Research Article

Equal Channel Angular Extrusion Simulation of High-Nb Containing β - γ TiAl Alloys

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TiAl alloys containing high Nb are significantly promising for high-temperature structural applications in aerospace and automotive industries. Unfortunately the low plasticity at room temperature limits their extensive applications. To improve the plasticity, not only optimizing the composition, but also refining grain size through equal channel angular extrusion (ECAE) is necessary. The equal channel angular extrusion simulation of Ti-44Al-8Nb-(Cr,Mn,B,Y)(at%) alloy was investigated by using the Deform-3D software. The influences of friction coefficient, extrusion velocity, and different channel angles on effective strain, damage factor, and the load on the die were analyzed. The results indicate that, with the increasing of friction coefficient, effective strain is enhanced. The extrusion velocity has little effect on the uniformity of effective strain; in contrast it has large influence on the damage factor. Thus smaller extrusion rate is more appropriate. Under the condition of different channel angles, the larger one results in the lower effective strain magnitude and better strain distribution uniformity.

1. Introduction

TiAl alloys containing high Nb are significantly promising for high-temperature structural applications in aerospace and automotive industries. However, the low room temperature ductility and poor hot deformability limit their practical applications [1–3]. Accordingly, many efforts have been devoted to preparing TiAl alloys with fine and homogeneous microstructures such as optimizing the composition, thermomechanical treatment. Ultra-fine grained materials have been widely investigated due to their improved mechanical properties such as high strength and ductility. Various techniques have been developed to obtain ultra-fine grained materials. Among them, the equal channel angular extrusion (ECAE), originally developed by Segal et al. [4], is one of the effective methods of obtaining materials with high strength and toughness. In ECAE, a sample is pressed through two intersecting channels with the same cross section and material is subjected to an intense plastic strain through simple shear [5]. Because the cross section of the sample remains the same during extrusion, the process can be repeated until the accumulated deformation reaches a desired level. High strain

can be achieved with multiple passes due to its cumulative nature.

Figure 1 shows the schematic diagram of ECAE die, where two channels of equal cross section intersect at an oblique angle Φ . The corner angle Ψ is defined as the angle subtended by the arc curvature. Analysis has shown [6] that the equivalent strain ε after one pass is given by the relationship

$$\varepsilon = \frac{1}{\sqrt{3}} \left[2 \cot \left(\frac{\Psi}{2} + \frac{\Phi}{2} \right) + \Psi \operatorname{cosec} \left(\frac{\Psi}{2} + \frac{\Phi}{2} \right) \right]. \quad (1)$$

The strain obtained from above equation is an average strain and does not show the local deformation behaviour or inhomogeneity of strain distribution in the cross section of the sample. Finite element method (FEM) has been widely used for the purpose of investigating the global and local deformation behaviour with various parameters such as friction factor, extrusion speed, and the back pressure at the outlet end.

Finite element method is one of the important approaches to understand the deformation occurring in the ECAE process. Many FEM-based analyses have been performed to

FIGURE 1: Schematic diagram of the ECAE.

determine the deformation behaviour of materials and to estimate the developed strain in the ECAE process. Nagasekhar et al. investigated the effect of the die channel angle on the deformation behaviour and punch pressure needed for extrusion [7]. Djavanroodi and Ebrahimi [8] studied the influences of die channel angle, friction coefficient, and back pressure in the ECAE die. They have reported that higher effective strain values can be obtained by using an acute die channel angle and high friction coefficient and applying back pressure. Prangnell et al. [9] analyzed the effect of friction on material flow and found that the inhomogeneous deformation at billet ends increases with friction. Semiatin et al. [10] demonstrated the influence of strain and strain rate hardening on the breadth of the shear zone and the uniformity of flow under isothermal conditions. Srinivasan [11] studied the effect of the bent angle between the channels on the deformation of billets for each pass. Using finite element simulation, Bowen et al. [12] investigated the dependence of the strain achieved in the billet on the die angle, friction conditions, and the application of a back pressure.

2. Finite Element Analysis

The isothermal two-dimensional plane-strain FEM simulations of the ECAE process were performed using Deform-3D. The die and punch were assumed to be rigid so that there is no deformation. The workpiece was assumed to be plastic and was divided into 8000 tetrahedra. The initial temperature of workpiece was set to 1300°C and the die and punch were set to 1200°C. Only half portions of die and workpiece were considered for analysis as shown in Figure 1, because of the symmetry about the parting surface. Automatic remeshing was applied to accommodate large deformation during the analysis and the symmetrical boundary conditions were applied because the model is symmetrical. In the simulations, the workpiece has the geometry of $30 \times 20 \times 100$ mm, the die channel angles $\Phi = 90^\circ$, and the outer corner angles

$\Psi = 0^\circ$ for different friction coefficient and different extrusion velocity cases. But, to understand the influence of channel angle, three channel angles, 75° , 90° , and 105° , with the outer corner radius 10 mm were considered for analysis.

The nominal composition of the material used for workpiece is Ti-44Al-8Nb-(Cr,Mn,B,Y)(at%) which is the optimised composition in the previous study [13]. The constitutive equation for flow stress at high temperature is obtained experimentally using compression test:

$$\dot{\epsilon} = 1.12 \times 10^{16} \left[\sinh \left(6.853 \times 10^{-3} \sigma \right) \right]^{3.45211} \cdot \exp \left(-4.92 \times \frac{10^5}{RT} \right). \quad (2)$$

The influences of friction coefficient, extrusion velocity, and different channel angle on effective strain and damage factor were analysed. The inside surface of die and the outside surface of workpiece are in close contact. Nominal values of coefficient of friction, extrusion velocity, and channel angle are listed in Table 1. Heat generation due to friction and deformation was ignored.

