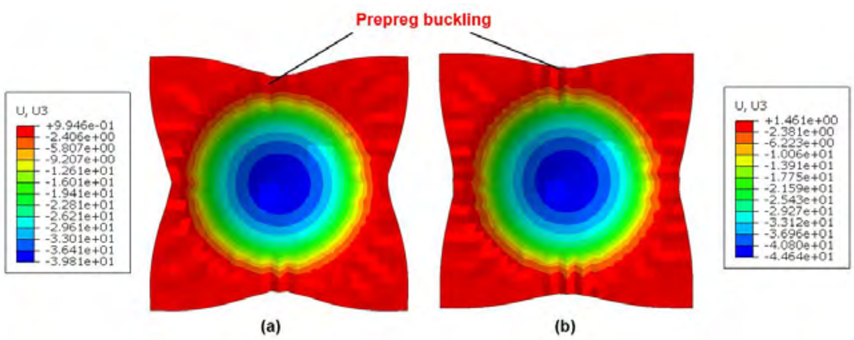


Fig.5: Numerical simulation on vertical displacement (U3) at the maximum value at room temperature and zero clamping force for stainless steel based hybrid materials: (a) CFRP; (b) GFRP

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3.2. Effect of clamping force

Fig.6 shows the simulation results on maximum draw depth and its corresponding failure mode under four clamping force conditions at room temperature. For the aluminium-based hybrid laminates with both CFRP and GFRP materials, the increase of clamping force tends to decrease the maximum draw depths even though the influence is limited. The reason is mainly due to the increase in biaxial stress which induces earlier cracking of the aluminium sheet. Besides, the main failure mode for such laminates is metal cracking and the prepreg layer witnesses no prepreg buckling. However, the larger draw depth with less clamping force does not mean a better formability for Al/CFRP and Al/GFRP laminates as the metal wrinkling may occurs at the flange regions. For the stainless steel-based hybrid laminates, the failure mode is complex under various clamping forces. The increase of clamping force from 0kN to 1kN increases the maximum draw depth and the failure of metal cracking occurs coupled with prepreg buckling. As the clamping force reaches 2kN, the metal cracking is dominated with lower failure depth while the phenomenon of prepreg buckling does not exist anymore. This indicates that the increase of clamping force delays the prepreg buckling. A more detailed graph on the different failure modes for Ss/CFRP laminates under 1kN and 2kN is exhibited in **Fig.7**. It is obvious to see that higher clamping force lowers the maximum failure depth and metal cracking occurs at the inner radius regions. The firm clamping on the four-square corners for CFRP reduces the occurrence of prepreg buckling by inducing tension forces in the prepreg layers through friction between draw bead-metal and blank holder-metal interfaces. In order to investigate the friction effects, the comparison between two clamping forces against the initial and final prepreg shapes for Ss/CFRP laminates at room temperature and draw depth of 40mm is presented in **Fig.8**. When the clamping force is 0 kN, the CFRP is easier to flow into the central region which increase the possibility of prepreg buckling. However, the four-square corners of CFRP have nearly no movement when the clamping force is 2kN. Since the clamping force only applies on the four-square corners of the CFRP layer, the effect on the deformability of the 0°/90° CFRP at four central edge regions is limited as the relative displacement is measured to be almost the same. Therefore, the clamping force at 1kN can be seen as an optimised value for a better deformability.

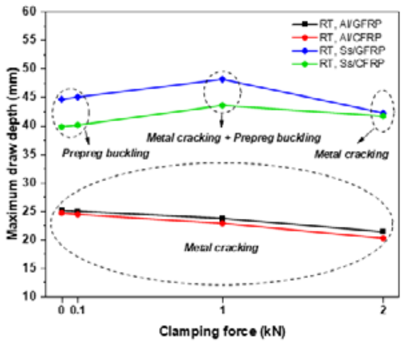

Fig.6: Numerical simulation on maximum draw depths and failure modes at room temperature under different clamping force for metal-composite laminates

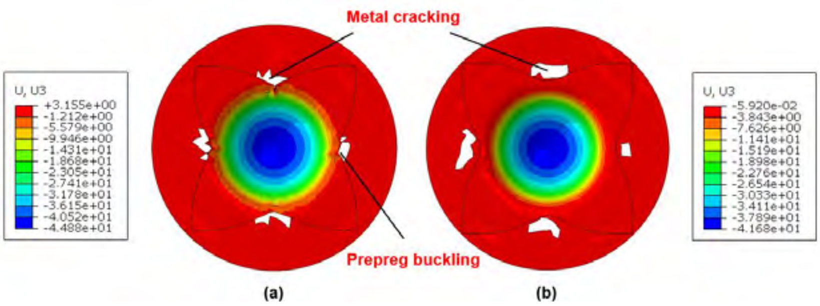

Fig.7: Numerical simulation on vertical displacement (U3) at the maximum value at room temperature for Ss/CFRP laminates under two clamping forces: (a) 1kN; (b) 2kN

