Multi-objective optimization and experimental investigation on hot extruded plate of high strength Al-Zn-Mg alloy

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1. Introduction

High strength Al-Zn-Mg (7xxx series) alloys have attracted considerable attention for aerospace engineering, automobiles, high-speed trains, and the engineering of large structural components, as they have the advantages of low density, high specific strength, and excellent weldability [1,2].

With the development of a lightweight design, the consumption of Al-Zn-Mg alloys rapidly increases, and their application can expand to more sophisticated fields, such as electronics and inspection equipment. Hence, it is of great importance to fabricate Al-Zn-Mg components with excellent quality.

Hot extrusion is one of the main plastic forming processes for Al alloys, and the extruded Al profile usually exhibits good performance. In practical production, the design of the extrusion die significantly affects the cost and quality of Al profiles. Thus, in the past decade, researchers have attempted to optimize the die structure by using numerical techniques. Chen et al. [3] proposed a novel route for optimizing a two-hole...
porthole die to enhance the homogeneity of the material flow velocity. Dong et al. [4] added a baffle plate and adjusted the bearing length of the die to improve the homogeneity of material flow at the cross section of the profile. Jo et al. [5] clarified the effects of the extrusion parameters on the material flow behavior, welding pressure, and extrusion loads by performing a non-steady numerical simulation. Zhang et al. [6] studied the evolution mechanism of a charge weld using a transient simulation model and analyzed the factors affecting the length of the charge weld. The aforementioned studies proved that the material flow behavior and the fields of the temperature, stress, and strain during the hot extrusion process could be obtained via numerical simulation, and this information is important and useful for die design.

However, the modification of an extrusion die based on simple numerical simulation strongly depends on the experience of designers, who should have a comprehensive understanding of the correlation between the material flow and die structures. Moreover, only the relatively optimum die structure can be obtained through several manual modifications. Hence, some researchers attempted to use more scientific approaches based on design of experiment to achieve the optimal die structure. Gagliardi et al. [7] optimized the structure of a porthole die for extruding an Al tube by using the Taguchi method and grey relational analysis. Barbara et al. [8] conducted multi-objective optimization for a porthole die by using meta-models in order to simultaneously enhance the die life, flow velocity, and welding strength. Zhao et al. [9] optimized the porthole die for an Al profile with irregular dimensions by using an intelligence algorithm and the Kriging model. Zhuang et al. [10] adopted the design of experiments and analysis of variance to establish a regression model between process parameters and the estimate index, and an optimized die structure was obtained.

In the aforementioned studies, the researchers focused on a porthole die for hollow Al profiles. In contrast, the flat die for fabricating solid Al profiles has rarely been investigated. A flat die usually includes the components of the feeder chamber, bearing, and die relief. During flat die extrusion, the material is pre-deformed by the feeder chamber, and then the second deformation occurs at the bearing exit to extrude the profiles with a certain cross section and dimension. The feeder chamber is mainly used to control the uniformity of the material flow velocity, which is helpful for reducing the twisting and bending deformation of the profile and extending the die lifetime, especially for thin-walled profiles with a high extrusion ratio. Thus, the proper design of the feeder chamber is essential for the flat-die extrusion process [11,12]. However, the optimization of the feeder chamber is still rarely reported, especially for 7xxx Al alloys. Moreover, the microstructure features and property response of 7xxx Al profile fabricated via a flat die with a feeder chamber have not been experimentally clarified.

Hence, the flat die extrusion process for extruding the 7075 Al plate was numerically and experimentally studied. First, the finite element simulation was performed on flat die extrusion. Then, the geometry of the feeder chamber was optimized based on surface methodology (RSM) and particle swarm optimization (PSO), with the objectives of improving the homogeneity of material flow, and reducing die displacement and extrusion load. In order to further clarify the microstructure of extruded 7075 Al plate and the response of mechanical properties, the flat die with the optimal feeder chamber was manufactured, and the extrusion experiment was performed. The grain structure and texture components were comprehensively analyzed. The microhardness of the center and edge areas of the extruded plate was measured, and tensile tests were conducted at angles of 0°, 45°, and 90° from the extrusion direction (ED). Thus, the optimal feeder chamber was achieved, and the microstructure features of the extruded plate were clarified.

