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Numerical simulation and experimental investigation of pure copper deformation behavior for equal channel angular pressing/extrusion process

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ABSTRACT

The mechanism of ECAP process for pure copper materials is studied in this paper by using finite element (FE) simulation and the experimental method. The optimal die geometrical conditions and proper process parameters are obtained by finite element simulations. The obtained research results can provide powerful guidelines for further theoretical analysis and experimental studies on ECAP process. In addition, in order to obtain bulk UFG metal materials at room temperature, and realize extrusion process consecutively and obtain an enough large accumulated effective strain and an enough refined grain size in the workpiece. On the basis of the simulations, the cold ECAP experiments are carried out by the optimized design of the channel die. The geometries of finally pressed workpieces and the microstructure of the processed samples are in good agreement with finite element analysis results.

1. Introduction

The inherent microstructure of materials has a significant influence on their macrostructure characteristics. According to Hall–Petch relation [1], it is known that the strength and the hardness of the materials usually increase with the decrease of the average size of grains [2]. Therefore, seeking the material refinement processing technology has a potential industrial prospect. Bulk ultra-fine grained (UFG) materials can be obtained by equal channel angular pressing (ECAP), Equal channel angular pressing (ECAP) is an innovative technique for obtaining ultra-fine grained (UFG) materials. It is one of the most promising processes for the industrial application. The process is extrusion workpiece through a die with two channels of equal cross-section intersecting at an angle [3]. The workpiece retains its cross-sectional area so that it is able to repeat the process to many cycles. Therefore, a very large effective strain can be accumulated in the workpiece and the grains of the workpiece can be refined. Compared with the conventional materials, the bulk UFG materials have many novel properties [4] and can be used as super high strength materials and super plastic materials. Recently, the small overall internal combustion engine and the highly strengthened thread articles with bulk UFG materials have been successfully applied in industry [5].

At present, many investigations have been done through theoretical analysis and experimental studies on the ECAP process. Meanwhile, the workpiece deformation behavior properties are obtained by finite element (FE) analysis. All of these analytical results provided useful guidelines for the ECAP experiments. However, the investigation on the deformation behavior at present have not been fully understood and clarified [6–10]. Especially, the relationship of material grain refinement and the deformation behavior needs to be studied further. Because the ECAP is a severe plastic deformation process, the die usually receives a high cavity pressure in the pressing process. Therefore, high strength die materials must be needed. At present, the warm extrusion or hot extrusion has been applied in the ECAP experiments. However, a high temperature can cause grain reversion, growing up and over burning, and also cause ECAP experiment more complex and expensive. Moreover, the useful life of die was essentially short in the experiments [11]. The above disadvantages are not suitable for industrial production of UFG materials. Therefore, it is necessary to study the better processing route, optimal die geometries and desirable friction condition as well as get a die design which satisfies extrusion pressure and ECAP deformation characters.

This paper performed a number of simulations for ECAP process of pure copper material. The mechanism of ECAP process for pure copper material is given by using FE method. The optimal die geometries and proper friction conditions are offered. On the basis of the simulations, a bulk UFG extrusion process at room temperature for

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pure copper materials was experimented. The experimental results including both workpiece's geometry and microstructure are in good agreement with those of FE analysis. The numerical and experimental results provided useful theoretical and experimental guidelines for ECAP process.

2. FE Analysis of deformation behavior

2.1. Simulation model

The principle of ECAP is illustrated schematically in Fig. 1. Two channels with an equal cross-section intersect at an oblique angle Φ called die channel angle, which commonly ranges from 90° to 150°. An additional angle Ψ defining the arc of curvature at the outer point of die angular is called die corner angle, which ranges from 0° to (180° − Φ). The grain refinement of the ECAP process depends on the accumulated effective strain in the workpieces. Therefore, die channel angle, die corner angle and frictions have an essential effect on the grain refinement of the workpiece [12–19].

Investigating deformation behavior of ECAP is aimed at realizing its industrialization. At present, ECAP process is still at the laboratory experiment period. Moreover, in the experimental investigations, the useful life of die is essentially short. Consequently, it has important theoretical values and industrial prospects to study the deformation behavior. The classical plasticity has been used to study the deformation behavior of ECAP process. But the results are usually inaccurate because of simplifying too much for the ECAP model. Therefore, it is necessary to investigate ECAP process by using FE method. The pressing process can be considered as a plane deformation problem. This paper uses a commercial metal forming FE code, CASFORM-2D for simulations. The dimensions of an initial workpiece are 10 mm in width and height for the transversal directions, and 80 mm in length for the pressing direction. The workpiece is hypothesized as rigid-plastic materials, and the relationship of the flow stress with the effective strain is supposed as $\bar{\sigma} = C\bar{\epsilon}^n$ for cold extrusion [20–22], where $\bar{\sigma}$ is the effective stress, $\bar{\epsilon}$ is the effective strain, the strength coefficient C = 402 MPa, and strain hardening exponent n = 0.20 for pure copper (Cu 99.9%). A constant ram speed of −2 mm/s is imposed, and the divided mesh system with the 1100 element is used for the simulations [21]. In order to improve the understanding of the ECAP process as well as to optimize the die design and obtain proper friction conditions, many different parameters, such as die channel angle, die corner angle and friction, were analyzed by the FE simulations.

