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OPTIMIZATION OF INDUCTION HEATING PARAMETERS WITH RESPECT TO FINAL SHAPE OF THE PREFORM

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Summary. *This article presents an attempt to use optimization on a complex multi-physics problem where magnetic, thermal and mechanical fields are coupled. The final shape of the hot forged cylinder depends on the thermal filed produced during the induction heating process. The objective of optimization procedure is to find the set of induction heating parameters which produces the target geometry of the specimen after hot forming. The results are compared against experimental data.*

1 INTRODUCTION

The electromagnetic field, produced by coil carrying the alternating current, induces eddy currents in the electrically conducting material, which passes trough the coil. As a result of induced eddy currents the material heats resistively. The phenomenon is also known as inductive heating where the thermal response is coupled with the magnetic behavior. Inductive heating is used for a wide variety of practical applications such as die-less forming, heat treatment and surface hardening. In the presented case the forming of the preforms for subsequent forging operations will be analyzed. The final preform shape, after hot forming between flat dies, depends on the temperature field achieved during the inductive heating.

Numerical analysis of the process consisting of induction heating and subsequent forming operation requires a model where magnetic, thermal and mechanical fields are fully coupled. To derive such a complex model a co-operative approach[1] to the solution of non-linear coupled problems has been developed.

The idea behind the co-operative approach is to combine several techniques such as, symbolic and algebraic approach, automatic differentiation, theorem proving, and automatic code generation, inside one single environment instead of combining several different systems. This approach proves to overcome several drawbacks observed in case of separate usage of these techniques.

The system based on co-operative approach is presented in Figure 1 and it consists of three related packages:

- AceGen[2]
- Computational templates[3]
- Finite Element Driver

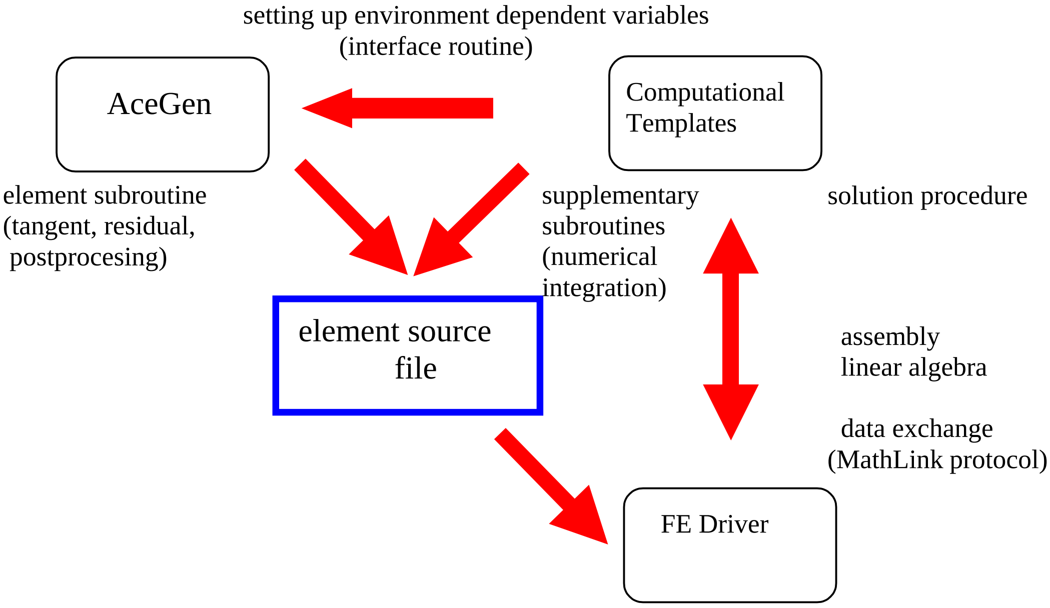

Figure 1 Schematic of the co-operative approach system

AceGen[2] is used for automatic derivation of formulae and code generation. The following techniques have been implemented into a single system: simultaneous expression optimization, simultaneous generation of code structure and automatic differentiation. Computational templates[3] package, which is a collection of, prearranged modules for the automatic creation of interfaces between the generated finite element code and finite element environment. Finite Element Driver represents a model FE solution environment, which allows direct testing and application of the generated code. The Computational templates use Finite Element Driver assembly and linear algebra functionality in its solution procedures. All the building blocks of the system are implemented in Mathematica since it provides all the required functionality.

