ACCURATE METAL FLOW ANALYSIS IN THE MICRO-EXTRUSION PROCESS OF ALUMINUM ALLOYS

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ABSTRACT

The micro-extrusion process had grown up as a popular means to fabricate the miniature metallic products even in mass production. Its study was mainly driven by experiments to understand the effect of the friction between dies and work materials as well as the effect of grain size of work on the micro-extrusion behavior. Since the work deformed elasto-plastically in the closed dies set, its metal flow could never be directly observed only by the experiments. To save this difficulty, numerical simulation provided a tool to describe the metal flow in the closed die cavity during the micro-extrusion. However, the conventional program codes by the Lagrangian model sometimes suffered from the difficulties in simulation; e.g., severe mesh distortion, inaccurate contact between mesh model and die surfaces, too much over-or under-estimate of the applied loads and so forth.

Authors (Khalid, 2015) proposed the ALE (Arbitrary Lagrangian-Eulerian)-based finite element methods to be completely free from the above difficulties. In the present paper, this ALE-based finite element method was applied to micro-extrusion simulation in order to accurately describe the metal flow in the micro-extrusion process of aluminum alloys. In correspondence with the experimental data for the metal flow of aluminum alloy work, the effect of friction coefficient on the metal flow was quantitatively studied to further the theoretical flame for establishment of micro-extrusion technology.

1. INTRODUCTION

Miniaturization of devices and sensors highlights as an industry demand for micro-meter sized parts. Micro-extrusion method was first proposed to fabricate the small sized parts and elements (Krishnan, 2005). With reduction of the product size, the surface expansion ratio inevitably increases so that the friction and wear as well as the grain size and texture of work materials play more important role than those in macro-manufacturing. Then, reliable simulation is indispensable to analyze the metal flow in the micro-extrusion process with consideration of friction and grain size refinement.

The finite element method provides a means to describe the metal flow in the closed die cavity during the micro extrusion processes. However, the conventional Lagrangian model for finite element simulation often encounters the mesh distortion and element entanglement during the extrusion process. On the other hand, the Arbitrary Lagrangian Eulerian (ALE) formulation can alleviate most of drawbacks intrinsic to the traditional Lagrangian and Eulerian formulations. (Chanda, 2000). The computational model needs not to adhere to the material nor be fixed in space but can be moved arbitrarily. This freedom in choice of a mesh velocity in the ALE method can be employed to reduce the error by computing the mesh velocity with the help of an error estimator (Donea, 2004). Owing to this mesh velocity control, a refined element mesh can be obtained in the region where the error estimation becomes large. For an example, the ALE method might well be employed to make meshing adaptive to the plastic zones. Accurate plastic deformation can be traced even when using a fine element mesh only locally. In addition, mesh distortion is saved with use of the mesh velocity control. The ALE method is useful to simulate the complicated process in the micro-extrusion, to verify the mesh motion scheme and to accurately describe the metal flow.

The present study concerns with the simulation of hot micro-extrusion at 688 K for A6063 aluminum billet by using the ALE-based finite element method. The metal flow of work billet is accurately simulated to find the onset of flow separation to the backward extrusion mode from the forward extrusion one. This metal flow is governed by the friction coefficient (μ). In the following simulations, the forward extrusion mode governs the whole metal flow when $\mu = 0.1$. When tuning the friction coefficient up to $\mu = 0.4$, the metal flow separates to the backward extrusion from the main forward extrusion flow.

2. THEORETICAL MODEL

Ansys-Autodyn 2D was employed to demonstrate the effectiveness of ALE molding and to describe the metal flow for micro-extrusion process simulation in the axi-symmetric situation. The experimental set-up in (Takatsuji, 2014) was used in this simulation. The work of aluminum alloy (A6063) with the diameter of 1.7 mm and the length of 6 mm is extruded down by the flat-head punch as shown in Fig. 1. The material of die and punch are SKD-11. The die was segmented to facilitate pin removal after extrusion. As noticed in Fig. 1, the work is mainly extruded in forward. Since the clearance is set up between die and flat-head punch, the work is possible to be extruded also in backward. In the forward mode, the work is thought to deform through the inner die hole. On the other hand, when the work is backward extruded in part, the upper part of work deforms up along the extrusion direction. This selection might be dependent on the friction coefficient as well as the grain size of aluminum alloy billets. The friction coefficient (μ) in experiments was varied in the limited range up to $\mu = 0.4$.

