PREDICTING WRINKLE FORMATION IN COMPONENTS MANUFACTURED FROM TOUGHENED UD PREPREG

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Abstract
Wrinkles in components made of composite materials are detrimental for the component integrity and need to be avoided. Even though process modelling techniques have considerably improved over the past 20 years or so, predicting the appearance of wrinkles arising from the manufacturing process remains very challenging. The paper proposes a new numerical framework for the prediction of wrinkle formation in composite manufacturing. Two industry relevant cases (i.e. a specimen mimicing gaps and overlaps arising from an automated fibre placement (AFP) process and a stepped laminate) are analysed using this new method. Model predictions for the internal ply geometries are compared to real samples micrographs.This demonstrates the model's ability to predict wrinkles formed during composite manufacturing and gives further validation of a consolidation model for toughened prepreg proposed earlier by the authors.

1. Introduction

In the last 40 years, the use of composites materials in the industry has risen quite dramatically. This is particularly true in the aerospace industry where the amount of composite used in the Airbus flagship plane has risen from just above 10% in weight in the A320 at the end of the 1980's to just above 50% in the A350 XWB nowadays. Composite materials offer a combination of high strength, high stiffness, high toughness and light weight that make them very attractive for an industry where the drive for lighter (more fuel efficient) and safer design is continuous. Components made using the prepreg technology are more costly to produce than their counterpart made from resin infusion of dry fibres. However the former is often favoured by the aerospace industry as it allows producing components of better quality. Nevertheless, components made from the prepreg technology remain quite exposed to the formation of fibre path defects such as wrinkles. These defects can be detrimental for the components' integrity (e.g. through thickness strength reduction greater than 50% have been observed and, in general, the reduction of the tensile and compressive strength can be as great as 30% [1]) and are therefore of great concern for the industry. Wrinkles in composite components can either originate from defects already present in the as received reinforcement/prepreg or be inherent to the design and manufacture of the component (e.g. the component geometry, the stacking sequence, the cure and pressure cycle etc…)[2]. It is the wrinkles arising from this second factor that are the most concerning as they are reproducible and are being formed every single time the said component is manufactured. In the case where such a wrinkle is formed, the entire part has to be scraped or re-worked, adding considerable extra cost to the part. Indeed, 80% of the total cost of a composite component is spent during the part development. Having a numerical tool able to simulate the manufacturing process and able to flag up cases where the part

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geometry and manufacturing conditions will lead to the formation of wrinkles would have the potential to save both time and money, allowing right-first-time design (which not only takes account of the part final mechanical properties but also of the manufacturing constraints).

Predicting residual stresses and global deformation patterns resulting from a composite manufacturing process has reached a certain maturity [3]. In the case of thermoset prepregs, models involved in such an analysis are traditionally based around Darcy's law and make the assumption [4,5] that any point within a piece of prepreg behaves the same as a point situated at the middle of a large flat panel. This is equivalent of neglecting any edge effect. On the other hand, wrinkles in composite processing are often formed in material produced by AFP or in tapered and shape transition regions which are characterised by the existence of gaps and overlaps, shorter plies etc. This suggest that in order to capture wrinkles the state of the art modelling technique for composite manufacturing processes will somehow need to be adapted. In a recent publication [6], Belnoue et al. have proposed a new modelling framework for the consolidation of toughened prepreg under processing condition. Considering the compaction of cruciform shape samples of different sizes and lay-up sequences, Belnoue et al. [6] have been able to formulate and extract a set of material parameters (evolving with temperature) that permitted accurate prediction of the thickness and width evolution with time of laminates subjected to complex pressure and pressure rate cycles. The model was verified and validated for two material systems: IM7/8552 and IMA/M21. Their analytical/phenomenological model was then adapted as a transversely isotropic hyperviscoelastic model that was subsequently implemented within a material subroutine (UMAT) for the commercial finite element (FE) package Abaqus/Standard.

In the present contribution, it is shown how the new flow-compaction model proposed in [6] can be coupled, in the same way as in [7], with cure simulation models. The emphasis is put on two cases that are representative of real manufacturing cases: automated fibre placement (AFP) gaps and overlaps, and stepped laminates. Model predictions for the internal ply geometries are compared to real sample micrographs. This demonstrates the model's ability to predict wrinkles formed during composite manufacturing and gives further validations for the flow compaction model. It is shown here that the model is not only able to predict accurately the wrinkle size and magnitude but also to give a proper description of the way the gaps originally present in the as layed-up components are filled upon consolidation.

