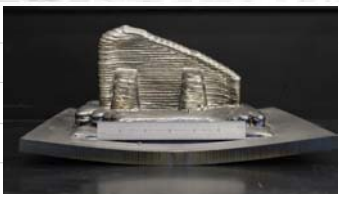
A Layer-by-Layer Approach for Simulating Residual Stresses in AM

Mikael Schill[1], Niclas Strömberg[2]

[1] Dynamore Nordic, mikael.schill@dynamore.se
[2] Örebro University, niclas.stromberg@oru.se

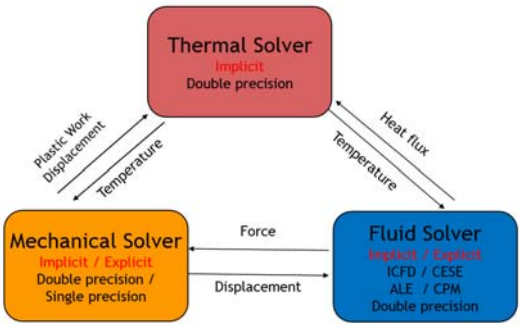
Outline

- Background & motivation
- Pre-processor *Pre4AM*
- *LOAD_HEAT_GENERATION
- *MAT_CWM_THERMAL
- *Tangent expansion coefficient
- *MAT_CWM
- Examples
- Summary

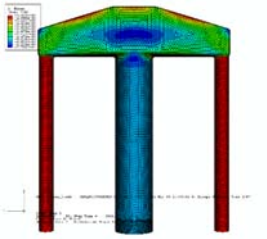


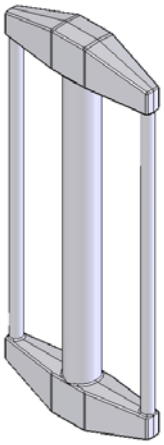
Aim & scope

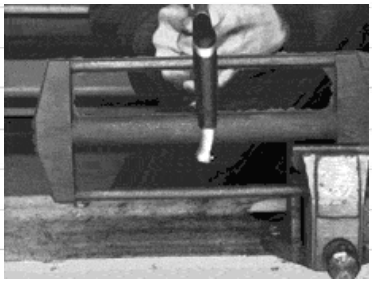
The aim of this project is to develop a rational approach for performing simulation of distortions and residual stresses developed in additive manufacturing (AM) of components using LS-Dyna. The approach must be easy to use in the design process and produces results in a reasonable computational time.



