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Finite element investigations of friction condition in equal channel angular extrusion

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Analysis and modelling

ABSTRACT

Purpose: This study concentrates on the investigation of contact phenomenon at the interface between dies and the workpiece in terms of material flow and forming load requirement.
Design/methodology/approach: The numerical simulations of an equal channel angular extrusion (ECAE) with a CP-Ti Gr-1 cylindrical specimen were carried out by applying the mixed finite element formulation with tetrahedral elements under the non-isothermal condition. Compression test was used for determination of the material data. The change of contact conditions during remeshing was also investigated in terms of variation of load requirements and volume losses after remeshing. In order to validate the numerical algorithm proposed, simulation results were compared with the experimental data.
Findings: It was found that the forming load simulated was very sensitive to the contact condition of the workpiece with the channel. The current investigation clearly showed the importance of proper handling of boundary conditions to improve the solution accuracy.
Research limitations/implications: Further applications of the proposed scheme are required.
Practical implications: The new numerical scheme will be beneficial in better understanding the deformation mechanics of the ECAE.
Originality/value: New contact algorithm to solve ECAE was developed to reduce the volume loss and load requirement after remeshing.
Keywords: Numerical techniques; Equal channel angular extrusion; Friction condition; Remeshing

1. Introduction

The ultra-fined materials have been widely investigated due to its mechanical properties such as high specific strength and ductility. Various forming techniques have been developed to obtain such mechanical properties. Among them, equal channel angular extrusion (ECAE) is an effective technique to improve the material strength by imposing severe plastic strain into the workpiece. Because of its prominent feature to fabricate the workpiece repeatedly without changing the geometry of the workpiece, many studies of the ECAE process have been conducted experimentally and numerically so far to investigate the effect of process parameters on material behavior and strain distribution [1,2].

Prangnell et al. [3] initially presented a finite element model of the ECAE process with a simple process condition in order to estimate the friction effect. Delo and Semiatin also [4] carried out FE analyses of the ECAE process to investigate the flow pattern due to flow softening and non-softening behavior depending on temperatures. Furukawa et al. [5] evaluated the shearing characteristics and patterns for the multi-pass ECAE processes which were differentiated by A, B, and C routes. Lee et al. [6] examined deformation patterns after the multi-pass ECAE in A and C routes using FE analyses under the plane strain condition in order to explore the effect of processing routes. Bowen et al. [7] suggested that die corner angles and friction factors should be lower to obtain more uniform strain while maintaining a constraining back pressure to the workpiece. Son et al. [8] categorized the application of back pressures as Type-I, Type-II, and Type-III and concluded that Type-III back pressing was more effective to achieve high and more uniform strain distributions in single or multi-pass ECAE processes.

The current study concentrates on investigation of the effect of various friction conditions under the non-isothermal condition on forming load and strain distribution of the workpiece. The contact points of the workpiece boundary at the channel were traced to better estimate forming load variations during the process. The contact point distributions after remeshing was also examined to determine the effect of proper handling of the boundary condition during the remeshing process on forming load and volume loss predictions. It has been found that the forming load was very sensitive to the contact condition between the workpiece and channel. It is clearly demonstrated in the present investigation that the small changes in friction conditions led a large variation of forming loads.

2. FE modeling

2.1. Finite element formulation

The finite element (FE) program based on mixed formulation with linear tetrahedral elements ($P1^+/P1$) was developed to carry out the three-dimensional ECAE simulations under the non-isothermal condition. The velocity and pressure fields were interpolated at vertices and one velocity component at the centroid of an element was added to prevent the locking phenomenon.

The constant shear friction model [9] used in simulations to apply frictional force between the interface of the workpiece and dies can be described in the following equation:

$$t_i^* = -m_f k_s \frac{2}{\pi} \frac{(\mathbf{v}_r)_i}{\|\mathbf{v}_r\|} \tan^{-1}\left(\frac{\|\mathbf{v}_r\|}{\psi}\right) \text{ on } S_C \qquad (1)$$

In this model, m_f and k_s represent the shear friction factor and shear yield strength of the material, respectively and v_r is the relative velocity between dies and the workpiece. The small positive number, ψ=0.05, was introduced to regularize the friction model since it cannot be defined when the relative velocity becomes zero. Since the numerical implementation of FE formulation was described in detail in reference [10] it is omitted here.

The material property of the CP-Ti specimen used in FE simulations was obtained from compression tests at temperatures in the range of 300°C to 600°C and strain rates from 0.001 s^{-1} to 10 s^{-1} using Gleeble 1500 [11]. The flow stresses were modeled with the third order polynomial fitting in log ($\overline{\sigma}$)-log ($\dot{\overline{\varepsilon}}$) scale for non-isothermal simulations. The modeled flow stresses were provided in a tabular form in FE simulations. The flow curves and modeled flow stresses according to different temperatures at constant strain rate of 1 s^{-1} are displayed in Fig. 1.