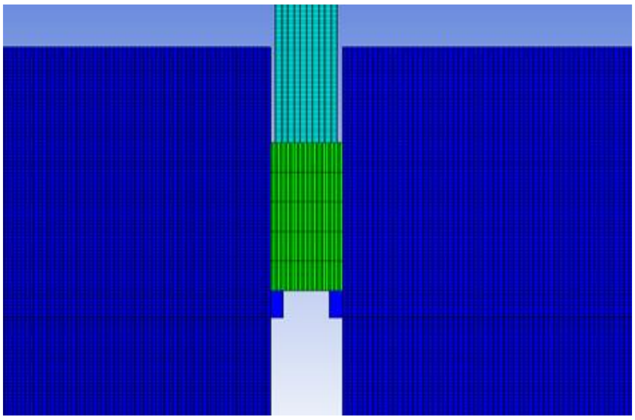

Fig. 1 ALE-based finite element model for the micro-extrusion.

3. Experimental Result.

The finite element analysis by the Lagrangian model, as seen in Fig.2, encounters severe mesh distortion at the vicinity of inner die hole during simulation. Every mesh traces the material movement during the extrusion process. In fact, an artificial clearance is induced between the aluminum billet and the inner die hole in the forward extrusion. Most of tool or die corners become a singular point, where the mesh velocity is not equal to the material one. The material flows up even on this corner in Fig, 2 since the mesh cannot move with materials but stays on this corner. The boundary condition prescribed on this mesh corner node in simulation. Hence, a mesh distorts and invades the die surface boundary

Figure 3 shows the calculated aluminum work flow at the displacement of 3.6 mm by the ALE-based simulation when $\mu = 0.1$. No mesh distortion is observed even at the die corners; the aluminum billet is mainly forward extruded through the inner die hole. In this ALE modeling, the mesh velocity is effective in preventing mesh distortion. In addition, the boundary conditions are also more accurately prescribed in this ALE method. In fact, a nodal point moves in arbitrary mode and stays at the end of the contact area with the die. In order to control this mesh movement, the length of finite elements are controlled to be as much as possible in the deformation direction; in other word, less element subdivisions are specified in the direction of metal flow. The deformation occur more smoothly without an error.

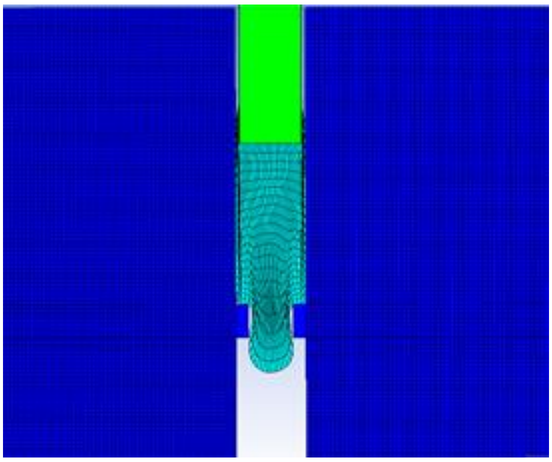

Fig. 2 Aluminum work flow by the Lagrangian simulation when $\mu = 0.1$.

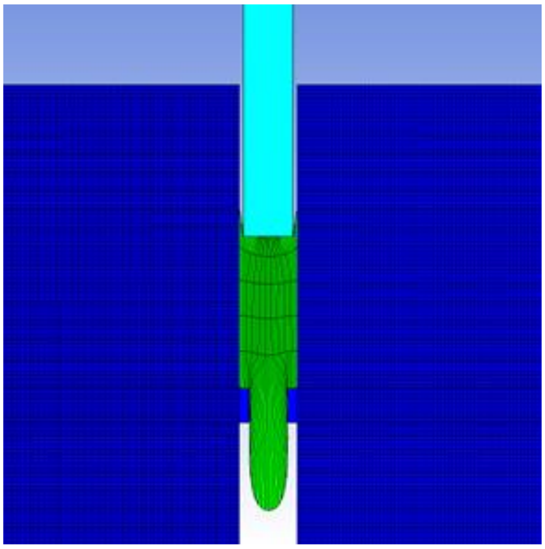

Fig. 3 Aluminum work flow by the ALE-based simulation when $\mu = 0.1$.