2. Methods

2.1. Numerical modeling

2.1.1. Initial design of feeder chamber

The extrusion setup and the structure of the flat die are shown in Fig. 1. The bone-shaped feeder chamber is designed in the upper die. The feeder chamber has three key dimensional variables—the arc radius (R), the width of the parallel section (W), and the distance between the centers of the two arcs (L), all of which are important for controlling the material flow behavior. R, W, and L are initially designed as 10, 15, and 60 mm, respectively. The outer diameter of the upper and lower dies is 180 mm, and the heights of these dies are 70 and 50 mm, respectively. The billet has dimensions of $\phi120 \times 300$ mm, and a rectangular plate with a cross-sectional area of 60 mm × 5 mm is extruded out. Accordingly, the extrusion ratio is approximately 37.68.

2.1.2. Numerical modeling

To obtain the material flow behavior and die strength during flat die extrusion, numerical modeling was performed using the finite-element method. Fig. 2 presents the meshing model, which mainly includes the following components: the billet,
feeder chamber, bearing, plate, upper die, and lower die. The bearing and plate were meshed by fine triangular prism elements with the size of 0.5 mm, as severe shearing deformation occurred in the bearing region. Relatively coarse tetrahedral elements with the size of 1.0–4.0 mm were used in the other regions, including the feeder chamber, billet, and dies. Via this meshing route, a balance between the calculation accuracy and the computation time was achieved.

The materials of the extrusion billet and die were commercial 7075 Al and H13 steel, respectively. Table 1 summarizes the required thermal and mechanical parameters of both materials. The sine-type hyperbolic law was employed as the constitutive model, and the material constants of 7075 Al were obtained from Chen et al. [13]. The preheating temperature of the billet was 753 K, and the temperature of the container and die was 723 K. The ram velocity was set as 1.5 mm/s. It is noted that the Coulomb friction model with the coefficient of 0.3 was set at the die bearing zone, while the sticking friction was set at the other zones. The detailed information about the friction and heat transfer conditions is shown in Table 2, which were obtained from Refs. [14].

### Table 2 – Boundary conditions set in the numerical modeling.

<table>
<thead>
<tr>
<th>Billet interacted with</th>
<th>Friction</th>
<th>Transfer coefficient</th>
<th>Temperature</th>
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</thead>
<tbody>
<tr>
<td>Container</td>
<td>Sticking</td>
<td>3000 W/m²·°C</td>
<td>723 K</td>
</tr>
<tr>
<td>Feeder</td>
<td>Sticking</td>
<td>3000 W/m²·°C</td>
<td>723 K</td>
</tr>
<tr>
<td>Upper die</td>
<td>Sticking</td>
<td>3000 W/m²·°C</td>
<td>723 K</td>
</tr>
<tr>
<td>Bearing</td>
<td>Visco-plastic (μ = 0.3)</td>
<td>Adiabatic</td>
<td>–</td>
</tr>
<tr>
<td>Plate</td>
<td>–</td>
<td>Adiabatic</td>
<td>–</td>
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</table>

The extrusion experiment was conducted to examine the microstructure features of the extruded plate. Fig. 3 shows the manufactured die with the optimal feeder chamber. A homogenized 7075 Al (Al-5.5Zn-2.35 Mg, wt%) bar with a diameter of φ125 mm was used as the extrusion billet. The temperatures of the billet, container, and die, as well as the ram velocity, were identical to those used for the numerical simulation. After extrusion, the obtained plate was rapidly cooled to room temperature.

The specimens for the microstructure analysis and tensile test are schematically shown in Fig. 4. As mentioned previously, the plate-shaped profile with a cross section of 60 mm × 5 mm was extruded out. The length, width, and thickness of the plate were defined as the ED, transverse direction (TD), and normal direction (ND), respectively. The microstructure was observed along the ED direction, and the specimens were located at the edge and center areas of the extruded plate. Moreover, the homogenized billet was examined to check the initial microstructure prior to extrusion. The grain morphology, second phase, and microtextures were analyzed using optical microscopy (OM), scanning electron microscopy (SEM), and electron backscatter diffraction (EBSD). The OM and SEM specimens were etched using a Graff Seagent reagent containing 1 mL of HF, 16 mL of HNO₃, 3 g of CrO₃, and 83 mL of H₂O. The EBSD specimens were electropolished using 30 mL