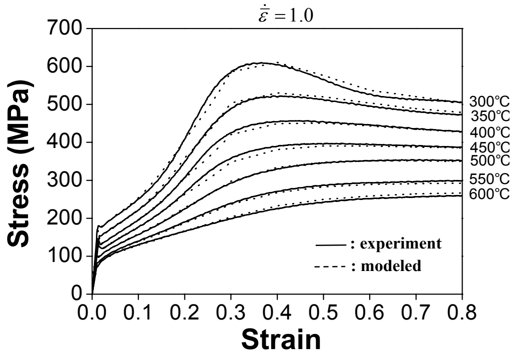

Fig. 1. Flow curves for CP-Ti obtained from the hot compression tests and flow stress modeling

2.2. Remeshing process

The drawback of updated Lagrangian forming simulations is that boundary elements tend to be deteriorated as the simulation proceeds. In this study, a new remeshing technique based on the mesh density distribution was developed to refine or coarsen the surface elements according to the mesh density distribution which was calculated by the gradient of effective strain rate, effective strain, and geometry variations. Then, the overall mesh density was defined with respective mesh densities in the following equation.

$$\rho^2 = w_{\dot{\varepsilon}}\rho_{\dot{\varepsilon}}^2(\dot{\varepsilon}) + w_{\varepsilon}\rho_{\varepsilon}^2(\varepsilon) + w_g\rho_g^2(g) \qquad (2)$$

where $\rho_{\dot{\varepsilon}}(\dot{\varepsilon})$, $\rho_{\varepsilon}(\varepsilon)$ and $\rho_g(g)$ are the mesh density for the effective strain rate, effective strain, and normal vector variation of boundary surface nodes, respectively. And $w_{\dot{\varepsilon}}$, w_{ε}, and w_g are weighting factors corresponding to each mesh density.

The tetrahedral elements were generated with advancing front technique based on the local optimization scheme to keep the fronts smooth, resulting in better mesh quality compared to conventional mesh generation algorithms according to the work by Choi et al. [12].

3. Results and discussion

Three-dimensional ECAE simulations of the circular-shape specimen using the developed program were carried out to investigate the effect of contact conditions on the behavior of forming load and strain distribution.

The effect of contact conditions according to the initial positioning of the workpiece and channel was first investigated. The initial positioning could lead to the full and partial contact conditions between the workpiece and channel. The full contact condition indicates that most parts of the workpiece at initial positioning stage were in contact with the channel, whilst the partial contact condition indicates that only small bottom part of the workpiece was in contact with the channel at the initial positioning.

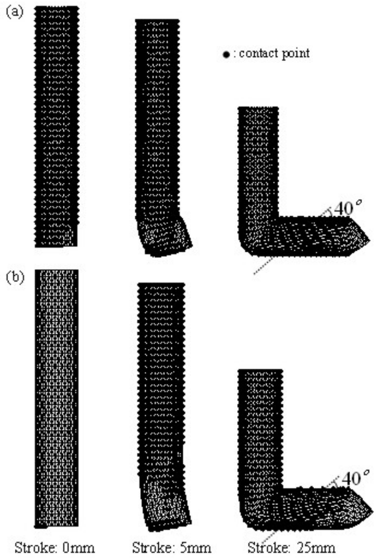

Fig. 2. Distributions of contact points with different strokes according to initial positioning under: (a) full contact and (b) partial contact conditions (m_f=0.13)

Fig. 2 shows the distribution of contact points of workpiece nodes as the workpiece deforms through the channel. In full contact condition, contacted nodes in the region of die corner were separated from the channel at the stroke of 5mm. However, in the subsequent stroke, most of the boundary nodes were in contact with the channel at the stroke of 25mm as shown in Fig. 2(a). This phenomenon can be explained from the distribution of contact points shown in Fig. 2(a). The excessive contact conditions at the time of initial positioning induced the abrupt increase of the load and these contact points were not separated in the subsequent deformation. On the other hand, surface nodes at the upper part of the workpiece in partial contact condition as shown in Fig. 2(b) were separated from the channel in the subsequent deformation. And in both cases, the shearing patterns predicted by simulations were similar to the result of reference [5] in terms of an inclined angle of the gird lines as shown in Fig. 2.

Because of these different distributions of contact points, Fig. 3 clearly shows that the contact conditions between the channel and workpiece greatly affect the forming loads. When the full contact condition was used for simulations, the load requirement and the load pick-up at the stroke of 5 mm could not be predicted. However, when the workpiece was partially in contact with the channel at the initial positioning, the abrupt increase of forming load at the stroke of 5mm was well predicted irrespective of the friction factors used in simulations. Such an abrupt increase of forming load is a typical phenomenon in the ECAE process since severe deformation of the workpiece was initiated around the die corner at this stroke. Even in partial contact condition, only the small difference in friction factors of 0.02 resulted in about two times larger errors in load predictions at the final stroke when the forming loads of friction factors of 0.13 and 0.15 were compared.

Fig. 4 shows the distribution of measured Vickers hardness data at the cross-section which was 10mm away from the right side of the workpiece and the distributions of strain obtained from simulations at the same locations. In this figure, the overall trend is likely to be the same between the hardness and strain distributions although there are some discrepancies between the two at certain locations.

