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Upper bound analysis of forging penetration in a radial forging process

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ABSTRACT

A theoretical model based on upper bound approach is proposed to study forging penetration in a radial forging process. Using the transformations for both the geometric coordinate system and the velocity field, the parabolic discontinuity boundaries in axisymmetric problem are mapped into straight lines in the transformed field. As a result, the present model is simplified and its implementation is analogous to the rigid block upper bound approach in plane strain problem. In order to quantify the penetration of plastic deformation, forging penetration depth is introduced and defined as the radial distance from the outside surface of the workpiece to the intersection point of the assumed plastic and rigid regions. This model is verified by comparing the predicted forging load with published experimental data, and by comparing the predicted forging penetration depth with that of the finite element simulation. Finally the effects of process parameters such as the radial reduction rate and the inlet angle of hammer on the forging penetration are investigated.

1. Introduction

Radial forging is a hot or cold forging process utilizing usually four hammer dies arranged radially around the workpiece to produce solid or tubular components, as illustrated in Fig. 1. Compared with conventional open die forging, a superior grain structure and crack-free deformation is achieved due to the restricted lateral spread resulted from the constraints of four hammers [1]. On the other hand, radial forging is an incremental forming process, where the total deformation is achieved by successive individual forming steps and passes. Actual deformation may take place only at the surface, namely incomplete forging penetration occurs, since the radial reduction during each pass is generally less than that in open die forging. The incomplete forging penetration is detrimental to the brokenness of coarse grains and the consolidation of defects at the interior of workpiece. As a result, the mechanical properties of the final product are significantly impaired. Therefore, it is of considerable importance to conduct research on the process design of radial forging to avoid incomplete forging penetration of workpiece.

Several models are presented for the analysis of a radial forging process. They are classified as analytical models based on the slab method, the upper bound approach or the slip-line field method, and numeric models represented by the finite element method. Utilizing a slab method, Lahoti and Altan [2] developed an analytical model which took into account the strain, strain rate and temperature effects on the material for radial forging of rods and tubes. Then, it was applied to the design of hammer dies with simple straight conical and compound angle entries [3]. Ghaei et al. [4] proposed an improved model for the design of hammer dies with various inlet zone shapes including not only simple straight conical but also convex, concave and hybrid surfaces. Based on Lahoti and Altan's model, Tseng et al. [5] used a one dimensional heat transfer equation to predict the thermo-mechanical behavior of the radial forging process. Although the slab analysis is an available method for the radial forging process, the existing models are incapable of solving forging penetration problems due to the basic assumption of the slab method that the deformation is homogeneous within a slab [6].

The upper bound approach is widely applied to the analysis of metal forming problems. For example, based on the proposed upper bound models, Hwang et al. [7] investigated the plastic deformation behavior in asymmetrical clad sheet rolling; Yeh and Wu [8] studied the bulge profile and forming energy in upset forging of rings; Ghassemali et al. [9] predicted the forming load, the critical blank thickness and the location of the neutral plane in open die forging/extrusion processes. In the analysis of the radial forging process, the upper bound method is generally conducted by assuming a deformation mode and then minimizing the energy consumed by the flow field with regards to some parameters, such as the location of the neutral plane. According to the changes of tube thickness between two steps, Ghaei et al. [10] obtained the average plastic strain in the deformation zones and proposed an upper bound model to investigate the influence of process

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parameters on forging load. Their co-authors, Sanjari et al. [11] developed a new model by assuming a simplified velocity field. Based on a kinematically admissible velocity field, the authors [12] proposed an axisymmetric model to study the axial metal flow in radial forging process and they improved the model by introducing inhomogeneous deformation mode into the assumed velocity field [13]. Essentially, forging penetration can be studied by upper bound approach if an inhomogeneous deformation mode is considered. However, the aforementioned velocity fields are classified as parallel velocity fields, in which the deformation along the radial direction is homogeneous, except Wu et al.'s model [13]. Under the assumption of plane strain, Yang [14] developed a theoretical model combining slip-line field theory with the upper bound theorem to discuss the cause of central bursts and the forging penetration within the cross section of the workpiece. Since the analysis is conducted in transverse direction of the workpiece, the effects of inlet angle of the hammer dies on the forging penetration cannot be considered.