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**Table 1 – Parameters of the 7075 Al and H13 steel used for the numerical modeling.**

<table>
<thead>
<tr>
<th>Material</th>
<th>Density, (kg/m³)</th>
<th>Specific heat, J/(kg K)</th>
<th>Thermal conductivity, W/(m K)</th>
<th>Thermal expansion coefficient, 1/K</th>
<th>Young’s modulus, MPa</th>
<th>Poisson’s ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>7075 Al</td>
<td>2810</td>
<td>960</td>
<td>173</td>
<td>0.00001</td>
<td>40000</td>
<td>0.35</td>
</tr>
<tr>
<td>H13 steel</td>
<td>7870</td>
<td>460</td>
<td>24.3</td>
<td>–</td>
<td>210000</td>
<td>0.35</td>
</tr>
</tbody>
</table>

**Fig. 2** – Meshing models of the (a) material flow regions and (b) upper and (c) lower dies.

**Fig. 3** – Manufactured die with the optimal feeder chamber for the extrusion experiment.
of nitric acid and 70 mL of methanol at 25 V for 15 s. The Vickers hardness of the extruded plate and the homogenized billet was obtained by applying a load of 1000 g for 10 s. The locations of the specimens used for the tensile test are shown in Fig. 4(b). The specimens were cut at angles of 0°, 45°, and 90° from the ED. The specimens cut at 0° in the center and edge areas of the plate were denoted as 0°-center and 0°-edge, respectively. The dimensions of the tensile specimens are shown in Fig. 4(b), where the length, thickness and width of the gauge are 20, 5, and 6 mm, respectively. The wire electrodischarge machining (WEDM) was employed to produce the tensile specimens, since WEDM has the advantages of high accuracy and no affection to the ductility of the edge [15]. The tensile tests were carried out at a constant stretching rate of 0.45 mm/min at room temperature, and the fracture surface was observed by SEM.

**Fig. 4 – Schematic of the specimens for the (a) microstructure analysis and (b) tensile tests (unit: mm).**

<table>
<thead>
<tr>
<th>Table 3 – Ranges of the design variables R, W, and L.</th>
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<tr>
<td>Design factors</td>
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<td>----------------</td>
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<tr>
<td>Arc radius (R)</td>
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<tr>
<td>Width of parallel section (W)</td>
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<td>Center distance of two arcs (L)</td>
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3. Optimization results and discussion

3.1. Simulated results based on RSM

The geometry of the feeder chamber was optimized based on a combination of the RSM and Box-Behnken design (BBD). First, BBD schemes with three levels and three factors were designed. As mentioned previously, the key dimensions of R, W, and L for the feeder chamber were selected as the three factors. The ranges of the design variables were determined according to practical production, as shown in Table 3.

The homogeneity of the flow velocity significantly affects the tolerance of the extruded plate. To quantitatively evaluate the homogeneity of the flow velocity at the cross section of the plate, the standard deviation of velocity (SDV) was introduced as the first optimization objective:

$$SDV = \sqrt{\frac{\sum_{i=1}^{n} (V_i - \bar{V})^2}{n}},$$

where $V_i$ is the velocity at node $i$, $\bar{V}$ is the mean velocity of all nodes, and $n$ is the number of selected nodes. All nodes located at the cross section of the plate were selected for calculating the SDV. In practice, the extrusion die is subjected to severe working conditions, and plastic deformation, abrasion, and cracks easily occur on the die. Hence, the maximum die displacement (Dis) was considered as the second objec-

<table>
<thead>
<tr>
<th>Table 4 – Simulated schemes based on the BBD and the results for SDV, Dis, and F.</th>
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<tr>
<td>Number</td>
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tive. As the third objective, the maximum extrusion load (F) plays an important role in selecting extruding equipment. An overlarge load can increase the product cost and lead to excessive wear of the extrusion die and can even cause die abandonment. According to the BBD, 17 groups of simulations were designed by collecting the variables R, W, and L. Then, the feeder chambers were designed using the corresponding R, W, L, and simulations were conducted. Subsequently, the values of the optimization objectives (SDV, Dis, and F) were calculated. The 17 simulated schemes and the corresponding results for SDV, Dis, and F are presented in Table 4.

