

**COST 526 – Project 'Automatic Process Optimization in Materials Technology' –  
(APOMAT)  
Final Report**

Optimization of sheet-metal blanking and bending-process. Application to the forming of High Strength Steel security parts.

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## 1. Introduction

The increasing demand for part quality and reliability in automotive industry is one of the main challenge the companies are faced to. The manufacturing of security parts is illustrated by figure 1 in which the most important stages are blanking and bending.

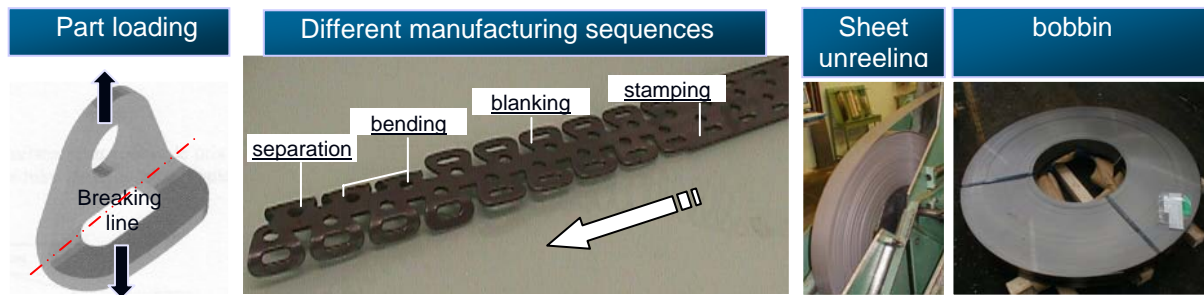


Figure 1- Different stages of sheet-metal parts manufacturing

The association of the material behaviour knowledge, which is highly dependent on the providers, with the mechanical process characteristics, is a technical locking to be overcome.

## 2. Goal of the project

The goal of the research was to provide engineers with a reliable tool allowing for accurate numerical simulation of the manufacturing process and prediction of the parts resistance when subjected to a shock. For that purpose, the optimisation of the part shape and process parameters has been carried out. It was necessary to account for the material behaviour evolutions during the process and this was done by defining a material damage function coupled with elasto-plasticity in the field of continuum mechanics.

At the end of the simulation it is possible to have an accurate knowledge of the stress and damage fields in the whole part after bending and then to predict the part resistance to a sudden shock.

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

The numerical simulation is carried out with ABAQUS Standard F.E. code and a User's Subroutine UMAT. The subroutine includes an incremental formulation fully consistent with the integration scheme. The material behaviour law was developed in the field of continuum mechanics with a fully coupled damage and elasto-plasticity theory.

### 3.1. Material characterisation

The first stage of the study was to characterise the material behaviour. The sheet-metal is a Low Alloyed Steel with a high elasticity limit. The stress- strain law is modelled by the following relation, including the damage function  $D$  [1]:

$$\sigma = (1-D)\mathbf{C}\varepsilon \quad (1)$$

$\sigma$  and  $\varepsilon$  are the stress and strain tensors.  $\mathbf{C}$  is the elastic tensor. The damage function depends on the plastic-strain evolution according to the incremental form:

$$\dot{D} = \frac{D_R}{\varepsilon_R - \varepsilon_D} \left[ \frac{2}{3}(1+\nu) + 3(1-2\mu) \left( \frac{\sigma_H}{\sigma_{eq}} \right)^2 \right] \dot{\varepsilon}_{pl} \quad (2)$$

$D_R$  is the damage value at rupture,  $\varepsilon_R$  and  $\varepsilon_D$  are the strain values at rupture and damage initiation point.  $\sigma_H$  is the hydrostatic stress and  $\sigma_{eq}$  is the von Mises equivalent stress.

### 3.2. Process simulation

The simulation was carried out by means the Finite Element code Abaqus Standard in which was implemented a special User's subroutine UMAT accounting for the material damage computation. The numerical results were compared to the experiences and a typical study is shown in figure 2.