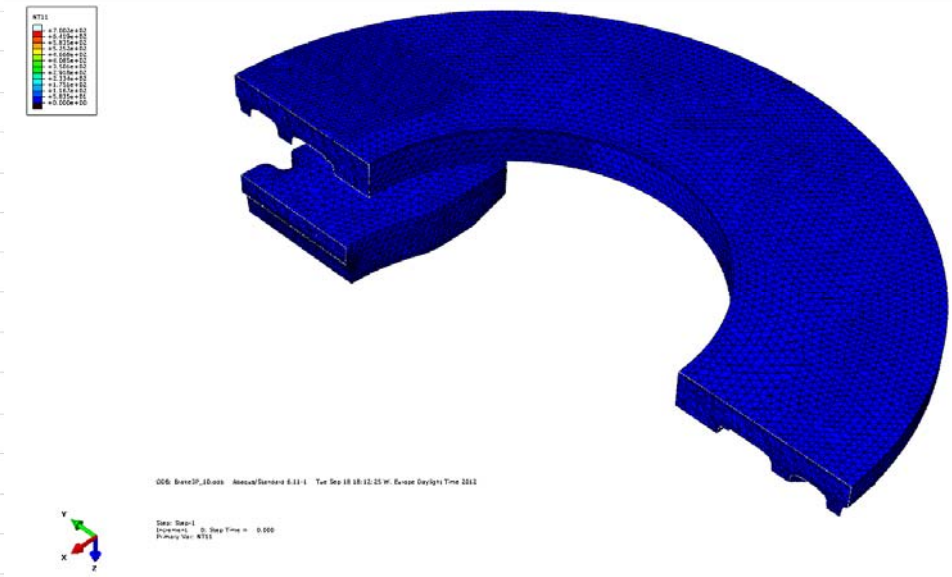
Residual stresses in castings



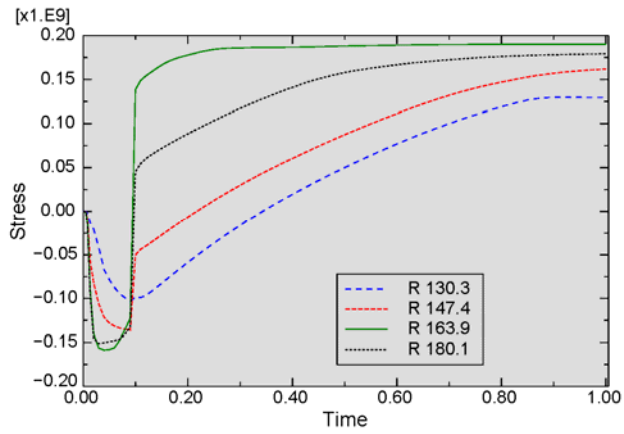


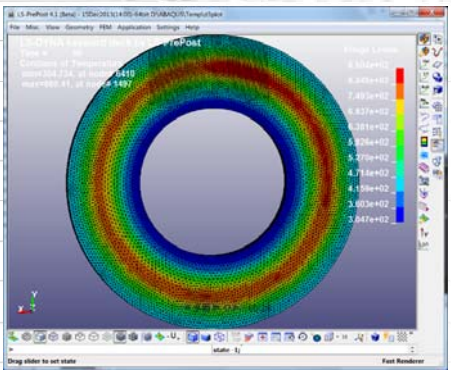


Residual stresses in brake discs

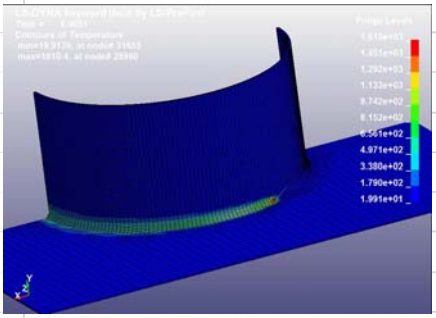


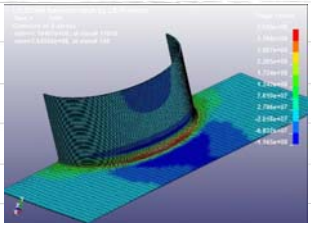
Residual stresses in brake discs

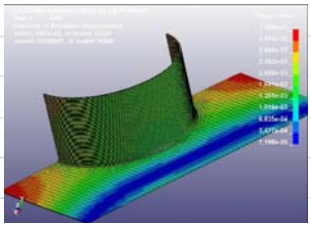




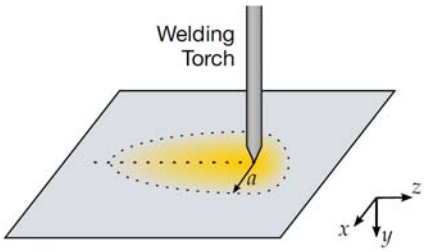
Residual stress in welding

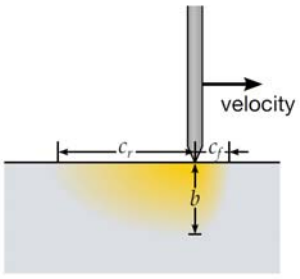






Goldak's heat source

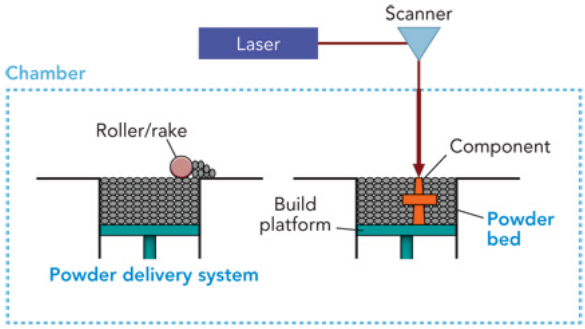




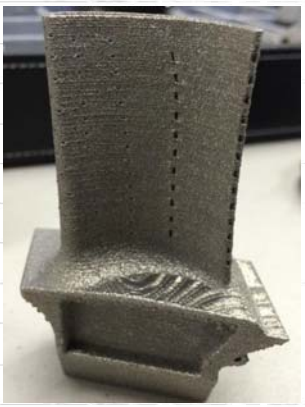
$$q = \frac{6\sqrt{3}FQ}{\pi\sqrt{\pi}abc}\exp\left(\frac{-3x^2}{a^2}\right)\exp\left(\frac{-3y^2}{b^2}\right)\exp\left(\frac{-3z^2}{c^2}\right)$$

*BOUNDARY_THERMAL_WELD

Additive manufacturing (AM)

