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Global optimisation of the production of complex aluminium tubes by the hydroforming process

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ABSTRACT

With the recent development of analysis software products, designers and engineers are able to design more complex parts to obtain better performance in the final products. In this study, the tube hydroforming process, including preceding processes, i.e. variable thickness tube drawing and two-step bending, are globally optimised to obtain parts without any problems like bursting or un-filled zones at the end of the forming processes. Unlike most previous studies which searched for an optimum hydroforming process by changing two hydroforming parameters, i.e. axial load feeding and internal pressure, in this study, the distribution of initial tube wall thickness and the variation of thickness due to bending steps will be taken into account in a global optimisation algorithm. The developed algorithm is a general-purpose algorithm that can encompass different processes and change various parameters in each process to be able to reach the global objective. The case study used was a part that needs two-step variable thickness tube drawing, and two bending steps before hydroforming. To verify the numerical results in each forming stage and at the end of all forming processes, extensive experiments were performed, and acceptable agreements were observed.

Introduction

Aluminium tubes, mostly produced by the tube hydroforming (THF) process, play an important role in transportation industries such as automotive and bicycle production. As shown in Fig. 1, in fabricating almost all THF parts, it is necessary to use some other preliminary processes like tube drawing, annealing heat treatment, tube bending, and preforming before the final THF process. The wider application of aluminium tubes by industry is hindered because of the reduced ductility and more complex material behaviour of aluminium in comparison with steels [1].

Various aspects of the THF process have been studied. Xu et al. [2] presented a paper to find the optimum loading path for a trapezoid-sectional die. Cheng et al. [3] studied distribution of thickness in a Y-shape tube by the finite element (FE) and experimental methods. Xu et al. [4] mathematically studied thickness distribution along the cross-section of a square-sectional hydroformed part. Fiorentino et al. [5] proposed a new procedure for friction estimation in THF processes. Koç et al. [26] presented experimental and analytical approaches to characterise materials for the THF process. Korkolis and Kyriakides [6] evaluated the effect of loading path on the failure of inflated aluminium tubes. Hashemi et al. [7] applied a stress-based forming limit diagram to obtain optimum loading paths in THF. Song et al. [8] evaluated the effect of flow stress characteristics of tubular material on forming limit in the THF process. Bortot et al. [9] determined a new test method to characterise the flow stress for the tubes in the hydroforming applications. Kang et al. [10] studied tube size effect on hydroforming formability. The publications above are examples of research performed in this field. However, on the subject of this paper, which is studying the THF process including the preceding processes, there is only little research. For instance, Koç [11] evaluated effect of die crushing and pre-bending on the thickness distribution and formability of complex tubes. Trana [12] showed that the preforming process can be performed by the hydroforming die closing, saving considerable time and production cost. Hwang and Altan [13] studied the crushing processes in combination with performance in a rectangular die. None of the above mentioned studies, however, included the initial tube

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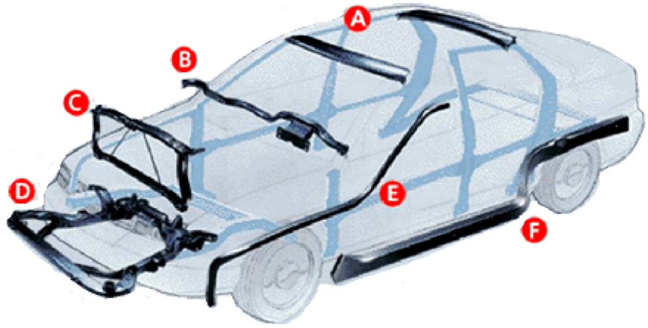

Fig. 1. Tubular automobile parts produced by the THF method. (A) Roof headers, (B) instrument panel support, (C) radiator supports, (D) engine cradles, (E) roof rails, and (F) frame rails [http://www.vari-form.com] [24].

thickness as an optimisation variable. There is also no specialised optimisation algorithm, nor an automatic method to manage the optimisation procedure.

Abedrabboa et al. [14] presented an optimisation process linked with a FE model to optimise the high-strength steel tube hydroforming process. In that study, despite having an optimisation algorithm for modification of the hydroforming parameters, they only took into account the THF process without preceding processes.

