COST 526 – Project *F5*
Final Report

Forging Process Optimisation

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1. Introduction

Optimization techniques are every year applied to more and more complex problems among which is forging. Forging is actually quite complex a process for which the process design is mainly based on the know-how of companies and people. At the beginning of this project, quite encouraging results were available for axisymmetrical parts [1-3], so the question aroused to extend the utilized approach the three-dimensional problems, with much more complex flows and requiring much larger computer resources. In order to simplify the problem and focus only on the main design parameters, only the last two forging steps (not considering possible final stages with very low deformations) were studied: the performing operation and the finishing one, for which most of process parameters can be "easily" determined. From the designer point of view, the main unknowns are the shapes of the performing tools, which are essential to produce a satisfactory part during the last operation.

The 2D approach was based on a gradient BFGS algorithm, using the FORGE2® commercial software for process simulation and newly developed modules to compute the gradients of the objective function, by a direct differentiation method. For a certain family of problems, quite encouraging results have been obtained, so showing the feasibility of optimisation methods in this field and how such algorithms can help the designer to find new solutions or to improve existing ones. However, for another family of problems, no satisfactory design could be found, very possibly because the utilized BFGS algorithm was not robust enough to find anything but local extrema.

Therefore, we started the Apomat project with the idea of: first, extending the utilized approach to 3D problems, second handling the problem of local extrema, and third to find very efficient algorithms in order to get an engineer solution within a limited number of problems simulations.

2. Goal of the project

The goal of this project is then:
1 – to extend the calculation of the 3D gradients, using the developed adjoint state method, for two stages forging problems when the contact surface is part of the optimization parameters,
2 – to improve the quality of some objective functions for practical applications,
3 – to study more global optimization algorithms, but keeping in mind the constraint of not overtaking 50 problem simulations.

3. Simulator, calibration, quality function and optimization algorithms, including assessment with respect to alternatives

Simulator: FORGE3® is the utilized simulator. It is marketed by the Transvalor company and is being developed at CEMEF for twenty years. It is a finite element software that is dedicated to 3D forging simulation. It uses linear tetraedra, with a velocity / pressure formulation, and an automatic mesh generator based on topological improvements, which is essential to handle the large material deformation.

Calibration: No further calibration of the software is actually required, as it is extensively used by large number of companies, providing quite satisfactory results, and because the studied optimisation problems are proposed by industrial partners who perfectly master the required input numerical data and who have already extensively calibrated the software for these processes.

Quality function: Some objective functions are straightforward, they do not need specific developments, like the total forming energy:

$$\Phi_{energy}\left(p\right)=\int_{t=t_0}^{t_{end}}\left(\int_{\Omega_t}\sigma:\dot{\varepsilon}dw+\int_{\partial\Omega_t}\tau.vds\right)dt \qquad (1)$$

Some other are much more complex, like a criterion for surface defects. Several formula have been investigated, but further studies of numerous industrial problems are still required to assess the robustness of the proposed one:

$$\Phi_{fold}\left(p\right)=\frac{1}{t_{end}-t_0}\int_{t_0}^{t_{end}}\left(\frac{1}{\int_{\partial\Omega_t^{free}}ds}\int_{\partial\Omega_t^{free}}\left(\frac{\dot{\bar{\varepsilon}}}{\dot{\bar{\varepsilon}}_{ave}}\right)^{\alpha}ds\right)^{1/\alpha}dt \qquad (2)$$

Shape parameters: 3D parameterisation of shape is quite difficult an issue, if we do not want to develop a new CAD system. This is still an open issue, although progresses are quite fast is this area. In this work, only axi-symmetrical perform tool shape have been considered (but the finishing operation is an actual 3D one with complex tools shapes that are not optimized). Bspline curves offer a simple and efficient way to parameterize 2D curves, which are later transformed into 3D ones by rotation.

Optimization algorithms: In the last decade, gradient algorithms appeared to be the only way to solve time consuming problems, like the studied one where a simple computation requires at least one day on a last generation P.C. It so required computing such gradients, and it order to do so efficiently, to differentiate all the simulation problem equations. This tough work was carried out in 2D, using the direct differentiation method [2]. In 3D, using an iterative algorithm to solve the problem equations, the adjoint state method offers a better efficiency, although much more complex to implement [4]. Gradient algorithms are not usually able to find global extrema, getting trapped in the nearest local extrema. At the end of the project, we came to evaluate the TCPIP algorithm, which is a gradient one that allows finding global extrema. Encouraging results have been found, but not for all situations.

Therefore, the more robust approaches rely on evolutionary algorithms, but they are usually quite expensive, requiring large numbers of problem evaluations. Meta-modelling offers an elegant way to disconnect the number of problem evaluations from the number of objective function evaluations. The Response Surface approach is comparable, although different, because it does not make it so natural to improve the Response Surface. Here, meta-modelling is combined to an Evolutionary Strategy, as developed at the Dormund University [5], or to a Genetic Algorithm, as in the hybrid approach that we have developed [6]. The evolutionary populations are evaluated totally or partially by the meta-model. At each generation, the meta-model is enhanced by a fixed and limited number of problem simulations.

4. Main scientific outcome

❖ *Gradient Calculations*

For the gradient calculations, the adjoint state method has been extended to handle two successive forging operations and contact surfaces that are parameterized (so that need to be differentiated). The work has been carried out using the semi-analytical method (a combination of analytical and finite difference differentiations). Quite accurate gradients are so obtained for 3D problems with and without remeshing: error less tan 5%.