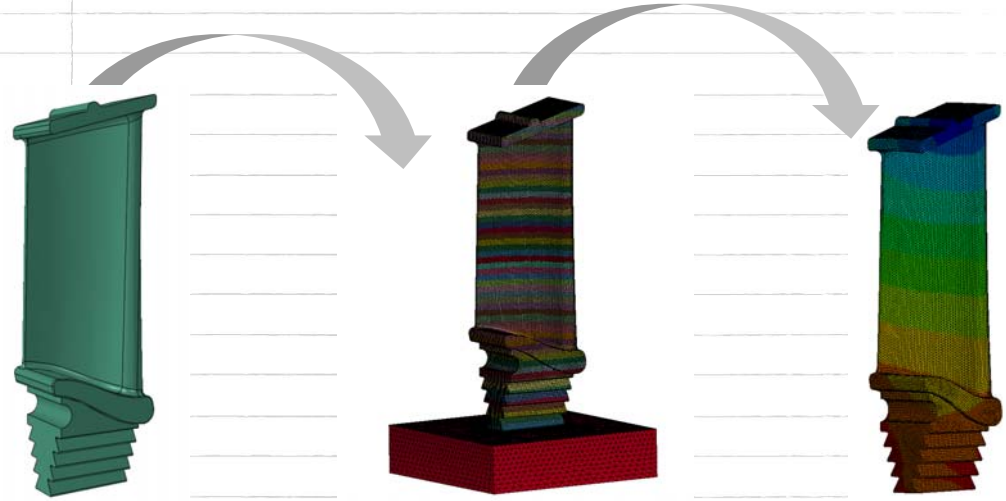


From http://www.industrial-lasers.com

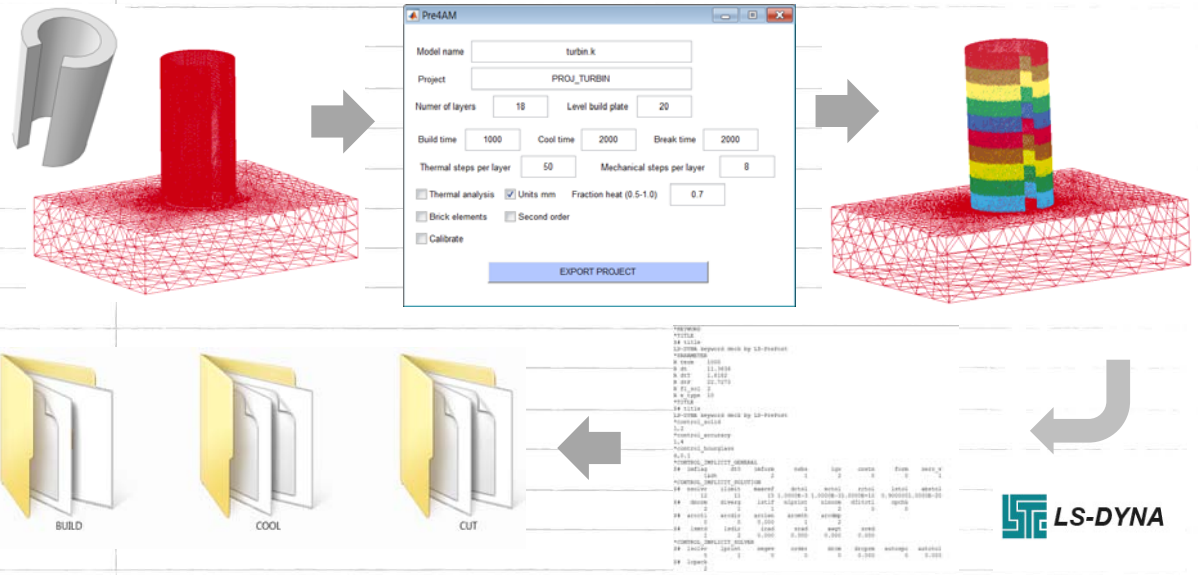


From http://www.additivemanufacturing.media

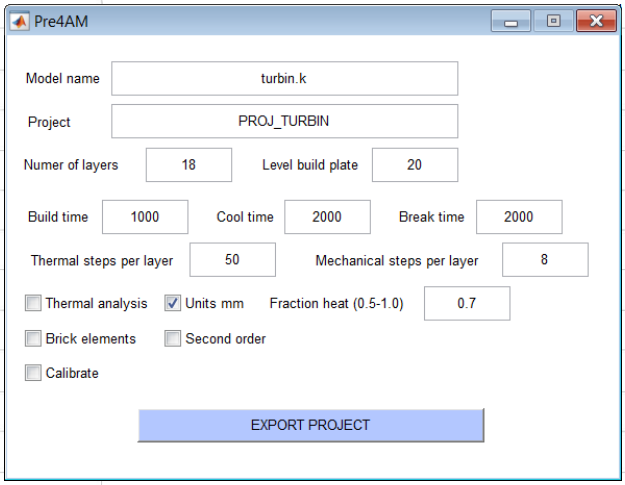
Aim & scope



Pre-processor (Pre4AM)



Pre-processor (Pre4AM)