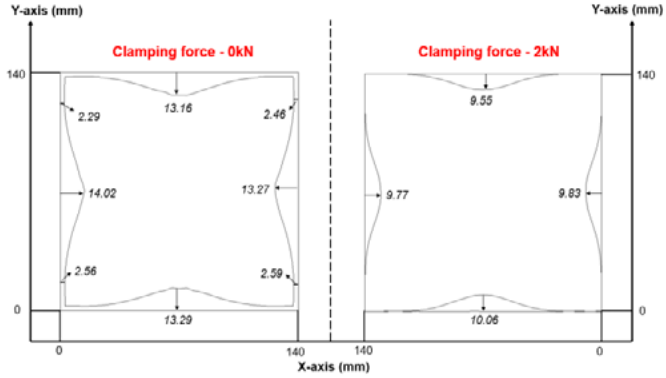

Fig.8: Comparison between two clamping forces against the initial and final prepreg shapes from the numerical simulation for Ss/CFRP laminates (Draw depth=40mm)

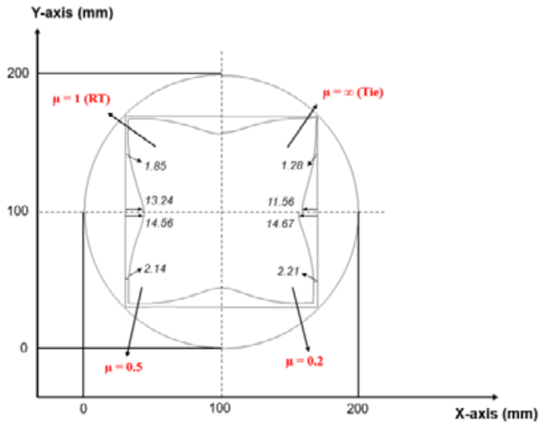

Fig.9: Comparison between inter-ply frictions against the initial and final laminate shapes from the numerical simulation for Ss/CFRP laminates under the clamping force of 1kN (Draw depth=40mm)

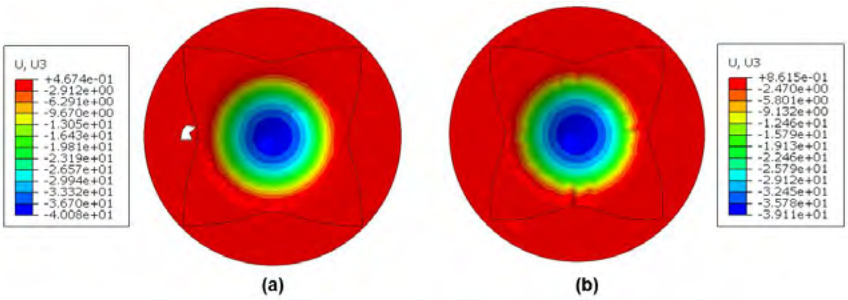

Fig.10: Numerical simulation on vertical displacement (U3,mm) before failure for Ss/CFRP laminates under the clamping force of 1kN and two inter-ply friction coefficients: (a) $\mu = \infty$; (b) $\mu = 0.2$

3.2. Effect of inter-ply friction

The importance of inter-ply friction can be underlined by conducting a “tie” constraint and simulations with different frictional coefficients. **Fig.9** shows the laminate shapes before and after forming at the draw depth of 40mm from the numerical simulation for Ss/CFRP laminates. The effect of friction on the inter-ply sliding is analysed by looking at the position of the edge of the prepreg layer. When the metal-prepreg interface is constrained which denotes a cured laminate, the maximum horizontal displacement for CFRP is 11.56mm and the horizontal gap at the centre location is small. With the decrease of inter-ply friction, the corresponding horizontal displacement and gap increases. This means that higher friction induces a limited sliding which constrain the deformation and delay the buckling of the CFRP material. However, the high friction and low friction condition seems to have distinct influence on the failure mode. **Fig.10** presents the numerical results at the maximum vertical displacement for Ss/CFRP laminates under the clamping force of 1kN. It is seen that the metal-prepreg interfaces with a “tie” constraint witness a higher failure depth with metal cracking, while the failure of prepreg buckling is dominated when the inter-ply friction coefficient is 0.2. Therefore, the result demonstrates that a proper selection of inter-ply friction coefficient may help to increase the uncured laminate formability without the failure of either metal cracking or prepreg buckling.

4. Conclusions

The simultaneous deformation of uncured metal-composite laminates is numerically investigated under different material composition, inter-ply friction and clamping force conditions. The proposed method applies a initial circle and square shape for the metal sheet and uncured fibre prepreg, respectively. The main conclusions are:

(1) The failure mode of the uncured hybrid laminates depends on the type of metal composition. The aluminium-based materials with a lower fracture strain exhibit a lower maximum forming depth with aluminium cracking. While for the stainless steel-based materials, the prepreg buckling dominates the laminate failure with a higher maximum forming depth. In addition, the Ss/GFRP undergoes a higher forming depth than the Ss/CFRP under the same condition, but the effect of fibre reinforced prepreg layer on aluminium-based materials is limited.

(2) The increase of clamping force contributes to the deformation of fibre reinforced prepreg and decrease the risk of prepreg buckling, while the increase of baixial stress as well as the hinder of sliding and material flow tend to induce metal cracking for the stainless steel-based materials. A medium clamping force of 1kN is regarded as a compromise forming parameter since the effect of clamping on metal sheet and fibre prepreg is opposite.

(3) A proper heating of the uncured hybrid laminates under a medium temperature and friction condition increase the laminate deformability without the failure of either metal cracking or prepreg buckling.

Acknowledgments

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

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