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Database for real-time loading path prediction for tube hydroforming using multidimensional cubic spline interpolation

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ABSTRACT

Tube hydroforming (THF) is a metal-forming process that uses a pressurized fluid in place of a hard tool to plastically deform a given tube into a desired shape. In addition to the internal pressure, the tube material is fed axially toward the die cavity. This process has various applications in the automotive, aerospace, and bicycle industries. Accurate coordination of the fluid pressure and axial feed, collectively referred to as a loading path, is critical to THF. Workable loading paths are currently determined by trial and error, which can be time consuming.

This study discusses an innovative technique for developing an interactive, real-time database that would be able to predict loading paths for many THF components and hence reduce the computational time required. By classifying most of the commercial THF parts into families, parameters such as material properties, part geometry, and tribological factors were simulated by category and stored in the database. Multidimensional cubic spline interpolation was implemented to enable an end user to request from the database a loading path for a wide range of conditions. Test results from the database for different THF families were shown to approximate the simulated results. In addition to reducing the computation time, the use of interpolation techniques eliminates the need for carrying out multiple simulations for similar THF parts.

1. Introduction

Hydroforming has found significant industrial utility in the present decade, although research on tube hydroforming started in the 1940s (Koc and Altan, 2001). Automotive parts that are typically produced using this process include exhaust manifolds, chassis, engine cradles, and radiator frames. Hydroforming allows weight reduction without compromising strength, which is of great significance in the automotive and aerospace industries. For example, conventional fabrication of a chassis involves welding several parts together, whereas hydroforming can manufacture a chassis in a single step, thus reducing weight and secondary operations.

Tube hydroforming (THF) is a metal-forming process in which a tube is plastically expanded into a die cavity by the simultaneous action of fluid pressure and axial material feed, such that the tube takes the shape of the die cavity. Success of THF depends on various process and material parameters. The two most important process parameters are internal pressure (Fig. 1a) given to the tube and axial material feed (Fig. 1b) applied to the ends of the tube. A graphical representation of the two parameters is called a loading path (Fig. 1c). Loading path depends on process conditions and materials and is independent of process time. Also, loading path has to be in a particular process window for the part to be successfully formed, as shown in Fig. 1c. Inaccurate loading path will lead to part failures such as wrinkling, bursting, or buckling. The details on the modes of failure and mathematical models for failure predictions are given by Dohmann and Hartl (1997) and Xia (2001), respectively.

Prediction of the proper loading path for a particular set of process conditions is one of the biggest challenges in THF. Since this process is relatively new, much is not known. Previous attempts to predict loading paths have mostly involved trial-and-error. Reducing the computational time required for loading-path prediction would increase the utility of THF. The following are some of the attempts to develop a faster and more systematic approach to loading-path prediction:

Trial and Error FEA Simulation approach: One of the first improvements over trial-and-error was the use of FEA analysis, where iterative FE simulations are carried out until acceptable forming results are obtained. This process is still extremely inefficient and time consuming (Strano et al., 2004). To reduce the number of simulations, the minimum axial feed of the materials can be established by carrying out simulation without forced axial feeding, i.e.,

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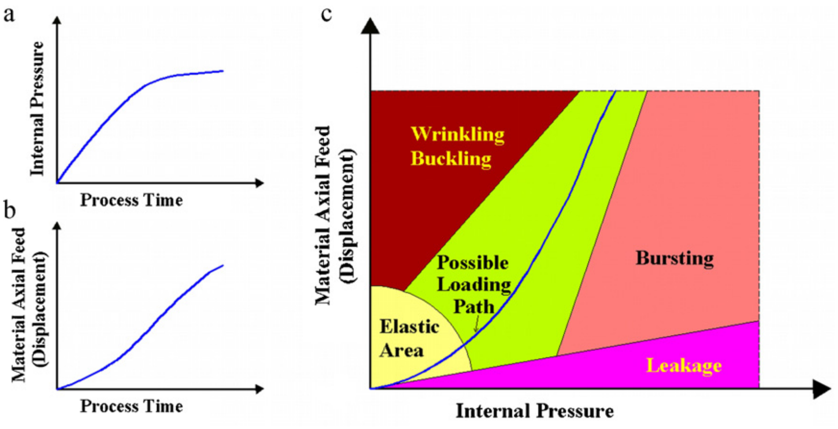

Fig. 1. Process window for THF process and loading path.

the axial feed obtained from this simulation is due to the action of internal pressure only. This technique is known as self-feeding and provides the initial loading path (Strano et al., 2004).