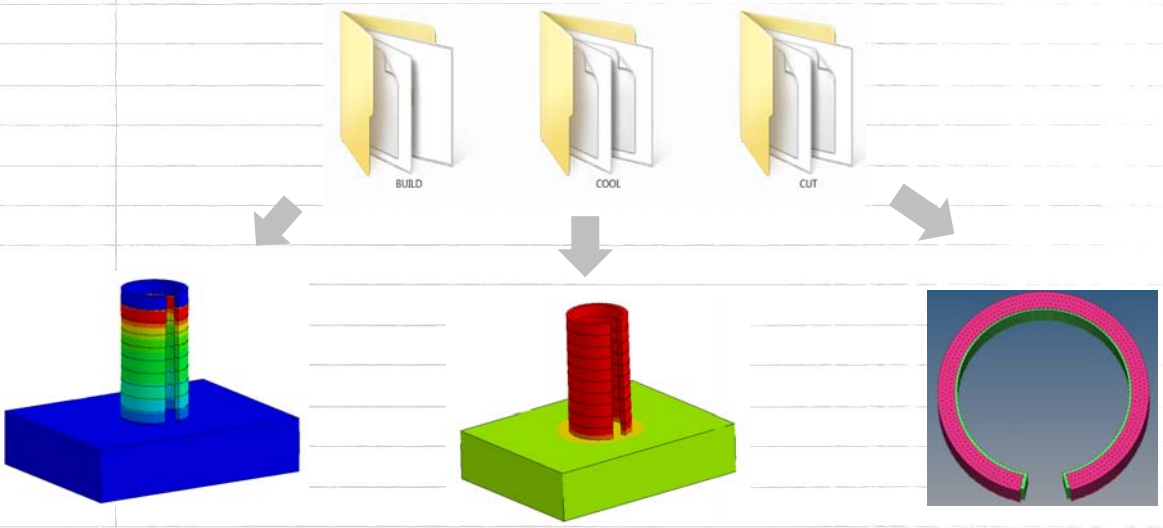
This GUI set up a LS-dyna simulation of residual stresses and distortions in AM.

A model is loaded and three analyses are created in the following maps: BUILD, COOL and CUT in the project map.

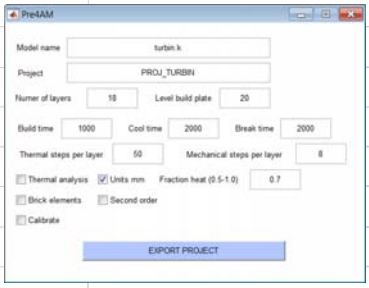
dynain_build, dynain_cool, temp_build.inc and temp_cool.inc are used for the restart analyses.

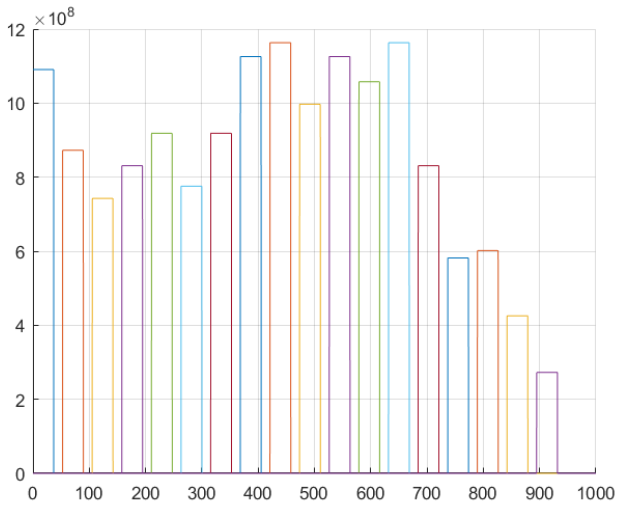
The following sets are needed: a node set for build plate temperature, a node set for cut displacement BC and two segments sets for convection BC, one for building and cooling, and the other one for cutting.

Pre-processor (Pre4AM)



*LOAD_HEAT_GENERATION





*MAT_CWM_THERMAL

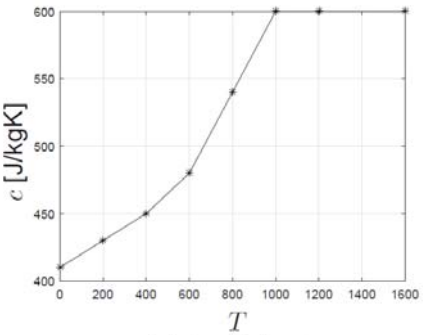
$$\rho c\dot{T} = k\Delta T + \boldsymbol{\sigma} : \dot{\boldsymbol{\epsilon}}^p + r$$

$$c(T) = c_m(T)\gamma + c_g(1-\gamma)$$

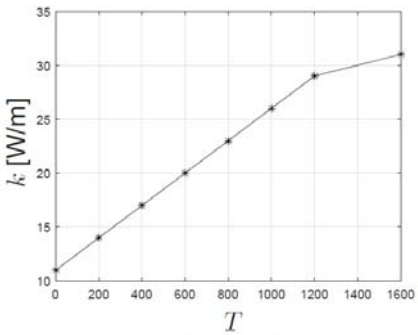
$$k(T) = k_m(T)\gamma + k_g(1-\gamma)$$

$$\gamma = \min\left[1, \max(0, \frac{T^{\text{max}} - T^{\text{start}}}{T^{\text{end}} - T^{\text{start}}})\right]$$

