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TIME HOMOGENIZATION FOR THE MODELING AND SIMULATION OF THE ULTRASONIC WELDING OF THERMOPLASTIC COMPOSITES

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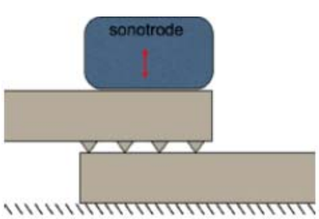
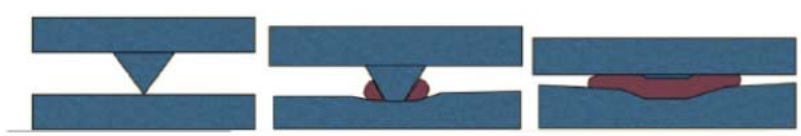
SUMMARY: The process of ultrasonic-welding is widely used in the industry. Nevertheless, its numerical modeling, essential for the aeronautic industry, is quite difficult. Indeed, there are two different time scales in the process, one "long" time which is the welding time and one short time which is the period of the ultrasonic mechanical loading. After explaining how the welding is proceeded, a method of time homogenization is presented in order to write down three different thermal and mechanical systems of equations. It is based on the use of asymptotic expansions which lead, starting from the general thermo-mechanical problem, to three coupled problem which are independent from the fast variable and are therefore suitable for numerical calculations. A numerical tool for solving these equations is finally introduced, based on the level-set method. First results are qualitatively satisfactory and show that physical understanding of the process can be obtained by such an approach.

KEYWORDS: Thermoplastic welding, ultrasound, time homogenization, simulation

INTRODUCTION



(a) Assembly overview.



(b) Melting and flowing of an energy director.

Fig. 1 Principle of ultrasonic welding of two composite plates.

This work aims at modeling an original welding process for composite material with thermoplastic matrix. Triangular “energy directors” are molded with matrix on a width of two centimeters on the border of one of the plates. The two plates are then positioned in order to cover each other on the width of the energy directors and an ultrasonic sinusoidal compression stress (20 KHz) is applied as shown in Fig. 1a and causes melting due to mechanical dissipation [1]. The triangles then flow on the whole interface and perform welding (see Fig. 1b). Such a process is to be improved to be suitable for large scale assemblies. The main difficulty of modeling and simulating such a process comes from the existence of two time scales, which would induce very fine time steps and so huge computation times. This process has been subject for few models. First we can mention Benatar [1] who described the process as the succession of five phenomena physical phenomena. Some authors like Suresh et al. [6] or Wang et al. [7] described the mechanical dissipation in a linear harmonic viscoelastic framework. Nevertheless, their models were limited to the thermal aspects only. We propose here a more general framework, which also enables to take into account the flow of polymer.

PROCESS MODELING

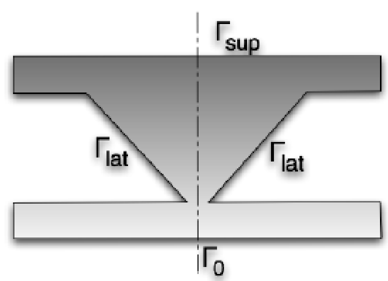


Fig. 2 Geometry of the initial energy director.

We focus on a single energy director as described in Fig. 2. The objective is to obtain a thermo-mechanical formulation able to describe the flow and heating of the polymer due to mechanical loading and internal dissipation caused by vibrations. Due to the high frequency and the rather long time of the process, a visco-elastic model for the polymer seems necessary. As a first approach, a Maxwell model in small displacement is used:

$$\lambda \dot{\underline{\underline{\sigma}}} + \underline{\underline{\sigma}} = 2\eta \dot{\underline{\underline{\varepsilon}}} \tag{1}$$

where λ is the relaxation time, η the viscosity and ε the strain tensor. Neglecting inertia terms and volume forces, the equilibrium equation can be written as:

$$div(\underline{\underline{\sigma}} - p\underline{\underline{I}}) = \underline{0} \tag{2}$$

where σ is the extra stress tensor and p the pressure. Composites plates being assumed perfectly rigid compared to the energy directors, the displacement of the tip of the director is supposed to be null, whereas the displacement of the upper part is split into a fast sinusoidal displacement $a\sin(\omega t)$ and a slow displacement u_d due to the squeezing of the director during the process. The whole mechanical problem can be summarized as follows:

