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Internal state variable plasticity-damage modeling of the copper tee-shaped tube hydroforming process

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ABSTRACT

This paper presents a parametric finite element analysis using a history-dependent internal state variable model for a hydroforming process. Experiments were performed for the internal state variable model correlation and for validating a 2-in. copper tee hydroforming process simulation. The material model constants were determined from uniaxial stress–strain responses obtained from tensile tests on the tube's material. In the finite element simulations, the mesh and boundary conditions were integrated with the geometry and process parameters currently used in industry. The study provides insights for the variation of different process parameters (velocity and pressure profiles, and bucking system characteristics) related to the finished product.

1. Introduction

Tube hydroforming is a metal forming process in which tubes are formed into complex shapes within a die cavity using internal pressure and axial compressive forces simultaneously. The development of the initial techniques and establishment of the theoretical background goes back to the 1940s (Koc and Altan, 2001). Grey et al. (1939) were the first to report on hydroforming of seamless copper fittings with T-branches. According to Ahmetoglu et al. (2000), tube hydroforming offers many advantages over conventional manufacturing methods including: part consolidation, weight reduction, improved structural strength and stiffness, lower tooling cost due to fewer parts, fewer secondary operations, reduced dimensional variations, and reduced scrap. They also report that most applications of tube hydroforming can be found in the auto and aircraft industries as well as manufacturing components for sanitary use.

The hydroforming process has some inherent problems that include bursting (fracture), wrinkling, and wall thinning, which strongly depend on the choice of the processing conditions. One particular hydroforming process in which these inherent problems often arise is a T-branch type use for fittings. As such the focus of our study is to analyze a 2-in. copper tee forming process with a history-dependent internal state variable plasticity model to better control the process outcome.

Modeling of hydroforming via FEM has been a focal point of much recent research. Chen et al. (2000) worked to obtain a fundamental understanding of the hydroforming process variables such as internal pressure, ram movement, and lubricant through corner fill modeling. Strano et al. (2001) used FEM to develop an adaptive simulation to select a feasible hydroforming loading path with a minimum number of runs. The adaptive technique detects the onset of defects (wrinkling, bursting, buckling) and adjusts the loading paths accordingly. Shirayori et al. (2002) investigated via FEM and experiments the free hydraulic bulging of copper and aluminum alloy tubes. They found that an increase in thickness deviation during free bulging depended on tube material and end boundary conditions. Koc (2003) used a finite element simulation to perform virtual experiments to obtain guidelines on the use of different loading path schemes. Smith et al. (2004) showed that a strain rate independent finite element model underestimates the burst pressure for materials featuring higher strain rate sensitivity. Shirayori et al. (2004) successfully used FEM to design loading paths for hydroforming processes. Jirathearanat et al. (2004) used finite element simulation to estimate the effects of processing parameters (pressure level, axial feed, initial tube length) and then to optimize

Abbreviations: DHP Copper, Deoxidized High Phosphorus Copper; EMMI, Evolving Microstructural Model of Inelasticity; OFHC, Oxygen Free High Conductivity.

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process inputs for a forming operation. Chu and Xu (2004) examined the different phenomena of buckling, wrinkling, and bursting in various aluminum alloys with the goal of obtaining optimal process parameters. Jansson et al. (2005) employed FEM to improve a hydroforming process and expressed the need for better constitutive models. Abrantes et al. (2005) used FEA to establish a basic understanding of the tube hydroforming process for aluminum and copper tubes. Kashani Zadeh and Mashhadi (2006) used finite element simulations to quantify the effects of coefficient of friction, strain hardening exponent, and fillet radius on the parameters, protrusion height, thickness distribution, and clamping an axial forces. Guan et al. (2006) developed and implemented a polycrystalline model into a finite element program and calculated texture evolution on several aluminum hydroformed components. Heo et al. (2006) used ANSYS parametric design language to design an adaptive FEM simulation for determination of a suitable hydroforming load path. They validated their model via experiments. Islam et al. (2006) used finite elements to verify the suitability of hydroforming double layer brass and copper tubes. Their results were verified experimentally. Daly et al. (2007) recently focused on the modeling of the post-localization behavior of low carbon steels in the hydroforming process. Islam et al. (2008) investigated internal stresses created by hydroforming double layered components. Kim et al. (2009) constructed a theoretical forming limit stress diagram to be used with FEM simulations to provide a better method for simulation-based design of hydroforming processes. (Mohammadi and Mosavi, 2009) determined the proper loading paths via FEM and a fuzzy controller.

