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Numerical modelling of the gas detonation process of sheet metal forming

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Abstract. Gas detonation forming is an unconventional technique, which has the potential to form complex geometries, including sharp angles and undercuts in a very short process time. To date, most of the numerical studies on detonation forming neglect the highly dynamic pressure profile of the detonation obtained from experiments. In the present work, it is emphasised that the consideration of the actual detonation pressure as measured in the experiment is crucial. The thickness distribution and radial strain are studied using a strain-rate dependent Johnson-Cook material model. The obtained results vary significantly with change in loading rate. Moreover, the model is capable of predicting extremely sharp edges.

1. Introduction

Gas detonation forming is a high-speed forming method that uses pressure energy of a shock wave, produced as a result of the detonation of a mixture of gases like Oxygen (O_2) and Hydrogen (H_2) [1]. This forming process has many well-known advantages, e. g., higher degrees of formability for various materials in comparison to more conventional methods, the capability to form extremely complex geometries including sharp angles and fine embossing without the need of relief angles, a clean combustion, an easy automation, and less safety regulations compared to the use of solid explosives. It is worth mentioning that the costs of the process and tooling are also reduced through the simplification of the tooling requirements, and a significant potential for steel forming compared to electromagnetic forming [2].

Yasar et al. conducted both experimental and numerical investigations of aluminium cup drawing using gas detonation process [3, 4]. Also, Mokadem [5] developed a dynamic forming limit diagram for this process. Wijayathunga and Webb [6] developed a finite element model to simulate the experimental tests for the impulsive deep drawing of a brass square cup with the presence of a soft lead plug. However, the highly dynamic detonation pressure profile, which obtains in the experiment, was not considered as it is. Due to sensing limitations and in order to reduce computational cost, in Yasar et al. works, simulations were carried out with linearly increasing and decreasing load over the forming process duration (triangular loading) [3, 4]. However, the pressure curve obtained from the experiments shows that the first peak occurs in a very short time period, and this is the most influencing peak for the deformation.

The present work numerically investigates the gas detonation forming of DC04 steel cups. The 3D explicit dynamic finite element analyses are carried out using the LS-DYNA explicit solver [7]. The Johnson-Cook plasticity material model is used to study strain-rate sensitivity.

2. Numerical modelling

Figure 1 shows the schematic representation of the experimental set-up and 3D finite element model, which includes the die, the holder and the workpiece. Due to the axial symmetry of the problem, only a quarter of the whole system with symmetric boundary conditions is considered to reduce the computational time. The die and the holder are modelled using solid rigid elements (MAT_020) [7] because of their high stiffness compared to the blank as well as they are not active components during forming process. The deformation in the blank is studied by modelling it with solid and shell elements for different cases. The shell element models predict better results, hence, only shell element models will be discussed in this work. Belytschko-Tsay shell elements [7] are used to create a meshed workpiece with 5 integration points, which results into a total of 11076 elements. The die and the holder are considered to be fixed and the contact between them is defined using surface to surface segment based contact formulation [7], assuming planer segments. The loading is applied only on the free surface of the blank. The mechanical properties of DC04 steel for simulations are a elastic modulus of $E = 180$ GPa, a Poisson's ratio of $\nu = 0.3$, a density of $\rho = 7870$ kg/m^3 and a tensile strength of $\sigma = 210$ MPa.

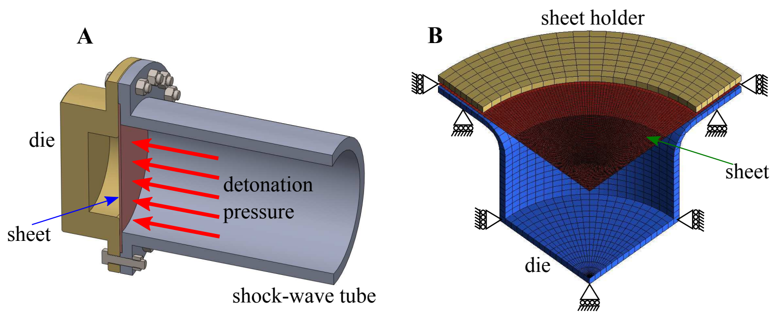

Figure 1. (A) Schematic representation of experimental set-up and (B) finite element model with symmetric boundary conditions.

The simulations are carried out with the Johnson-Cook phenomenological model [9], i. e., it is not based on traditional plasticity theory that reproduces several important material responses observed in impact and penetration of metals. In this plasticity model, the three key material responses are considered strain hardening, strain-rate effects, and thermal softening. These three effects are combined, in a multiplicative manner. The flow stresses as are expressed as:

$$\sigma_y = \left(A + B\bar{\varepsilon}^{p^n}\right)\left(1 + C\ln\frac{\dot{\bar{\varepsilon}}^p}{\dot{\varepsilon}_0}\right)\left(1 - \left[\frac{T - T_{room}}{T_{melt} - T_{room}}\right]^m\right), \tag{1}$$

where $\bar{\varepsilon}^p$ is the effective plastic strain, T_{room} the ambient temperature, T_{melt} the melting point or solidus temperature, T the effective temperature, A the yield stress, B the hardening modulus, n the strain exponent, m the temperature exponent and C the strain-rate factor. Also, $\dot{\varepsilon}_0$ represents the strain-rate for the quasi static reference loading $\dot{\varepsilon}_0 = 5.6 \times 10^{-4} s^{-1}$ [8]. The required material parameters for simulations are given in Table 1 [8].