$$\begin{cases} \lambda\,\dot{\underline{\underline{\sigma}}} + \underline{\underline{\sigma}} = 2.\eta\,.\dot{\underline{\underline{\varepsilon}}} \quad on\,\Omega \\ div(\underline{\underline{\sigma}} - p\underline{\underline{I}}) = \underline{0} \quad on\,\Omega \\ div(\underline{u}) = 0 \quad on\,\Omega \end{cases} \quad \text{and} \quad \begin{bmatrix} \underline{u} = \underline{u_d}(t) + \underline{a}\sin(\omega t) & (\Gamma_{sup}) \\ \underline{u} = \underline{0} & (\Gamma_0) \\ (\underline{\underline{\sigma}} - p\underline{\underline{I}}).\underline{n} = 0 & (\Gamma_{lat}) \end{bmatrix} \tag{3}$$

In the thermal problem, a fraction α of the viscous part of the mechanical energy $\underline{\underline{\boldsymbol{\sigma}}} : \dot{\underline{\underline{\boldsymbol{\varepsilon}}}}$ is supposed to be dissipated during the process. Taking the Maxwell constitutive law (1), the thermal problem can be written as:

$$\begin{cases} \rho c\dot{\theta} = k\Delta\theta + \frac{\alpha}{2\eta}\underline{\underline{\sigma}} : \underline{\underline{\sigma}} \\ k.\underline{grad}(\theta).\underline{n} = 0 \; on\,(\Gamma_{lat} \cup \Gamma_0 \cup \Gamma_{sup}) \end{cases} \tag{4}$$

In the homogenization process, the initial problem is transformed into a dimensionless problem, using characteristic orders of magnitude of the process described below:

- Viscosity: $\eta_0 = 10^7$ Pa.s, at temperature $\theta=\theta_g=143$°C
- Length: e=300 µm, initial height of the director.
- Temperature: a temperature θ is transformed into a dimensionless temperature θ^* by $\theta^*=(\theta-\theta_{amb})/\theta_{ref}$, where θ_{amb} is the ambient temperature and $\theta_{ref}=\theta_{melt}-\theta_{amb}$.
- Time: the time λ_0=1s, duration of the process is used as characteristic time.
- Other variables: we also introduce dimensionless stress, displacement and strain:

$$\underline{\underline{\boldsymbol{\sigma}}} = \frac{\eta_0}{\lambda_0}\underline{\underline{\boldsymbol{\sigma}}}^* \qquad \underline{\underline{\boldsymbol{\varepsilon}}} = \underline{\underline{\boldsymbol{\varepsilon}}}^* \qquad \underline{\boldsymbol{u}} = e\underline{\boldsymbol{u}}^* \tag{6}$$

- Operators: dimensionless space operators are introduced

$$grad \equiv \frac{1}{e}grad^*, \quad div \equiv \frac{1}{e}div^* \quad \text{and} \quad \Delta \equiv \frac{1}{e^2}\Delta^* \tag{7}$$

Time Scale - Homogenization Technique

The process being characterized by two different time scales, we now introduce dimensionless times t^* and τ^* such as $t = \lambda_0 t^*$ and $\tau^* = \omega t$. One than can define the time scale factor:

$$\xi = \frac{t^*}{\tau^*} = \frac{1}{\omega\lambda_0} \sim 10^{-5} \tag{8}$$

Taking advantage of this good scales separation, fields of the problem are searched as asymptotic expansion [2]:

$$\phi = \phi_0 + \phi_1\xi + \phi_2\xi^2 + \ldots \tag{9}$$

where functions ϕ_i are functions of the two time variables t^* and τ^* periodic with respect to τ^*. The time derivative of ϕ can therefore be written as:

$$\dot{\phi} = \frac{d\phi}{dt} = \frac{1}{\lambda_0}\frac{\partial\phi}{\partial t^*} + \frac{1}{\lambda_0}\frac{1}{\xi}\frac{\partial\phi}{\partial\tau^*}$$

(10)