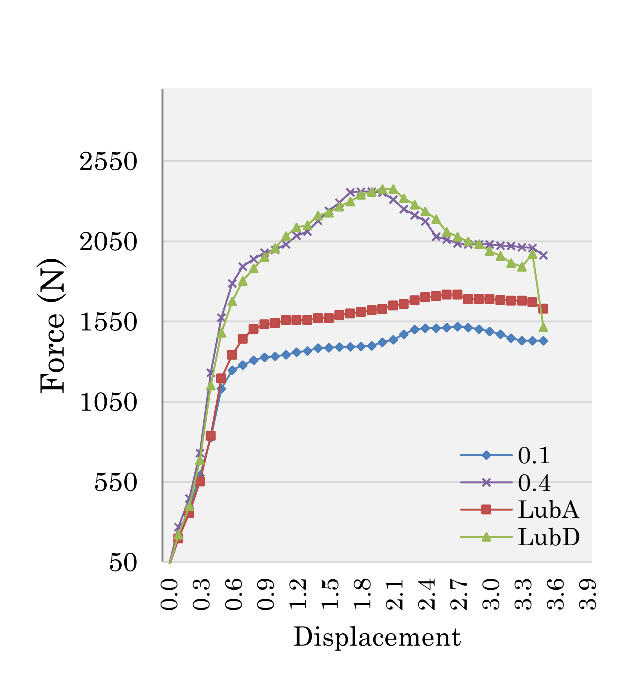

Fig.4 Relationship between the applied force and the displacement by varying the friction coefficient.

4. DISCUSSION

4.1 Numerical Method

In the Lagrangian model, most of tool or die corners become a singular point, where the mesh velocity is not equal to the material one. During extrusion process, the material flows up even on this corner; however, the mesh does not move but stays on this corner. The boundary condition must be prescribed on this mesh corner node in simulation. Hence, a mesh distorts and invades the die surface boundary in the Lagrangian model. This Lagrangian description allows an easy tracking of free surfaces and interfaces between different materials. It also facilitates the treatment of materials with history dependent constitutive relations. Its weakness is its inability to follow large distortions of the computational domain without recourse to frequent remeshing operations.

In the ALE model, the mesh velocity control as well as the remapping of state valuables play a role to preserve the accuracy and reliability in the computational mechanics. As a mesh relocation techniques, the equivalent plastic strain indicator is used to make mesh-control together with the transfinite mapping algorithm by the nodal relocation. Then, the shape and size of elements is preserved in high quality without distortion and change in mesh topology. Two coordinate systems are defined; the material meshing moving with material deformation, and, the computational point which moves independently from materials. That is, the actual material velocity and the mesh velocity are simultaneously utilized in computation with the one-to-one mapping between material and computational domains. In the mesh motion design, the overall strategy for the motion of the mesh is predetermined to decide what type of motion is best suited to each region of the mesh on the basis of physical understanding of metal forming process in whole.

4.2 Material Flow

In the Lagrangian model, the metal flow in the forward extrusion is retarded; however, the backward extrusion is exaggerated as a branch of the whole aluminum billet in extrusion. This reveals that use of Lagrangian model not only causes the numerical errata in every spot of simulation but also induces the misunderstanding of metal flow especially in the micro extrusion process design.

In the ALE model, the metal flow of aluminum alloy work is controlled by the friction coefficient (μ). When μ = 0.1, main metal flow takes place in the forward extrusion stream with a slight backward extrusion flow. Hence, the extrusion force increases monotonically with displacement, as shown in Fig. 4. This reveals that mechanical equilibrium state during the micro-extrusion is not affected by this slight flow separation under the low friction condition. However, the ratio of metal flow in the backward mode to that in the main forward mode increases with the friction coefficient.