According to the results of Table 4, the quadratic regression function is recommended as the fittest model for SDV and F, and the two-factor interaction function is recommended for Dis. Analysis of variance (ANOVA) can be employed to evaluate the correctness of functions [16]. As shown in Table 5, the F values of three represented functions are 68.52, 64.09, and 83.08, respectively, which indicates that these functions are significant. The determination coefficients \( R^2 \) of the three functions are 0.9888, 0.9747, and 0.9908, respectively, which implies that a sample variation that is 98.88%, 97.47%, and 99.08% of the total variation can be illustrated by these functions. Hence, the quadratic regression function and the two-factor interaction function are suitable for this analytical work. Additionally, the \( R^2_{adj} \) values of the functions are very high, indicating the high significance of the functions. The \( R^2_{pred} \) values of the functions show reasonable agreement with the high \( R^2_{adj} \) values.

The values of PRESS are 0.53, 2.463E–005, and 1101.27, which evidence the good fitting. According to the foregoing analysis, the final fitting functions of SDV, Dis, and F are as follows.

\[
SDV = 3.10760 - 0.23793 \times R + 0.073208 \times W - 0.053968 \times L - 0.017698 \times R \times W + 3.80139 \times 10^{-3} \times R \times L + 2.54167 \times 10^{-5} \times W \times L + 7.22083 \times 10^{-3} \times R^2 + 8.09550 \times 10^{-3} \times W^2 - 4.89583 \times 10^{-5} \times L^2
\] (2)

\[
Dis = 0.080946 - 1.91792 \times 10^{-3} \times R - 2.26942 \times 10^{-3} \times W + 1.98750 \times 10^{-4} \times L + 1.06667 \times 10^{-4} \times R \times W - 1.37500 \times 10^{-5} \times R \times L + 2.08333 \times 10^{-6} \times W \times L
\] (3)

\[
F = 1168.00139 - 30.57778 \times R - 14.00375 \times W + 2.35382 \times L + 0.66550 \times R \times W + 0.29597 \times R \times L - 0.13217 \times W \times L - 0.10111 \times R^2 + 0.29330 \times W^2 - 0.028403 \times L^2
\] (4)

3.2. **Optimization based on PSO**

The purpose of the optimization is to reduce the SDV, die displacement, and extrusion load when R, W, and L are in the ranges of 10–16, 10–20, and 60–72 mm, respectively. According to the RSM, the three fitting functions for SDV, Dis, and F in terms of R, W, and L were established (Eqs. (2)–(4)), and the quality of fitness is good. To simultaneously minimize the val-

Fig. 5 – Flowchart of the PSO algorithm.

Fig. 6 – Relationship between the number of iterations and the Gbest value.
ues of SDV, Dis, and F, the Gbest function was introduced for multi-objective optimization, which is expressed as follows:

\[
\min_{x \in R} Gbest(x) = \| f(x) - f(x^*) \|_n = \sqrt{\sum_{j=1}^{n} | f_j(x) - f_j^* |^n },
\]

(5)

where \( f(x) \) is the objective function including SDV, Dis, and F, and \( f(x^*) \) is the minimum value of the objective function. To achieve an accurate minimum value of Gbest, the PSO algorithm was applied in this work, and a detailed flowchart is shown in Fig. 5. The PSO algorithm considers the solution of the optimization as a particle in the searching space. The solution quality is determined by the fitting function. For satisfying the constraints of solving problems, each particle updates its speed and position via continuous tracking according to its best location \( (p_d) \) and the best place \( (p_g) \) where the entire population have passed and finally reaches the position of the global optimal solution. The velocity and position update formulas are as follows:

\[
v_{id}(t + 1) = \omega \times v_{id}(t) + c_1 \times r_1 \times (p_{id}(t) - x_{id}(t)) + c_2 \times r_2 \times (p_{gd}(t) - x_{id}(t))
\]

(6)

\[
x_{id}(t + 1) = x_{id}(t) + v_{id}(t + 1).
\]

(7)

where \( v_{id} \) is the particle velocity, \( x_{id} \) is the current position of the particle, \( r_1 \) and \( r_2 \) are random numbers in the range of \([0, 1]\), \( c_1 \) and \( c_2 \) are learning factors, and \( \omega \) is the weighted coefficient (inertial weight), which is between 0.1 and 0.9. In this paper, the initial population has 50 individuals, both learning factors are 2, and the maximum number of iterations is 100. Through constant learning and updating, the particle eventually moves to the location of the optimal solution, and the searching process ends.