After writing the initial problem in terms of dimensionless quantities, the homogenization technique then consists in injecting asymptotic expansions (9) in the equilibrium Eqns. (3) and (4). By identifying each order of power of ξ, several problems are obtained. At the first relevant orders of ξ, we get the three following self-consistent coupled problems:

$$\left\{ \begin{array}{c} \Lambda \frac{\partial \underline{\underline{\sigma_0}}}{\partial \tau} = 2N \frac{\partial \underline{\underline{\varepsilon_0}}}{\partial \tau} = 2N \underline{\underline{D}}(\underline{v_{-1}}) \\ div(\underline{\underline{\sigma_0}} - p_0 \underline{\underline{I}}) = \underline{0} \\ div(\underline{v_{-1}}) = 0 \end{array} \right. \qquad \left[\begin{array}{cc} \underline{v_{-1}} = \underline{R}.sin(\tau) & (\Gamma_{sup}) \\ \underline{v_{-1}} = \underline{0} & (\Gamma_0) \\ \underline{\underline{\sigma_0}}.\underline{n} = 0 & (\Gamma_{lat}) \end{array} \right. \tag{P1}$$

$$\left\{ \begin{array}{c} \Lambda \frac{\partial < \underline{\underline{\sigma_0}} >}{\partial t} + < \underline{\underline{\sigma_0}} > = 2N < \underline{\underline{D_0}} > \\ div(< \underline{\underline{\sigma_0}} > - < p_0 > \underline{\underline{I}}) = \underline{0} \\ div(< \underline{v_0} >) = 0 \end{array} \right. \qquad \left[\begin{array}{cc} < \underline{v_0} > = \underline{v_d}(t) & (\Gamma_{sup}) \\ < \underline{v_0} > = \underline{0} & (\Gamma_0) \\ < \underline{\underline{\sigma_0}} > .\underline{n} = 0 & (\Gamma_{lat}) \end{array} \right. \tag{P2}$$

$$\frac{\partial \theta_0}{\partial t} = A \Delta \theta_0 + \frac{B}{N} < \underline{\underline{\sigma_0}} : \underline{\underline{\sigma_0}} > \tag{P3}$$

In these equations, $\langle \phi(t,\tau) \rangle$ denotes the average of f over one ultrasonic period. $\Lambda = \lambda / \lambda_0$ and $N = \eta / \eta_0$ are respectively the dimensionless relaxation time and viscosity, and thermal parameters A and B are such as:

$$A = k\lambda_0 \big/ \rho c e^2 \quad ; \quad B = \alpha \eta_0 \big/ \rho c \theta_{ref} \lambda_0 \tag{11}$$

- (P1) is a hypo-elastic problem equivalent to an elastic problem in the small displacement framework. It describes a stress fluctuation of order ξ^0 linked to a velocity of order ξ^1 (derivative of $\underline{\boldsymbol{u}}_0$ with respect to τ). The boundary condition on Γ_{sup} is a harmonic condition so that the solution can be searched as a harmonic function. In this idea, a simple elastic resolution, independent of τ, is possible for this micro-chronological mechanical problem.

- (P2) is the macro-chronological mechanical problem which describes the slow mechanical evolution as a visco-elastic Maxwell flow. The stress average is of order ξ^0 as well but is linked to an average velocity of order ξ^0.

- (P3) is the bulk equation for order 0 temperature θ_0 and thus can be called the macro-chronological thermal problem. θ_0 is proved to depend on t only and evolves according to a classical heat equation with an additional source term which is the average mechanical dissipation over one ultrasonic period.

NUMERICAL PROCEDURE

Although the macro-chronological problem should strictly be visco-elastic, it was set as a purely viscous problem. Nevertheless, for a better representativeness of the deformed shape, a strain rate dependent viscosity was used, therefore implying a non-linear flow problem. Moreover, though rigorously valid above the glassy transition the homogenized equations were used over the whole temperature range, but it was checked that the present formulations could be formally extended to the whole process range.

Systems (P1-P3) are solved using a classical Galerkin FEM. For each time step the three systems of equations are solved iteratively until simultaneous convergence of the three variational forms. The resolution is performed on a fixed mesh where the free surface is described by a level-set field. This is done using the X-FEM library. At each time step, once the three physical problems are solved, the level-set is propagated using a Hamilton-Jacobi method [5]. Then the temperature field is convected using a SUPG technique.