Inconel 718



(a) Specific heat



(b) Conductivity

*MAT_CWM

$$\boldsymbol{\epsilon} = \boldsymbol{\epsilon}^e + \boldsymbol{\epsilon}^p + \boldsymbol{\epsilon}^t \qquad \dot{\boldsymbol{\epsilon}}^t = \alpha(T)\dot{T}\boldsymbol{I}$$

$$E(T) = E_m(T)\gamma + E_g(1-\gamma),$$
$$\nu(T) = \nu_m(T)\gamma + \nu_g(1-\gamma),$$

$$\alpha = \alpha(T) = \alpha_m(T)\gamma + \alpha_g(1-\gamma)$$

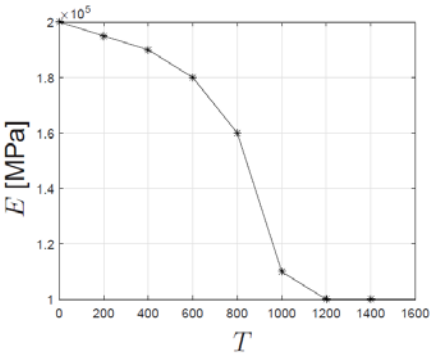
Tangent expansion coefficient

$$\boldsymbol{\alpha}(T) = \frac{\mathrm{d}\boldsymbol{\epsilon}^t}{\mathrm{d}T} \qquad \boldsymbol{\epsilon}^t = \hat{\alpha}(T)(T - T_0)\boldsymbol{I}$$

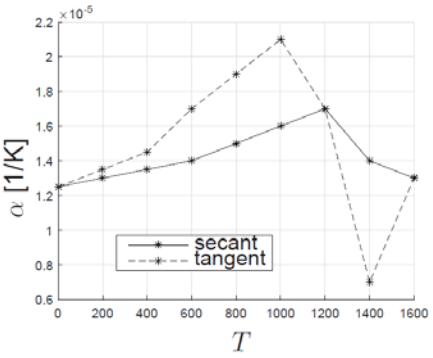
$$\dot{\boldsymbol{\epsilon}}^t = \frac{\mathrm{d}\hat{\alpha}(T)}{\mathrm{d}T}\dot{T}(T - T_0)\boldsymbol{I} + \hat{\alpha}(T)\dot{T}\boldsymbol{I}$$

$$\boldsymbol{\alpha}(T) = \frac{\mathrm{d}\hat{\alpha}(T)}{\mathrm{d}T}(T - T_0)\boldsymbol{I} + \hat{\alpha}(T)\boldsymbol{I}$$

Inconel 718



(a) Young's modulus



(b) Thermal expansion

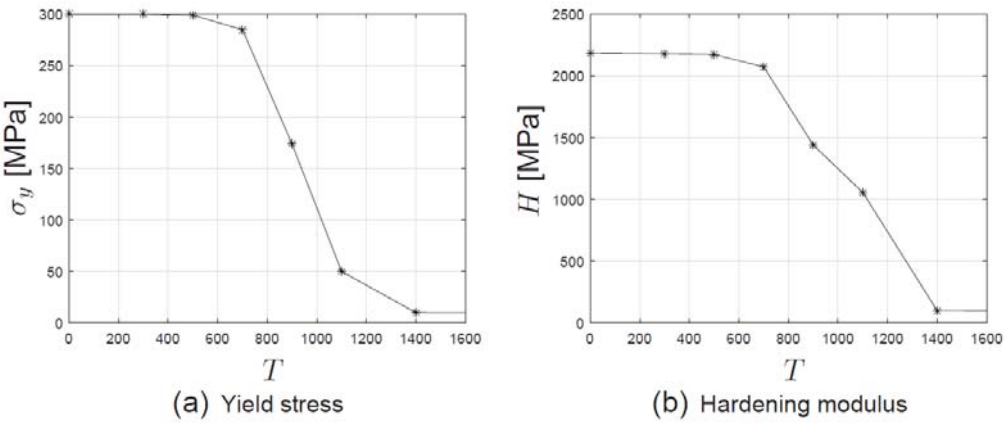
*MAT_CWM

$$f = \sqrt{\frac{3}{2}(\boldsymbol{s}-\boldsymbol{\eta}) : (\boldsymbol{s}-\boldsymbol{\eta})} - \sigma_y(T) - \beta H(T)\epsilon^p$$

$$\epsilon^p_{n+1} = \epsilon^p_n \max\left[0, \min(1, \frac{T - T^e_a}{T^s_a - T^e_a})\right],$$