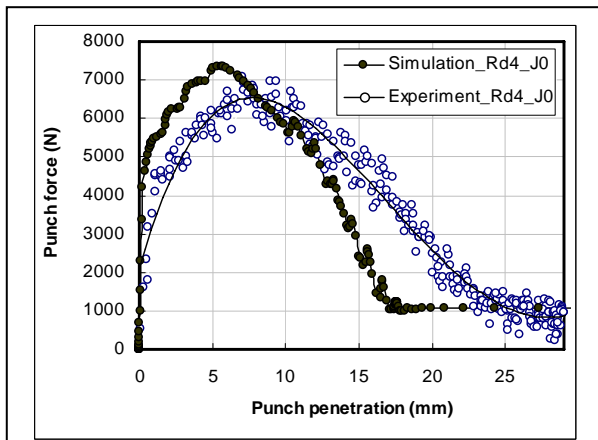


Figure 2- Punch force evolution in bending

#### Calibration procedure

The accuracy of the simulation is carried out by comparing the punch force values between computation and experience.

The computed punch force evolution is found to be quite different to experimental results due to the press behaviour during the loading and the unknown friction-coefficient evolutions. The difference is about 8% for the maximum punching force, which is assumed to be sufficiently accurate for the following investigations.

The simulation of specimen bending (figure 3) leads to the determination of the stress and damage fields around the central hole where they take their higher values..

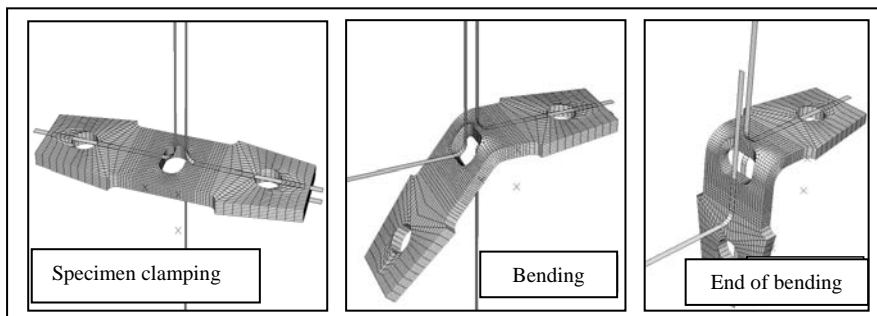


Figure 3- Virtual representation of the specimen bending

### 3.3. Quality functions

The numerical study of wiping-die bending of specimens with oblong hole was led to predict their behaviour when subjected to a sudden unbending.

Taking into account the preceding observations, the aim of the study is double:

- 1- Maximisation of the part strength during use: this is realised by minimising the residual stress field  $\sigma_{VM}$  and the material damage  $D$  generated during the bending operation.
- 2- Minimisation of the forces undergone by the tools: this is realised by minimising the maximum bending load  $F_{bmax}$  applied by the punch on the part.

These optimisation problems are subjected to technological and mechanical constraints such as: obtaining an accurate shape of the part and avoiding cracks initiation and wrinkling of the sheet.

The general parameters of the process are related to:

- a) The material: the corresponding variables are mainly the modulus of elasticity  $E$ , the Poisson's ratio  $\nu$ , the work hardening law and the damage law evolution.
- b) The geometry of the tools: the associated variables are related to the punch and die radius  $R_d$ , the clearance  $J$  between tools and sheet, the bending angle resulting from the die shape.
- c) The manufacturing process: the corresponding variables are the lubrication and its effects on the friction between part and tools, and the punch stroke.

### 3.4. Optimisation algorithm

The optimisation strategy (figure 4) is based on functions approximations, Response Surface Methodology [2] and Evolution Strategies [3].

This is carried out by means of an algorithmic loop between a CAD software (Solidworks), a Visual Basic routine exchanging the design parameters of the part shape, a fortran program in Abaqus which starts the computation of the stress and damage fields values and writes the results in a text file. The corresponding flow chart can be viewed on figure 5.

#### - Application to the part shape optimisation

The part shape was optimised by changing step by step the radius and the length of the oblong hole as well as the external form of the triangular part by means of the above mentioned algorithm.

