Ultrasonic Welding of Thermoplastic Composites, Modeling of the Process.

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ABSTRACT: The process of ultrasonic welding is widely used in the industry. Nevertheless, its numerical modelling, essential for the aeronautic industry, is quite difficult because of the two time scales present in the process. After explaining principle of the welding, a method of time homogenization is presented in order to write down three different thermal and mechanical systems of equations. Since one of those problems implies moving free surface, a numerical tool using the level-set method was used to solve them.

Key words: Polymer, Welding, Time-homogenization, Visco-elasticity, Numerical simulation, Level-set.

1 INTRODUCTION

This work aims at modeling an original welding process for composite material with thermoplastic matrix. Triangular bulges, called “energy directors” are molded with matrix only, on a width of two centimeters on the border of one of the plate to be welded. The two plates are then positioned in order to cover each other on the width of the energy directors. The process then consists in applying an ultrasonic (20 KHz) sinusoidal compression stress between the two plates as shown in figure 1.

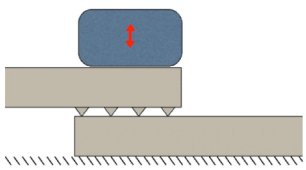

Figure 1 : Ultrasonic welding of two plates

The strain concentrates at the interface, in the energy directors, that melt because of the viscous dissipation [1]. The triangles then progressively flow on the whole interface and perform welding of the two composite planes (see figure 2). Even if no fiber crosses the interface, the cover is wide enough to transmit the stress which allows the process to be used for large scale assemble.

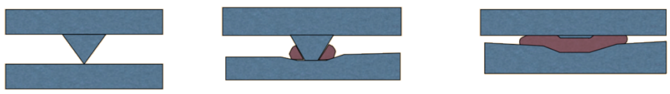

Figure 2 : Melting and flowing of an energy director.

The main problem for modelling such a process comes from the existence of two time scales. Indeed, simulating each ultrasonic cycle would induce huge calculation times since the whole process is performed over thousands of cycles. Such a drawback can be overcome by the time-homogenization technique.

2 MODELING OF THE PROCESS

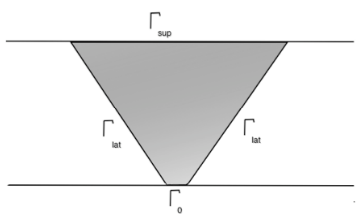

Figure 3 : Geometry of the initial energy director.

2.1 *Mechanical problem*

Let us consider a single energy director as described in figure 3. The mechanical problem is written down using a Maxwell visco-elastic law:

$$\lambda \dot{\underline{\underline{\sigma}}} + \underline{\underline{\sigma}} = 2\eta \underline{\underline{D}} \quad (1)$$

where λ is the relaxation time, σ is the extra stress tensor, η the viscosity and D the strain rate tensor.

The composites plates are supposed to be perfectly rigid compared to the energy director. The displacement of the tip of the director is then supposed to be zero, whereas the displacement of the upper part can be decomposed into a "micro-chronological" sinusoidal displacement α.cos(ωt) due to the short period of the ultrasound (around 50 micro-seconds), and a "macro-chronological" displacement u_d due to the squeezing of the director during the process (around one second).

The whole mechanical problem can finally be written as follow:

$$\begin{cases} div(\underline{\underline{\sigma}} - p\underline{\underline{I}}) = \underline{0} & (2) \\ \lambda \dot{\underline{\underline{\sigma}}} + \underline{\underline{\sigma}} = 2.\eta.\underline{\underline{D}};\ div(\underline{v}) = 0 \\ \left[\begin{array}{ll} \underline{v} = \underline{v}_d(t) + \underline{a}\sin(\omega t) & (\Gamma_{\sup}) \\ \underline{v} = \underline{0} & (\Gamma_0) \\ (\underline{\underline{\sigma}} - p\underline{\underline{I}}).\underline{n} = 0 & (\Gamma_{lat}) \end{array} \right. \end{cases}$$

2.2 Homogenization.

First, dimensionless time scales t^* and τ^* are introduced such as $t=\lambda_0 t^*$ and $\tau^*=\omega t$, where $\lambda_0=1s$ is the characteristic time of the process. t^* being the large time variable and τ^* the short time variable traducing the fast variations. Then, one can define the scale factor ξ :

$$\xi = \frac{t^*}{\tau^*} = \frac{1}{\omega \lambda_0} \approx 10^{-6} \quad (4)$$

The two time sales are well separated. This will reasonably allow us to use a technique of homogenisation in time to model the process [2].