Fig. 6 shows the curve of the relationship between the number of iterations and the Gbest value. The particle reached the optimal position after nine iterations. After rounding, the optimal R, W, and L values of the feeder chamber were determined as 16, 18, and 60 mm, respectively. To verify the optimized results, a new simulation was conducted using the optimal structure of the feeder chamber, and the results are presented in Table 6. After optimization, the SDV value was approximately 0.499 mm/s, with a reduction of 65.7% from that for the initial design of the feeder chamber. This agrees well with the predicted SDV value of 0.502 mm/s. The maximum value of Dis decreased from 0.050 to 0.041 mm after optimization, which is a reduction of approximately 22.0%. Moreover, the F value decreased from 905.49 to 868.79 tons. For comparison, Figs. 7 and 8 show the velocity distributions and die displacement before and after optimization. Before optimization, the material flowed more quickly in the plate center than in the plate edge. However, after optimization, the uniformity of the flow velocity was greatly enhanced, with a smaller SDV value, as more materials were provided at both ends of the plate owing to the higher value of R. As shown in Fig. 8, the area with large displacement was reduced after optimization, which is beneficial for enhancing the die strength and lifetime. This is because the volume of the feeder increased after optimization, which reduced the deformation degree when the billet flowed into the feeder, and the extrusion load was consequently reduced. A large feeder volume provides more area to sustain the high pressure. Both of these factors contribute to the smaller displacement of the feeder surface. Thus, the optimization of the feeder chamber conducted in this study can significantly improve the uniformity of the flow velocity and reduce the die displacement and extrusion load.

### 4. Experimental results and discussion

#### 4.1. Grain morphology

Fig. 9 shows the microstructure of the homogenized 7075 Al billet obtained via EBSD analysis. Equiaxed grains with a uniform size distribution are observed. The calculated mean grain size is approximately 71.23 μm. Moreover, the texture distribution is scattered, with a low density value, which means that the initial texture of the homogenized 7075 billet has relatively weak components.

Fig. 10 presents the OM and SEM microstructures at the center and edge areas of the extruded 7075 Al plate. The typical fibrous structure is clearly observed, and both the center and edge areas have elongated grains and numerous equiaxed grains with the size of several microns. It is seen from Fig. 10(a) that the fine grains have a morphology with a flocculent feature, and the surrounding coarse grains are distributed in clumps. Compared with the center area, the grains in the edge have a more obvious fibrous feature and are elongated along the ED with relatively flat grain boundaries, which is attributed to the fact that the material of the edge area flowed slowly during the extrusion process. Moreover, Fig. 10(c) shows that the grain width is significantly smaller in the edge area, because the deformation degree is far higher in this area [17]. On the other hand, massive particles are aligned along the ED, as shown in Figs. 10(b) and (d), which indicates that the coarse secondary-phase particles of the initial homogenized 7075 Al were broken into fine particles owing to severe deformation or dissolved into the Al matrix because of the elevated temperature. The similar phenomenon was also reported in previous studies [18,19].

Fig. 11 shows the EBSD maps and distribution of misorientation angle in the center and edge areas of the plate. The grey lines indicate the low angle grain boundaries (LABs) with the misorientation angle between 2° and 15°, while the black lines indicate the high angle grain boundaries (HABs) with the

<table>
<thead>
<tr>
<th>Response</th>
<th>SDV</th>
<th>Dis</th>
<th>F</th>
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</thead>
<tbody>
<tr>
<td>Model</td>
<td>Quadratic</td>
<td>2FI</td>
<td>Quadratic</td>
</tr>
<tr>
<td>F value</td>
<td>68.52</td>
<td>64.09</td>
<td>83.80</td>
</tr>
<tr>
<td>P value</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>R²</td>
<td>0.9888</td>
<td>0.9747</td>
<td>0.9908</td>
</tr>
<tr>
<td>R² adj</td>
<td>0.9743</td>
<td>0.9594</td>
<td>0.9790</td>
</tr>
<tr>
<td>R² pred</td>
<td>0.8204</td>
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<td>0.8529</td>
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<td>Adeq Precision</td>
<td>30.373</td>
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</tr>
<tr>
<td>PRESS</td>
<td>0.53</td>
<td>2.463E-005</td>
<td>1101.27</td>
</tr>
</tbody>
</table>
Fig. 7 – Simulated results for the flow velocity (a) before and (b) after optimization.