2. Modelling strategy

2.1. Consolidation model

The flow-compaction model used here follows directly from Belnoue et al. [6] where more details are given. Only the main model assumptions and equations are summarized. One of the model's main feature is that it is capable to account for both squeezing and bleeding flow. This is important for the modelling of toughned prepeg as they have been shown [8] to exhibit a somehow hybrid behavior between what would be expected from a thermoplastic based prepreg system (e.g. the variation of the material response with the tape width and thickness) and what is usually observed for systems using thermosets (e.g. the existence of a compaction limit).

The model uses the general thermodynamical framework proposed by Limbert and Middleton [9] for transversely isotropic solids. Although the framework was first formulated for the description of soft biological tissues (muscles), it is very relevant for the description of uncured prepreg as both materials are highly viscous and present one strong direction of anisotropy. It is assumed that the general thermodynamic potential, ψ, is additively decomposed into an elastic part (ψ^ewhich is related here to the deformation of fibres) and a viscous part (ψ^v related to the flow of matrix). Noting $\boldsymbol{C}$ the right Cauchy-Green deformation tensor, we can then express the second the Piola-Kirchhoff stress tensor as:

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$$\boldsymbol{S} = \boldsymbol{S}^e + \boldsymbol{S}^v = 2\left(\frac{\partial \psi^e}{\partial \boldsymbol{C}} + \frac{\partial \psi^v}{\partial \dot{\boldsymbol{C}}}\right) \tag{1}$$

where $\dot{\boldsymbol{C}}$ denotes the derivative of $\boldsymbol{C}$ with respect to the time.

The expression of the elastic potential follows from Bonet and Burton [10]

$$\psi^e = \frac{1}{2}\mu_T(I_1 - 3) - \mu_T\, ln(J) + \frac{1}{2}\lambda(J-1)^2 + \left[(\mu_T - \mu_L) + \frac{\alpha}{4} ln(J) + \frac{\beta}{8}(I_4 - 1)\right](I_4 - 1) + \frac{1}{2}(\mu_T - \mu_L)(I_5 - 1) \tag{2}$$

where $\mathbf{1}$ is the second-order unit tensor, $I_1 = \mathbf{1}{:}\boldsymbol{C}$, $I_2 = \frac{1}{2}\left[{I_1}^2 - (\mathbf{1}{:}\boldsymbol{C}^2)\right]$, $I_3 = J^2 = \det(\boldsymbol{C})$, $I_4 = \boldsymbol{N}_0{:}\boldsymbol{C}$ and $I_5 = \boldsymbol{N}_0{:}\boldsymbol{C}^2$. The material parameters α, β, λ, μ_T and μ_L in eqn. (2) can all be expressed as a function of the engineering constants. $\boldsymbol{N}_0$ is the structural tensor which characterizes the local directional properties of the material and is defined as $\boldsymbol{N}_0 = \boldsymbol{n}_0 \otimes \boldsymbol{n}_0$ (where $\boldsymbol{n}_0$ is the fibre orientation).

The expression for ψ^v follows from a phenomenological model proposed in [6] which strongly builds on the work by Rogers [11] and Kelly [12]. Based on experimental results, the existence of a transition mechanism between squeezing (typically at low temperature and low pressure) and bleeding flow is postulated. This transition mechanism is thought to be related to what many authors have described in the past as locking which corresponds to the point in time when the fibre bed reaches a configuration that is such that it cannot deform anymore. It is further assumed that after locking a change of direction of the resin flow between the fibres takes place, from transverse squeezing to bleeding. To ensure a smooth transition between the 2 mechanisms, squeezing flow theories are used in both cases. This means that bleeding is mathematically represented as squeezing along the fibres. Another consequence of this is that, unlike traditional flow models for thermosets prepreg which uses Darcy's flow, the model assumes that the apparent viscosity of a piece of prepreg subjected to pure compressive loading can be multiplicatively decomposed into the product of a strain rate dependent term (assumed to behave as power law fluid) and a strain dependent term. Multiscale theories then allow to further multiplicative decomposition of the later term into a component pertaining to the macro-scale deformation of the tape and a term (at the micro scale) expressing the evolution the inter-fibre channels. All this development finally leads to the formulation of two expressions for ψ^v. Prior to locking, the transverse behavior of the material is controlled by the viscous potential given in eqn. (3). After locking, ψ^v is expressed as in eqn (4).

