Experimental validation of optimisation strategies in hydroforming of T-shaped tubes

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ABSTRACT: For three dimensional tube hydroforming operations (i.e. T or Y shaped tubes) the calibration of both material feeding history and internal pressure path during the process is crucial and many approaches to such optimization were presented; the authors developed some procedures to optimize pressure paths and punch velocity histories with the application of an integrated method FEM - Gradient based optimization tools. In this paper, an experimental validation campaign of the utilized optimization strategies is presented with the aim to assess the effectiveness of the developed procedures. An optimization procedure (gradient based techniques) was applied on the process parameters leading to the determination of an optimal pressure path. Finally, a testing machine was set up to carry out hydroforming operations on T-shaped tubes. The developed equipment allows a computer assisted control of both the internal fluid pressure paths and the punches actions (material feeding paths). The experimental evidences validated the results obtained by the optimization strategies utilized to design the process parameters.

Key words: Tube hydroforming, Optimisation algorithms, Experimental validation

1 INTRODUCTION

The increasing interest on tube hydroforming operations in automotive field have pushed a strong scientific interest in the investigation of such processes. In particular, relevant efforts were made to study process mechanics and operative parameters even for complex shape components production.
It is well known that tube hydroforming processes take place thanks to the concurrent actions of pressurized fluid and mechanical feeding which allow to obtain tube shapes characterized by complex geometries [1]. The calibration of such actions is the main topic in the design of tube hydroforming operations in order to prevent bursting and/or buckling defects. Recently, many researches have proposed several approaches to the optimization of the tube hydroforming operative parameters such as gradient based optimization methods integrated with numerical simulations [2,3]. As well, one of the main research fields was focused on three dimensional processes such as the ones aimed to the production of T or Y shaped tubes: some authors analysed the effects of operating parameters on the final part quality [4]; other researchers investigated the optimization of loading paths basing on finite element method [5,6] or utilizing fuzzy logic [7,8]. Recently, the authors developed some procedures to optimize pressure paths in a fully three dimensional tube hydroforming operation aimed to produce a T-shaped tube [9]. In particular, in the early stage of the research project on T-shape tube hydroforming, the authors developed a numerical simulations campaign in order to analyze the influence of pressure path on the final product quality. The basic idea of the investigation concerned the possibility to determine useful wrinkles at an early stage of the process in order to achieve good results in terms of maximum thinning on the final part together with satisfying final geometry of the component. The numerical campaign developed on T-shape tube hydroforming led to a knowledge base about the process mechanics which was utilised in order to implement

an optimisation procedure. In this paper, a gradient based optimization technique was developed, basing of the available knowledge base, in order to determine optimal pressure paths to reduce fracture danger in a T-shape tube hydroforming operation also with the aim to increase the height of the tube bulged zone. Moreover, the developed optimisation procedure was experimentally validated by setting up a proper experimental equipment able to apply the optimised pressure path. In the following, the optimisation methodology and the experimental campaign will be discussed and the results of the validation procedure will be presented.

2 THE OPTIMISATION PROBLEM

The investigated process optimisation was developed through the application of a gradient based optimisation technique.

The formulation of the optimisation problem was performed according to the following steps:

- definition of the set of design variables;
- identification of the objective function;
- solution of direct problems (i.e. numerical simulations aimed to evaluate the values assumed by the objective function at the varying of the design variables);
- determination of the optimum values of the design variables.

The analytical formulation of the above mentioned problem can be assessed as follows:

1. identify the design variables by a vector x;
2. choose the initial values: $x_k \in R_n$ with $k=0$ (k denotes the method iteration number);
3. calculate the gradient of the objective function $f(x_0)$: if the convergence is reached the algorithm can be stopped;
4. else calculate an updated value of the design variables $x_{k+1}= x_k+\alpha_k d_k$ (where the scalar $\alpha_k \geq 0$ is called "step size" or "step length" at iteration k and indicates the entity of design variables adjustment at iteration k; d_k is the direction of movement i.e. the direction along which the objective function goes towards a minimum;
5. verify that $f(x_k+1) < f(x_k)$;
6. repeat step 4 and 5 until convergence is reached.