Fig. 8 – Simulated results for the die displacement (a) before and (b) after optimization.

Fig. 9 – (a) Grain morphology and (b) \{011\} pole figure of the homogenized 7075 Al billet.

Fig. 10 – Microstructure of the extruded 7075 Al plate: (a, c) the center area and (b, d) the edge area.
misorientation angle higher than 15°. The average grain size in the center and edge areas is 5.59 and 5.88 μm, respectively. The grain orientation spread (GOS) was introduced to distinguish the dynamically recrystallized (DRXed) grains from the deformed grains. Allain-Bonasso et al. [20] proposed that the deformation usually caused the grain distortion and high GOS values. In contrast, the DRXed grains were freely deformed, and their GOS values were relatively low. In Fig. 11, the red region represents DRXed grains (GOS<2°), and the yellow region represents deformed grains (GOS ≥ 2°). It is obvious that the microstructures of both the center and edge areas are composed of deformed grains and a low fraction of DRXed grains. More DRXed grains are observed in the edge area than those in the center area, indicating that the dynamic recrystallization (DRX) process was slightly promoted in the edge area. As shown in Figs. 11(b) and (d), the fraction (f) of LABs in the center and edge areas is as large as 81.40% and 80.70%, respectively, which is the evidence that the plates experienced a high degree of DRV. The work hardening, DRV, and DRX occurred simultaneously during the hot deformation of Al alloys [21]. Moreover, 7xxx Al alloys have a high stacking fault energy, which resulted in the occurrence of DRV easier [22].

Fig. 12 presents the EBSD maps of the extruded plate at high magnification. Large amount of LABs can be observed inside the coarse elongated grains in both the center and edge areas, which means that lots of subgrains were formed during the hot extrusion process due to the occurrence of DRV. Moreover, some fine equiaxed grains distributed between the elongated grains. Since the number of these fine grains is quite few, it again proves that the DRX degree is slight, and it is far lower than the degree of DRV. Lang et al. [23] have reported the mechanism of DRV process during hot deformation process. The dislocations are firstly generated around the precipitated phase owing to the stored strain energy. With the accumulation of strain, the dislocation multiplication rapidly increases, and the dislocation climb and cross-slip along the slipping surfaces and shearing zones, resulting in the crushing of initial grains and the formation of substructures with LABs. Moreover, the continuous dynamic recrystallization (CDRX) is the main DRX mechanism for 7xxx Al alloys. During CDRX pro-

| Table 6 – Key dimensions and corresponding simulated results before and after optimization. |
|----------------------------------|--------|--------|--------|----------------|--------|--------|
| Before optimization             | 10     | 15     | 60     | 0.827          | 0.050  | 905.49 |
| After optimization              | 16     | 18     | 60     | 0.499          | 0.041  | 868.79 |

![Fig. 11 – EBSD maps and misorientation angle for the (a, b) center and (c, d) edge areas of the extruded 7075 Al plate.](image)

![Diagram](image)
Fig. 12 – EBSD maps at higher magnification at the (a) center and (b) edge areas of the extruded 7075 Al plate.

Fig. 13 – (110) pole figure of the (a) center and (b) edge of the 7075 Al plate, and (c) standard (110) pole figure.

Fig. 14 – ODF sections obtained from EBSD analysis of the extruded 7075 Al plate: (a) center area, (b) edge area.

Fig. 15 – Location of the main ideal orientations in FCC materials of $\varphi_2 = 45^\circ$, 65°, and 90°.
cess, the dislocations accumulated into the grain substructure, which is called the sub-crystal. Then, through the rotation of the sub-crystal, LABs gradually transformed into HABs. Based on above analysis, it is known that DRV was the primary restoration mechanism of the 7075 alloy during the flat die extrusion, and partial CDRX also occurred.

