

Thermo Mechanical Behavior of Heat Exchangers

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Abstract: Nowadays, to go along with sustainable development and for cost matters, heat exchangers are built with less and less aluminum and the process costs are being cut. In the industry, they are currently designed to resist to the highest stresses they see in the most harmful life cycle. The aim here is to propose a fatigue criterion for brazed heat exchangers.

A finite element model was built under COMSOL Multiphysics to describe the behavior of the aluminum tubes. A time dependent simulation was conducted using a thermal loading gathered from the filming of a heat exchanger, under realistic conditions, with an Infra Red (IR) camera. The mechanical behavior law takes into account the plastic hardening.

The originality of our study is the use of an external thermal field entered in our model, which avoids us doing a thermal simulation, but also the implementation of a new elasto-plastic law with cyclic hardening and a fatigue criterion in COMSOL Multiphysics.

Keywords: Heat exchanger, Aluminum, Elasto-plasticity, Chaboche, Fatigue

1. Introduction

Today heat exchangers are designed under the most critical conditions. Because of the high complex geometry of the heat exchanger, mechanical designers use large thermal loading patterns applied on the whole heat exchanger to simulate the fluid flow in the tubes. Using constant thermal maps applied to the mesh and an elastic behavior law, the design is based on a VonMises post processing criterion to detect plastic strain areas.

Here we will be using a realistic tube model, submitted to the real thermal field. The model is an elasto-plastic Chaboche [1] type model, from which it will be possible to calculate an energy fatigue criterion.

The usual place where the first crack appears is at the inlet, where the hot fluid enters the heat exchanger (fig. 1). It is more precisely on the

extremity of the tube located at the inlet of the heat exchanger.

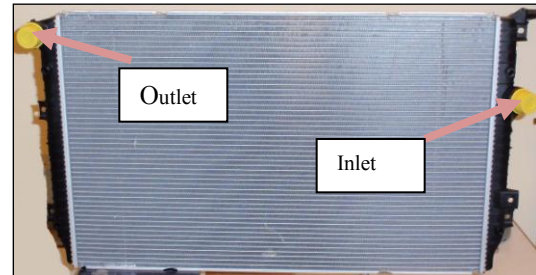


Figure 1. Automotive linear heat exchanger.

2. Thermal history of heat exchangers

We have used an IR (InfraRed) Camera to film and obtain the real thermal conditions for the heat exchanger. We have filmed a heat exchanger on a thermal bench, where we have reproduced realistic loadings and boundary conditions.

The emissivity was adjusted by setting the minimum and maximum temperature on the camera as equal to known temperatures given by a temperature probe.

Once the emissivity set, we were able to export the temperature function of time from any spot on the film (Fig. 2), and import it in COMSOL as a function.

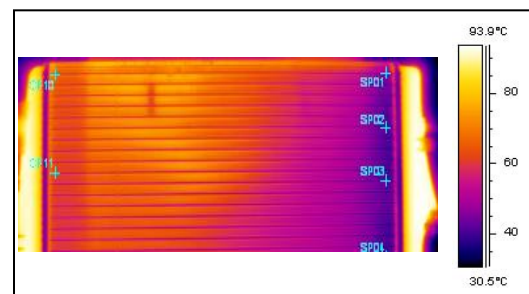


Figure 2. Thermal flow in a heat exchanger.

Figure 3 shows the thermal history at the inlet. This evolution is periodic and has constant temperature parts, which correspond to a constant thermal loading. As the global

temperature is low we can neglect viscosity, and then for constant temperatures there is no evolution of plasticity and stress fields. So we can shorten the constant parts of the thermal history.

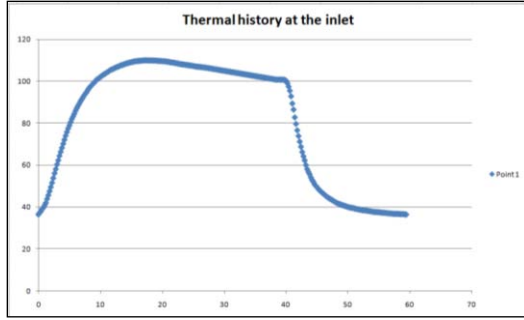


Figure 3. Shorter thermal history at the inlet (Temperature in C° vs Time in s).

