Finite Element Simulation of Thermomechanical Spinning Process

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Abstract

Spinning is frequently used for manufacturing axisymmetric shapes where press tooling might not be justified on grounds of size and production volumes. Spinning also has the possibility of producing parts that could not be deep drawn. The temperature effect is significant on the metal forming processes; for the quality of products and the tools life are extremely affected by it. In this paper, a three-dimensional explicit finite-element analysis (FEA) is employed to simulate the spinning process of an aluminium circular sheet and also we investigate the thermal effects on the conventional spinning process by the explicit finite element method. The energy terms in this study include the plastic strain energy, the frictional sliding energy, and the heat transfer energy. The various mesh types are examined in the simulations. The main benefit of the proposed model will save the tremendous costs in the die designing and the experimental works. The parameters and techniques using in the numerical model are helpful for the design of forming process and the coupling thermal-mechanical analysis.

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Selection and peer-review under responsibility of ICM11

Keywords: spinning process; FEA; experimental tests; thermomechanical analysis

1. Introduction

Metal spinning refers to a group of forming processes that allow production of hollow, axially symmetric sheet metal components. The basic technique of spinning, which is common to this group of
processes, consists of clamping a sheet metal blank against a mandrel on a spinning lathe, and gradually forming the blank onto the mandrel surface by a roller, either in a single step or series of steps. Alternatives to spinning such as press forming are also used for the production of axisymmetric sheet metal components. However, spinning has a number of advantages when compared with these manufacturing methods. Localised deformation of the material under the roller requires low forming forces. Moreover, simple and non-dedicated tooling provides flexibility and has the potential for net shape forming. Lastly, formed components have high quality surface finish and improved mechanical strength [1].

In spinning process, the sheet metal blank is clamped firmly against the mandrel from the centre and a partial loading is applied by the spinning forming tool. This will force the blank towards the mandrel, whereas both the mandrel and the blank are rotating. In most cases, a complex shape may not be achieved in one spinning pass; therefore, a multipass forming process may be required to transform the shape of the blanks to the profile of the mandrel. During the process, the loading is applied locally on the blank surface and a localized plastic deformation takes place. The majority of plastic deformation is concentrated around the tool/worksheet contact area. This local plastic contact can reduce the total required forming force and increase the reduction ratio to considerable high values that may not be achieved by the deep drawing process [2, 3].

In metal forming, the effect of temperature is an important design consideration, but the development of coupling thermal-mechanical analysis is rather slow. Hsu had described in his book, the solutions to the problems involve simultaneous applications of mechanical and thermal loads make the coupling treatment become extremely complicated [4]. In the past decade, a large number of literatures dealing with the influences of temperature variation on forming processes are published. But the papers focus on the static-implicit or static-explicit finite element method, the solving procedure and estimating time are very long. The literature still contains few studies of the dynamic finite element method coupled with thermal effect. The most valuable benefit in the dynamic finite element method is the low computational cost of a solution, it is due to the direct substituting and estimation algorithm, no linear equation solver is needed for the stiffness matrix.

In general, heat is generated during forming processes due to plastic deformation of material and friction contact between the tool and workpiece; therefore, the coupled thermo-mechanical analysis is essential in most of the forming processes, which affects the resulting outputs such as stresses, strains, deformation energy, etc. When the FE method is used for simulation of such processes, a thermo-mechanical analysis is often necessary for realistic modelling of these processes. The previous works show the importance of considering these thermal effects [5–8]. In some works, which are especially applicable in the spinning process, a heat source is used instead of heat generated from plastic deformation and friction contact between tool and workpiece to handle thermal effects. These works introduced an interesting approach in simulation of thermo-mechanical forming processes such as spinning process. In this article, spinning process of a conical shape and a hemispherical shape are investigated numerically. Three-dimensional (3D) elastic–plastic dynamic/explicit FE analyses are applied for numerical simulation of the process, and all the presented FE results are extracted from thermo-mechanical FE analysis of strains.

