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Sheet metal bending optimisation using response surface method, numerical simulation and design of experiments

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Abstract

Bending is one of the processes frequently applied during manufacturing of automotive safety parts that are obtained by successive sequences of blanking and bending. This paper describes a 3D finite element model used for the prediction of punch load and the stress distribution during the wiping-die bending process. The numerical simulation has been modelled by means of elastic plastic theory coupled with Lemaître's damage approach. Numerical simulations were carried out by using the ABAQUS/Standard FE code, for a sufficient number of process parameters combinations, particularly the die radius and the gap between the punch and die. An algorithmic loop, programmed in the Script Language of ABAQUS, was developed in order to investigate the mechanical response of parts bent on a mechanical press for each combination of process parameters. The punch load and stress distribution can be predicted in view of optimising the values of the main parameters involved in the process. Finally, a response surface methodology (RSM) based on design of experiments (DOE) was used in order to minimise the maximum punch load during the bending operation. Numerical results showed the suitability of the proposed model for analysing the bending process. Associated plots are shown to be very efficient for a quick choice of the optimum values of the bending process parameters.

Keywords: Bending process; 3D finite element modelling; Script; Optimisation; Design of experiments; Response surface methodology

1. Introduction

Nowadays, numerical simulations has become a powerful tool in manufacturing processes such as stamping, bending and blanking in order to optimise sheet-metal forming. The optimisation is closely related to the physical characteristics of the material and its behaviour after forming. Most sheet steels commonly used for automotive and other manufacturing applications, have good mechanical properties, such as high ductility and yield strength. Quality criteria for end products are related to geometrical shape accuracy and mechanical performance. Parniere [1] pointed out that the success of a product manufactured by stamping, deep drawing or more particularly by wiping-die bending, primarily depends on three factors: (a) the material characteristics, (b) tool geometry and (c) the lubrication associated with the forming operation. These three factors are not independent; a good choice of tool geometry in some cases may compensate the poor mechanical properties of the sheet-metal.

Apart from material bendability, the prediction of punch load evolution and maximum stresses arising within the sheet are important aspects of bending. These predictions can be handled using analytical methods, approximate numerical analyses and the finite element method. Davies et al. [2] conducted one of the few experimental studies available in the literature on straight-edge flanging (wiping-die bending). They studied the influence of die radius, punch and die gap, the kind of steel and yield stress on sheet springback. They established that for a given relative die radius R_d/t and a given material, the springback angle increases linearly with increasing punch and die gap.

Chou and Hung [3] studied the influence of the process design corresponding to industrial practice, on the reduction of springback occurring in the production of U-channel parts. Four techniques were investigated for that purpose: arc bottoming, the pinching die technique,

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spanking operations and movement operations. In each case they used an optimisation program (MOST) coupled with Abaqus and the results were analysed by response surface methodology (RSM). Contour surface plots were used to observe the effect of each of the parameters in each method on the springback. Karafillis and Boyce [4] developed a tool design algorithm to compensate for springback errors based on FE simulation results of stamping processes for 2D and 3D geometries.

The optimisation of forming processes aimed at the production of precision components and high resistant products, is nowadays one of the fundamental research topics in the automotive. As a reliable methodology, design of experiments associated with response surface approximation are retained in several cases for the analysis and optimisation of sheet-metal forming problems. More widely, design of experiments (DOE). and RSM. are useful methods for engineering purposes such as the quality control of mechanical and geometrical properties of a workpiece.

Todoroki et al. [5] presented a new method of experimental design to obtain a response surface for the buckling load of laminated composites. The new experimental design is a set of stacking sequences selected from candidate stacks using a *D-optimality* criterion. Consequently, the *D-optimal* set of laminates is deduced from design of experiments and the corresponding response surfaces. This is shown to be an effective method for maximisation of the buckling load of composite structures.

An optimum process design system for sheet fabrication was developed by Ohata et al. [6] by using the response surface method. The aim of this optimum system for process design, is to assist the decision of material process-conditions for making a sheet-metal with the best formability for stamping. This system is carried out by combining finite element analysis and discrete optimisation algorithms. In this system, the optimisation algorithm is required to search the optimum condition quickly. Therefore, the response surface method used to improve the efficiency of the retrieval.

An inverse simplified approach (IA) is developed by Naceur et al. [7] and combined with a BFGS algorithm for the numerical simulation and optimisation of deep-drawing of thin metallic sheets. This IA takes into account the a priori knowledge of the final shape of the workpiece and involves a discretisation of 3D surfaces by triangular facet membrane/shell elements and the computation of the inverse deformation gradient-tensor to estimate the large logarithmic strains.

Optimisation of the forming process by the traditional trial and error approach based on the adjustment of empirical rules is not usually applicable to complex geometries or materials without a large database of experiments. It involves changing one independent variable of the problem while all other parameters are fixed in a given level [8]. This is highly time-consuming and expensive for a large number of variables. To overcome this difficulty, experimental factorial design and response surface method can be employed to optimise a multi-parameters problem [9–11]. In this paper, a numerical simulation has been carried out in order to decide suitable process parameters in the bending operation. Bending of specimens with special shapes is modelled by using a FE code. Numerical results are obtained for an extensive combination of die radius values and the clearance between tools and blank. An algorithmic-loop programmed in the script language of ABAQUS was developed to investigate the mechanical response of each combination of parameters. The results are plotted for the characterisation of the bending loads and stress fields at the end of the bending stage, before springback occurs. The objective functions which are the maximum bending load and the stresses located at the most loaded finite element, are analysed by applying a RSM. Hence, it is possible to predict the best choice of the process parameters in order to avoid any fracture or macro-crack initiation resulting from the material damage of workpiece.

2. Elasto-plasticity material behaviour coupled with damage

The main difficulty encountered in simulating this operation, is to describe continuously the sheet behaviour, from the beginning of the operation up to the end of the bending step [12]. Accurate knowledge of the failure process is essential to the selection of a suitable damage model. In the case of sheet-metal forming, numerous authors have studied the different physical mechanisms leading to the final rupture and proposed their own models.

In this paper, the Lemaître [13] damage formulation is fully coupled with the behaviour laws of elasto-plasticity. The von Mises yield criterion holding for isotropic materials completes the full set of constitutive equations which are retained to simulate the process. The algorithms generally implemented in finite element codes for integration of non-linear constitutive equations are based on radial return algorithms, and incremental formulation of equations. They are based on the notion of an elastic predictor–plastic corrector where a purely elastic trial state is followed by a plastic phase [14]. The integration methods of non-linear constitutive equations are based on the use of a special algorithm which solves the equations in incremental form.

2.1. Basic formulation

In this study, the material is assumed to be isotropic and the material damage is a scalar function D of the accumulated effective plastic strain $\bar{\varepsilon}^{pl}$. The Lemaître formulation based on equivalent strain leads to the following relation between the stress and strain tensors $\boldsymbol{\sigma}$ and $\boldsymbol{\varepsilon}$:

$$\boldsymbol{\sigma} = (1 - D)\ \mathbf{C}_{el}\ \boldsymbol{\varepsilon}^{el}, \tag{1}$$