$$\psi^v = \left(\frac{w_0}{h_0}\right)^2 \frac{\sqrt{\chi_l}}{\chi_f} \frac{4Jke^b}{(a+2)} \left(\frac{1}{{I_1}^s}\right)^{-\frac{3}{2}} \left(\left(\frac{k}{\sqrt{{I_1}^s} - \frac{k}{\sqrt{\chi_f}}}\right)^2 + 3\chi_f\right) \left(\frac{1}{2[(I_1-1)^2 + 2I_3]}\right)^{\frac{a+2}{2}} {J_2}^{\frac{a+2}{2}} \tag{3}$$

where ${I_1}^s = \frac{1}{2}\left((I_1 - 1) - \sqrt{(I_1-1)^2 - 4I_3}\right)$.

$$\psi^v = \left(\frac{l_0 w_0}{d h_0}\right)^2 \frac{\chi_l}{\chi_f} \frac{4Jke^b}{(a+2)} \left(\frac{1}{{I_1}^b}\right) \left(\frac{k}{\sqrt{{I_1}^b} - \frac{k}{\sqrt{\chi_f}}}\right)^2 \left(\frac{1}{2{I_1}^{b^2}}\right)^{\frac{a+2}{2}} {J_2}^{\frac{a+2}{2}} \tag{4}$$

where ${I_1}^b = I_1 - (1 + \chi_l)$.

Most of the terms in eqs (3) and (4) are known *a-priori* as they are linked to the geometry of the tape and of the unit cell. l_0, w_0 and h_0 are the initial tape length (i.e. along the fibre direction), width and

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thickness respectively. Whilst χ_l and χ_f are the aspect ratios of a unit cell at locking and at the compaction limit respectively and d is the size of the fibres in the plane perpendicular to the fibre direction. Therefore, one of the most elegent aspects of the model is that it can describe the transverse behavior of prepreg under processing conditions from the knowledge of the evolution with temperature of 3 parameters only. The parameters *a* and *b* are two power law parameters controlling the behavior of the rate dependent term of the apparent viscosity whilst the parameter *k* controls the size of the inter-fibre channels at the micro-scale. As shown in [6], these parameters can be easily determined by fitting straight lines through experimental data obtained from simple compaction tests perform on cruciform shaped samples.

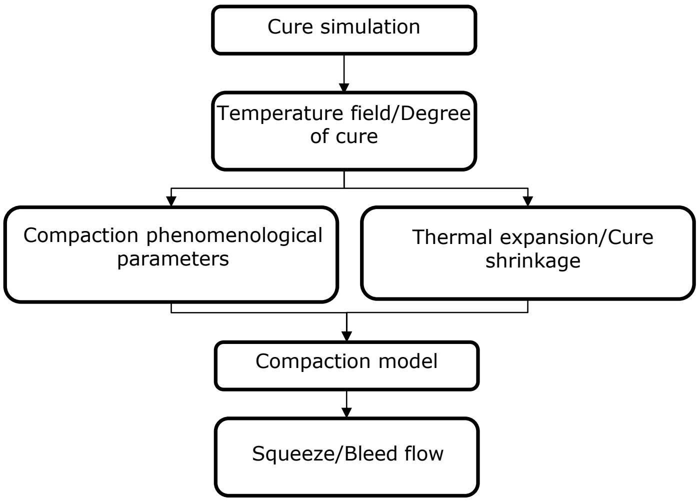

Figure 1: Schematic representation of the thermo-mechanical model.

2.2. Cure simulations

As an advance on the model from [6] summarized in the previous section, it is here coupled to a cure simulation model allowing for the evolution of properties with temperature and degree of cure. Thus accurate analysis of the full manufacturing cycle is possible and the point at which the defects are "frozen" into the final part configuration can be predicted. A coupled three-dimensional transient thermo-mechanical model is developed within the implicit FE package Abaqus/Standard. A staggered solution approach is adopted (see Figure 1). The heat transfer analysis is carried out first, followed by the mechanical analysis [7].