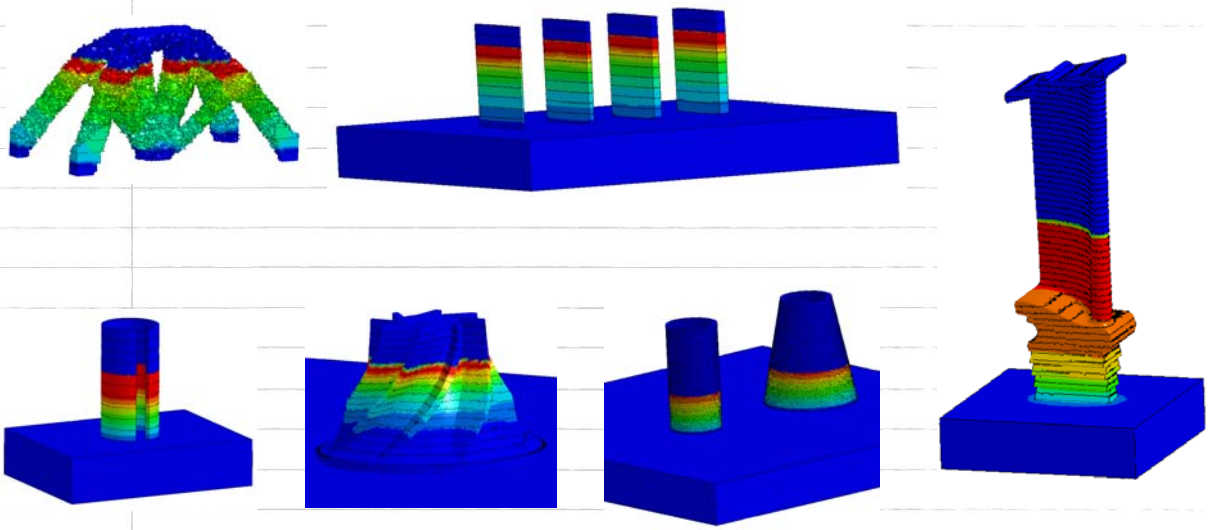
$$\boldsymbol{\eta}^p_{n+1} = \boldsymbol{\eta}^p_n \max\left[0, \min(1, \frac{T - T^e_a}{T^s_a - T^e_a})\right]$$