3. Result and Discussion

3.1. Influence of Friction Coefficient on the Workpiece. Examination of the predicted strains provided more quantitative insight into the deformation during ECAE. Figure 2 shows the influence of different friction factor of 0.05, 0.1, 0.2, and 0.3 on the homogeneity of effective strain after one pass. The maximum effective strains are shown in Figure 3. So it can be obtained that, at the cross of the two channels, the strain is higher relatively and increasing the friction coefficient results in larger gradient of effective strain. However, effective strain is nonuniform. The deformation of the top and end of the workpiece is little, where the value of the effective strain is about 0.07. The top of the four samples appears to be not filling

FIGURE 2: The effective strain distribution of the workpiece after ECAE process with different friction coefficient: (a) $\mu = 0.05$, (b) $\mu = 0.1$, (c) $\mu = 0.2$, and (d) $\mu = 0.3$.

TABLE 1: The nominal value of friction coefficient, extrusion velocity, and channel angle.

Number	Friction coefficient	Extrusion velocity	Channel angle
1	0.05	10	90°
2	0.1	10	90°
3	0.2	10	90°
4	0.3	10	90°
5	0.1	2.5	90°
6	0.1	5	90°
7	0.1	10	90°
8	0.1	15	90°
9	0.1	10	75°
10	0.1	10	90°
11	0.1	10	105°

the die completely. The uneven deformation leads to different size of grains, which is against improving the mechanical property.

The various friction coefficients do not affect the damage factor obviously. As shown in Figure 4, when μ ranges from 0.05 to 0.3, the damage areas are similar and they mainly distribute on the surface which is close to the inner corner.

FIGURE 3: The maximum effective strain with different friction coefficient.

Figure 5 shows four points P1, P2, P3, and P4 fixed on the sample during the extrusion processing and analysis of the three stages A, B, and C. The value of damage factor in the first stage shown in Figure 5(a) is nearly zero. When the sample reaches the cross of the two channels, the value increases

FIGURE 4: The damage distribution with different friction factor.

TABLE 2: The maximum and minimum effective strain and damage factor with different extrusion velocity.

Extrusion velocity	2.5 mm/s	5 mm/s	10 mm/s	15 mm/s
The maximum strain	4.13	4.23	4.34	3.89
The minimum strain	0.101	0.0822	0.0749	0.0899
The maximum damage factor	0.783	0.848	0.872	0.888

sharply. The inner corner is the main factor which relates to the damage distribution.

As shown in Figure 6, increasing friction coefficient results in the larger load on the bottom die, which goes against the protection of the die. Therefore, we should consider the advantage and disadvantage of the friction coefficient comprehensively.

3.2. Influence of Extrusion Velocity on the Workpiece. The previous study [14] reported the extrusion velocity can affect the ECAE process. To examine the influence of velocity on the effective strain, several processes with different extrusion velocity 2.5 mm/s, 5 mm/s, 10 mm/s, and 15 mm/s are simulated. Figure 7 shows the distribution of effective strain with different velocity. The maximum and minimum effective strains with different extrusion velocity are listed in Table 2, from which the conclusion that the extrusion velocity does not much affect the effective strains can be drawn.

As shown in Table 2, the value of damage factor continuously increases, with the increasing of extrusion velocity.

In addition, the increasing extrusion velocity leads to an increase of the die load. So, the higher value of damage factor will increase the risk of generating macrostructure and microstructure cracks. Also, in Figure 8 the higher extrusion velocity aggravates the die load, which is not beneficial to the service life of the die. Therefore, a slow extrusion velocity is more appropriate for the extrusion processing.

3.3. Influence of Channel Angle on the Workpiece. In order to obtain proper information about the deformation behaviour of the sample during ECAE process, effective strain contours for $\Phi = 75^\circ$, 90° , and 105° are shown in Figure 9. As can be seen, decreasing the die channel angle causes a higher magnitude of effective strain that is imposed on the sample. With an increase in the die channel angle to 105° from 75° , the magnitude of the effective strain decreases to 1.61 from 3.09. From the overall samples, the nonuniform distribution of strain becomes obvious from 105° to 75° . In general, die channel angle has more influence on the magnitude rather than homogeneity of effective strain.

4. Conclusions

The influence of friction factor, extrusion velocity, and different channel angle on effective strain and damage factor was investigated by using 3D-FEM. From this study, the following conclusions were drawn:

- (1) In ECAE process, various friction coefficients were simulated to estimate the value of effective strain, the

FIGURE 5: The different damage factor distribution in three stages during the extrusion processing. (a) Time is 8.52, (b) time is 9.94, and (c) time is 11.36.

FIGURE 6: The load of the die with different friction coefficient.

FIGURE 7: The effective strain distribution of the workpiece after ECAE process with different extrusion velocity: (a) $v = 2.5$, (b) $v = 5$, (c) $v = 10$, and (d) $v = 15$.

FIGURE 8: The die load with different extrusion velocity.

damage factor, and the load on the die. Increasing the friction factor results in a larger magnitude of effective strain and an increase value of the die load. Also,

the inhomogeneity of deformation increases, which is not beneficial to the whole extrusion processing. The various friction factors do not affect the damage factor obviously.

- (2) The extrusion velocity affects effective strain small but affects the damage factor greatly. With the extrusion velocity increasing, the damage factor and the die load increase, which tend to generate macrostructure and microstructure cracks and shorten service life of the die.
- (3) The FEM results indicated that increasing the channel angle to 105° from 75° results in lower effective strain magnitude and better strain distribution uniformity.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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FIGURE 9: The effective strain distribution of the workpiece after ECAE process with different extrusion velocity: (a) $\Phi = 75^\circ$, (b) $\Phi = 90^\circ$, and (c) $\Phi = 105^\circ$.

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