To proceed, each variable Φ of the problem is written as a function of t^* and τ^*.The time derivative of Φ can then be written as :

$$\dot{\Phi} = \frac{d\Phi}{dt} = \frac{1}{\lambda_0}\frac{\partial \Phi}{\partial t^*} + \frac{1}{\lambda_0}\frac{1}{\xi}\frac{\partial \Phi}{\partial \tau^*} \quad (5)$$

Dimensionless equations corresponding to the system (2) can be deduces. The constitutive equation and the boundary condition on Γ_{sup} become:

$$\begin{cases} \lambda^* \dfrac{\partial \underline{\underline{\sigma}}^*}{\partial t^*} + \lambda^* \dfrac{1}{\xi}\dfrac{\partial \underline{\underline{\sigma}}^*}{\partial \tau^*} + \underline{\underline{\sigma}}^* = 2.\eta^* \underline{\underline{D}}^* \\ \underline{v}^* = \underline{v}_d^*(t^*) + \underline{R}\xi^{-1}\sin(\tau^*) \quad (\Gamma_{\sup}) \end{cases} \quad (6)$$

where all the stared quantities are dimensionless and quantity R is of order 0 in ξ.

Asymptotic expansion in time [3] consists in writing each unknown as an expansion in power of ξ starting from power -1 because of the velocity condition (6).

$$\Phi^* = \Phi^*_{-1}\xi^{-1} + \Phi^*_0 + \Phi^*_1\xi + \Phi^*_2\xi^2 ... \quad (7)$$

where each Φ_i are periodic in τ.

Using identification of first orders of ξ and averaging over a period, we can extract from the original thermo-mechanical problem two coupled systems of equations.

2.3 The two mechanical problems to solve

The first system of equations is the micro-chronological mechanical problem, which is an hypo-elastic problem in the director. The velocity condition of which is sinusoidal and comes from the -1 order:

$$\begin{cases} \lambda^* \frac{\partial \underline{\underline{\sigma}}_0^*}{\partial \tau^*} = 2\eta^* \underline{\underline{D}}_{-1}^* & (8) \\ div^*(\underline{\underline{\sigma}}_0^* - p_0^*\underline{\underline{I}}) = \underline{0};\ div(\underline{v}_{-1}^*) = 0 \\ \left[\begin{array}{ll} \underline{v}_{-1}^* = \underline{R}.\sin(\tau^*) & (\Gamma_{\sup}) \\ \underline{v}_{-1}^* = \underline{0} & (\Gamma_0) \\ (\underline{\underline{\sigma}}_0^* - p_0^*\underline{\underline{I}}).\underline{n} = 0 & (\Gamma_{lat}) \end{array} \right. \end{cases}$$

The second is called macro-chronological problem. It consists in a visco-elastic flow. Its solution will give the geometry changes needed for solving the other system of equations.

$$\begin{cases} \lambda^* \frac{\partial <\underline{\underline{\sigma}}_0^*>}{\partial t^*} + <\underline{\underline{\sigma}}_0^*> = 2\eta^* <\underline{\underline{D}}_0^*> & (9) \\ div^*(<\underline{\underline{\sigma}}_0^*> + <p_0^*>\underline{\underline{I}}) = \underline{0};\ div(<\underline{v}_{-0}>) = 0 \\ \left[\begin{array}{ll} <\underline{v}_0^*> = \underline{v}_d^*(t^*) & (\Gamma_{\sup}) \\ <\underline{v}_0^*> = \underline{0} & (\Gamma_0) \\ (<\underline{\underline{\sigma}}_0^*> + <p_0^*>\underline{\underline{I}}).\underline{n} = 0 & (\Gamma_{lat}) \end{array} \right. \end{cases}$$

In this equations <.> denotes the time average over an ultrasonic period.

