



**COST 526**  
**“Automatic Process Optimization in Materials Technology”**  
**(APOMAT)**  
**Half-Yearly Report**

To be sent to [V.Tesch@access.rwth-aachen.de](mailto:V.Tesch@access.rwth-aachen.de) until **February 28, 2004**

<b>1. Reporting Period</b>	<b>1.7.2003 – 31.12.2003</b>
Project title	Forging Process Optimization
Project leader Organization	Lionel FOURMENT CEMEF, Ecole des Mines de Paris
Main collaborators involved	Tien Tho Do, Mehdi Laroussi

<b>2. Funding Situation</b>	
Amount of money received specifically for COST	730.6 kEuros
Other resources partially used for the project	kEuros

<b>3. International Collaboration</b>
(mention group and type of work done in collaboration during the reporting period)
Participation in the Working Group Meeting in Krakow + project progress report
<input checked="" type="checkbox"/> YES
<input type="checkbox"/> NO
<b>Work done in collaboration:</b> French National funded project "OPTIMAT" gathering all the French partners of the project "APOMAT" for similar goals.

<b>4. Industry participation</b>
(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, ASCOMETAL
Industrial 3D shape optimization problem: forging a gear

<b>5. Meetings, visits, exchange of scientists, short-term scientific missions</b>	<b>Location, date</b>
Exchange program: Short-term scientific mission of Michael Emmerich from Dortmund University – Germany to CEMEF.	CEMEF – Ecole des Mines de Paris Sophia Antipolis Cedex From 18th to 21st November 2003

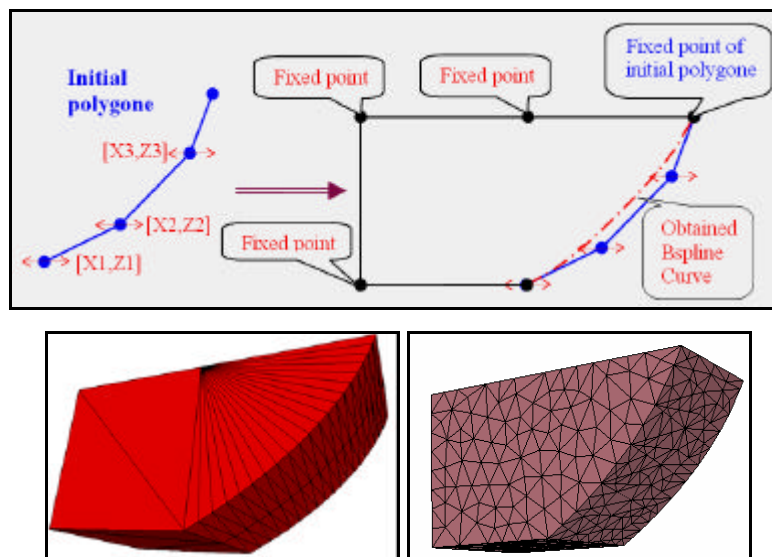
## 6. Progress within the reporting period

(Not exceeding 3 pages, including tables and figures)

**Abstract.** Several optimization approaches are used for 3D forging optimization. The process simulation is carried out using the FORGE3® finite element software. Several objective functions are considered, like the total forging energy, the forging force or a surface defect criterion. Both local and global optimization algorithms are tested for 3D applications with a notched cube. The local (gradient based) approach uses the sensitivity analysis that provides the gradient of the objective function. It is obtained by the adjoint-state method and semi-analytical differentiation. The study of global approaches aims at comparing genetic algorithms and evolution strategies. Numerical results show the feasibility of such approaches, i.e. the achieving of satisfactory solutions within a limited number of 3D simulations, less than fifty. For a more industrial problem, the forging of a gear, encouraging optimization results are obtained.

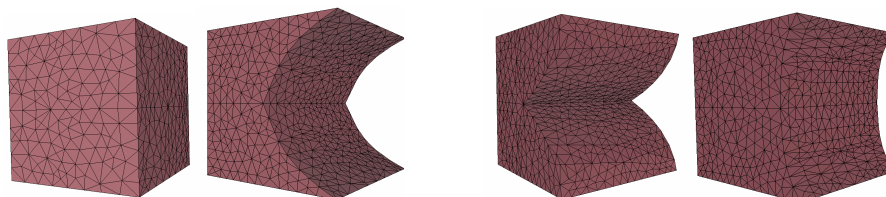
### A. TEST OF FEASIBILITY OF EVOLUTIONARY ALGORITHMS (EAs)

In order to consider the feasibility of evolutionary algorithms using in 3D forging optimization problem, we have tested them with an academic benchmark problem, in which a notched cube is upset between two flat dies. The notched part of the cube is parameterized by a B-spline curve with four control points. The problem parameters are the abscissa of three of the control points (the other one is fixed) (see Fig. 1-top). From this 2D curve, we build a simple 3D surface mesh (see Fig. 1-bottom left). Finally, the 3D volume mesh (see Fig. 1-bottom right) of the notched cube is created by the mesh generator of the FORGE3® package. FORGE3® can then be utilized to simulate the upsetting and compute one of the considered objective functions for this problem, the total forming energy or the folding defect criterion.