Modeling of copper tube hydroforming has received some attention as well. Shirayori et al. (2002) investigated the use of a volume control method for free bulging of copper tube. They found the volume control method was better for reaching the maximum hydroforming pressure. Hama et al. (2003) developed a finite element code for hydroforming analysis and compared the hydrostatic bulge simulation to experiments for a copper tube and found good agreement. Abrantes et al. (2005) used FEM to establish a basic understanding of hydroforming of aluminum and copper tubes with the end goal of finding a process window. Kocanda and Sadlowska (2006) used FEM simulations and predicted strain localization and bursting via the forming limit curve. They found that the forming limit curve underestimates the hydroforming limit for X-joints. Carrado et al. (2008) studied residual stresses in drawn copper tubes and their relation to geometrical changes in the tube.

The use of advanced physics-based constitutive models for the behavior of materials during hydroforming is a promising possibility. Cherouat et al. (2002) used FEM with a thermodynamically coupled constitutive model including thermodynamic state variables accounting for isotropic hardening and isotropic ductile damage to investigate the effects of friction coefficient, material ductility, and hydro bulging condition on the hydroformability of various thin tubes. Varma et al. (2007) used a anisotropic version of the Gurson model to predict localized necking in an aluminum alloy. They compared their simulation results with the experiments of Kulkarni et al. (2004). Butcher et al. (2009) performed computer simulations incorporating a variant of the Gurson–Tvergaard–Needleman constitutive model to account for the influence of void shape and shear on coalescence. They performed a parametric study to determine appropriate void nucleation stress and strain. They found their calibrated model to agree well with experimentally determined burst pressure. Along these lines, this study has used the Evolving Microstructural Model of Inelasticity, EMMI (Marin et al., 2006), to describe the material response during the hydroforming process. This model has been formulated in the context of internal state variable theory and couples isotropic plasticity and isotropic damage. The model also has the ability to capture strain rate and multi-axial stress state effects, features needed for simulating complex deformation processes. A brief description of the model is presented in the text.

2. The hydroforming process

A copper blank is formed into a copper tee via the hydroforming process using six components: top and bottom dies, left and right rams, the bucking system, and a copper blank. The dies are made of tool steel which is machined to the profile of the desired copper tee fitting. The rams are also tool steel and are machined to provide the proper inner radius for the tee fitting. The bucking system comprises a bucking bar, two bucking punches, and a hydraulic press. The bucking punches are simply solid steel cylinders the size of the tee branch. The punches fit into the tee branch cavity of the hydroforming die and inhibit the copper flow into the branch cavity as the tee is forming to prevent process failure due to bursting. As the bucking punches contact the tee, both the punches and the bucking bar are lifted until the bucking bar contacts the hydraulic cylinder, which provides a resistant force additional to the weight of the bucking bar and bucking punches so that the tee branch will not form upward too quickly and experience a burst failure.

With the top die raised and the rams retracted, the copper blank is placed into the bottom die. The top die lowers as the rams move towards the ends of the copper blank. The ram tips are tapered and as they enter the copper blank, an interference fit is created. A mixture of water and a water soluble oil solution called whitewater is injected into the blank via holes bored through the center of the rams, thus pressurizing the inside of the blank for hydroforming. The rams enter the blank until the inside diameter of the blank fits over the outside diameter of the ram and the end of the blank sits against the ram shoulder. At this point, a sufficient seal has been produced for very large pressures to be created inside the blank for the forming process.

In the next phase of the forming process, the rams compress the copper blank as the internal pressure, due to the whitewater, is built gradually to approximately 35–40 MPa. As the rams compress the blank and the pressure builds, the tee branch forms within the branch cavity of the top die. As the branch moves upward, it forms against the bucking system. The bucking system simply exerts a constant force on the growing tee branch.

After the branch overcomes the bucking force, it continues growing upward until it hits the hard stop which stops growth at the desired tee branch height. At a set distance from the hard stop, the whitewater pressure ramps into what is called coining. During coining, the whitewater pressure ramps from the forming pressure of about 35 MPa to approximately 75 MPa. The purpose of coining is to make sure the radii of the hydroformed tee match the radii of the forming dies, coining the part, and finishing the process.

The ram movement and the white water pressure are controlled by time history curves defined by the process control system using input data from the operator. Fig. 1 presents typical ram velocity and pressure curves for the hydroforming process. In general, the quality of the product (tee-shaped copper tube), and hence, the robustness of the process, depends on the details of these curves. When the process is not robust, the tube can be ruined. For example, Fig. 2 illustrates the difference between a well-processed tee with one that incurred wrinkling and one that fractured during the processing.

3. Simulating the hydroforming process

In order to accurately simulate the complex hydroforming process described in this paper, three key features need to be addressed: material model, meshing, and boundary conditions.