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Technical Paper

Investigation and numerical analysis of impulsive hydroforming of aluminum 6061-T6 tube

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ABSTRACT

Nowadays impulsive forming processes have become popular among scientists and industrial companies due to their unique capability at increasing formability in various materials and reduction in production time and cost. In this research, finite element analysis of impulsive hydroforming on the sheet and tube was carried out using an explicit scheme and the interaction between the fluid and the shell elements representing the workpiece was approximated through the use of the surface based acoustic-structural interaction. This allowed transferring the pressure from the electrical discharge in the fluid medium, determined by the Geers and Hunter model, to the nodes representing the workpiece. The behavior of the sheet and tube was assumed to follow the Johnson–Cook structural model and the physical constants for the model were taken from other research papers. The proposed finite element model was verified by comparing the results of the model to the experiments published by another researcher and were found to be in good agreement. The FE model was applied to the impulsive forming of the tube so that the effect of discharge energy, die radius and friction coefficient could be studied in the tube electrohydraulic forming process. It is observed that the discharge energy value has major effect on the process and the friction coefficient has minor effect relative to the others. Results showed that Al6061-T6 tube did not sustain any damage even by experiencing stresses near the ultimate strength stress due to the high strain rate of the process. Elastic spring back of the tube decreased with increasing in the energy level, die radius and friction coefficient, due to the impact with the die and the lower induced stresses. Material flow into the die cavity improved by increasing in the die radius, resulting in formability improvement.

1. Introduction

Main idea of investigating the underwater explosion phenomena has long history and returns to studying the destructive effects of explosions during world war II. By controlling the explosion parameters such as explosion energy, these processes, categorized as impulsive forming methods, may be implemented as production methods which have important advantages such as improving formability of various metals, improvement of mechanical properties of materials and reduction in spring back behavior resulting from collision with the die.

Impulsive forming methods consist of various processes such as electromagnetic forming, electrohydraulic forming and explosive forming. Electromagnetic forming process is based on the energy of the electromagnetic field induced into the metallic workpiece with good conductivity such as aluminum and copper alloys. In electrohydraulic forming method, the electrical discharge between two electrodes evaporates the water and radiates shock waves which applies pressure on the sheet or the tube wall and forms it to the die shape. In the explosive forming method, explosive material is used as the source of energy. If this process occurs under water (UNDEX), it resembles to the electrohydraulic forming method.

In order to analyze the dynamic response of submerged or floating structures, e.g. submarines and ships, under shock waves generated by the explosion, experimental works of detonating explosives such as TNT or HBX-1 were conducted with enormous cost and destructive effects on the marine ecosystems with low repeatability. For example United States of America spent lots of money on the experiments on USS John Paul Jones and USS Winston Churchill in 1994 and 2001, respectively [1]. Hence scientists developed finite element methods to investigate and analyze these processes.

Kwon and Cunningham [2] obtained the dynamic response of the stiffened beam and cylinder by combining explicit finite element DYNA3D code and boundary element code based on doubly asymptotic approximation. During 90s Kwon and Fox [3]

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studied nonlinear dynamic response of a cylinder under side explosion loading by numerical and experimental methods. Sun and McCoy [4] investigated explosion effects on submerged cylinder by combining ABAQUS finite element package and fluid-structure interaction code based on doubly asymptotic approximation method. Similarly other scientists analyzed fluid-structure interaction by combining finite element and boundary element codes [5,6]. Furthermore, they carried out various studies to obtain the dynamic response of simple structures and imported the fluid-structure interaction procedure, compression wave distribution and boundary reflection conditions into the ABAQUS finite element commercial code.

Nowadays, scientists have started using underwater electrical discharge process as a forming method that is called electrohydraulic forming (EHF) which has similarities to the underwater explosion process. Although the accomplished studies returns to 1960s but the simplicity, repeatability and accessibility of this process attracted industrial and scientific attention once again.

During 1990s Balanethiram et al. [7,8] carried out experiments to investigate formability of sheets made of copper, steel and aluminum alloys by electrohydraulic forming process. Bonnen [9] implemented pulsed electrohydraulic forming to analyze the die designing effects, electrode corrosion and formability of the sheet metals. Rohatgi et al. [10] accomplished forming of sheets made of steel and aluminum alloy by electrohydraulic forming process using digital image correlation method. Gillard et al. [11] studied formability of dual phased steels using electrohydraulic forming. Hassannejadasl et al. [30] also studied the EHF process of DP590 steel by the manner similar to Rohatgi [10], experimentally. The authors further investigated the process by finite element analysis using Coupled Eulerian Lagrangian (CEL) technique. The results were found in good agreement with the literature and experimental results.