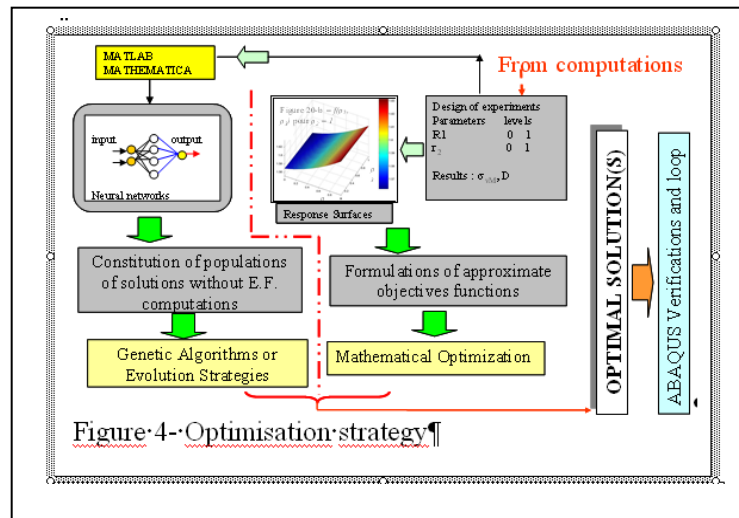


Figure 4- Optimisation strategy

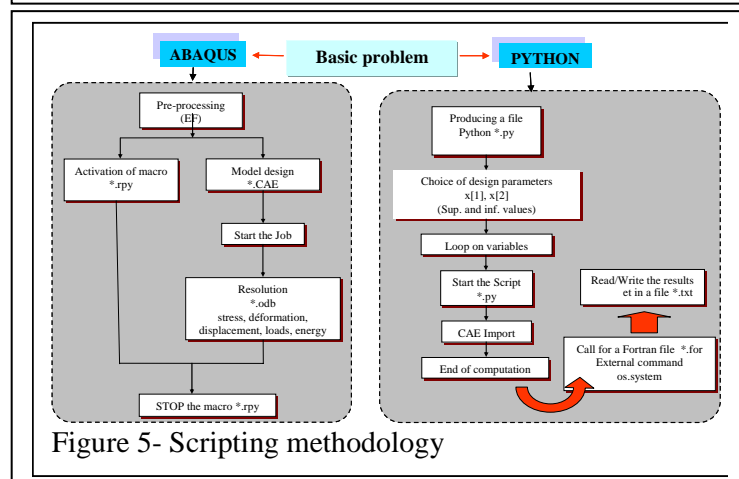


Figure 5- Scripting methodology

### 3.5. Process parameters optimisation

The two objective functions, that is maximum material damage and von Mises stress values, are shown on figure 6. They depend on the two design parameters  $R_d$  and  $J$  related to the bending process. The objective functions are approximated by polynomials (equation 3) and they are represented in the form of Response Surfaces reported on figure 7 and 8.

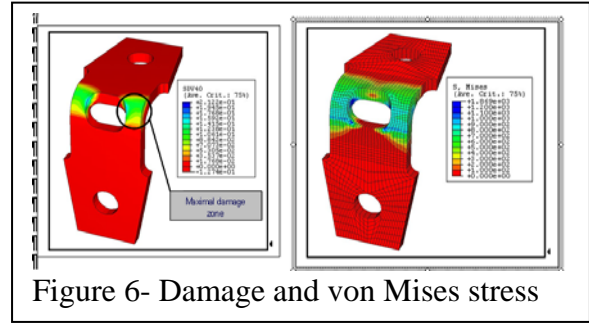


Figure 6- Damage and von Mises stress

$$f = \alpha_0 + \sum_{i=1}^n \alpha_i x_i + \sum_{i=1}^n \alpha_{ii} x_i^2 + \sum_{i < j} \alpha_{ij} x_i x_j + \sum_{i=1}^n \beta_{ii} x_i^3 + \sum_{i=1, i \neq j} \beta_{ij} x_i^2 x_j + \sum_{i=1}^n \gamma_{ii} x_i^4 + \sum_{i=1, i \neq j} \gamma_{ij} x_i^3 x_j + \prod_{i=1}^n \xi x_i^2 \quad (3)$$

The  $x_i$  are the process parameters and the  $\alpha_{ij}$   $\beta_{ij}$   $\gamma_{ij}$  are computed by a least squares minimisation technique.