The finite element method (FEM) has already been proved to be a powerful computational tool for metal forming. Several FEM models were developed to study various issues during radial forging process, such as the thermomechanical history [15], residual stress [16] and deformation mechanism of internal void defects [17]. Forging penetration was studied by Zhou et al. [18] from the viewpoints of the effective plastic strain, the mean stress and the mean plastic strain distribution. Comparing with the theoretical analysis, the results simulated by FEM models are generally more accurate, but it is not an efficient way to search for the optimum condition over a whole combination of various process parameters due to the great consumption of time and memory. Instead, for a complete optimization procedure, it is suggested to reduce the scope of process conditions rapidly by the analytical model before FEM simulation is performed.

In this study, an axisymmetric model based on the upper bound approach is proposed to simulate the forging penetration in radial forging process. The transformations for both the geometric coordinate system and the velocity field, which were proposed by Wilson [19], are applied to simplify this model. As a result, the implementation of the present axisymmetric model is analogous to the rigid block upper bound approach in plane strain problem. Then this model is verified by comparing the predicted forging load with published experimental data, and by comparing the predicted forging penetration depth with that of the finite element simulation. Finally the effects of radial reduction rate and the inlet angle of hammer on the forging penetration are investigated.

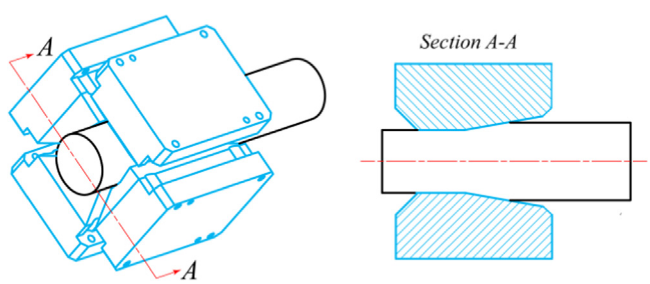

Fig. 1. Schematic representation of the radial forging process.

2. Mathematic modeling

In radial forging process, the workpiece is deformed under strikes of multiple hammers arranged radially while fed by chuck-head in both radial and circumferential directions simultaneously. Generally, it is simplified to be axisymmetric in theoretical modes by neglecting the rotation of workpiece and the clearance between every two hammers. Thus, a cylindrical coordinate system is defined in the longitudinal section of the workpiece.

2.1. Transformation of the geometric coordinate system and the velocity field

For axisymmetric problems, the incompressible continuity equation is expressed as

$$\nabla\cdot\left(r\vec{v}\right)=0 \tag{1}$$

where $\nabla=\left(\frac{\partial}{\partial z},\frac{\partial}{\partial r}\right)$ is the Hamilton operator and $\vec{v}=(v_z,v_r)$ is a velocity vector with an axial component v_z and a radial component v_r.

A particular solution to Eq. (1) is adopted to be the velocity field in this model and it is given by

$$v_z=C_1$$
$$rv_r=C_2 \tag{2}$$

where C_1 and C_2 are arbitrary constants.

Be similar to the rigid block upper bound approach in plane strain deformation, the deformation field in this axisymmetric model can be built up of regions separated by velocity discontinuities. However, it is worth noting that: (a) the deformation regions are no longer rigid blocks because of the occurrence of radial deformation, as shown in Eq. (2); and thus (b) the boundaries of velocity discontinuity are no longer straight lines. Fig. 2(a) shows the velocity discontinuity boundary of two adjacent regions *I* and *II*. For any position on the boundary, the velocity continuity along the normal direction Δv_n and that along the tangent direction Δv_τ are given by

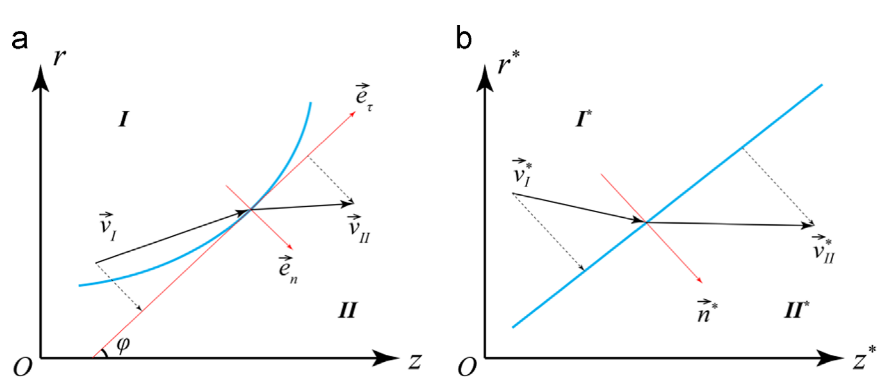

Fig. 2. Schematic representation of axisymmetric velocity discontinuity in (a) the absolute z–r plane and the transformed z^*–r^* plane.