Continuous dynamic recrystallization prediction in multi-direction loading forming of 7075 aluminum alloy tee valve

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Abstract. In multi-direction loading forming of 7075 aluminum tee valve, continuous dynamic recrystallization (CDRX) will occur and affect the final microstructure and performance. In this paper based on the developed physically-based internal state variable model and finite element (FE) simulation, under the reasonable forming parameters, the evolution behavior and law of the dislocation density, subgrain size, average misorientation of subgrain boundary and average grain size were revealed, especially in the intersecting region at different multi-direction loading forming stages. It is also shown that when the horizontal and vertical punches are loaded simultaneously, the CDRX degree decreases while grain size increases gradually from the inner to outer wall of branch tube. In the intersecting region, the average grain size increases from the inside to outer corner. The results can provide a guide for the quick prediction of CDRX and selection of the reasonable forming parameters for multi-direction loading forming of tee valve.

1. Introduction

Multi-direction loading forming, in which the billet is loaded in the horizontal and vertical directions at the same time or in sequence, provides an efficient approach to integrally form multi-cavity complex components[1,2], which are widely used in aerospace fields and the high-performance is needed. However, under the coupled effects of multifactors the metal undergoes complicated inhomogeneous deformation and extremely complex microstructure evolution, which is sensitive to deformation conditions and directly determines the quality, mechanical property, and usage life-span of the formed valves[3]. Hence, it is necessary to accomplish a quick prediction and control on the microstructural evolution in the multi-direction loading-forming process of valve body.

Normally, for aluminum alloys with the high-stacking fault energy, although dynamic recovery is dominant in hot deformation, dynamic recrystallization (DRX) also occurs frequently, especially the continuous dynamic recrystallization (CDRX)[4,5]. Different from discontinuous dynamic recrystallization (DDRX), CDRX does not require nucleation, but relates to the formation of subgrains via dynamic recovery, the increment of the subgrain boundary misorientation angles, and eventual the emergence of new fine grains[6,7], further determining the final grain size, distribution and the part properties. Therefore, it is a key problem to reveal the CDRX evolution law in the 7075 tee valve forming.

Finite element (FE) method combined with microstructure models has received an increasing attention in modelling and simulation of microstructure evolution in hot plastic forming. Several approaches have been applied for constitutive modelling of metals, of which a physically-based
The internal state variable (ISV) method is advantageous in revealing the physical mechanisms of deformation\cite{8-11}. Although some studies on microstructural evolution have been conducted for multi-direction loading, the work related to physical meanings is insufficient.

Xu numerically simulated the grain evolution of AZ31 magnesium alloy tee part during isothermal multi-direction loading process based on Yada empirical model\cite{12}, and the grain size at different temperatures and loading speeds were presented, which provided a valuable reference to actual production. Guo established an empirical model for dynamic recrystallization of 7075 aluminum alloy based on Yada model\cite{13}, and studied the microstructure evolution of tee part during multi-direction loading process. The influence of forming parameters on the DDRX volume fraction and grain size of tee part was revealed and the reasonable combination was determined. The hot deformation and microstructural evolution behaviors of AISI 5140 steel triple valve were studied by combining the Avrami empirical model with DEFORM 3D software platform, and the DDRX volume fraction and grain size models were regressed by Sun and Yang\cite{3}. The above researches mainly focused on the influence of forming parameters on the DDRX volume fraction and grain size of tee parts, while the specific CDRX mechanism was not involved and the microstructure prediction of CDRX rarely involved.

Zhu found that for a tee valve in the intersecting region between horizontal and vertical branches, great stress concentration is the most likely to occur\cite{14} and the partial yield might occur even under the normal working pressure. So the intersecting region was considered to be the weakest part, determining the mechanical properties of the whole tee valve. Therefore, how to ensure the intersecting region with the good microstructure and mechanical properties has become the key problem of the multi-direction loading technology of valves.

In this paper, taking a AA7075 tee valve as an object, the CDRX evolution law based on ISV method is investigated through FE simulation on a DEFORM 3D software platform with the view to control the microstructure and quality of the formed valves, especially in the intersecting region.

2. FE modelling and verification

2.1. FE modelling

To predict the dynamic microstructure development in multi-direction loading forming, the developed finite element model (FEM) based on a DEFORM 3D software platform is shown in figure 1, because the equal diameter tee valve is symmetrical in structure, only the 1/4 structure was modelled by applying a constraint on the symmetry plane to save computation time. The material of billet is 7075 aluminum alloy and the detailed modelling procedure was described in our previous study\cite{2}. Later, Sun revealed the CDRX mechanism and established a model of CDRX during hot deformation based on the ISV method\cite{15}. In this paper, through the secondary development of the DEFORM-3D user subroutine, the 7075 ISV-based CDRX model is combined with the FE analysis system to realize microstructure simulations.

