COST 526

"Automatic Process Optimization in Materials Technology"

(APOMAT)

Half-Yearly Report

To be sent to **V.Tesch@access.rwth-aachen.de** until **February 28, 2003**

1. Reporting Period	**1.7.2002 – 31.12.2002**
Project title	Forging Process Optimisation
Project leader Organization	Lionel FOURMENT CEMEF, Ecole des Mines de Paris
Main collaborators involved	Mehdi Laroussi

2. Funding Situation	
Amount of money received specifically for COST	730,6 Euros
Other resources partially used for the project	kEuros

3. International Collaboration (mention group and type of work done in collaboration during the reporting period)
Participation in the Working Group Meeting in Budapest + project progress report ⋗ YES ❒ NO
Group: "Bulk product processing" Work done in collaboration: Submission and acceptation of a French national funded project in the frame of Apomat, and organisation of it after its acceptance

4. Industry participation (mention name of companies and work done in collaboration during the whole project)
Setforge, Sifcor (French forging companies) , Cetim (Technical Center of Mechanic Industry), CREAS • Industrial forging examples for the definition of objective functions and optimisation parameters, and for validation of the sensitivity analysis in forging

5. Meetings, visits, exchange of scientists, short-term scientific missions	**Location, date**
Project meeting Other connected project meeting	Budapest, Nov 28/29, 2002. Sophia Antipolis, March 6, 2003

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6. Progress within the reporting period

(Not exceeding 3 pages, including tables and figures)

Abstract.

Sensitivities of objective functions with respect to several parameters are calculated for metal forming problems. Based on the differentiation of the discrete equations, the adjoint state method is used for non-steady processes with large deformations, contact evolution and remeshing. A backward analysis is carried out as a post-process, which requires additional storage of variables. The semi-analytical technique is used to compute the main derivatives. The accuracy of the sensitivity results is evaluated by comparison to finite difference scheme.This paper is more specifically focused on the determination of new objective functions for the evaluation of forging die filling and the estimation of possible fold formation.

Recent results.

To validate our sensitivity analysis based on the adjoint state method, it has been applied to the upsetting of a portional cylindrical workpiece between two complex dies in order to obtain a tripod (see figure 1). The initial height of the workpiece is about 60 *mm* and the mesh contains 894 nodes and 2507 elements. Only the upper tool has a vertical velocity, the lower tool is fixed. The objective function is the total energy of the forming process :

$$\Phi_{en} = \int_{t_0}^{t_{fin}} \left(\int_{\Omega} K\left(\sqrt{3}\dot{\bar{\varepsilon}}\right)^{m+1} dw + \int_{\partial\Omega_t} \alpha K \left\| \Delta v_t \right\|^{q+1} ds \right) dt$$

This problem is very interesting because the contact surface is changing a lot during the process, as can be seen in figure 1. Using the symmetry properties, we only deal with the upsetting of a sixth of cylinder. The cylinder radius is regarded as the optimisation parameter. Let us consider a cylinder of radius r_0 :

$$r(\mu) = r_0 + \mu$$

An equivalent relation can be written in the frame $(\vec{x}_1, \vec{x}_2)$. The cylinder coordinates X_1 and X_2 are deduced from the initial coordinates x_1 and x_2, the initial radius r_0 and the shape parameter μ :

$$\forall i = 1,2, \quad X_i = x_i \left(1 + \frac{\mu}{r_0}\right)$$

In order to evaluate the sensitivity analysis, the derivatives that are computed by the adjoint state method (ASM) are compared with those computed with a finite difference approximation. The finite difference sensitivities are evaluated by the central scheme:

$$\left.\frac{d\Phi}{d\mu}\right|_{FD\,central} \approx \frac{\Phi(\mu + \Delta\mu) - \Phi(\mu - \Delta\mu)}{2\left\|\Delta\mu\right\|}$$

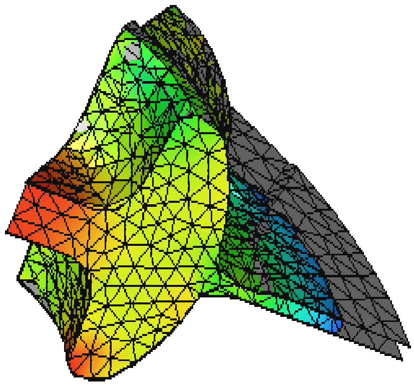

Figure 1: 3D upsetting of a cylindrical workpiece (initial and final configurations)

The tests are carried out in the viscoplastic case $\left(K = 1.693.10^6\, , m = 0.139\right)$ with the Norton friction law at the tool/workpiece interface $\left(\alpha = 0.4\, , q = 0.139\right)$. The upsetting height is 10mm. The best agreement is obtained for $\Delta\mu = 10^{-6}$ mm.

The relative error between the adjoint and the finite difference derivatives is less than 0.1%. It shows that the adjoint state method has been successfully implemented for a non-steady forging problem and it validates the contact differentiation.

In the folding zones, there is a high concentration of strains due to the shearing of the material, as can be seen in the example of a pre-folded workpiece upset between flat dies (see figure 2).