Optimization approach: This approach aims at optimizing local tube-wall thickness distribution by sensitivity analysis. Repeated simulations are carried out until an optimal loading path is obtained (Gelin and Labergere, 2002).

Adaptive approach: The adaptive method is faster than the above methods in that it determines the process-loading curve by running a single simulation. The method monitors the failure modes of wrinkling and bursting with the use of indicators inside the FEA simulation itself. This is done by defining failure indicators, namely, the wrinkle indicator and the bursting indicator (Nordlund, 1998). The control strategy identifies the wrinkle or bursting with the help of these indicators and gives feedback to the simulation, where changes are made to prevent failure

Fuzzy Load Control method and Neural Network Analysis method: Fuzzy Load Control (FLC) involves development of fuzzy logic rules based on previous knowledge of the THF process window (Ray and Mac Donald, 2004). Using these rules, failure indicators based on threshold for wrinkling and buckling, are decided. The simulation procedure differs from the adaptive approach such that here the failure indicators are decided based on fuzzy logic rules. Ray and Mac Donald (2004) used FLC to predict loading paths for T-shape THF. Lin and Kwan (2004) presented four-layer and five-layer abductive network models to predict the process parameters of THF for an acceptable T-shape product. They chose a material with a constant shear friction and varied the geometrical parameters of the die cavity and the internal pressure input to get a total of 75 sets of parameters. Then they obtained the training data by performing FEA simulation on those 75 sets using the commercial FEA simulation software DEFORM 3D.

All the methods discussed above expend considerable time in searching for a loading path that will result in a successful part. Moreover, most of those methods can only be used to obtain a loading path for a specific material and geometry, i.e., they must be rerun if the THF geometry or material has changed. This study proposes the development of a database that through interpolation could instantly provide continuous loading-path data for THF parts with different materials and geometries.

2. Objectives and approaches

The objectives of this study are to (a) develop a database containing loading-path data for forming numerous THF components with different materials, geometries, and tribological conditions and (b) establish a multidimensional interpolation scheme in conjunction with the FE-based simulation database that will facilitate determination of real-time continuous loading paths for THF parts. The approaches taken to achieve the above objectives are presented in the flowchart shown in Fig. 2.

3. Classifications of THF components

A thorough review on commercially available THF components was carried out in order to classify THF families for the database as shown in Fig. 3. However, the scope of this study is limited to the families that require both axial feed and internal pressure for forming. Hence seven families were selected for this study namely Bulge shape (B), Single Y shape (SY), Aligned Double Y shape (DY), Single T shape (ST), Aligned Double T shape (DT), Non Aligned Double T shape – opposite side (DTOS) and Non Aligned Double T shape – same side (DTSS). Fig. 4 shows schematics of the seven THF families.

4. Pressure curve generation and strategy

Pressure and material feed profiles are the two components that build up the loading paths for THF. This section will focus on pressure curve generation and the next section will be devoted on material feed curves. The strategy taken in generating the loading paths was to obtain a generic pattern for the pressure profile. That is, the pressure curves which will have the sample pattern for all THF families. Having a generic pressure profile will lead to a robust interpolation scheme as compared to using different patterns of pressure profiles for different THF families. It should be noted that the loading path for THF is composed of the pressure loading and material feed profiles as shown in Fig. 1a and b. Theoretically, infinite routes are possible to obtain the loading path (material feed vs. pressure) shown in Fig. 1c. For example, three different scenarios to obtain the same loading path shown in Fig. 1c can be examined. In scenario A, one could fix material feed profile and vary the pressure profile, whereas in scenario B, pressure profile could be fixed and the material feed profile could be varied. In scenario C, both pressure and material feed profiles could be varied. The common boundary conditions for all three scenarios are (a) at the end of the process a certain maximum forming pressure will be needed to ensure that the desired corner radii are formed and (b) at the end of the process a certain amount of material should have been fed to the die cavity to ensure that the part is successfully hydroformed. In this study scenario B was adopted, where the pattern of the pressure profile is fixed for all THF families.

The unit pressure curve shown in Fig. 5 was adopted for this study. The specific profile in Fig. 5 shows various stages in the THF