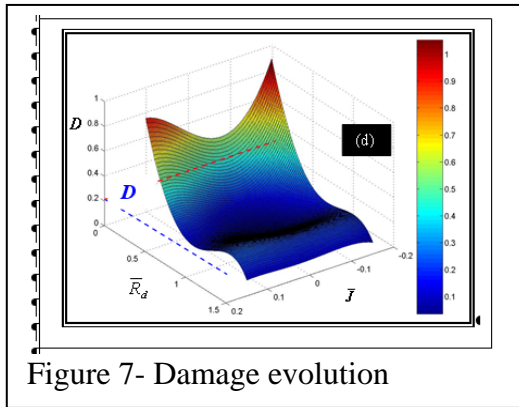


Figure 7- Damage evolution

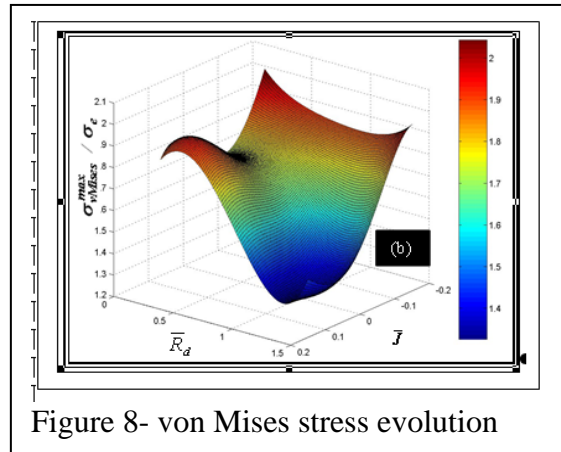


Figure 8- von Mises stress evolution

The optimum values are found by using a Moving Least Squares methodology [4] and an Evolution Strategy.

### 4. Main scientific outcome

The COST project was an opportunity to enter in some new optimisation methods for us, like Response Surface Methodology, Evolution strategies, Moving Least Squares or more generally Meshless approximations. A methodology based on these methods was defined and implemented in commercial F.E. code for process simulations. Robust algorithm for material damage characterisation has been developed during the work as well as the implementation of Script algorithms in Python language.

### 5. Main technical outcome

The process parameters optimisation allows for industrial applications in sheet-metal forming industry. Experimental and numerical investigations have shown the accuracy of the proposed methodology.

### 6. Collaboration within COST 526

Short term scientific mission

Dr Slim Ben Elechi from "Université de Technologie de Compiègne" (France) which is a COST partner, spent a week in our laboratory in Angers. He provides us with a Moving Least Squares approximation technique for the bending process optimisation.

Implementation of his work allows us to enhance the accuracy of the optimum search parameters values in bending process optimisation. The algorithm he developed in Matlab language is now available in our methodology.

All COST meetings were places of stimulating ideas exchange and our research team is very grateful to the European Community to manage such programs.

### **7. Cooperation with industry**

A direct cooperation has been developed all along the project time with the french company: Société DEVILLÉ S.A. Zone Industrielle de Beauregard  
49150 BAUGÉ (France) tel : 00 33 (0)2 41 84 41 41

The company is a European leader in manufacturing automotive security devices. The work done in collaboration is focused on the industrial characterisation of the material and further, the behaviour of security parts subjected to shocks. An industrial device was let at our disposal in order to realise shock experiences on the specimen related to the real part.

Many special press tools and materials were also provided by the company. A technical engineer work with us at 10% of its working time.

### **8. References**

[1] J. Lemaître, J.L. Chaboche. *Mécanique des matériaux solides*. Dunod Paris, ISBN2-04-018618-2, 1988, p 343-444, (in french)

[2] Myers RH, Montgomery DC. *Response Surface Methodology. Process and Product Optimisation using Designed Experiments*. John Wiley and Sons, Inc., New York, USA, 2<sup>nd</sup> ed. 2002

[3] N. Hansen, A. Ostermeier. Completely derandomised self-adaptation in evolution strategies. *Evolutionary Computation*, (9) 2 p 159- 195

[4] P. Breitkopf, A. Rassineux, P. Villon. An Introduction to Moving Least Squares Meshfree Methods. *Revue Européenne des Eléments Finis* Vol 11, 7-8, p 825- 868, 2002,

### **9. Related main publications**

1- MKADDEM A., HAMBLI R., POTIRON A. "Comparison between Gurson and Lemaitre damage models in wiping die-bending process", *International Journal of Advanced Manufacturing Technology*, Vol 61 issue 2, August 2004 p 303-315.

2- MKADDEM A., BOUDE S., DAL-SANTO P., POTIRON A. "Springback evaluations in wiping die-bending processes with experimental verification", *International Conference on material forming ESAFORM 2004*, Apr.28-30, Trondheim Norway.

3- MKADDEM A., BAHLOUL R., POTIRON A., DAL SANTO P. "Experimental and numerical investigation in sheet bending processes using Response Surface Methodology", *Congress of materials and manufacturing engineering and technology COMMENT 2005*, May 16-19, Gliwice-Wista Poland, pp 156.

4- MKADDEM A., BAHLOUL R., POTIRON A. "Numerical analysis and response surface method to investigate friction effects in sheet bending application", *International conference on material forming ESAFORM 2005*, April 27-29, Cluj-Napoca Romania, pp 261-264.