2.2. FE Model validation

Cylindrical billet with the size $\Phi 10 \times 15 \text{mm}$ was prepared, and the compression tests with constant temperature and strain rate were conducted for FE model validation. The average grain size, subgrain size, average subgrain misorientation (ASM) and dislocation density under uniaxial compression were investigated. Four groups of forming conditions were considered in the simulations as follows.

- **Case 1**: Deformation temperature $T=350 \, ^\circ \text{C}$, deformation reduction is 30\%, and strain rate is $1 \text{s}^{-1}$.
- **Case 2**: Deformation temperature $T=400 \, ^\circ \text{C}$, deformation reduction is 50\%, and strain rate is $10 \text{s}^{-1}$.
- **Case 3**: Deformation temperature $T=450 \, ^\circ \text{C}$, deformation reduction is 70\%, and strain rate is $0.1 \text{s}^{-1}$.
- **Case 4**: Deformation temperature $T=450 \, ^\circ \text{C}$, deformation reduction is 50\%, and strain rate is $0.1 \text{s}^{-1}$.

The simulation model is seen in figure 2 and the simulation results of grain size in case 1–case 3 are shown in figure 3. The relative errors between simulated and experimental results are indicated in table 1, which are less than 5\%.
Furthermore, the subgrain size, ASM and dislocation density in case 4 is simulated using FEM. The simulation results are shown in figure 4, and the relative errors between simulated and experimental results are allowed, as shown in table 2.

![Figure 1. Schematic diagram of tee valve: (a) FE model; (b) geometric structure.](image1)

![Figure 2. FE model of hot pressing.](image2)

![Figure 3. Simulation results of grain size /µm: (a) T=350°C, ε=1s⁻¹, ε=30%; (b) T=400°C, ε=10s⁻¹, ε=50%; (c) T=450°C, ε=0.1s⁻¹, ε=70%.](image3)

![Figure 4. Simulation results of microstructure: (a) subgrain size /µm; (b) average misorientation angle of subgrain/°; (c) dislocation density/ 10¹⁰m⁻².](image4)

### Table 1. Error analysis of grain size.

| Deformation condition | Simulated result/µm | Experimental result/µm | Relative error |
|-----------------------|---------------------|-----------------------|----------------|
| (a)                   | 54.7                | 52.53                 | 4.13%          |
| (b)                   | 46.1                | 46.32                 | -0.47%         |
| (c)                   | 32.6                | 31.9                  | 2.19%          |

### Table 2. Error analysis of microstructure.

| Microstructure                  | Simulated result | Experimental result | Relative error |
|---------------------------------|------------------|---------------------|----------------|
| subgrain size                   | 4.39µm           | 4.07µm              | 7.86%          |
| average misorientation of subgrain | 3.93°            | 3.80°               | 3.42%          |
| dislocation density             | 451×10¹⁰m⁻²       | 10¹²−10¹⁵m⁻²        | allowed        |
In summary, it is shown that the FEM of multi-direction loading forming for 7075 aluminum alloy can not only meet the requirement of reliability macroscopically, but also meet the requirement of precision in microstructure simulations. Therefore, the model can provide a reliable basis and platform for the study of CDRX behaviors in intersecting region of tee valve under different process parameters.

3. Microstructure evolution of 7075 tee valve by multi-direction loading forming

In this section, the horizontal and vertical punches are loaded at the same time, the initial deformation temperature is 450°C, the corner radius of punches is 8mm, the friction factor is 0.2, and the loading speed of punches is 20mm/s. Under this forming scheme, the evolution law of dislocation density, subgrain size, ASM and grain size of the tee valve are studied.

3.1. Dislocation density evolution

Figure 5 shows the distribution of dislocation density at different forming stages, of which the statistical diagram is on the left. When the horizontal punch is loaded for 40mm, as shown in figure 5(a), the maximum dislocation density appears at the corner of horizontal punch, where the strain rate is high and the deformation degree is severe. The smallest area of dislocation density is the billet bottom, of which the center area is difficult to deform, therefore the dislocation proliferation is not obvious. When the horizontal punch is loaded for 50mm, as shown in figure 5(b), the vertical punch begins to contact with the billet. The strain rate at the front end of vertical punch is large and the deformation degree is the most severe, the dislocation density here increases to about $1.2 \times 10^{13} \text{m}^{-2}$. When the horizontal punch is loaded for 60mm, as shown in figure 5(c), the flange part of horizontal punch contacts with the billet, the metal at the right end of horizontal tube is deformed, and the dislocation density proliferates obviously. When the horizontal punch is loaded for 66mm, as shown in figure 5(d), vertical punch flange comes into contact with the billet, increasing the dislocation density. After the total hot deformation, the highest dislocation density is $2.27 \times 10^{13} \text{m}^{-2}$, the lowest dislocation density is $1.46 \times 10^{12} \text{m}^{-2}$, the average dislocation density is $6.71 \times 10^{12} \text{m}^{-2}$, and the dislocation density of intersecting region is about $8.5 \times 10^{12} \text{m}^{-2}$.