Taking this history as a function we avoid a preliminary thermal calculation; although we have a more realistic thermal field it reduces the calculation time enormously.

3. Aluminum behavior law

In this study we have implemented in COMSOL Multiphysics a Chaboche type behavior law, which combines both isotropic and non linear kinematic hardening. This new COMSOL behavior law meets the material's real behavior best. Indeed figure 4 shows that by combining isotropic and kinematic hardening one can approach better the experimental response during cyclic test.

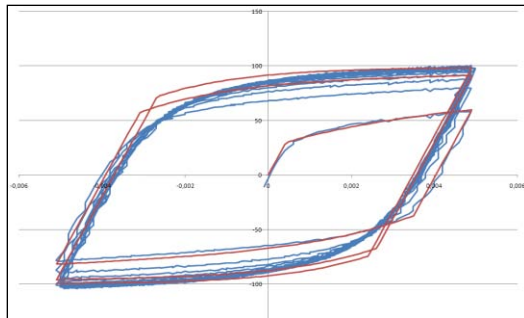


Figure 4. Aluminum 3916 tensile test and numerical elasto-plastic model.

To implement such a behavior law in COMSOL, we used the mechanical module to

solve the usual elasticity problem with its boundary conditions, combined to a PDE module.

Following are the equations describing our model.

$$\sigma = \left(K - \frac{2}{3}G \right) Tr(\varepsilon - \varepsilon_p) \mathbf{1} + 2G(\varepsilon - \varepsilon_p) \quad (1)$$

$$f = J_2(\sigma - X) - R - \sigma_y \quad (2)$$

$$R = Q(1 - e^{-bp}) \quad (3)$$

$$\dot{X} = \frac{2}{3}C\dot{\varepsilon}_p - \gamma X\dot{p} \quad (4)$$

$$\dot{p} = \frac{1}{h}H(f) \left\langle \frac{3(\sigma' - X') : \dot{\sigma}}{2J_2(\sigma - X)} \right\rangle \quad (5)$$

$$h = C - \frac{3}{2}\gamma \frac{(\sigma' - X') : X}{J_2(\sigma - X)} + b(Q - R) \quad (6)$$

$$\dot{\varepsilon}_p = \frac{3}{2}\dot{p} \frac{\sigma' - X'}{J_2(\sigma - X)} \quad (7)$$

$K, G, \sigma_y, Q, b, C,$ and γ are constants depending only on the used material, described in table 1. $H(f)$ is the Heaviside function: $H(f)=0$ if $f<0$, and $H(f)=1$ if $f \geq 0$. $\langle a \rangle$ corresponds to the positive part of a .

X' and σ' are the deviators of respectively X and σ . And J_2 is the second invariant of the stress deviator.

The calculated plastic strain subtracted from the total strain in the behavior law (1) is implemented by modifying the elastic usual behavior law in COMSOL.

The equation (2) represents the yield surface.

The equation (3) calculates the isotropic hardening variable R .

The equation (4) is the PDE governing the kinematic hardening tensor X .

Equations (5) and (6) describe the evolution of the accumulated plastic strain variable p .

And equation (7) describes the evolution of the plastic strain ε_p .

In addition to these two modules, we use the options constants to define our material and the global expressions to solve the equations that are not PDEs.

5. Application to the design of heat exchangers

5.1 Mechanical response

The model considers the joint between a tube and the collector. As shown in figure 5, only a quarter of the structure is modeled, because of the symmetry of the problem.

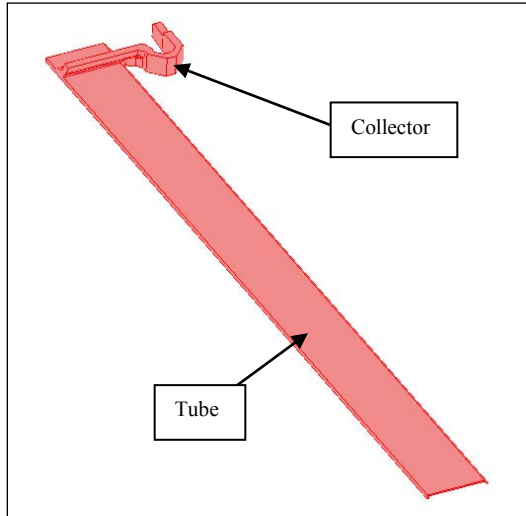


Figure 5. Our model corresponding to a eighth of a tube with its clamping in the collector.