In this paper, ABAQUS finite element commercial code was used to simulate the underwater electrical discharge process of forming tube made of Al6061-T6 using UNDEX approximation. Geers and Hunter volumetric model was applied in the analysis to simulate the discharge phenomenon and the generated shock waves. In the present work, the effects of several parameters such as discharge energy, die radius and friction coefficient were studied through finite element analysis.

2. Underwater explosion process

Electrohydraulic forming and underwater explosion forming processes have common manner in forming principles. The only difference between these two methods relates to the energy source of the processes; electrical discharge energy and explosive detonation energy for electrohydraulic forming and underwater explosion forming processes, respectively. Hence, it is concluded that the electrohydraulic forming process can be approximated and modeled with underwater explosion process.

2.1. Sequence of events in underwater explosion

When an explosive materials such as TNT or HBX-1 detonates under water, the shock wave emerges from the explosion and moves away from the explosive and the generated gas bubble starts expanding. As far as the internal pressure of the bubble decreases to the cavitation limit and the hydrostatic pressure of the surrounding water prevents further expansion, the bubble starts contracting. The contraction continues until internal high pressure of the bubble prevents further contraction. Again the bubble starts expanding and this time, pulse wave emerges and moves away from the bubble. These sequences continue until internal pressure of the bubble is damped by the surrounding water or eventually the bubble reaches the water free surface. These sequences is shown in Fig. 1.

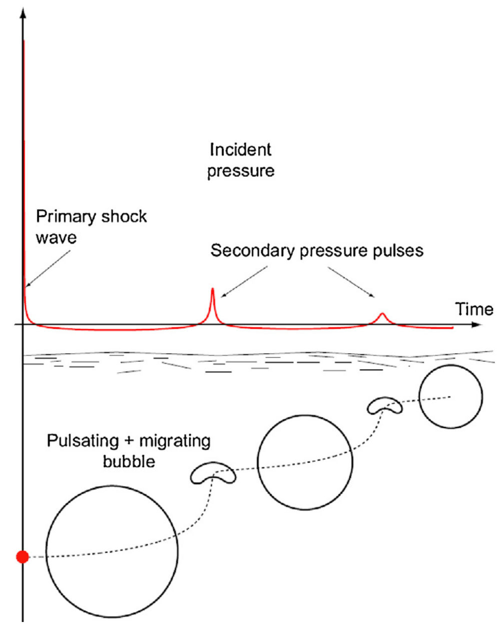

Fig. 1. Sequence of events for an underwater explosion bubble [13].

In the present study, the discharge phenomenon is modeled by Geers and Hunter volumetric model and the water is discretized by acoustic elements in which the shock waves can propagate and interact with the structure. Another approach to model the discharge process is using Coupled Eulerian Lagrangian (CEL) method, as reported in the literature [12]. The first method has advantage over the second one due to the reduction in the analysis time and cost. Since the CEL model is so complicated and needs high performance machines to run the simulations, the first method is chosen in this present study.

According to the most engineering problems that water is assumed incompressible, the water around the explosive material is compressed partially due to the severe pressure of the shock wave. The generated pressure wave moves away radially with the velocity of the acoustic wave in water. The shock wave front is keen followed by an exponential decrease. The maximum pressure of the wave front is decreased by propagating of the shock wave in the water [14].

2.2. Geers and Hunter model

Geers and Hunter introduced mathematical model to analyze the underwater explosion phenomenon; dividing this process into the shock and pulse phases in which the first phase determined initial conditions for the lateral phases. According to this model, volumetric acceleration of the bubble during the shock and pulsed phases are given as [15]:

$$\ddot{V}(t) = \frac{4\pi a_c}{\rho_f} P_c \left[0.8251 \exp\left(-1.338 \frac{t}{T_c}\right) + 0.1749 \exp\left(-0.1805 \frac{t}{T_c}\right) \right] \quad (1)$$

P_c and T_c are expressed as [16]:

$$P_c = K \left(\frac{m_c^{\frac{1}{3}}}{a_c} \right)^{1+A} \quad ; \quad T_c = k m_c^{\frac{1}{3}} \left(\frac{m_c^{\frac{1}{3}}}{a_c} \right)^{B} \quad (2)$$