In this paper, in the first step, a code was developed to assign various thicknesses to the initial tube wall. This shell with various thicknesses is considered as the tube issued from one- or two-step variable wall thickness tube drawing. It is worth mentioning that because of the annealing heat treatment after tube drawing, it is assumed that all material properties return to the initial state and there are not any residual stresses induced by the drawing. After assignment of thickness to the shell tube, the FE model is transferred automatically to the bending steps, and afterward the bent tube is transferred to the hydroforming step. Depending on the defined objectives and constraints, the optimisation loop will return to the initial step to change tube thickness and/or some parameters in the hydroforming step to reach the objective. All of the changes in the parameters of the preceding processes and hydroforming step are performed automatically without any user interaction.

In the next sections, the processes and their FE models that are involved in the production of the case study part are explained. The experimental section explains the geometric features of the part and the experimental rig.

Cold forming processes prior to hydroforming

In general, for most THF processes, some preform processes are necessary. Without them, the tube cannot be positioned in the THF die appropriately. Furthermore, the quality of the preceding operations has a direct effect on the quality of final workpiece. In the following sections, the important cold forming processes prior to THF are studied numerically and experimentally.

Variable thickness tube drawing

Production of variable thickness tubes

The variable thickness tube drawing process is a new enhancement applied to the classic tube drawing method to produce tubes with variable thickness along the tube's length and/or in the radial direction. As explained in more detail in prior publications like Bihamta et al. [15,16], in this method, the desired variation of wall thickness can be induced through the application of axial displacement of the conic mandrel. However, in this process some parameters like material heat treatment, its alloying elements, and tool geometry, limit the minimum attainable thickness in one step; if smaller than that is required, it should be performed in more than one step. On the other hand, if two or more tube drawing steps are necessary, the synchronisation between two passes is a crucial factor. If the location of thickness reduction in the second step is not in the appropriate zone, there is a possibility of tube fracture. There are two solutions to avoid this problem.

The first solution consists of applying a very accurate non-destructive measurement mechanism, such as a laser, to accurately measure the thickness along the tube axis and implement very precise axial displacement to the tube in the next steps. The implementation of the first solution requires very precise and expensive equipment. Another alternative is the application of mild transition between zones with variable wall thicknesses. This mild transition can guarantee that if there is inaccuracy in the second pass, the tube will not experience any rupture.

In the zones that are more prone to bursting in the hydroforming step, augmentation of thickness in the initial tube can eliminate the chance of bursting, and the final thickness in the tube can be controlled. On the other hand, if a zone in the part undergoes lower loads than other regions when in service, the thickness of this region can be reduced to diminish overall weight of part.

Details of the numerical and experimental studies on this process are outside the scope of this paper; interested readers can see Bihamta et al. [15,16].

Tube thickness as an optimisation variable in the THF process

In this study, it was possible to use solid elements or shell elements to include initial tube thickness in the global THF process optimisation. If solid 3D elements are to be used in the tube bending and THF steps, four-node 2D elements can be used in the tube-bending step. Due to the axi-symmetric geometry of the tube drawing process, the results can then be rotated and converted to complete a 3D tube. In comparison with shell elements, this kind of element has more precision in prediction of thickness variation in the THF process [17], but utilising them seems to be computationally very expensive. On the other hand, application of shell elements for the simulation of THF and tube bending processes seems to be more efficient computationally, and provides acceptable results.

Since it is common to do annealing heat treatment after one- or two-step tube drawing, the material property in the drawn tube (after heat treatment) is considered to be the same as the initial material. Therefore, the inclusion of the tube drawing processes in the global optimisation loop seems to be unnecessary, and will increase the computation time. Consequently, the parameter that was included from the tube drawing process is variation of thickness in the tube.

For implementation of thickness in the initial tube, a code was developed and included as a part of the preprocessor in the optimisation loop to update values of thickness in the optimisation loop based on the optimisation iterations. This code reads coordinates of various elements and applies the different thicknesses upon request of the optimisation engine. An example of output of this code is presented in Fig. 2.

Heat treatment

Because of cold deformation in the tube drawing process, the ductility of tubes is reduced, increasing the risk of fracture in the rest of the production cycle, i.e. tube bending and THF. Figs. 3 and 4 show that for tubes drawn in one and two steps the ductility of tubes is reduced considerably with increasing thickness reduction;