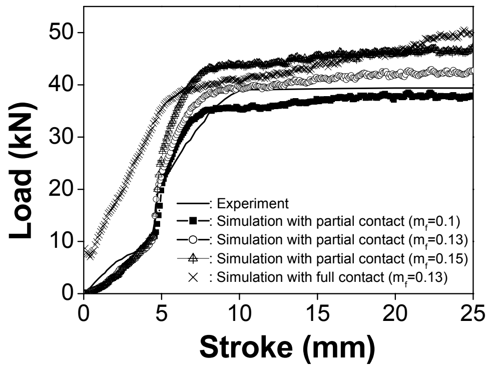

Fig. 3. Load-stroke curves according to the full and partial contact conditions with different friction factors

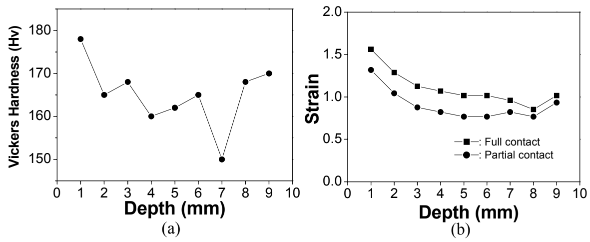

Fig. 4. (a) Measured Vickers hardness data and (b) strain distribution data at different depths in the cross-section

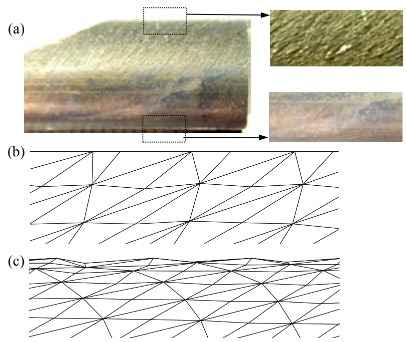

Fig. 5. Comparison of surface mesh views of the extruded specimen between the (a) experiment and simulations with: (b) full contact and (c) partial contact conditions (m_f=0.13)

The magnified surface mesh views of the extruded part of the workpiece at the stroke of 25mm in full and partial contact conditions are displayed in Fig. 5. In partial contact condition, the upper part of the specimen became rugged although the surface meshes in full contact condition were flat as shown in this figure. The contacted surface nodes were separated in the corner region of the intersected channel for the partial contact condition, then again contacted afterward as deformation continued. This repeated process made the surface meshes wavy in the remaining strokes as clearly shown in Fig. 5(c).

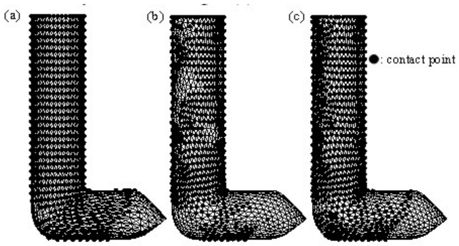

Fig. 6. Distributions of contact points during remeshing: (a) before remeshing, (b) conventional scheme using tolerance and (c) modified contact region approach (m_f=0.13)

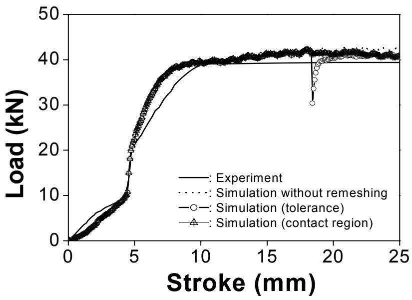

Fig. 7. Load-stroke curves with different contact conditions according to remeshing scheme (m_f=0.13)

The effect of the contact condition on forming load due to the remeshing process was also examined with different treatment of contact conditions. At the stroke of 18.3mm, the remeshing was required due to mesh penetration into the channel geometry. Fig. 6 shows the variation of contact points after the remeshing process by applying different contact schemes. If the normal distance from die surfaces was within the prescribed tolerance (0.02mm), the boundary nodes were set to be contacted in conventional simulations. As shown in Fig. 6(b), the contact points were not fully recovered from the original one before remeshing according to the conventional scheme.

This phenomenon resulted in excessive drop of the forming load as shown in Fig. 7. To resolve this problem, the modified contact region approach was introduced such that new boundary nodes were assumed to be contacted if their positions were located in the contact regions of the old boundary nodes. The distribution of contact points according to this scheme is displayed in Fig. 6(c). The contact areas were quite well agreed with the original one before remeshing as shown in Fig. 6(a). This modified contact scheme could reduce the load drop in Fig. 7 and resulted in 0.35% in volume loss compared to 0.77% in the conventional approach.

4. Conclusions

In this study, the effect of contact condition on forming load and material flow in the ECAE process was investigated using the three-dimensional mixed finite element formulation. It was found that the forming loads varied very sensitively depending on the friction conditions. The new modified contact scheme was effective in reducing the errors involved with load predictions and volume losses after remeshing. According to current numerical simulations, it can be concluded that it is very important to preserve the contact condition in order to accurately predict the material behavior in FE analyses of the ECAE.

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