Figure 5 depicts the extruded aluminum billet at the displacement of 3.6 mm. Different from Fig. 3, the micro-extrusion process takes place together with the metal flow separation. In correspondence with this separation in metal flow, the extrusion force changes with displacement. Up to the displacement of 0.6 mm, the extruded force increases monotonically with displacement in the similar manner to the case for m = 0.1. Higher force is needed to extrude the aluminum work through the inner die hole by higher friction coefficient. To be noted, this extruded force takes maximum at the displacement of 1.8 mm, and, decreases with the displacement beyond. Considering that the frictional force works against the forward extrusion flow, higher force is needed to push down the billet through the die. At the time when the metal flow separates to the forward and backward directions, the extruded forces balances with two frictional force; i.e. the friction forces against the forward and backward streams. Since the frictional force against the backward flow works in opposite to the former friction against the forward flow, the applied force decreases from this critical displacement. This reveals that the critical limit on the extruded forces is driven by the onset of significant metal flow separation during the micro-extrusion.

This frictional effect on the metal flow plays an important role to reconsider the micro-extrusion process design. The ratio (R) of backward extruded length to the forward extruded one is employed as a physical parameter to describe the frictional effect. With use of the calculated R-m relationship, the actual friction coefficient might be estimated by measurement of R in practice.

Let us make some comments on the comparison of the relationship between the applied extrusion force and the displacement between experiments and simulations. Using the stress – strain rate equation as well as the mechanical constants at the holding temperature in the micro-extrusion, both are quantitatively in agreement in Fig. 4. This reveals that the ALE-based process simulation is indispensable to quantitatively describe the metal flow and stress equilibration during the micro-extrusion process with consideration on the process tribology.

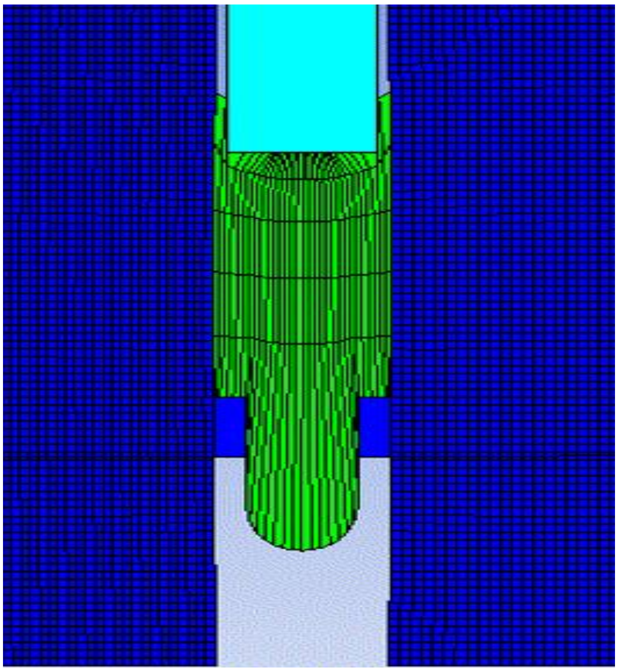

Fig.5 Aluminum workflow by the ALE-based simulation when $\mu = 0.4$.

CONCLUSION

Micro-extrusion process requires for a non-traditional approach to be free from severe mesh distortion, and to accurately describe the metal flow. In the present ALE-based modeling, no mesh distortion occurs at the die corners, since re-meshing is automatically performed in the same mesh topology. Through simulation, the effect of friction coefficient on the metal flow in extrusion is quantitatively discussed to describe the material flow branching into backward and forward extrusion modes. The effect of the friction coefficient on the metal flow separation is directly analyzed through the accurate prediction on the transients of extruded forces with displacement. Quantitative agreement on these transients for variety of friction coefficients between micro-extrusion experiments and simulations proves that the ALE-base modeling enables to physically describe the micro-extrusion process with sufficiently accuracy.

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