❖ *Optimization algorithms*

The main outcome of this work is in the results from the comparison of various optimisation algorithms, for two representative forging benchmarks:

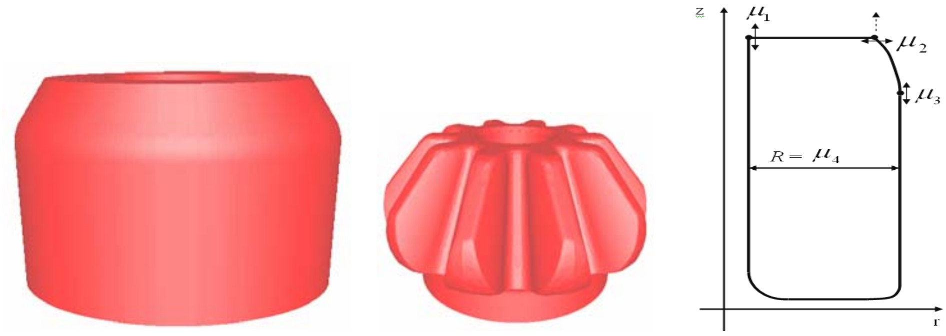
- the shape optimisation of the perform that is utilized to forge a gear, in order to minimize the total forming energy, or a combination of the total forming energy and the surface quality criterion.
- the shape optimisation of the performing tools, for a two-stages process for producing a spindle, in order to avoid the formation of a folding defect

Evolution Strategies based on Meta-modelling: ES-META [5]*:* The algorithm is quite robust, simple to use and efficient. In most cases, it provides the best solution, or the improvements brought by more complex algorithms is not significant

Hybrid algorithm based on clustering: GA-MGC [6]. For the current population of any generation of a genetic algorithm, a clustering algorithm gathers the individuals into a prescribed number of clusters. The objective function and its gradient are then calculated at the gravity centre of these clusters. A linear interpolation can then be applied inside each cluster, allowing to compute an approximation of the function for all the individuals of the cluster. This way, whatever the population size, the function and its gradient are only evaluated for a prescribed number of points. The performances of this algorithm are quite similar to ES-META, but it allows finding a better solution in a shorter time. If we take into account the additional time required by the gradient evaluation (which is not required by ES-META), this algorithm still outperforms it, but less significantly. So the gradient information is a quite interesting way to improve the meta-model.

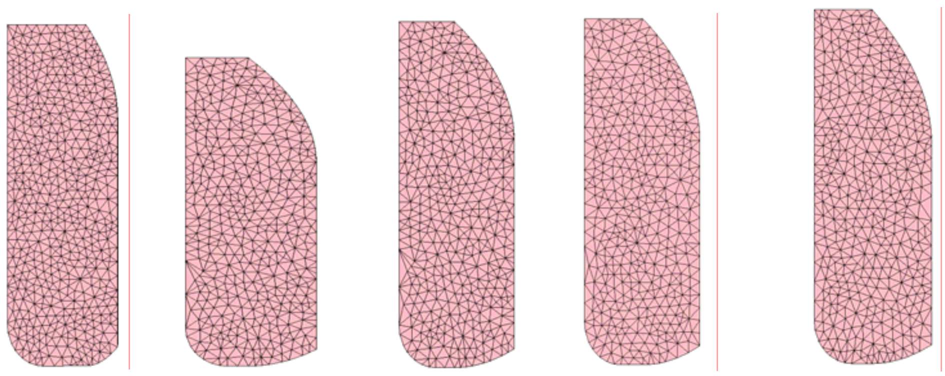
Hybrid algorithm based on Liszka-Orkisz extrapolation: GA-MGO [6]. The previous algorithm, GA-MGC, does not have memory, so it can be improved by taking into account the values evaluated during the previous generations. The objective function is then continuously approximated by a local finite difference scheme proposed by Liszka and Orkisz. At each generation, a criterion helps finding the best locations for the next function evaluation, in order to provide the best enhancement to the meta-model. Benchmarks results show that GA-MGO is very often more efficient than the previous algorithm. In some cases, it allows reducing by a factor of two the number of function evaluations to obtain a result that is comparable to ES-META.

Figure 2 shows the best preforms proposed the four tested algorithms (including the BFGS algorithm, which get trapped into a local optimum, in this case) for the gear forging problem (see Figure 1).



(a) (b) (c)

Figure 1: . Full perform to be optimized (a) and gear shapes (b) *(not real scale)* - Parameterization of the geometry of the radial plane (c)



(a) (b) (c) (d) (e)

Figure 2: .Preform suggested: the forging company (a), BFGS (b), ES-META (c), GA-MGC (d), GA-MGO (e)

The following table shows the number of required simulations and improvement of the objective function.

	ref	BFGS	ES-M	MGC	MGO
	1.19	1.15	1.08	1.075	1.06
%	0	3%	9%	9.3%	10.3%
Nb	0	7 (stag)	50	40	40

5. Main technical outcome

The feasibility of 3D shape optimisation has been demonstrated for complex metal forging applications. A 2D version of the software has been developed and implemented into a forging company, which uses it to solve tough design problems.

6. Collaboration within COST 526

- French funded project "OPTIMAT" gathering all French partners of APOMAT (MECALOG, LMA, UTC, ENSAM, CEMEF) and TRANSVALOR (software house) and Amis (forging company) following same objectives as APOMAT, the optimization of metal (sheet, bulk, powder) forming processes.
- University of Dortmund, Germany, Chair of System Analysis, collaborative work on Optimization Algorithms based on Evolutionary Algorithms
- University of Twente, Netherlands, Faculty of Engineering Technology, collaborative work on Optimization Algorithms based on Meta modelling

7. Cooperation with industry

This work has been carried out in collaboration with the following companies: Setforge, Sifcor, Forge de Bologne, Snecma (French forging companies) and Cetim (Technical Center of Mechanic Industry). They have participated to the project by providing industrial problems for testing and validating Optimization Algorithms and Methodology.

8. References

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