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Technical Paper

3D finite element modeling and analysis of radial forging processes

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ABSTRACT

This paper presents a novel 3D finite element model for the radial forging process with consideration of mandrel. As different with the previous works, the proposed model captures more accurately the features of the radial forging process. The proposed model is validated. With the proposed model, a comprehensive analysis of the deformation for the tube is presented. The contributions of the present work are: (1) a full 3D finite element model which captures more features of the radial forging process than the models in literature, (2) a proof that a full 3D finite element model is needed, (3) a proof of the effectiveness of the spring bar in stabilizing the contact between the hammer die and work-piece, and (4) the spindle speed has little effect on forging load. Finally, this model can be well used for the analysis and comprehensive understanding of the radial forging process and optimization of the process in future.

1. Introduction

The radial forging is a process that four radially arranged dies simultaneously press the work piece with high frequencies. Fig. 1 shows the schematic of the pushing radial forging process. The system consists of work-piece, counter holder, die, chuck head, spindle, etc. For the purpose of adapting different diameters of round bars or tubes, the flat-faced forging dies are often used. The work-piece performs both rotation and translation. The rotation is intended to achieve a round shape and the translation is to achieve a feeding of the work-piece to the dies for press. In order to prevent the work-piece from twisting, the work-piece will gradually stop rotating during the hammer die press, and the spring bars are used to equalize the angular displacement between the work-piece and the spindle.

The radial forging process can be performed in cold or hot state of metals such as steel alloys, titanium alloys, beryllium, tungsten, and high-temperature super-alloys. Radial forging processes can achieve good surface finish, tight geometry tolerance, high production rate, considerable material saving, and less defects in the forged products. The radial forging process is therefore used in the applications such as reducing the diameters of shafts, tubes, stepped shafts and axles and for creating internal profiles for tubes such as rifling the gun barrels [1–6].

There are a few methods for modeling of the radial forging process, for example, slab method, upper bound method, and finite element method. Using the slab method, Lahoti and Altan [1] analyzed the mechanical property of radial forged tubes with compound-angle dies. Ghaei et al. [2] studied the effects of die geometry on deformation of a work-piece in the radial forging process using the upper bound method. Ghaei et al. [3] further developed a model to find an upper bound limit for the deformation load and predict the effects of the process parameters in the radial forging process. Sanjari et al. [4] predicted the forging load and the location of neutral plane by using the upper bound theory and minimizing the deformation power. However, the highly simplified slab and upper bound methods do not provide accurate results.

Finite element method (FEM) has been proven to be a more accurate tool to model the radial forging process. However, most of the previous studies using the FEM simplified the radial forging process as a 2D axisymmetric model. Domblesky et al. [5] used a two-dimensional (2D) axisymmetric finite element model to investigate the mechanical and thermal behavior of the process. Fan et al. [6] investigated the effects of the process parameters on the stress and forging load in the radial forging process for fabricating the gun barrel by a 2D FE model. The 2D axis-symmetric FEM models are limited in terms of the behavior of the process they can represent. For instance, the models cannot include the process parameters such as rotational speed of the work-piece and the geometry of flat-faced forging die.

3D FEM modeling is promising. Ghaei et al. [7] developed a 3D FEM model to study the die design in the radial forging process. Ameli et al. [8] and Jang and Liou [9] developed a 3D FEM model to study the residual stress and forging load in a cold radial forging process. However, these models usually consider 1/4 of the

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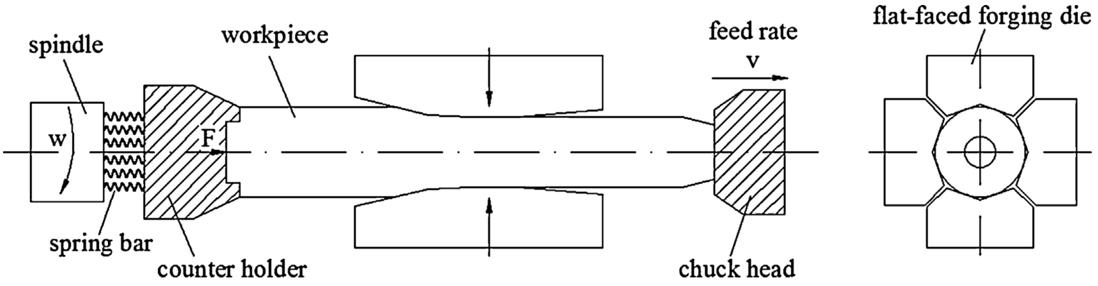

Fig. 1. The schematic of radial forging process.

system due to some symmetrical property in the radial forging process and they have not considered the movement of the work-piece. Chen et al. [10] developed a three-dimensional nonlinear finite element model to simulate the hot radial forging process. Circumferential movement of the work-piece and thermal effects on material properties are considered. However, die shape and the boundary condition in their work are not suitable to the cold forging with pushing and displacement boundary condition.