2.4 *Thermal Analysis*

For the sake of simplicity, thermal analysis was not accounted for. Nevertheless, one has to do it simultaneously since the material parameters at each point depend on the temperature field θ. Starting from the initial thermal problem where the dissipation energy is introduced as a source term:

$$\begin{cases} \rho c(\dot{\theta} + \underline{grad}\theta.\underline{v}) = k\Delta\theta + \frac{1}{2\eta}\underline{\underline{\sigma}} : \underline{\underline{\sigma}} \\ \begin{cases} k.\underline{grad}(\theta).\underline{n} = 0 & (\Gamma_{lat}) \\ k.\underline{grad}(\theta).\underline{n} = h.(\theta - \theta_{\inf}) & (\Gamma_0 \cup \Gamma_{\sup}) \end{cases} \end{cases} \qquad (10)$$

and applying the same analysis, we can extract the dominating first order system:

$$\begin{cases} \frac{\partial\theta_1^*}{\partial t^*} + \underline{grad}\theta_1^*.\underline{v} = A.\Delta^*\theta_1^* + B < \underline{\underline{\sigma_0^*}} : \underline{\underline{\sigma_0^*}} > \\ \begin{cases} \underline{grad}^*(\theta_1^*).\underline{n} = 0 & (\Gamma_{lat}) \\ \underline{grad}^*(\theta_1^*).\underline{n} = Q < \theta_0^* > & (\Gamma_0 \cup \Gamma_{\sup}) \end{cases} \end{cases} \qquad (11)$$

The source term turns out to be given by the micro-chronological problem only. Values of A, B and Q can be calculated from thermal parameters and be found of order 0 in ξ.

3 NUMERICAL PROCEDURE

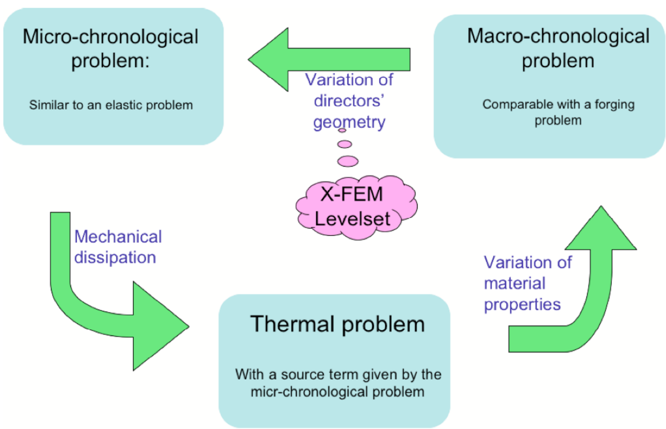

Figure 4 : Solving scheme.

For each time step the three systems of equation (9), (10) and (11) are solved successively. Since coupling between the three systems is rather weak, the three problems are solved iteratively until the residual of the three variational forms are simultaneously smaller than a prescribed tolerance. To solve each problem (which can be non-linear) a Newton-Raphson method was used. The global procedure is explicit in time, but the thermal problem is solved by an implicit backward euler formulation.

3.1 *Interpolation*

The elastic problem was solved in term of displacement, with a second order interpolation. A second order was also set for the temperature. The flow problem was solved by a mixed formulation in velocity and pressure, with a conventional P2/P1 approximation.

3.2 *Management of the free surface*

Since moving of free surface occurs in the macro-chronological problem. A level-set method was used in an eulerian framework. This was performed using the C++ library X-Fem developed in the laboratory. The global evolution of the domain is then managed by the calculation of the level-set. It is updated at each time step using the solution of the macro-chronological problem.

3.3 *Meshing*

The mesh is made of regular triangles over the whole domain, which is reduced to a half energy director, a part of the lower plate and the void between directors. It is shown in figure 5.