Such general approach can be refined according to different techniques with respect both to the gradient calculation and to the definition of step size and step direction. Among the different possibilities available in the literature, the procedure proposed in this paper is the steepest descent method. Such method is based on the hypothesis that if a minimum of the objective function is required then the search direction is given by the opposite of the function gradient. In this way, a finite difference method was utilized in order to calculate the gradient; fixing a perturbation of the design variables ε it was possible to calculate the gradient as follows:

$$\nabla f(x_k) = \frac{f(x_k+\varepsilon)-f(x_k)}{\varepsilon}. \qquad (1)$$

The calculation of the gradient required the evaluation of the objective function values for each value and for each perturbation of the design variables. Such evaluation of the objective function was obtained through a FEM code which provided the desired values of the objective function at each iteration of the applied method. As the step size evaluation is concerned, a line search procedure was utilized in order to determine the most performing value. The method is stopped when the convergence is reached, i.e. when the function gradient is equal to zero and the objective function is minimized. It is worth pointing out that, the solution reached in the presented application is optimal from a technological point of view: if the reached optimum is satisfying in terms of product quality, it can be considered a good solution for the given design problem. More in details, the aim of this paper was the optimization of a T-shape tube hydroforming operation. The main goal of the optimization was the minimization of maximum thinning and the increasing of the bulge height obtained at the end of the process. Thus, the objective function utilized in this application consisted of two terms: the former is the maximum thinning on the tube walls ($t\%$) and the latter measuring the distance (d) between the desired bulge height (h_{tot}) and the obtained one. The optimisation was focused on the internal pressure vs. punch stroke curves in order to determine the optimal internal pressure paths. According to previous experience on the analysed operation, the hypothesised shape of such curves consists of a former phase in which internal pressure is kept constant and a latter phase in which the internal pressure had a linear trend reaching a maximum value. In particular the pressure value in the early phase of the operation was fixed to a value which guarantees the avoidance of wrinkling defect; such value was chosen on the basis of the knowledge base (numerical and experimental) available on the operation. Thus, two design variables were chosen to implement the optimization procedure, namely the pressure peak value in (p_{max}) and the punch stroke value corresponding to the beginning of the latter phase (s_1). The chosen tube material is AA 6060-T6 alloy with a tube initial thickness equal to 1mm and an external diameter equal to 50mm. The application of the above mentioned optimisation procedure led to an optimal pressure vs. punch stroke curve which was experimentally reproduced on the available equipment. The experimental campaign and fixtures as well as the optimisation results and validation are presented in the following sections.

3 THE EXPERIMENTAL EQUIPMENT

A suitable tube hydroforming machine was designed and built in order to carry out the experimental campaign. The construction scheme was developed with the aim to obtain a flexible equipment able to produce hydro formed parts characterized by different shapes just varying the dies profile. Figure 1 shows a sketch of the equipment utilised to obtain the T-shaped tube investigated in this paper. Both the upper and lower dies are made of 38NiCrMo4 steel and were manufactured on a 4 axes Mazak milling machine. One of the fundamental equipment components is the so-called axial push unit; it allows the material movement and it can be split in five different components (Figure 2). The inner bar was designed in order to unload the water pressure directly on the equipment frame reducing the punch force necessary to carry out the forming process. The water and the oil pressure, used, respectively, to guarantee the tube inner shove and the cylinders movement, were generated and managed thanks to separate circuits composed by a pump, an electro valve and an accumulator. The latter one plays an important role in order to avoid the sudden pressure variation that is a typical phenomenon for the volumetric pumps. The maximum available water pressure is about 70MPa, while the cylinders can provide a force which can reach a value of 100kN. A third punch that escorts the material moving during the forming phase is, instead, managed by a suitable pre-load spring. An overview of the available equipment is shown in Figure 3: it is able to reproduce the pressure paths obtained by the optimisation procedure as it will be discussed in the following. The equipment frame presents a symmetrical lay-out whose dimensions are reported in Figure 4. It was designed to let a good assembly of each machine component.

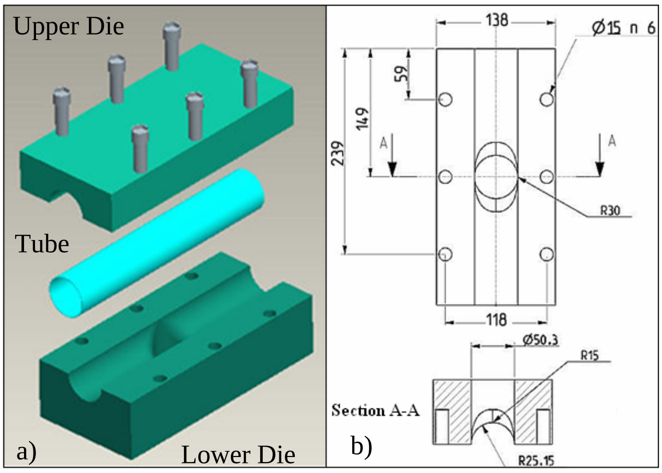

Figure 1: a) tube and dies; b) lower die dimensions.