The heat transfer solution appropriate for simulating the cure process can be expressed by a three-dimensional energy balance combined with Fourier's heat conduction law and incorporating the exothermic heat generated due to the chemical reaction of the resin following [13]:

$$\rho c_p \frac{\partial T(r,T)}{\partial t} = \nabla \cdot \boldsymbol{K} \nabla T(\boldsymbol{r},T) + \mathrm{v_r}\, \rho_\mathrm{r} \mathrm{H_T}\, \frac{\mathrm{d}\alpha}{\mathrm{dt}} \quad (5)$$

Here ρ and c_p are the density and the specific heat capacity of the composite, respectively, $\boldsymbol{K}$ is the thermal conductivity tensor, T the temperature, t and $\boldsymbol{r}$ the time and spatial coordinate and α the degree of cure. The rate of heat generation due to cure is expressed as the product of the resin volume fraction v_r, the density of the resin ρ_r, the total heat of reaction H_T and the cure reaction rate $d\alpha/dt$. The heat transfer solution is coded within a UMATHT subroutine for Abaqus/Standard. It yields the evolution of temperature and degree of cure of the laminate. This information is then passed to a UMAT subroutine where the mechanical model of section 2.1 is coded. The coupling between the heat transfer solution and the consolidation model is carried out using the evolution of parameters *a* , *b* and *k* with temperature. The thermal and chemical strains occurring during the process cycle are taken account of considering the thermal exapansion and cure shrinkage coefficients of the material.

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3. Wrinkle formation prediction

Manufacturing induced wrinkling in two industry relevant cases is studied using the multi-scale and multi-physics numerical approach described in section 2. As can be seen from the subsequent Figures 2, 3 and 4, a ply-by-ply approach was adopted. Algorithms were implemented within Matlab® for automatic meshing of the plies and automatic assignment of the material properties based on the plies' dimensions. The model predictions were compared to experimental results. The material system Hexcel IM7/8552 was considered. Out of all the constants needed for the full definition of the elastic potential presented in eqn. (2), only the Young's modulus (E) in the fibres direction was considered and all the other elastic constants were set to zero. E was set up so that the bending rigidity of a ply (which is important for wrinkles) was accurate rather than its behaviour in tension. The value of 100 MPa determined in [14] was used. As fas as the transverse behaviour of the tape was concerned, the parameters determined in [6] were used. The cure kinetics model used here is a combination of a n_{th} order model and an autocatalytic model [15]. The specific heat capacity is defined based on the rule of mixtures whilst a geometry-based model is implemented to compute the thermal conductivity [15,16]. The fibres' specific heat capacity and thermal conductivity present a linear dependence on temperature [16], whilst the resin specific heat capacity and thermal conductivity depend on both temperature and degree of cure [15]. The composite thermal expansion and cure shrinkage coefficients were calculated based on data found on the literature [17].

3.1. AFP gaps and overlaps

3.1.1 Isothermal analysis

Flat panels manufactured by hand lay-up do not wrinkle. The current trend in composite manufacturing however is to use automatic lay-up methods such as AFP which can considerably increase the production rate. AFP machines automatically lay-up a laminate using a number of separate narrow tows (typically 8mm or less) of prepreg materials. Due to the difficulty in achieving precision associated with the placement of these narrow tapes, laminates produced by AFP tend to have gaps and overlaps between the tapes, which act as seeds for potential wrinkle development upon consolidation. Understanding how the internal ply structures develop around this gaps and overlaps upon application of pressure is therefore of great interest for the improvement of the quality of engineering components built by AFP.

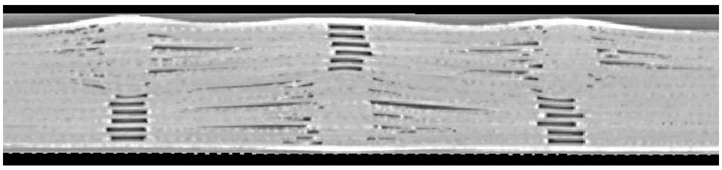

Figure 2: CT scan of a gaps and overlaps cross-ply test specimen prior to consolidation.

