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Upper bound analysis of axial metal flow inhomogeneity in radial forging process

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A B S T R A C T

An axisymmetric upper bound method model is proposed to analyze the inhomogeneity of axial metal flow in the radial forging process from the viewpoint of end profile in the meridian plane of the workpiece. The velocity fields are newly derived using stream function approach so that they can automatically satisfy the volume constancy as well as the velocity boundary conditions on the contact surface between the hammers and the workpiece. The assumed stream function has considered the inhomogeneous deformation mode. As a result, compared to the parallel velocity fields proposed in previous studies, reasonable predictions of radial load can be achieved even though the value of radial reduction is relatively low. Besides, the axial flow inhomogeneity along the radial direction can be described by this model because the axial velocity is no longer independent of the radial position. This model is verified by comparing the predicted forging load with published experimental data. Finally, the influences of axial feed and radial reduction on the end profile in the meridian plane of the workpiece are investigated.

1. Introduction

In industrial metal forming processes, redundant or unwanted deformation such as bulged profiles of upset forging occurs commonly. The material undergoes more strain than required for the area reduction and consequently strain hardens more and is less ductile [1]. To obtain the optimum conditions for the minimization of increased forming energy or the improvement of inhomogeneous strain distribution due to the redundant work, investigations on various processes such as upset forging [2,3], bar or wire drawing [4,5], flow forming [6], are conducted. On the other hand, by affecting the kinetics of recrystallization and the microstructure during subsequent annealing, such redundant deformation can also influence the mechanical properties of materials [7–9].

Deformation in radial forging results from a large number of short-stroke and high speed pressing operations by usually four hammer dies, arranged radially around the workpiece, as illustrated in Fig. 1. The workpiece is enclosed by forging dies and is therefore only able to flow axially, thereby avoiding or reducing greatly the redundant work spending on lateral spread. However, the frictional effects between the hammers and the workpiece still lead to redundant deformation characterized by an inhomogeneous distribution of axial metal flow in the radial direction. The surface layers are sheared relative to the center so that the plane sections will no longer remain plane [1]. As a result, concave or sometimes convex profiles occur in the meridian plane of the workpiece, which usually have to be cut off in industrial production. Therefore, it is necessary to study the inhomogeneity of axial metal flow to avoid excessive concave or convex profiles in the meridian plane.

Radial forging process is generally studied by two approaches: theoretical analyses such as the slab method and upper bound method, and numerical analyses represented by the finite element method. It is known that slab analysis is based on making a force balance on a differentially thick slab of material, thus it is employed to predict the forging load or pressure distribution. For example, Lahoti et al. [10,11] developed an analytical model which takes into account the strain, strain rate and temperature effects on the material for radial forging of rods and tubes. Ghaei et al. [12,13] studied the effects of hammer geometry on the radial pressure and consequently drew conclusions for forging dies design. In essence, slab analysis cannot solve displacement field, so it is incapable of solving inhomogeneous metal flow problems. Upper bound analyses for the radial forging process are usually conducted by assuming a kinematically admissible velocity field and then minimizing the deformation power with regards to the location of the neutral plane. In this way, Ghaei et al. [14] and Sanjari et al. [15] investigated the influence of process parameters on forging load in the case of radial forging of rods and tubes. Wu et al. [16] studied the axial metal flow, especially the forward flow in the cold radial forging process of rods. However, the aforementioned velocity fields

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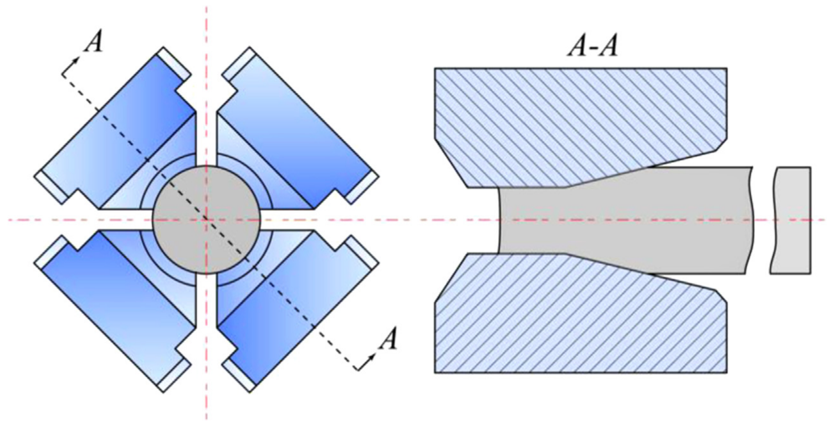

Fig. 1. Schematic representation of the radial forging process.

did not consider the redundant deformation mode. They are called the parallel velocity fields since the axial velocity was assumed to be completely independent of the radial position. Above all, an available theoretical model for the study of axial metal flow inhomogeneity in radial forging process has not been proposed.