Inconel 718

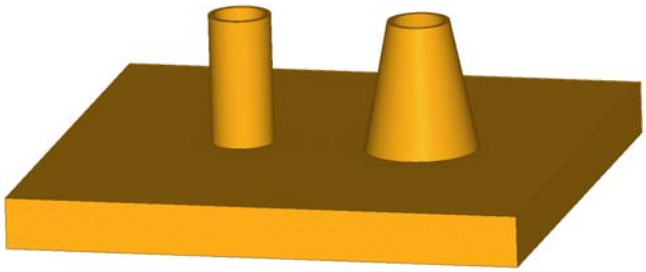


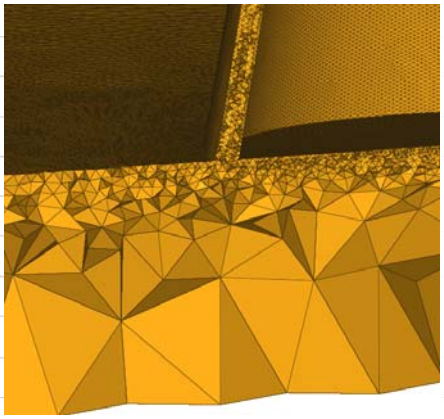
(a) Yield stress (b) Hardening modulus

Examples



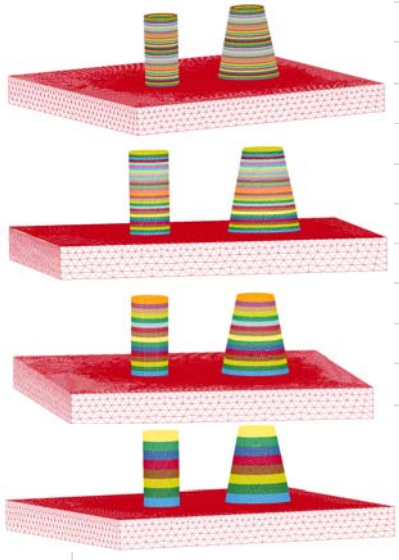
Benchmark – number of layers, CPU-time

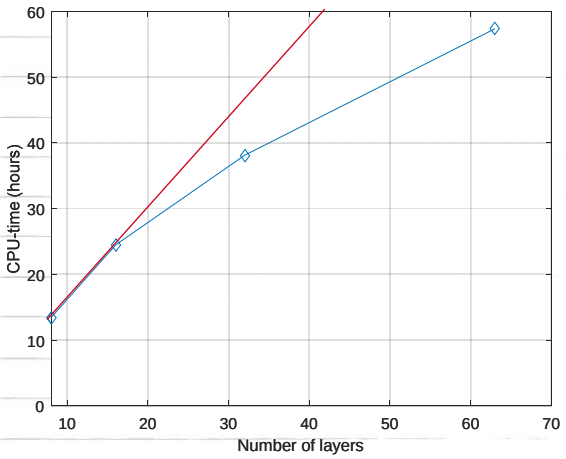




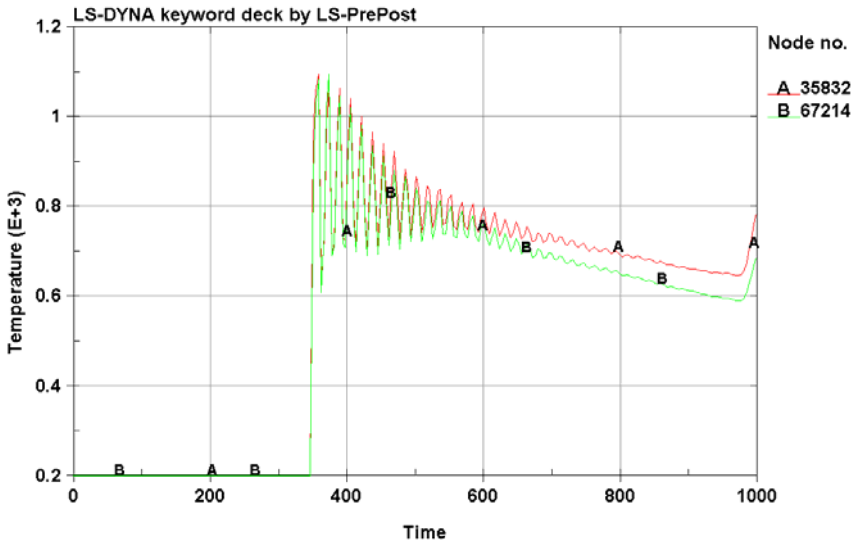
Benchmark of a cylinder and cone with more than 2 million elements.