In order to provide validation of the model, an experimental program whereby gaps and overlaps (Figure 2) were introduced within *100 mm * 100 mm* flat laminates was set up. Isothermal experiments were carried out (at T=70°C) where the laminates where loaded over 5 min to 1 bar, 3 bar and 7 bar respectively and then these levels of pressure were maintained over 1 hour. The obtained laminates were then fully cured in an oven (without pressure) and micrographs were taken.

The FE models corresponding to the 3 load cases were set-up. Predicted thickness evolutions were compared to those measured during the experiments. Excellent agreement was observed. Similarly good agrement was obtained comparing the the final ply spatial distribution predicted by the model with the samples' micrographs. The model is able to take account of the way the gaps are filled by the flow of adjacent pre-preg material. Two competing mechanisms are observed. Upon compaction, the gaps can either close due to the overlaps falling into the gaps (the wrinkle then becomes steeper) or can be filled

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laterally due to squeezing flow (this prevents the wrinkle angle to increase). Figure 3 illustrates, the variation of “gap filling” with the applied pressure.

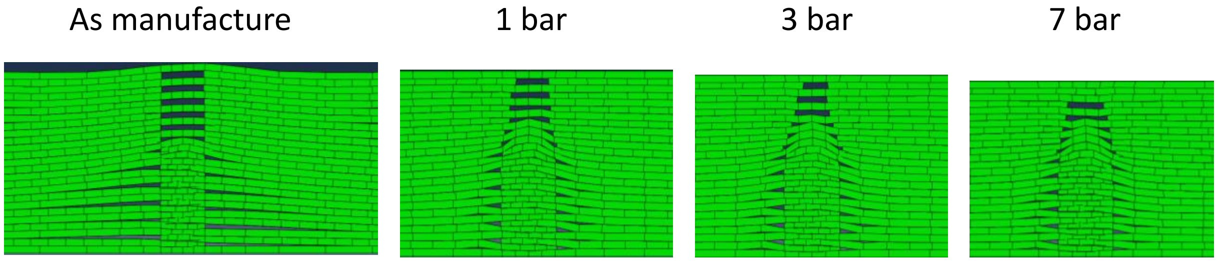

Figure 3: Prediction of the evolution of the ply configuration with the applied pressure.

3.1.2 Full cure evolution

Further experiments where the laminates were subjected to a full cure cycle were also performed. This was simulated using the coupled model. The nominal cure and pressure profile [18] were used. Figure 4a depicts the thickness evolution of the laminate, whilst Figure 4b presents a micrograph and the corresponding simulation result. As it can been observed the coupled model is able to predict the thickness evolution of the laminate during consolidation accurately. In addition, comparison of the simulation results with the micrograph shown in Figure 4b indicates that the model is able to predict wrinkle formation caused by the gaps and overlaps.

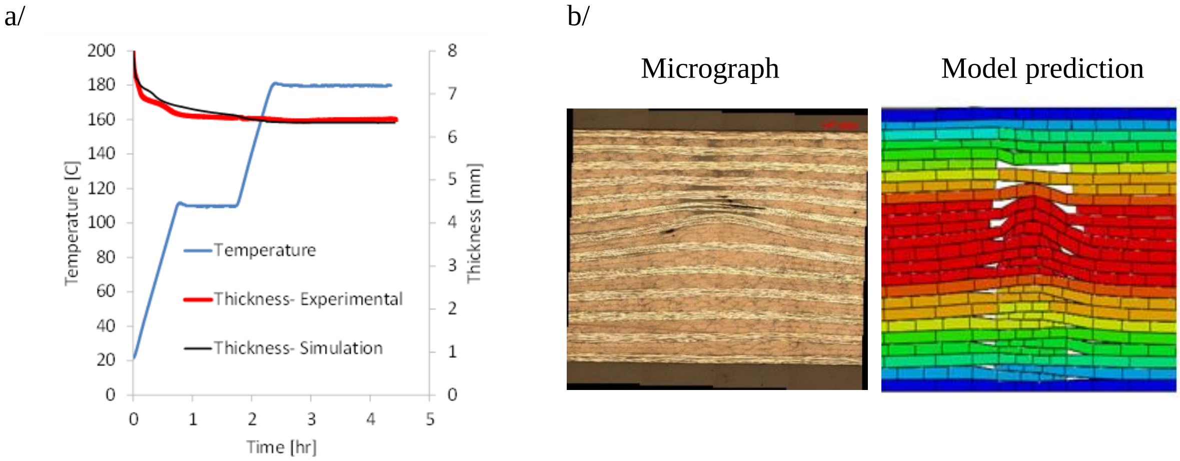

Figure 4: a) Coupled solution, b) gaps and overlaps.