Comparing with the solutions of theoretical analyses, the finite element method can be more practical and more accurate, especially for the prediction of strain fields. Domblesky and Shivpuri [17] developed a finite element model to study the plastic strain distribution along the radial direction for multiple-pass radial forging. For the prediction of plastic strain and temperature along the axial and hoop directions in the deformed workpiece, Chen et al. [18] presented a 3D nonlinear thermo-mechanical coupled model. Furthermore, utilizing the finite element method verified by the microhardness test, Sanjari et al. [19,20] studied the effects of process conditions on heterogeneity of the strain field, which was defined as an inhomogeneity factor. In summary, numerical method is available for the study of axial metal flow inhomogeneity, but it has not yet been discussed from the viewpoint of end profile in the meridian plane in the literature.

In the present work, an axisymmetric upper bound method model is proposed to simulate the axial metal flow from the viewpoint of end profile in the meridian plane in the radial forging process. The velocity fields are derived from a specific stream function considering inhomogeneous deformation mode. Consequently, it can automatically satisfy the volume constancy as well as the velocity boundary conditions on the contact surface between the hammers and the workpiece. This model is verified by comparing the predicted forging load with published experimental data. Then the influences of axial feed and radial reduction on the axial metal flow inhomogeneity are investigated.

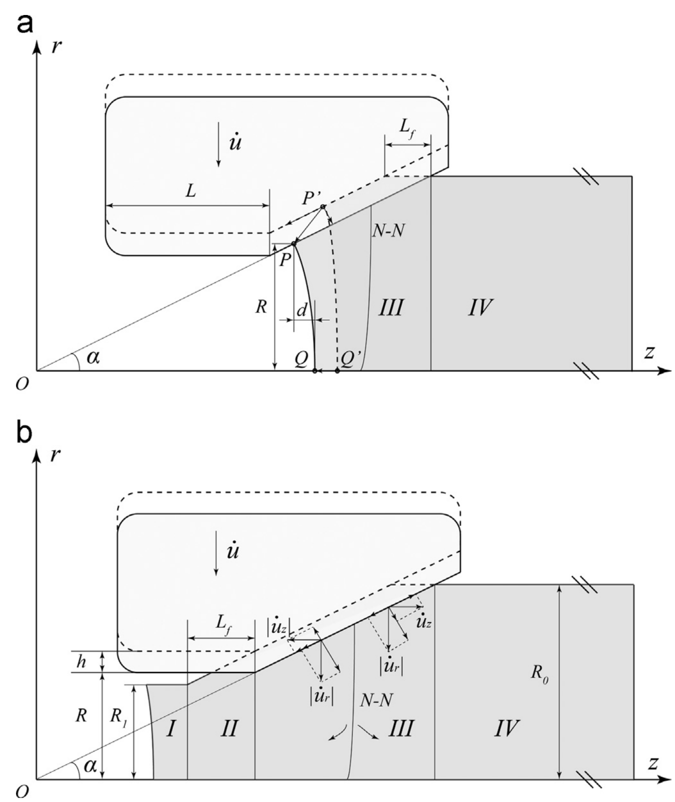

Fig. 2. Schematic diagram of the upper bound method model: (a) the pre-forging state and (b) the steady state of the radial forging process.

2. Mathematic modeling

In the following analysis, the upper bound method model is based on the assumptions that (a) the deformation mode is simplified to be axisymmetric [10,14,15]; (b) the material is rigid-plastic and strain-hardened; (c) shear frictional law is applied on the contact surface; and (d) the front-pull and back-push forces are neglected.

Compared to the previous studies [10,21], it is worth noting that the end surface of workpiece no longer remains planar because the distribution of axial metal flow along the radial direction is actually inhomogeneous. The concave or convex depth of end surface is defined as the difference between the axial distance of particles on the outside surface and that at the centerline of the workpiece, as marked with d in Fig. 2(a). A positive value of d means that the end profile of the workpiece is concave. A negative value indicates a convex surface. The concave or convex depth reflects the degree of deformation inhomogeneity: the larger the absolute depth, the more inhomogeneous the deformation. In the present model, a redundant deformation mode has been considered, so the concave or convex depth can be solved and it is adopted to analyze the axial metal flow inhomogeneity in the radial forging process.

In general, the analytical models are built at the steady state of the radial forging process. However, in order to solve the end profile in the meridian plane, it needs to be modeled since the first stroke of the hammers. Fig. 2 shows the schematic diagram of this model in meridian plane. At the beginning of each pass, the workpiece is fed axially; therefore the contact surface between the workpiece and the pre-forging part of hammers increases gradually until the workpiece is fed to touch the sizing part of hammers. This process usually contains first several or dozens of strokes and it is called the pre-forging state of radial forging in this paper, as seen in Fig. 2(a). Then, the hammers are in full contact with the workpiece at the end of each subsequent