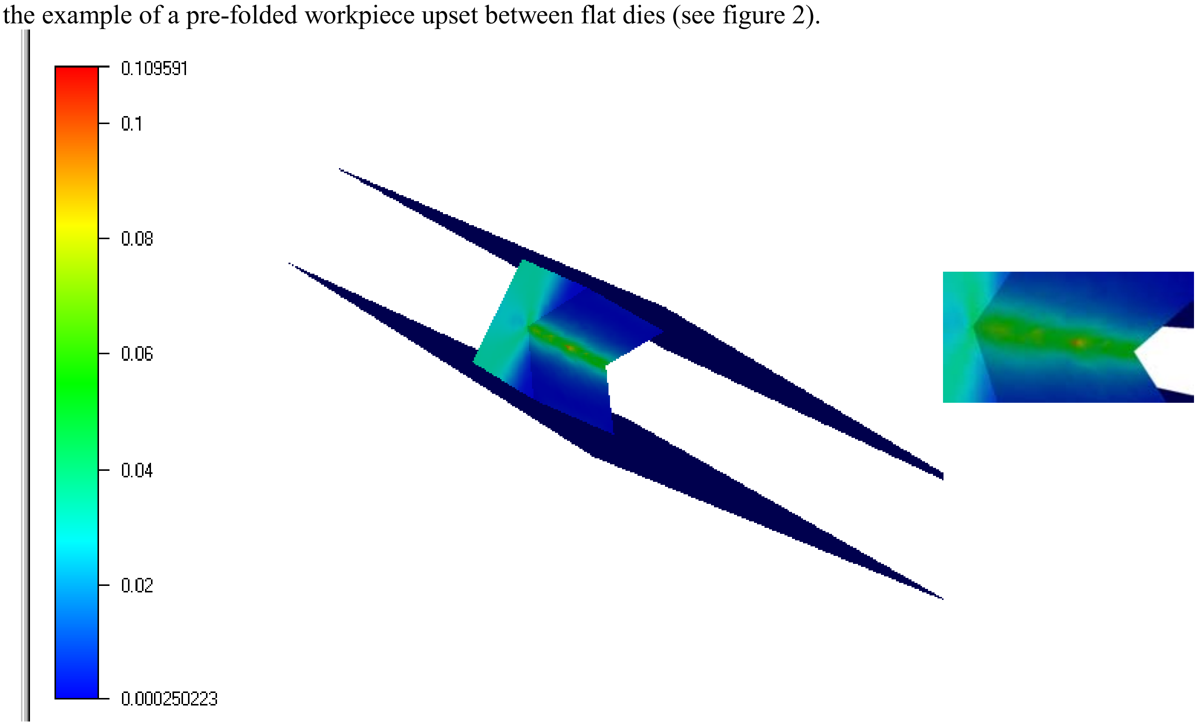

Figure 2 : Upsetting of a pre-folded workpiece between flat dies : unusual increase of $\dot{\bar{\varepsilon}}$ in the folded zone

In the folded zone, the value of the equivalent strain $\dot{\bar{\varepsilon}}$ rate is about $0.1 s^{-1}$ whereas the average value of $\dot{\bar{\varepsilon}}$ is around $0.01 s^{-1}$ in the other zones. Therefore, an objective function[i] can be derived from the strain rate values along the free boundary $\partial_{free}\Omega$:

$$\Phi_{fold} = \int_{t=t_0}^{t=t_{end}} \left(\int_{\partial_{free}\Omega} \left(\dot{\bar{\varepsilon}}\right)^{\alpha} ds \right) dt$$

This function allows to measure the severity of the fold, when it occurs, and the distance of the solution to a possible fold. By taking the coefficient α greater than 1, it allows us to give more importance to the zones where the values of $\dot{\bar{\varepsilon}}$ are high. The folds detection is then better. A standard cube and a "V" cube (see figure 2) have been upsetted between flat dies. The length of the cube edge is 50 mm and the upsetting height is 10 mm. The following table summarizes the values of the "fold" objective function for different values of α:

α	1	2	3	4
Φ_{fold} "V" cube	1490	3419	9674	35 427
Φ_{fold} cube	2106	4687	10 476	23 510

Even though the folding zone only appears in the "V" cube upsetting, the total value of the objective function is higher in the case of the standard cube for $\alpha < 4$. The folding zone is very small so only few values of $\dot{\bar{\varepsilon}}$ are high. As long as the coefficient α is less than 4, the folds are not well detected. However previous works have shown that with $\alpha = 1$, this objective function provides an adequate function for removing folds in an optimisation procedure.

The sensitivity analysis with respect to this function is very similar to that of the total forming energy.

Conclusion:

The sensitivity analysis for non-steady problems with contact evolution has been developped in the frame of a mixed velocity/pressure resolution where the contact condition is handled by a penalty method, and the adjoint state method has been described for this type of application.

The implementation of the adjoint state method is significantly more complex than the direct differentiation one, especially the requirement of storing the problem variables for backward calculation. However, it is more efficient for a large number of parameters.

The application to the academic example of the tripod shows the accuracy of the proposed method. These results are quite encouraging and show that there is no major obstacle to apply the adjoint state differentiation method to large industrial 3D problems. We have also introduced in the FORGE3® software two new objective functions, the folding criterion and the filling defect of the forging dies, and applied them to different examples. We have handled the problem of material folds and die filling because they often occur during forming processes. Preliminary developments about how computing the derivatives of these objective functions have been presented. Next step will be to obtain sensitivity results and to deal with more complex forging problems, which include several operations and with more general parameters (shape and process).

7. List of publications

a) Published

M. LAROUSSI, L. FOURMENT « The adjoint state method for sensitivity analysis of non-steady problems. application to 3d forging » in press: Int. J. of Forming Processes, vol. xxx, n°xxx, xxx, (2003)

S. H. CHUNG, L. FOURMENT' J. L. CHENOT, M. HWANG "Adjoint state method for shape sensitivity analysis in non-steady forming applications", in press: International Journal for Numerical Methods in Engineering (2003)

b) Submitted for publications

M. LAROUSSI, L. FOURMENT « Sensitivity Analysis of 3D Forging using the Adjoint State Method : Extension to folds detection and die filling », VII International Conference on Computational Plasticity, COMPLAS, Barcelonna, April 7-10 2003

c) In preparation