Topology Optimization of an Asymmetric Elliptical Cone Subjected to Blast Loading

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Abstract

This paper describes a numerical procedure for the blank shape design of thin aluminum components achieved by explosive forming. The objective is to specify the initial blank shape considering the geometry of the final product. The numerical procedure consists of three steps: At first, the forming process of an asymmetric blank in an elliptical cone die cavity and without blank holder is simulated. To rectify the wrinkles without optimization the square of the primary blank will be increased. In the next step, topology optimization is employed to obtain the optimum geometry of the blank whose diameter has been increased finally, the modified blank achieved previous step is used in the new simulation to check whether or not the wrinkles mentioned in first step has been rectified. Results show the proposed numerical procedure can provide the optimal blank shape in a few iterations.

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1. Introduction

Sheet metal components have broadly applications everywhere from containers, automotives and buildings to aircrafts [1]. One of the most important problem that manufacturers face to is the sheet metal parts by means of press forming is a cost-effective process since it expurgates expensive machining and welding operations achieving a better quality finished product [2]. Deep drawing is one of the widely employed sheet metal processes in industry to manufacture cup shaped components at a very high production rate [3]. Deep drawing of asymmetric parts is
considered a complicated process due to, irregular contact conditions between blank and die, and the different forming characteristics from those of axisymmetric circular deep drawing [4]. The mentioned complexities are intensified while the product is a cone [5]. Therefore, conical parts are typically made by spinning [6-8], explosive forming [9], or multi-stage deep drawing processes [10].

In the case of explosive forming process, the sheet metal is always subjected to blast loading. Eliminating adverse effects of punch which are exist in the conventional deep drawing process is one of the most important advantages of explosive forming [11]. But depends on the apex angle of the cone, material, thickness an diameter of the blank, earing [3], wrinkling [5] and failure may occur [12]. Although increase the diameter of the primary blank can somewhat result to improve the wrinkles in the product however, this solution way may constitute to have an inevitable flange in the external edge of final product. The mentioned issue leads to increase the waste material for manufacturing parts. Not only cutting the flange consists of the extra cost of manufacturing, but also in some cases the apex angle of product changes.

It is desired to optimize blank diameter so that the final part dimensions can be controlled as much as possible. There is an approach to use the finite elements method for optimizing the geometrical specifications of primary blank [3, 13, 14]. The most part of these studies have focused on optimization in the area of low-rate forming process with symmetrical geometry [15-17]. The main objective of this study is to use the finite elements approach to estimate and optimize an asymmetric primary blank shape for a conical product manufactured by a high rate forming in which the blast loading is contributed.

2. Methodology

In this paper, the methodology used for the blank shape design consists of three steps. First, the forming process of an asymmetric blank in an elliptical cone die cavity and without blank holder is investigated. For this part of study, an user defined subroutine, DLOAD [18], is implemented in Abaqus software. The role of DLOAD in this simulation is to apply the blast load on the blank according to the energy method [19] and decaying exponential function [20]. Performing the first step, the flags specially wrinkling in the final product are identified. To rectify the wrinkles without optimization the square of the primary blank will be increased.

In the next step, topology optimization is employed to obtain optimum geometry of the blank whose diameter has been increased. Topology optimization further refines the model by modifying the surface of the component by
moving the surface nodes to reduce local stress concentrations [21]. Minimum volume of blank material and minimum strain energy are considered as the objective and design response process of optimization, respectively. The blank geometry achieved in this step is generally not feasible to apply for metal forming process and need to be modified regarding the process concept.

In the final step, the modified blank achieved previous step is used in the new simulation to check whether or not the wrinkles mentioned in first step has been rectified. Fig. 1 illustrates the numerical procedure based on finite elements analysis and shape optimization algorithm approach.

3. Principle of the numerical procedure

3.1. Geometry and material

Numerical simulations for blast loading of the blanks were done using Abaqus software based on subroutine user-defined. A solid 3D element for the sheet and a rigid element for the die were applied. The optimum size of elements was estimated to be about 0.5 all hexahedral. Surface-to-surface contact was used for contact between the blank and the die. The die fixed in all degrees of freedom and the bank was located on die with no special boundary condition. The explicit method was employed to solve the problem. All the blanks were simulated as 1.5mm thick Aluminium. Johnson-cook material model was used for blanks which is purely empirical and Eq.1 is given for the flow stress [22]

\[ \sigma(\varepsilon, \dot{\varepsilon}, T) = A + B(\varepsilon)^n \left[ 1 + C \ln(\dot{\varepsilon}^*) \right] \left[ 1 - (T^*)^m \right] \]

(1)

where \( \varepsilon \) is the equivalent plastic strain, \( \dot{\varepsilon} \) is the plastic strain-rate, \( T \) is temperature, and \( A, B, C, n, m \) are material constants. The normalized strain-rate and temperature in Eq.1 are expressed as

\[ \dot{\varepsilon}^* = \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \]

(2)

\[ T^* = \left( \frac{T - T_0}{T_m - T_0} \right) \]

(3)

In Eq.2, \( \dot{\varepsilon}_0 \) is the effective plastic strain-rate of the quasi-static test used to determine the yield and hardening parameters \( A, B \) and \( n \). In Eq. 3, \( T_0 \) is a reference temperature, and \( T_m \) is a reference melt temperature. Fig. 2 shows a sample of Abaqus assembled and meshed models. The parameters of the Johnson - cook equation for Aluminium used in this study have been identified and displayed in table 1.