**FIGURE 1.** Parameterization and mesh creation procedure of a quarter of a notched cube.

This test aims at evaluating the efficiency of evolutionary algorithms for 3D forging applications and at comparing genetic algorithms (Gas) and evolution strategies (ESs). The GA code of Carroll [3] is used with the micro GA option, elitist selection, a uniform crossover rate of 0.7, and a population size of 5. Meanwhile, the ES code EPO [4] is used with the strategy (4+4) (4 parents and 4 children).



(2a) Forming Energy Problem

(2b) Folding Defects Problem

**FIGURE 2.** Non-optimized and optimized shapes for both academic problems.

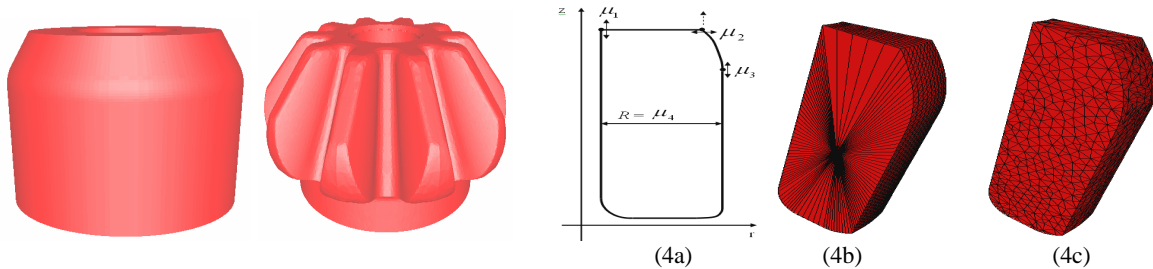
The minimization of the total forming energy is a quite academic that is not favorable to GAs because the optimal solution lies in a corner of the parameter space. With GA, the expected solution is found after more than 60 evaluations, while 40 evaluations are enough with the ES (see Fig. 2a).

The elimination of the folding defect by a proper preform is a less academic problem. We can define a minimal value of the folding defect objective function for which the process is regarded as satisfactory, i.e. without any risk of folding defect. With GA, the threshold value is obtained after 21 evaluations, while 12 evaluations are enough with the ES (see Fig. 2b).

These academic cases show that a satisfactory solution can be found within less than 50 simulations for 3D optimization forging problems. ES also look more efficient than AG for these problems.

## B. OBTAINED RESULTS WITH AN INDUSTRIAL PROBLEM

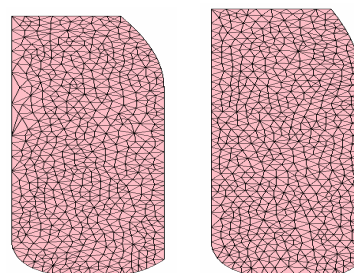
After viewing the feasibility of EA, we try to apply them to solve a more industrial problem: forging a gear and try to compare them to some gradient based methods (steepest and BFGS). This optimization problem consists in improving the preform shape for the forging of a gear (see Fig. 3), in order to minimize the forging force and so reduce the tool damage. The axisymmetrical preform is parameterized in 2D, by a combination of straight lines and quadratic curves (see Fig. 4a). This surface interpolation is extrapolated inside the domain for computing the domain derivatives in the sensitivity analysis. From this 2D geometry, a simple 3D surface mesh is created (see Fig. 4b). The volume mesh (see Fig. 4c) is finally generated by an automatic topological mesh generator. Because of the problem symmetries, only 1/20 of the gear is studied. The volume of the preform must be kept constant during optimization iterations. This constraint is handled by condensation, reducing the number of unknowns from 4 initial shape parameters (see Fig. 4a) to only 3, the preform radius  $R$  being eliminated.



**FIGURE 3.** Full preform and gear shapes (*not real scale*) **FIGURE 4.** Parameterization of the geometry of the radial plane showing the 4 shape parameters. Simple surface mesh and volume mesh of 1/20 of a gear preform (*not real scale*)

The computational time for a simulation with fine meshes and actual non-linear constitutive equations is about 12h on a PC (Pentium4 - 2.4Ghz), which is regarded as too large for optimization iterations. Therefore, a simplified optimization problem is also considered, where the mesh is coarser and the material behavior is linearized. The computational time is now quite acceptable: about 30 minutes.