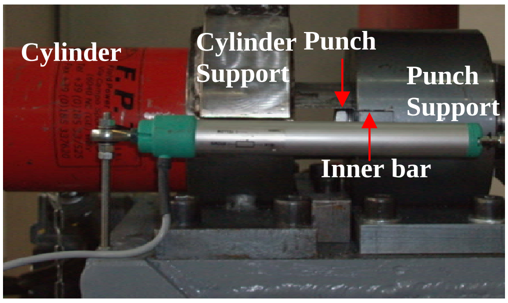

Figure 2: The axial push unit.


Figure 3: T tube hydroforming equipment.

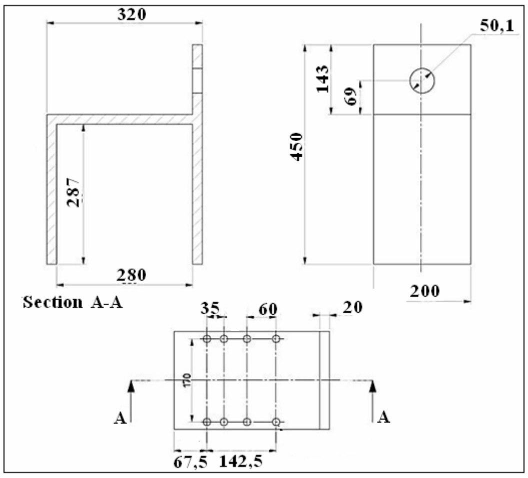

Figure 4: Equipment frame dimensions.

4 RESULTS AND CONCLUSIONS

The optimisation procedure described in section 2 led to the optimal pressure curve shown in Figure 5 (in comparison with the initial curve) after only two iterations of the method.

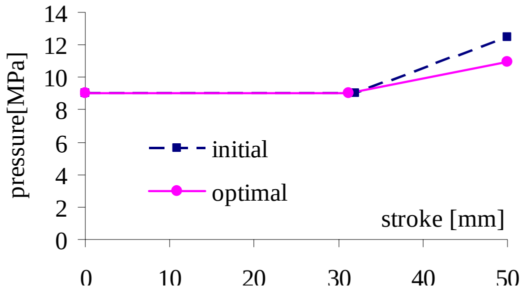

Figure 5: Initial and optimal pressure curves (thickness: 1mm).

It has to be underlined that the results of the optimisation procedure did not allow to obtain a T-tube of the desired bulge height since, with the utilised tube thickness, a strong wrinkling effect was detected. In fact, the experimental validation of the results confirmed such predictions: in Figure 6 a good matching between numerical and experimental test is observed utilising the optimal pressure curve, nevertheless the desired geometry is not reached. The main reasons of such results is related to the utilised tube thickness, thus the optimisation procedure was again applied but utilising 1,5mm thick tubes. Actually, the good matching between numerical prediction and experimental results obtained with 1mm thick tubes allowed to validate the optimisation predictions.

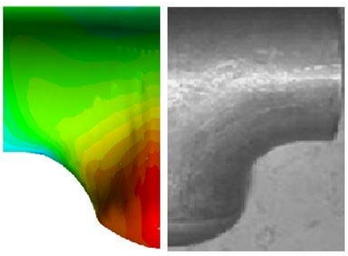

Figure 6: T tube hydroforming equipment.

The optimisation result for 1,5mm thickness are illustrated in Figure 7: with the optimised pressure curve a bulge height of about 36mm was reached with a maximum thinning of 8%. The numerical predictions show a sound final component (Figure 8) proving the effectiveness of the proposed approach. Further experimental tests will be set up in the next future to reach a better tuning of the optimisation procedure also for different tube shapes.

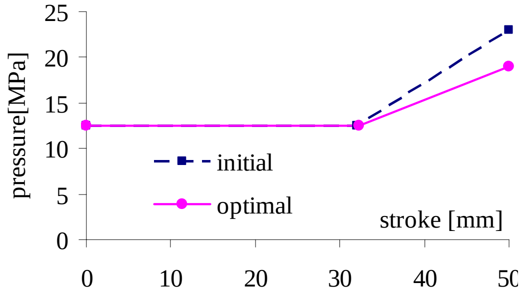

Figure 7: Initial and optimal pressure curves (thickness: 1.5mm).

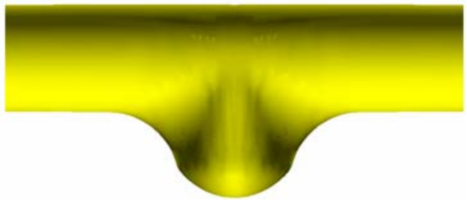

Figure 8: The final component (thickness: 1.5mm).

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