Table 1. Values for the Johnson-Cook material model parameter

A [MPa]	B [MPa]	n	C	m
162	598	0.6	0.07	0.009

A smoothed stress-stain curve is used to simulate the deformation process. Since deformation takes place within a very short time period (a few hundred microseconds), the loading curves

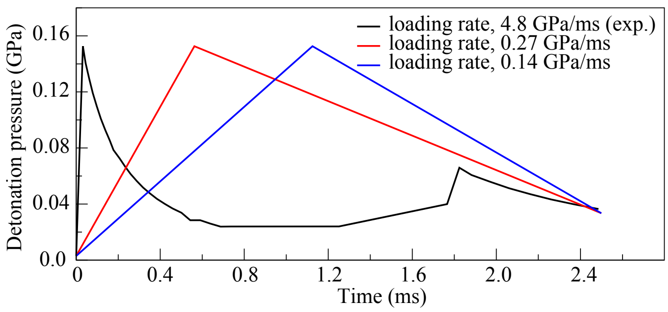

Figure 2. Load curves - different loading-rates for simulations.

are considered up to 2.5 milliseconds. One of the major factors influencing the shape as well as the distribution of strain in the formed cup is the rate at which the load is applied. Therefore, it becomes necessary to study the effects of this loading rate on the formed cup. The different loading curves as a function of time are shown in Figure 2.

3. Results and discussion

Figure 3 depicts the shape of the deformed blank with respect to loading time with a peak load of 1500 bar using the experimental loading rate. The analysis of blank shape with respect to the time highlights the fact that the whole deformation process takes place within the first peak-load and the reflected waves do not play a major role in the formation of the cup.

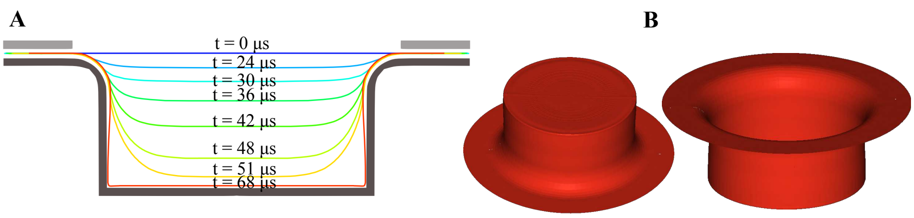

Figure 3. (A)Cup shape formation during simulation and (B) final deformed shape of the blank.

Figure 4A shows the variation of the thickness with respect to the initial radius for different loading rates. One of the main objectives of this work is to correctly predict the thickness distribution along the base and the wall of the deformed cup for different loading-rates. In the literature, thickness distribution has been studied using finite element models. However, experimental loading-rates were not considered, but simulation results were obtained using a triangular loading. Therefore, triangular loadings shows a smooth variation of the thickness and an overestimation of the magnitude (see Figure 4A). In case of experimental loading rate, thickness variation is not smooth and minimum thickness goes up to 35 % at the sharp bottom corners. The model is clearly able to predict a local maxima in the thickness value close to the 90^o bend and a decrease in the thickness on side of the bend. It can be clearly observed that a decrease in the loading rate results in an increased wall thickness.
Figure 4B depicts the variation in the radial strain given by $\varepsilon_r = \frac{u_r}{r}$ as predicted by the Johnson-Cook material model for actual and triangular loading with respect to the initial radius. As expected, the radial strain is the highest in the areas where a maximum reduction in thickness is obtained. Like thickness variation results, triangular loadings show a smooth variation of the radial strain compared to the experimental loading rate.

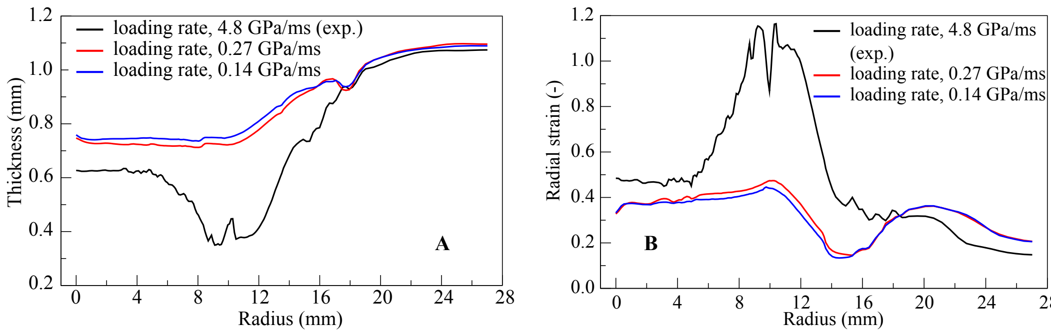

Figure 4. (A) Thickness variation in the deformed cup with respect to initial radius. (B) Radial strain in the deformed cup with respect to initial radius.

4. Conclusions and future work

Numerical simulations were carried out with the Johnson-Cook plasticity model, which can be fit over a wide range of strain, strain-rate and temperature, and hence it changes yield point. This plasticity model is the best choice to predict deformation during the forming process due to its moderate complexity and well established methods to predict the material constants. The proposed finite element model is able to predict the cup shape of the blank, including the sharp edges at the bottom corners. Moreover, the model concludes that obtained results are very sensitive to the loading-rates. Therefore, it highlights the fact that the accurate measurement of the loading rate and its consideration in the simulation process becomes very important.
Further improvements can be made to the model by systematically performing a higher number of experiments using different shaped geometries. Also, numerical studies can be performed on different shaped geometries including the temperature effects.

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