2.2. Effect of die channel angle

Die channel angle has an essential effect on the deformation behavior in the workpiece. Several different die channel angles were analyzed by using FE method. Fig. 2 provides the effective stress distribution in the workpiece for the different die channel angle Φ of 90°, 120° and 150°. The effective stress of the workpiece is centralized to the upper part metal near the inner corner of the die channel. It can be seen that the upper part metal near the inner corner die cavity undergoes the biggest pressure. In Fig. 3, the workpiece width at the die corner, A–B, is depicted for the effective stress distribution at different die channel angles of Φ with fixed Ψ = 37°. The effective stress distributions are similar for different die channel angles. However, as the die channel angle decreases, the effective stress gradient increases. Meanwhile, it can be observed that the effective stress distribution for Φ = 90° has a bigger change range than those of other die channel angles.

Punch load–stroke curves at different die channel angles of Φ with fixed Ψ = 37° are shown in Fig. 4. At the beginning of the pressing stage, the workpiece keeps in touch with the outer corner of the die channel. The punch load begins to increase rapidly and the workpiece takes place of severe plastic deformation. After that, the punch load reaches a maximum, and then the workpiece reaches a steady deformation stage. For the die channel angle of 90°, the maximum punch load is 34,000 N, and for the die channel angle of 120°, the maximum punch load is 18,000 N, while for the die channel angle of 150°, the maximum punch load decreases to 8000 N accordingly. It shows that the maximum punch load of Φ = 90° is twice time of the maximum punch load of Φ = 120°, and probably fourth time of the maximum punch load of Φ = 150°. The resistance to deformation of the materials is obviously raised when Φ = 90°, and a higher punch load can be caused. Therefore, a contradiction occurs between the punch load and deformation accumulation. If die material is strengthened enough, a lower die channel angle is preferred in order to accumulate a high effective strain. If considering the useful life of die, a bigger die channel angle is a good choice. Therefore, the die channel angle of ECAP should be carefully considered and selected.

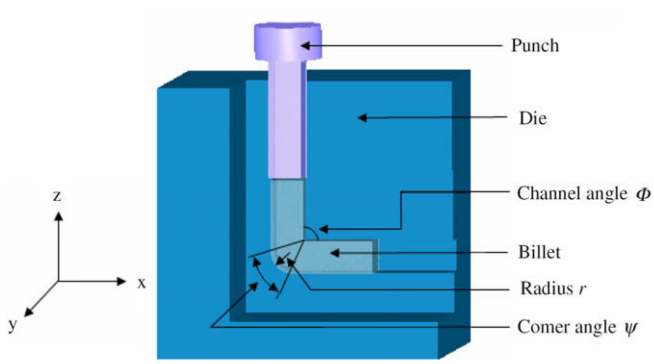

Fig. 1. Schematic diagram of an ECAP die channel angle Φ and the corner angle Ψ.

2.3. Effect of die corner angle

The microstructure evolution and formation of deformation behaviors are directly linked to the level of effective strain distributions, the analysis of the effective strain developed in the workpiece is then very important. Fig. 5 shows the effective strain distribution of the pressed workpiece. Fig. 5a shows the effective strain distribution in the workpiece for the first-pass pressing process, where the die channel angle Φ is equal to 90°. The pressed workpiece can be divided into three deformation zones along the pressing direction: the head of deformation zone (HDZ), the main deformation zone (MDZ) and the tail deformation zone (TDZ). The firstly pressed HDZ has a non-uniform effective strain distribution. The MDZ occupies about 3/4 region of the whole workpiece and its effective strain distribution is perfect along the pressing direction. The TDZ is an incompletely deformed area. For consecutive pass pressing process, the next coming workpiece will gradually push the uncompleted deformed area of former workpiece into the MDZ. We know that the deformation uniformity of the pressed workpiece for consecutive pressing process is independent on the pressing direction. Therefore, it can be thought that the deformation distribution in a cross-section of the MDZ indicates that of the whole workpiece. In order to obtain proper information about the effective strain uniformity of the workpiece, variation of the effective strain across the width of the workpiece is only selected for analysis. Accordingly, effective strain is plotted across the workpiece width, C–D.

Fig. 5b shows the effective strain distributions in the workpiece for the ECAP, where the Φ = 90° for different die corner angle. The effective strain is uniform in the upper part near the point C. As the die corner angle increases, the effective strain value in the lower