In order to exploit full potential of the co-operative approach high abstract mathematical formulation of implicit solution methods for non-linear systems is applied. For the numerical solution of direct analysis finite element method was used.
Axisymetric magneto-thermo-mechanical[4] element used in the direct solution has the following set of unknowns for node *i*:

$$\mathbf{a}=(A_{im},A_{re},T,u,v) \tag{1}$$

where A_{im},A_{re} are the real and imaginary component of magnetic vector potential, T is temperature and u,v are displacements.

There are additional set of unknowns at the integration point *k*:

$$\mathbf{b}=(\varepsilon_{xx}^{pl},\varepsilon_{yy}^{pl},\varepsilon_{zz}^{pl},\varepsilon_{xy}^{pl},\lambda) \tag{2}$$

where λ is plastic multiplier and $\varepsilon_{xx}^{pl},\varepsilon_{yy}^{pl},\varepsilon_{zz}^{pl},\varepsilon_{xy}^{pl}$ are plastic strains.
The complete system of element equations is of the following form:

$$f(\boldsymbol{\sigma}(\boldsymbol{\varepsilon}_e^{trial}))\geq 0 \quad \begin{cases} \boldsymbol{\Phi}=\begin{Bmatrix} \boldsymbol{\varepsilon}_p - {}^{p}\boldsymbol{\varepsilon}_p - \lambda \dfrac{\partial f}{\partial \boldsymbol{\sigma}} \\ f(\boldsymbol{\sigma}(\boldsymbol{\varepsilon}_e^{trial})) \end{Bmatrix}=0 \\ \boldsymbol{\Psi}=\begin{Bmatrix} \int_\Omega \rho c_p \dfrac{\partial T}{\partial t}\delta T\, d\Omega + \int_\Omega \nabla\delta T\cdot(k\nabla T)d\Omega - \int_\Omega q\,\delta T\, d\Omega \\ \int_\Omega \dfrac{1}{\mu}\nabla A\cdot\nabla\delta A\, d\Omega + \int_\Omega (\dfrac{1}{\mu r^2}+i\,\omega\,\gamma)A\,\delta A\, d\Omega - \int_\Omega J_g\,\delta A\, d\Omega \\ \int_\Omega \boldsymbol{\sigma}(\boldsymbol{\varepsilon}_e^{trial}):\dfrac{\partial\boldsymbol{\varepsilon}_e^{trial}}{\partial \mathbf{u}}\, d\Omega \end{Bmatrix} + \boldsymbol{\Psi}^{external} \end{cases} \tag{3}$$

$$f(\boldsymbol{\sigma}(\boldsymbol{\varepsilon}_e^{trial}))< 0 \quad \begin{cases} \boldsymbol{\Phi}=\begin{Bmatrix} \boldsymbol{\varepsilon}_p - {}^{p}\boldsymbol{\varepsilon}_p \\ d\,\lambda \end{Bmatrix}=0 \\ \boldsymbol{\Psi}=\begin{Bmatrix} \int_\Omega \rho c_p \dfrac{\partial T}{\partial t}\delta T\, d\Omega + \int_\Omega \nabla\delta T\cdot(k\nabla T)d\Omega - \int_\Omega q\,\delta T\, d\Omega \\ \int_\Omega \dfrac{1}{\mu}\nabla A\cdot\nabla\delta A\, d\Omega + \int_\Omega (\dfrac{1}{\mu r^2}+i\,\omega\,\gamma)A\,\delta A\, d\Omega - \int_\Omega J_g\,\delta A\, d\Omega \\ \int_\Omega \boldsymbol{\sigma}(\boldsymbol{\varepsilon}_e^{trial}):\dfrac{\partial\boldsymbol{\varepsilon}_e^{trial}}{\partial \mathbf{u}}\, d\Omega \end{Bmatrix} + \boldsymbol{\Psi}^{exter} \end{cases}$$

Material parameters of all three fields were treated as temperature dependent although some of them are highly non-linear.

The developed element was used to simulate process of preform forming during which the final shape is obtained regarding the temperature filed achieved during the inductive heating. The stages of the process are presented on Figure 2.

The parameters used for control of the heating stage are electric current, frequency and voltage. The objective of the optimization procedure was to find a set of optimal induction heating parameters in order to obtain the required shape. The shape of the workpiece was parameterized and the objective function, which has to be minimized, was defined as deviation of the shape with respect to the target shape. For the solution of optimization problem the Inverse[4] optimization shell was used.

Figure 2: Process stages of preform forming

The series of industrial measurements were performed in order to validate the numerical model. Temperature measurements were performed using thermograph camera while the measurements of the magnetic field were performed using Hall probe.

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