Benchmark – number of layers, CPU-time

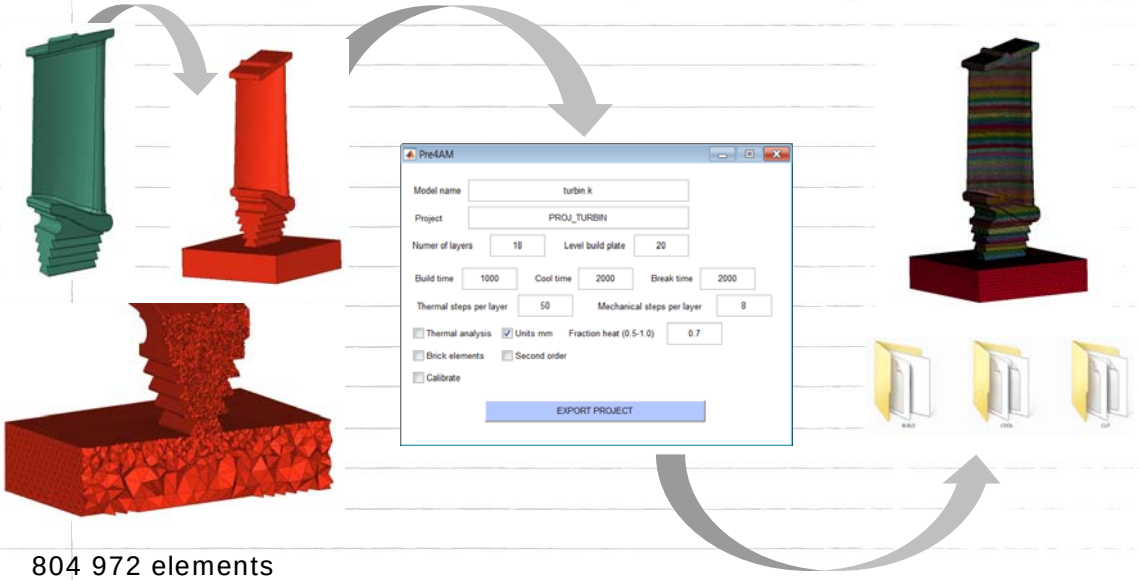




Benchmark – temperature history

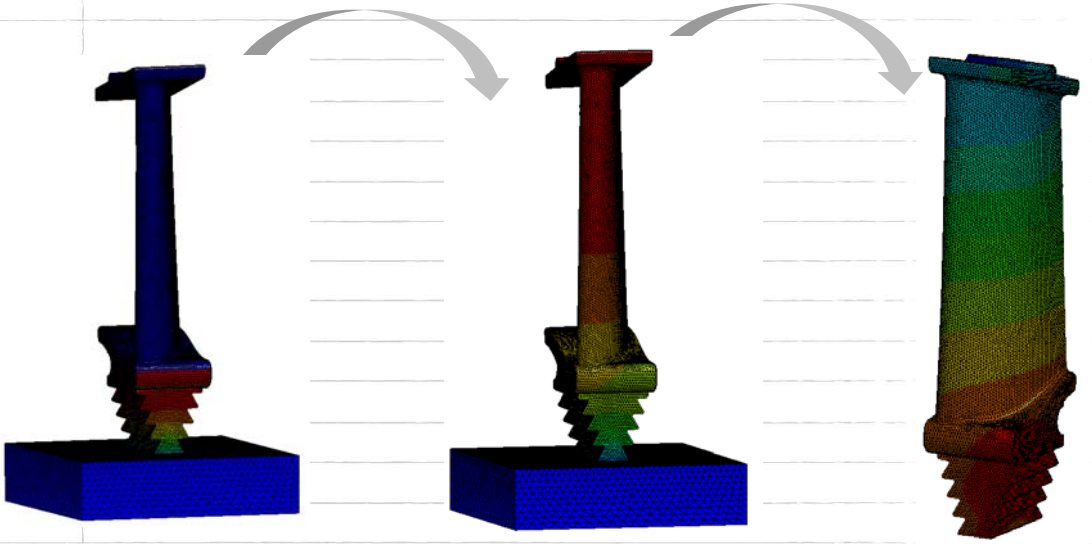


Example – Pre4AM

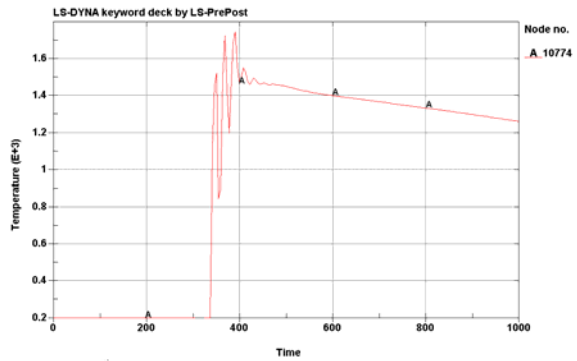


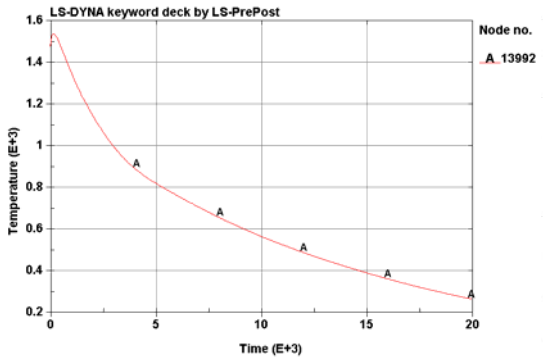
804 972 elements

Example – build, cool, cut

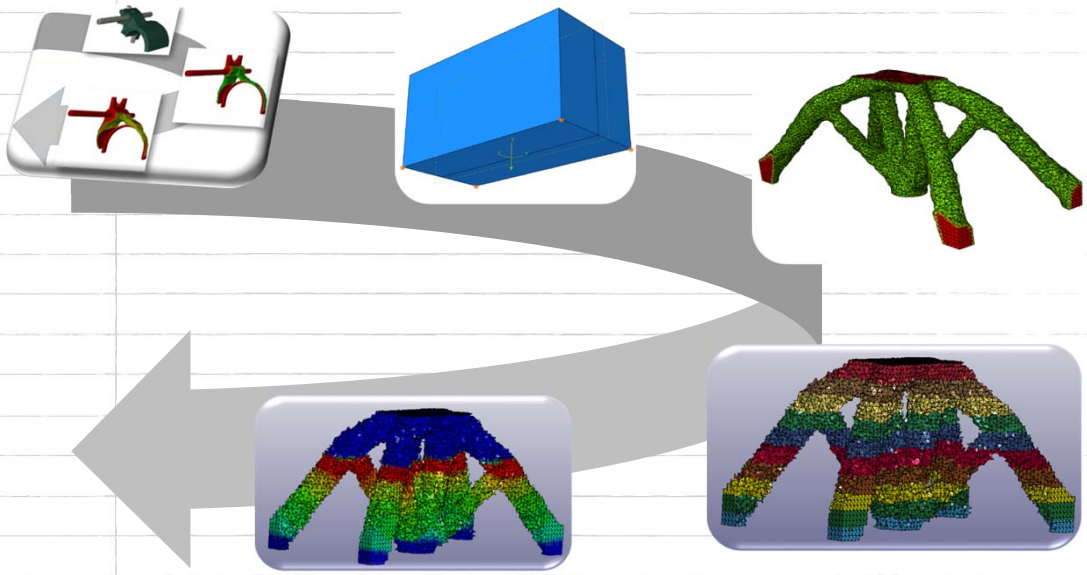


Example – temperature history





CAE design for AM – www.digi3d.org



Summary

- ✓ A layer-by layer approach for simulation of distortions and residual stresses developed in AM using *LOAD_HEAT_GENERATION, *MAT_CWM_THERMAL and *MAT_CWM is suggested.
- ✓ A first version of a pre-processor (Pre4AM) for setting up LS-Dyna simulations of proposed layer-by-layer approach is developed.
- ✓ Inconel 718 is implemented.
- ✓ Several examples are solved.
- ✓ The approach will be further developed within the project www.digi3d.org.