Thermo-chemical and mechanical coupled analysis of swelling charring and ablative materials for re-entry application
OUTLINE

- Astrium
- Norcoat Liege
- Phenomena overview
  - Aerothermodynamics
  - Conductive heat transfer
  - Pyrolysis
  - Ablation
  - Swelling
- Experimental validation
- Numerical simulation
- Conclusions & perspectives
Astrium: part of EADS, a global leader in aerospace and defence

Astrium Space Transportation

The European prime contractor for civil and military space transportation and manned space activities

RE-ENTRY SYSTEM & TECHNOLOGY DEPARTMENT

Thermal protection systems for interplanetary probes

ISS servicing

Interplanetary exploration

All the space you need
A material: **Norcoat Liege**

**Harvest of cork bark**

From tree "*Quercus suber" to space

**Stockpiling**

**drying of bark**

**Grinding**

in granules

**Mixing-Curing**

**NL sheets**

**Back cover of ARD**

**Beagle2 Heat-shield**

**NL molding**

**Phenolic Resin**

**Additives**
PHENOMENA OVERVIEW & MODEL

Close up view on a side cut of the heat shield
PHENOMENA OVERVIEW & MODEL

Free stream flow

Boundary layer

Thermal protection material

Aero-shell

Astrium
Norcoat Liege
Phenomena overview and model:
Side view
Experimental validation
Numerical simulation
Conclusion
Computation of the viscous boundary layer heat transfer:
- convective heat flux
- shock radiation
- wall shear stress
- equilibrium and non equilibrium air chemistry
**PHENOMENA OVERVIEW & MODEL**

- Computation of the conductive heat transfer in the material:
  - standard Fourier's law
  - material state (density) default linear dependency

\[
\lambda = \lambda_v - \alpha [\lambda_v - \lambda_c]
\]

\[
\alpha = \frac{\rho_v - \rho}{\rho_v - \rho_c}
\]
Under heating, organic material compounds start to degrade:
- kinetics of the pyrolysis approached by multiple Arrhenius law
  \[ \dot{\chi}_i = A_i (\rho_v)^{N_i} \left[ \rho_v - \rho_c \right]^{N_i-1} (1 - \chi_i)^{N_i} \ e^{-E_i/RT} \]
- momentum conservation of the gaseous products follows Darcy's law for porous media (and perfect gas law)

\[ \dot{\rho}(t) = \sum_{i=1,Narrh} \Delta \rho_i \chi_i / \rho_v \]

\[ \vec{m}^g = -K \rho \nabla P \]
PHENOMENA OVERVIEW & MODEL

- Enthalpy of pyrolysis gas supposed at thermal and chemical equilibrium with charred material

\[ \Delta H_{\text{pyro}}(T, P) = H_{\text{gaz}}(T, P) - \bar{H}_{NL}(T) \]

Using quasi-steady state assumption for pyrolysis gas advective heat term

\[ \left| \frac{\partial}{\partial t} \rho^g H_{\text{gaz}}(T, P) \right| \ll \left| \nabla \left( \vec{m}^g H_{\text{gaz}}(T, P) \right) \right| \]
PHENOMENA OVERVIEW & MODEL

- Surface material is removed by:
  - heterogeneous chemical reactions (oxydation with temperature dependent rate)
  \[ \dot{m}_c = f_c(T_w) \]
  - Heat of ablation taken into account
  \[ \Delta H_c = \Delta H_c(T_w) \]
  - mechanical spalation under shear stress
  \[ \dot{m}_m = f_m(T_w, \tau_w) \]

Astrium
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Phenomena overview and model:
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Volume expansion generated by:

- in-depth structural and chemical decomposition initiated by heat transfer
- internal pyrolysis gas product pressure in cork cell

Prismatic cork cells membranes are made of 2 main molecules:

- Suberin
- Lignin

responsible for flexibility and rigidity

Temperature increase triggers mass exchange between the 2 structural molecules

⇒ cells wall become more brittle
At higher temperature:
- Cell membrane thickness becomes thinner (mass loss)
- Membranes start to stretch
- Membranes break-off