Material parameters used in the simulations were adapted from the literature [3, 4]. For the micro-chronological problem, a linear approximation was set for the elasticity modulus *E*:

$$E = 3.7e9 - 1e7 \times T(°C) \;\; Pa \qquad (28)$$

In the macro-chronological mechanical problem, a Carreau law for the viscosity was chosen, with an Arrhenius type temperature dependency:

$$\eta = \eta_0(T)\left(1 + \left(\lambda_{carreau} D_{eq}\right)^a\right)^{\frac{m-1}{a}} \quad \text{with} \quad \eta_0(T) = A\exp\left(\frac{E_a}{RT}\right) \qquad (29)$$

where $a = 0.7$, $m = 0.54$, $E_a = 74400$ and $A = 5.6e^{-3}$. For the thermal problem, we adopt a simple linear form for ρc and k:

$$\rho c = 1.31 + 5103 \times T(°C) \; J.m^{-3}.K^{-1} \quad ; \quad k = 0.24\,W.m^{-1}.K^{-1} \qquad (212)$$

RESULTS AND DISCUSSION

Fig. 3 shows the evolution of the level set negative part, which is the material domain. We clearly observe a flow of polymer that begins at the tip of the director. As the loading is pursued the flowing zone increases and fills the gap between the two plates. This is in agreement with the deformed shape of the micrography of Fig. 4, made on a sample obtained with a stopped experiment. It would correspond to the simulated shape at time $t = 1.10$ s. Next step would be to obtain better controlled interrupted experiments. This shape is clearly associated to the temperature field, and is consistent with results of literature [1, 7].

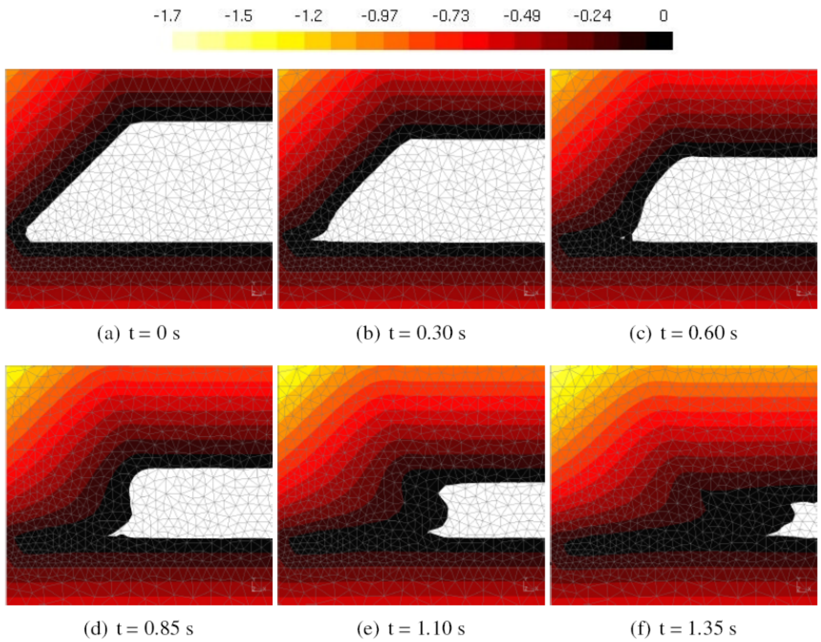


Fig. 3 Evolution of the level-set, negative part only.

Despite those good first results, at this stage of developments, the maximal temperature only reaches 0.4 T_{melt}, which is low regarding the expected welding at T_{melt} in the real process. This shows the need for finer instrumented experiments and material parameter identification which are the subject of ongoing works.

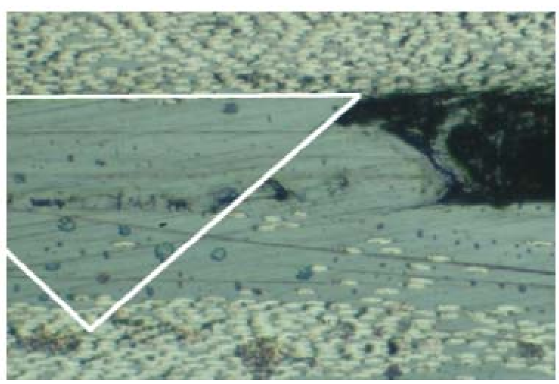


Fig. 4 Micrography of a stopped experiment.

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