In the present paper, a full 3D FEM model for cold pushing radial forging is proposed. The model can describe four-hammer dies with their shape in cross-section, a mandrel, and a tube, which becomes possible to study the deformation of the work-piece during forging. In addition, the model captures the circumferential and axial feed motion of the work-piece. The boundary condition with the model is as follows: constant moving block at the end of check head, and spring bars and pressure at the end of the counter holding. It is noted that this boundary condition model is the most accurate to the best of authors' knowledge. The proposed 3D FEM model provides the opportunity to study the effect of the parameters such as the stiffness of spring bar, rotation speed and the geometry of flat-faced forging die. The output parameters such as deformation of the work-piece and forging load are greatly affected by those input process parameters. They are closely related to the quality of the radial forging process, for example, the heterogeneous deformation of forging area will cause the residual stress of the produced profile. Analysis of these parameters through modeling is an important task, which is the focus of this paper.

2. Model development

The model was developed and implemented with the commercial finite element code, Abaqus/Explicit, and the model accounts for contact and material nonlinearities. The model includes the meshes for work-piece, inner mandrel, four hammer dies, chuck head, and spring bar. The inner mandrel, four hammer dies and chuck head are modeled as rigid bodies for the purpose of reducing computational cost without loss of the simulation accuracy. The 3D FEM model of radial forging is shown in Fig. 2 for an impression.

During the forging process simulation, the chuck head moves forward with a constant axial feeding velocity, and the end of the tube keeps contacting with the chuck head under the counter holder plunger pressure in the other unformed end. The spring bar with an appropriate torsional stiffness and damping ratio is also connected with the preformed end of the tube, and the other end of the spring element has a constant spindle rotation speed. When the hammer die does not contact with the work-piece, the work-piece will move forward with the axial feeding velocity and rotation with spindle speed simultaneously. When the hammer die contacts with the tube, the spring is used to equalize the angular displacement between the work-piece and the spindle.

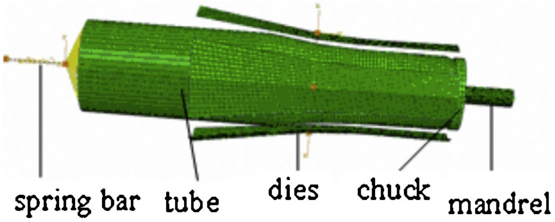

Fig. 2. The 3D FEM model of radial forging.

Table 1
Mechanical properties of the work-piece material.

Elasticity modulus	Poisson's ratio	Initial yield stress	K	n
214 GPa	0.29	926 MPa	1225	0.065

The material of the work-piece is 30SiMn2MoVA. The radial forging process is performed under normal temperature because of the constant liquid cooling in the process. So the effects of the temperature and the strain rate on the flow stress are neglected. The property is obtained through tensile test [12], and a power law for strain hardening is used ($\sigma = K\varepsilon^n$). The elastic–plastic properties for the work-piece material are given in Table 1.

A reduced integration strategy with hourglass control (C3D8R) is used for the work-piece element to avoid the shear-locking problem. As the radial forging process is a large deformation process, the ALE (Arbitrary Lagrangian–Eulerian) adaptive meshing method is used. The penalty formulation is used to model the friction in the contact surfaces. It is assumed that the limiting shear stress can be found by $m\overline{\sigma}/\sqrt{3}$, where $m = 0.15$ is the friction coefficient commonly used for cold forging processes and $\overline{\sigma}$ is the flow stress. Additionally, a finite sliding method is employed for modeling the sliding between the contact surfaces.

The motion of the die conforms to a sine curve, and the curve function is $y = 3.5\sin(0.0714t)$, where the forging frequency is 680 per minute. The geometrical parameters of the tube and hammer die (shown in Fig. 3) and the process parameters in this study are shown in Table 2. The spring element with appropriate torsional stiffness (6000 Nm) and damping ratio (0.4) are used as the spring bar, details of which are referred to [11].

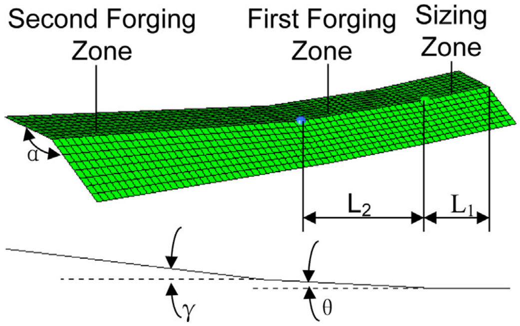

Fig. 3. The shape of a hammer die.