2. Finite Element Procedure and Numerical models

The Spinning process is simulated numerically using dynamic/explicit FE analysis. In one case a circular sheet blank, 204mm in diameter and 1mm thick, is utilized as the workpiece, and hemispherical shape was selected as a mandrel. The circular blank is clamped between the mandrel and the tailstock as shown schematically in Fig. 1(a). The top section of the mandrel is considered flat to let the tailstock clamp the blank rigidly against the mandrel. And in another case conical shape was selected as a mandrel.
The mandrel and spinning tools are several times stiffer than sheet metal; these are modelled as analytical rigid bodies, which will result in a significant computational time reduction. The blank is modelled as a deformable solid sheet and is meshed using linear hexahedral continuum elements. Although the geometry of the mandrel and the blank follows the axisymmetric configuration, due to the asymmetric nature of loading process and also the local contact between the spinning tool and the blank surface, a completely 3D model is needed. Figure 1(b) illustrates the FE model developed for this work. Figure 2(a) shows the dimensions and figure 2(b) illustrates the FE model developed for another case when conical shape was selected as a mandrel.

The spin rate and feed rate are \( \omega_{\text{mandrel}} = 710 \text{ rpm} \) and \( u_{\text{roller}} = 0.2\text{mm/rev} \), respectively. The Surface-to-Surface contact mode is used between the roller and sheet with Coulomb friction coefficient \( \mu = 0.02 \) and the mode of heat transfer, radiation, does not consider in this study. The material of the circular sheet is commercial aluminium Al 1100-O with the constitutive equation \( \sigma = 168e^{0.2628} \text{ MPa} \), \( E = 69 \text{ GPa} \), \( \rho = 2710(\text{kg/m}^3) \), \( \nu = 0.33 \), \( k = 300 \text{ W/m°C} \), \( c = 320 \text{ J/kg°C} \), and heat expansion effect \( \alpha = 10^{-5} \text{ °C}^{-1} \). The initial temperature is 20°C for the environment, work piece, and tools. In this article, Von-Mises yield criterion and isotropic hardening plasticity are used for sheet material in FE simulations. The explicit algorithm of commercial FE code (ABAQUS™) is used for simulation of dynamic spinning process analysis, and for this purpose, several independent explicit loading steps are defined. In FE simulation, the authors use hexahedral structure C38DR element and the number of total elements are 1116. These
loading steps, which include certain displacement and rotation motions of the tool, are schematically shown in Figure 2 and refer to four multi-pass movements of spinning tool during the forming process. The multi-pass process has a great influence on the improvement of the surface roughness and forming limit of sheet metal [9, 10].

3. Results and discussion

Figure 3 shows the distribution of stress during the spinning process when hemispherical shape was selected as a mandrel.

Fig. 3. Distribution of stress in the final deformation with hemispherical shape mandrel.

Fig. 4. Distribution of stress in the final deformation with conical shape mandrel.
Figure 4 shows the distribution of stress and figure 5 shows the distribution of temperature during the spinning process when conical shape was selected as a mandrel. The results show for this cases, the locations of maximum temperature are all near the contact area under the roller. Figure 6 depicts the curves of the temperature against the forming time at the node 1189. The node 1189 is about located at the radius of 115.384 mm on the original sheet shape.

Fig. 5. Distribution of temperature in the final deformation with conical shape mandrel.

Fig. 6. The variations of temperature at node 1189.
4. Conclusions

Numerical investigation of spinning process is carried out during this study. In numerical simulation, a 3D explicit FE analysis is employed to simulate the spinning process of an aluminium circular sheet. The dynamic finite element method coupled thermomechanical analysis in the spinning process is performed successfully. The proposed model is drawn for the industry necessity, which is strong coupling with the simple elastic-plastic material, conduction and convection conditions, and the frictional sliding energy.

The conclusions are summarized as follows:
1. Consider the conduction mode only, will cause the temperature of the work piece rising too high.
2. Consider the effects of the conduction and convection at the same time, can obtain the reasonable result. If the sliding energy is applied to the model, a quite satisfactory result will be achieved.
3. The improved model in this study is suitable for the spin forming analysis. Besides, it is also available for the analysis of the contact problem with the dissipation of the sliding energy.
4. The effects of frictional sliding energy should be paid more attention to study. And the properties of temperature dependent material should not be neglected.

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