![Figure 5. Distribution of dislocation density at different forming stages/10^{10}\text{m}^{-2}: (a) the load distance 40mm; (b) the load distance 50mm; (c) the load distance 60mm; (d) the load distance 66mm.](image)

3.2. Subgrain size evolution
Figure 6 shows the distribution of subgrain size at different forming stages. When the horizontal punch is loaded for 40mm (figure 6(a)), the average subgrain size at its front end is about 4μm, this is due to the high temperature caused by plastic deformation, the dynamic recovery is prone to occur, i.e., the identical dislocations are arranged into dislocation walls along the direction perpendicular to the slip plane by climbing and intersecting, forming a small angle subgrain boundary, which then evolves into a complete subgrain. While in the regions with low deformation degree, such as the bottom center of billet, the subgrain size increases to about 12μm, indicating that the subgrain grows up. The reason may be that the dislocation proliferation in this region is not obvious, and almost no new fine subgrains form through dynamic recovery, meanwhile the subgrain boundary is not stable and grows in the way of projecting through the polygonal dislocation wall or the way of subgrain amalgamation mechanism. With the loading of punches, the hard deformation area becomes smaller, so as the subgrain size. After the total deformation, the minimum subgrain size is 1.34μm at the upper end of vertical branch, the maximum one is 12.3μm at the right end of horizontal branch tube, the average is 5.08μm, and the subgrain size of the intersecting region is about 3.8μm.

Figure 6. Distribution of subgrain size at different forming stages/μm: (a) the load distance 40mm; (b) the load distance 50mm; (c) the load distance 60mm; (d) the load distance 66mm.

3.3. ASM evolution
Based on the CDRX mechanism, the ASM reflects the CDRX degree to some extent and so need to be analyzed. The ASM of the 7075 initial billet is 2.69°, which is observed through EBSD. Figure 7 shows the distribution of ASM at different forming stages and the statistical diagram is on the left. At the initial stage of forming (figure 7(a)), the ASM at the front end of horizontal punch increases to about 3.5°. The reason is that at high temperature, the thermal activation ability of atoms is strong, and the dislocations move easily to the subgrain boundary through climbing and intersecting slip, thus increasing the ASM, which results in the subgrain rotation. Besides, there is a small ASM increase around the horizontal punch but no obvious ASM change in other regions. With the loading of punches, the range of large ASM becomes wider. However, the ASM in the intersecting region is not consistent, the value is about 3.2° near the shoulder corner due to small deformation, while about 3.8° far away from the shoulder corner caused by complicated deformation.
3.4. Grain size evolution

Grain size is an important factor affecting the yield strength and crack growth resistance of materials, so it is necessary to analyze the change of grain size. In this section, the varying grain size is the result of mutual action and competition between CDRX and grain growth, figure 8 is the grain size distribution at different forming stages. When the horizontal punch is loaded for 40mm (figure 8(a)), a large number of fine recrystallization grains appear at the inner wall of horizontal cavity because of large deformation and high temperature, promoting the CDRX. The further from horizontal pipe, the weaker CDRX and the larger grain size. As the deformation continues (figure 8(b)), the CDRX range is enlarged, and the average grain size decreased to 44.5μm. As the horizontal punch loads for 60mm (figure 8(c)), the deformation in intersecting region is stable and grain size is uniform, the value is approximately 35μm. At the last stage of loading (figure 8(d)), the grain size is refined to about 20μm by CDRX at the front end of vertical and horizontal punches. While a long and narrow longitudinal region of fine grains appears at the intersecting region, and grains show an increasing trend from the inner to outer corner, having a good effect on resisting deformation and cracking under compressive stress. Therefore, when the horizontal and vertical punches are loaded simultaneously to form 7075 tee valve, the grain size displays as the minimum value 12.4μm, the maximum 59.1μm, the average 35.3μm in the final part, and the average value 30.68μm in the intersecting region.

Figure 7. Distribution of ASM at different forming stages/°: (a) the load distance 40mm; (b) the load distance 50mm; (c) the load distance 60mm; (d) the load distance 66mm.
Figure 8. Distribution of grain size at different forming stages/μm: (a) the load distance 40mm; (b) the load distance 50mm; (c) the load distance 60mm; (d) the load distance 66 mm.

4. Conclusions
(1) Under the reasonable forming parameters, the dislocation density, subgrain size, average misorientation of subgrain boundary and average grain size evolution law were analyzed. At the initial stage of forming, on the contact part of horizontal punch and billet, the obvious dislocation proliferation, increase in ASM, CDRX, and decrease in grain size were found. After the vertical punch was loaded, the dislocation density in intersecting region increased and subgrains formed, which led to an enlarged range of CDRX. At the last forming stage, in the intersecting region CDRX occurred adequately and resulted in a long and narrow longitudinal region of fine grains.

(2) When the horizontal and vertical punches were loaded simultaneously to form 7075 tee valve, the CDRX degree decreases while grain size increases gradually from the inner to outer wall of branch tube. In the intersecting region, the average grain size increases from the inside to outer corner.

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