Considering:
- Volume phenomenon
- Thermo-chemically decomposition linked mechanical expansion
- Non-elastic expansion
- Choice of an Arrhenius kind law for the strain rate evolution:

\[
\begin{align*}
\partial_t \varepsilon_s & \propto (\rho_v)^{1-N_s} [\rho_v - \rho_c]^{N_s-1} (1 - \chi_s)^{N_s} e^{-E_s/RT} \\
\end{align*}
\]
PHENOMENA OVERVIEW & MODEL

- Swelling numerically treated by a staggered coupling scheme involving:
  - *Amaryllis* for the thermal and ablative response
  - *Mecano* for the mechanical response
  - Supervisor as the interface and the synchronisation of the chore modules

- Need to implement A.L.E (arbitrary Lagrangian Eulerian) solution in *Mecano* to take into account for the mesh deformation (due to ablation) sent by *Amaryllis*

- $T, \rho, \chi_i, P, X$ exchange at every time step and are used to solve for the stress and strain

\[
\begin{align*}
\tau_{ij,j} + f_i &= 0 \\
\frac{\partial P}{\partial x_i} &= \tau_{ij} = C_{ijkl}(T, \rho)\varepsilon_{kl} \\
\varepsilon_{ij} &= \varepsilon_{ij}^{\text{tot}} - \alpha \delta_{ij} \Delta T - F(T, P, \rho, \chi_i) \\
\end{align*}
\]

Eulerian + Lagrangian
EXPERIMENTAL VALIDATION

Observation of swelling under various environment

Radiative furnace
- Flat plate configuration
- Max cold wall heat flux: ~500 kW/m²
- Duration: ~80 s
- Inner face thermocouple

Inductive plasma torch: Comete
- Stagnation point configuration
- Max cold wall heat flux 800 kW/m²
- Internal thermocouple

Arcjet plasma: Simoun
- Air/CO2 atmosphere
- Max cold wall heat flux 1.8 MW/m²
- Duration: ~60 s
- Thermocouple plugs
- Laser recession
EXPERIMENTAL VALIDATION

Radiative furnace

Perspective view of the specimen during exposure to radiative heat flux

Post-test direct measurements

Swell timeline

Specimen sheet after test

Final thickness

Initial thickness

Specimen sheet before test

All the space you need

Astrium Norcoat Liege Phenomena overview and model: Experimental validation Numerical simulation Conclusion
EXPERIMENTAL VALIDATION

Comete inductive plasma torch

Heat flux ~800 kW/m²

T=0 s  T=45 s  T=150 s

Specimen before test

Specimen after test

Comparison of surface scanned geometry before/after test

Post-test direct axial measurements

Heat flux ~800 kW/m²

Strong lagged swelling effect on thickness

Expansion

Recession

Specimen before test

Specimen after test

Comparison of surface scanned geometry before/after test

Post-test direct axial measurements

Strong lagged swelling effect on thickness
EXPERIMENTAL VALIDATION

- Simoun arc-jet plasma test

Specimen before test

Specimen after test

Cross section:
Charred, pyrolysis and virgin layer

Top view of the sample at thermocouple plug location

Due to high convective exchange coefficient, recession is dominating expansion
NUMERICAL SIMULATION

- Surface kinetic rebuilding including
  - Surface chemical recession
  - Surface mechanical recession
  - Volume swelling

⇒ Optimization of the ablation law, and the swelling Arrhenius law parameters to fit the surface motion, density gradient and thermal thermocouple history.
CONCLUSION

- New development in *Amaryllis* and *Mecano* were successfully applied to model the behavior of a cork based Thermal Protection Material including:
  - conductive heat transfer
  - chemical decomposition (pyrolysis) kinetics and energy
  - chemical and mechanical ablation
  - thermally-generated volume swelling

- For cork based material, ablation and swelling cannot be dissociated in model rebuilding. Lagged effects of swelling must be considered for checking the reliability of post-test direct measurements

- *Samcef* modules enable full coupling between thermal, thermo-chemical and mechanical response various industrial issues when coupled thermal and mechanical loads play an important role could be treated
CONCLUSION & FUTURE

- Future model will focus on 2D orthotropic swelling material properties

- Design a specific instrumentation for in-depth characterization of swelling phenomena