3.2. Stepped laminate

To demonstrate further the model’s ability to accurately predict wrinkle formation, a second industry relevant case was analysed. Wrinkles can be typically formed at the skin-stringer junction of an aircraft design (see Figure 5a). When using soft upper tooling, upon bag bridging at the corner of the stringer, non homogeneous pressure is applied to the component, leading to the creation of a wrinkle. A stepped laminate representative of such case was manufactured. A *6 mm*-thick *100 mm * 100 mm* block with a quasi-isotropic lay-up was placed in the middle of similar block of *200 mm * 200 mm* in plane dimensions. The obtained sample was bagged up and cured within an autoclave. Micrographs of the obtained wrinkle were taken (see Figure 5b).

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An FE model that uses the coupled approach (section 2.2) was set-up. The bag was modelled using membrane elements. In order to model the vaccum bag process, the bag (under a 1 bar pressure) was formed onto the sample. The nominal cure cycle [18] was then applied. As illustrated in Figure 5, good agreement was observed between the model predictions (see Figure 5 c) and the wrinkle micrograph shown in Figure 5 b.

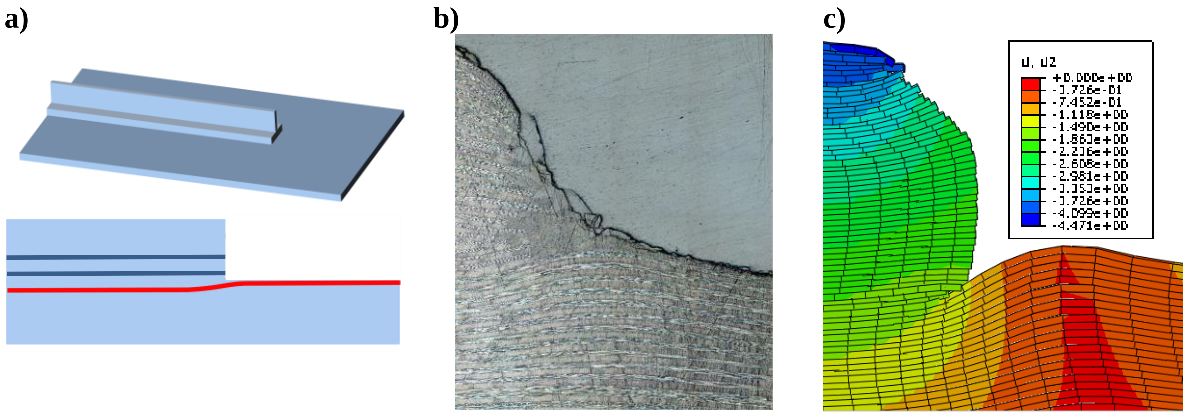

Figure 5: Stepped laminate a) schematic of stringer foot and wrinkle formation mechanism, b)micrograph from experimental sample, c) model prediction of wrinkle formation (the contours indicate the displacement field in the compaction direction)

4. Conclusions

A new multi-scale and multi-physics modelling framework for composite processing was set-up based on a consolidation model proposed by Belnoue et al. [6]. Using a method previously used by Johnston et al. [7], the consolidation model was coupled to a heat transfer model for accurate description of the full cure cycle. Two industry relevant cases, a sample mimicing the gaps and overlaps observed in AFP tape deposition and bag bridging in a stepped laminate, were analysed using this new modelling framework. The model ability to predict wrinkle formation arising from composite processing was highlighted by comparing model prediction to micrographs obtained from real specimens. The model also allows to predict the thickness evolution, temperature overshoot and underconsolidation (i.e. volume fraction). The new numerical framework paves the way towards a fully virtual framework for the prediction of the mechanical properties of engineering components made from composite materials.

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