![Fig. 2. Assembled and meshed models](image)
Table 1. The parameters of Johnson-cook equation for blanks.

| A (MPa) | B (MPa) | C   | m   | n   |
|---------|---------|-----|-----|-----|
| 240     | 200     | 0.005 | 0.2 | 2   |

3.2. Loading process

The pressure history of the shock wave at a given point starts with an instantaneous pressure increase to a peak pressure, followed by a decaying exponential function, which is given in MPa by equation 4 [23].

\[ P(t) = P_m e^{-t/\theta} \]  

where \( P_m \) is the peak pressure of the shock wave; \( \theta \) is the exponential decay time constant; it is the time since the shock wave front arrived at the target point in ms. The peak pressure \( P_m \) of an exponentially decaying underwater shock wave that is generated at a stand-off \( S \) in m which is greater than ten times the radius of the charge of equivalent TNT weight \( W \) in Kg is given in MPa as [20]

\[ P_m = 52.16\left(\frac{W^{1/3}}{S}\right)^1 \]  

and the decay constant \( \theta \) in ms which is the time taken by the peak pressure to fall to 1/e times its initial value is given as [24]

\[ \theta = 0.0894W^{1/3}\left(\frac{W^{1/3}}{S}\right)^{-0.185} \]  

The explosive mass of this test was determined via energy method [19]. Replacing the mentioned values in the equations 5 and 6, the decay constant and peak of pressure will be determined. Finally, using the determined values, the function of pressure versus time is plotted. The mentioned load is defined using a DLOAD subroutine and applied to the top surface of the blank.

3.3. Optimization process

The term of optimization in this study is addressed an iterative process which leads to refine the designs. Abaqus supplies two approaches to structural optimization: topology optimization and shape optimization. Topology optimization commences with an initial model and determines an optimum design by modifying the properties of the material in selected elements, effectively removing elements from the analysis. Shape optimization further refines the model by modifying the surface of the component by moving the surface nodes to reduce local stress concentrations. Both topology and shape optimization are governed by a set of objectives and constraints.

Typically, the objective of a topology optimization is to minimize stress, strain, volume and etc. using the results of a related analysis to modify the surface geometry of a component until the required parameter level is reached. In this study, minimum strain energy and volume are used to implement the optimization process.

4. Results and discussion

Fig. 3a and Fig. 3b show the contours of von mises stress in primary blank and increased square blank, respectively. As shown in the mentioned figure the primary blank has the observable wrinkles in parallel with the big diameter of the elliptical die cavity. Whereas, the increased square diameter blank the wrinkles have been eliminated remarkably.
Some studies believe that the onset of wrinkling takes place when the ratio of the plastic strain increment reaches a critical value. This critical value is plotted against the ratio of initial blank diameter to initial thickness of the sheet blank. It means that while the ratio of blank diameter to the thickness is not less a critical value, the wrinkles do not occur [12]. Although increase the blank diameter versus thickness can be counted as a remedy to rectify the wrinkles and creases however, it leads to waste the material and time to obtain the final favored product. Therefore, optimization can assist the manufactures to avoid time and money.

Fig. 4 shows the iterations implemented to obtain optimum blank shape via topology optimization algorithm. The minimum volume of blank material and minimum strain energy are considered as the objective and design response process of optimization, respectively.

![Fig. 3. Contours of von mises stress in (a) primary blank, and (b) increased square blank](image)

![Fig. 4. Iterations implemented to obtain optimum blank shape via topology optimization algorithm](image)

![Fig. 5. Contours of von mises stress of the final blank shape](image)
The strain energy refers to the energy due to bending deformation and circumferential stress. It means when wrinkling happens the strain energy increases due to the excessive deformation. Therefore, minimum strain energy has been selected as a criteria for the optimization process. Figures 4a to 4f shows that the optimization process has been started from the area of blank, which is exposed to wrinkling more than another area.

The optimum blank shape obtained in the previous step with a slight change, to ease of production, has been used for final simulation. Fig. 5 shows the contours of von mises stress of the final blank shape. As shown in Fig. 5 the final product is improved greatly comparing to the primary design and wrinkles and creases have been rectified considerably.

5. Conclusion

Combining aspects such as large strain plasticity, blast loading, minimum strain energy and geometrical complexity, numerical design of the blank shape of high precision thin metallic part represents a challenging task. The design of the optimal blank shape using numerical procedures based on the combination between finite element analysis and topology optimization algorithm has been presented in this paper in the case of an elliptical cone obtained by explosive forming. The finite element analysis is generated by a subroutine user-defined. It is obvious that the numerical procedure has demonstrated its efficiency to provide an optimal solution in a few iterations with acceptable accuracy. The optimization algorithm based on the finite element analysis can be generally applied for various geometries. It can make the designer work easier by reducing considerably the design period and material cost.

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