The boundary conditions represent the symmetry conditions, and in addition there is a clamping of the collector, which is realistic seen the difference in thickness between the collector and the tubes.

The thermal loading is applied on the model as a function of time and space, to simulate the heat wave propagation through the tube.

The elasto-plastic calculation takes approximately an hour per cycle for 16000 DOFs, using a 2.5GHz speed processor and 2Go of RAM.

We obtain a coherent stress map and plastic variable.

Figure 6 shows that two critical points appear at the binding between the tube and the collector. The high stresses at the top of the collector are due to the fixed boundary condition.

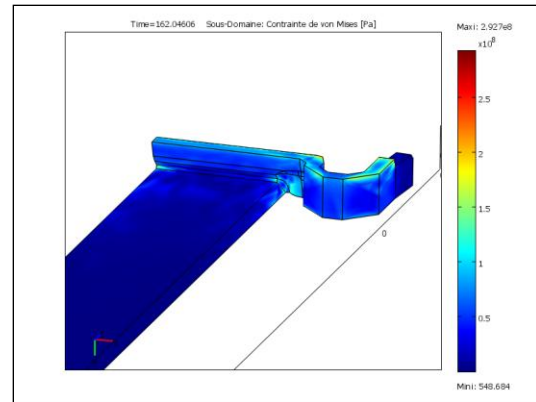


Figure 6. VonMises stress field at high temperature time.

The localization of the critical point of the tube is enhanced using the accumulated plastic strain post processing shown in figure 7.

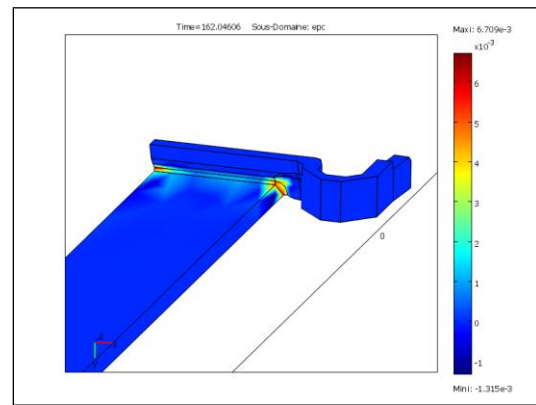


Figure 7. Accumulated plastic strain at final time of third cycle.

5.2 Fatigue post processing

An energy based fatigue criterion can be used to detect the critical part of the heat exchanger.

We need to define an extra global expression to calculate the energy, which is defined per cycle as in equation (8).

$$Wp = \int \sigma : \varepsilon_p dt \quad (8)$$

In figure 8 we have plotted $\sigma : \varepsilon_p$, then we only need to integrate that value over time, to evaluate the energy dissipated at every cycle. We can also notice that the energy per cycle is increasing.



Figure 8. Work over time at the most critical point.

6. Conclusions

Our elasto-plastic Chaboche type model is programmed in COMSOL Multiphysics to describe the thermomechanical behavior of aluminum alloys that is used in the studied heat exchangers and will now permit us to design in fatigue the heat exchanger. Although the computational times are bigger than for the elastic models used in industry, we can detect the critical zone of the exchanger with an enhanced design method.

7. References

1. Lemaitre and Chaboche, *Mécanique des Matériaux solides*. Dunod (2009).
2. Comportement élasto-plastique de Chaboche, Aster code
3. Amiable, *Comparaison de modélisations numériques appliquées à une expérience de fatigue sous choc thermique*

8. Appendix

Table 1: Parameters of Aluminum 3916 used in the elasto-plastic model

Constant	Value	Unit
E Elasticity module	69000	MPa
ν	0.33	
K	67500	MPa

G	20780	MPa
σ_y	70	MPa
Q	59	MPa
b	93.6	
C	11000	MPa
γ	600	