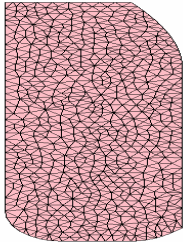
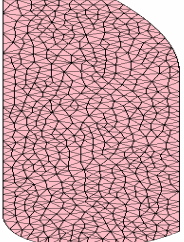
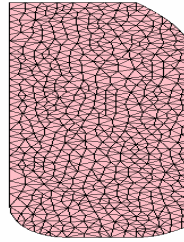
TABLE 1. Objective function values		
Average forging force $F$ by	Initial Preform	Optimal Preform
<i>Simplified</i>	$2.45 \times 10^9$	$2.25 \times 10^9$
<i>Actual</i>	$3.25 \times 10^9$	$3.05 \times 10^9$



**FIGURE 5.** Initial and "optimized" shapes obtained with a "manual" steepest gradient method (*not real scale*).

The optimization problem is first handled by using the sensitivity information (provided by the adjoint state method [2]) in a very simple way. The shape parameters are “manually” modified in a direction opposite to the gradient. Figure 5 shows the initial and modified shapes with this approach. Table 1 summarizes the obtained results in terms of objective function. As the modified preform reduces the value of the objective function for the coarse problem (by about 8%), the simulation is also carried out for the actual one. The averaged effort is then reduced by about 6%.

In order to go further with the optimization and starting from the newly improved preform, BFGS [1] and ES-meta-model [5] algorithms are applied, following the same approach: coarse problem for optimization and fine problem for verification. After 15 simulations (function evaluations), the BFGS method provides an additional improvement of 11%. The ES-meta-model finds a very different solution (see Fig. 6) that makes it possible to reduce by 14% the objective function value. 18 simulations have been required, which is not much for a non-gradient algorithm. Carrying out the simulations with the actual material and numerical parameters for the optimized preform, the objective function improvement is about 8% for both solutions, although they are quite different (see Fig. 6).

Averaged forging force F	Initial preform	Preform optimized by BFGS	Preform optimized by ES Metamodel
<i>Simplified</i>	2.45*10 <sup>9</sup>	2.19*10 <sup>9</sup>	2.11*10 <sup>9</sup>
<i>Actual</i>	3.25*10 <sup>9</sup>	3.03*10 <sup>9</sup>	2.99*10 <sup>9</sup>
Preform shapes (not real scale)			

**FIGURE 6.** Shapes and Objective function values, both for the initial and optimized preforms, resulting from both BFGS and ES Metamodel algorithms.

### C. CONCLUSION AND OUTLOOK

The obtained results are quite encouraging for the future of Evolutionary Algorithms applied to complex 3D forging optimizations. Interesting solutions are found with a limited number of 3D simulations, while making it possible to discover more global optima. Our precious work with sensitivity analysis also provides a very accurate and efficient tool for improving a 3D design in a single step. Coupling these two approaches should results into even more efficient algorithms.

### REFERENCE

1. Fourment, L., Vieilledent, D. and Chenot, J. L. "Shape optimization of the axisymmetric preform tools in forging using a direct differentiation method", International Journal of Forming Processes. Volume 1 – N° 4/1998, pp. 399 to 423
2. Laroussi, M., Fourment, L., « The adjoint state method for sensitivity analysis of non-steady problems. application to 3D forging » to appear in Int. J. of Forming Processes, 2004
3. Carroll, D. L, <http://cuaerospace.com/carroll/ga.html>
4. Roosen, P., "EPO V0.9a: The Evolutionary Parameter Optimizer shareware", Aachen University, Dortmund, Germany, 1998.
5. Emmerich, M., Giotis, A., Özdemir, M., Bäck, Th. and Giannakoglou, K., "Metamodel-assisted evolution strategies" In J. J. Merelo Guervos et al. (eds.): Parallel Problem Solving from Nature VII, Proc. Inte'I Conf, Granada, September 2002.

## **7. List of publications**

### **a) Published**

Ph. D. thesis of Mehdi Laroussi "The adjoint state method for the calculation of the sensitivity analysis derivatives: application to non-steady 3D forging". CEMEF – ENSMP, December 2003

### **b) Submitted for publications**

TT. Do, L. Fourment, M. Laroussi, "Sensitivity Analysis and Optimization Algorithms for 3D Forging Process Design", NUMIFORM 2004, Columbus, USA.

### **c) In preparation**