3.4 *Material Data*

The material parameter used in the simulation were adapted from values given by [4, 5]. They are given in table 1.
For the elastic micro-chronological system, the material was assumed to be isotropic. In a first approximation the Young modulus was set as an affine function of temperature. The Poisson ratio was set to 0.49 in order to approach incompressibility of equation (9).
Although the macro-chronological problem should be visco-elastic, it was reduced to a viscous problem. Indeed, the macroscopic time of the process is rather long compared to the characteristic Maxwell time of the visco-elastic law. A power law given by equation (13) was used to model the viscosity.

$$\eta = \eta_0 . D_{eq}^{n-1} \quad (12)$$

where D_{eq} is the equivalent strain rate and η_0 is the Newtonian viscosity which is temperature dependant. In a first approximation, it is set as an affine function of temperature. Further on, it may be implemented as an Arrhenius law.
The conductivity and heat capacity were also supposed to be linear functions of the temperature.

Table1. material data

Elastic	
Young Modulus	$E=3.5e9-1e7(T-T_{ref})$ Pa
Poisson Ratio	$\nu=0.49$
Flow	
Newtonian viscosity	$\eta_0=4e7-3.5e5(T-T_{ref})$ Pa/s
Power index	n=0.54
Thermal	
Reference temperature	$T_{ref}=50°C$
Capacity	$\rho C=1.6e6+2200(T-T_{ref})W/K.m^3$
Conductivity	$k=0.25\ W/m^2K$

4 FIRST RESULTS

Even though the convection of the temperature field (that will be handled using operator splitting methods) and the propagation of the levelset is not implemented yet, first results can be presented.

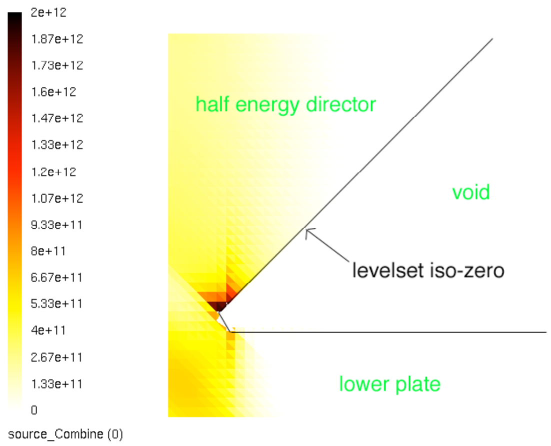

Figure 5 : Source term calculated from the elastic problem for the first time step.

The three coupled systems of equation were resolved and gave similar results to the literature [6]. Namely that the hotter zone is located near the tip of the energy director as shown in figure 6. This is in agreement with the source term repartition of figure 5. Moreover, the fast temperature rising at the tip of the director shows that it is efficient for concentrating energy.

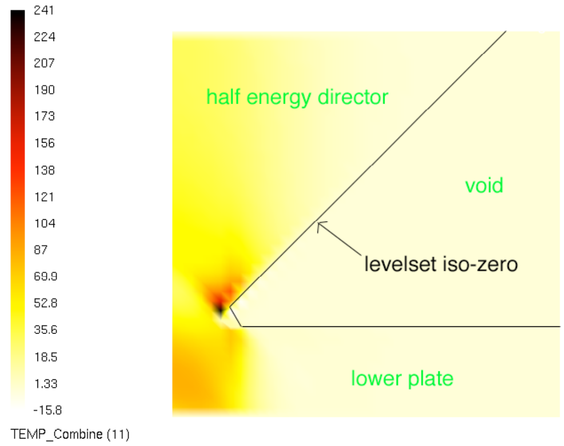

Figure 6 : Temperature field calculated at time 2.3 ms which is equivalent to the 12th time step.

5 CONCLUSIONS

A new method was developed to handle multiple time scales. The three resulting problems were solved using original numerical tools. First results are in agreement with literature and further development should allow geometry changes. Taking into account finite deformations may be an improvement of our modelling.

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