4.2. Microtexture

Microtexture is an important factor affecting the material properties. Fig. 13 presents the ⟨110⟩ pole figures for the extruded plate and the standard pole figure for a face-centered cubic (FCC) material. As shown, the texture of both the center and edge areas is mainly concentrated in the ⟨113⟩, ⟨110⟩, and ⟨01-3⟩ orientations, and the weak textures in ⟨1-1-1⟩ and ⟨3-12⟩ are also observed. Compared with the homogenized billet, the strong texture was formed after flat die extrusion owing to the severe plastic deformation [24]. Compared with the edge area, the plate center had a more concentrated distribution and higher density, as more deformed grains existed in the center area.

Fig. 14 presents the orientation distribution function (ODF) sections for precise determination of the texture distribution of the center and edge areas. The main ideal orientations in FCC materials of ϕ2 = 45°, 65°, and 90° are presented in Fig. 15. As shown in both the center and edge areas, Brass, S, and Copper are obviously strong, whereas Goss and Cube are weak. According to the previous study [25], the components of Brass, S, Copper and Goss are typical deformation textures, whereas Cube is a typical recrystallization texture. During the extrusion process, the grains of 7075 Al rotated to adjust their orientations toward the same direction, and then the aforementioned textures were formed. The fraction of the texture components in the center and edge areas of the extruded plate is presented in Table 7. The fraction significantly varied in the center and edge areas owing to the severe inhomogeneous deformation. The texture evolution is closely related to the deformation conditions [26]. With the increase of the deformation energy during extrusion, the Copper component was replaced by the Brass orientation. Additionally, there were numerous dislocation slips in the primary system, and the slip plane rotated away from the position with the maximum shearing stress until the crystal orientation reached the symmetry midpoint [112]. Consequently, as reported in the previous studies [27,28], the typical S component transformed into Copper. The variation of the texture fraction in the plate center and edge indicates that the stress, strain, and DRX fraction significantly affected the texture evolution. Moreover, the Cube component of the plate edge had a higher fraction than that of the center, indicating that the DRV degree of the edge area was higher, in agreement with Fig. 11.

<table>
<thead>
<tr>
<th>Specimens</th>
<th>Texture components (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brass (011) &lt;211&gt;</td>
<td>S (123) &lt;634&gt;</td>
</tr>
<tr>
<td>Center</td>
<td>48.4</td>
</tr>
<tr>
<td>Edge</td>
<td>30.8</td>
</tr>
</tbody>
</table>

Fig. 16 – Results of Vickers-hardness tests.

4.3. Mechanical properties

Fig. 16 shows the results for the Vickers hardness of the homogenized and extruded 7075 Al. Compared with the homogenized billet, the hardness of the extruded plate was greatly improved, and the center area had higher hardness than the edge area. Generally, the hardness is affected by the grain size, dislocation density, LABs, and precipitations. Because of the finer grains and higher fraction of LABs, the extruded plate had higher hardness than the homogenized billet, and the plate center exhibited slightly higher hardness than the edge area. Fig. 17 shows the engineering stress-strain curves, ultimate tensile strength and elongation obtained from the tensile tests. As is seen from Fig. 17(a), the specimens continue to be hardened until the appearance of fracture, without the obvious necking phenomenon. The elongation and ultimate tensile strength of the 0°-edge were 26.2% and 541.7 MPa, respectively, and both of them are higher than those of the 0°-center. This is because that the edge area had a more obvious fibrous feature and the fraction of the texture components differed from that of the center area. Additionally, both the elongation and ultimate tensile strength were lowest for the 45° specimen. According to the study of Moghaddam et al. [29] concerning the tensile test, the dislocation activation promotes the ⟨111⟩ <110> slip system easily in 45° specimen owing to its low resistance from the horizontal and vertical directions. Thus, the 45° specimen exhibited the lowest elongation and ultimate tensile strength. Overall, the tensile properties of the 0°-center, 45°, and 90° specimens exhibit differences, which implies that anisotropy is a common phenomenon for the extruded Al-Zn-Mg plate.
Fig. 17 – Tensile test results of the (a) engineering stress-strain curves and (b) the tensile properties.

Fig. 18 – Fracture morphology of the specimens (a) 0°-center, (b) 0°-edge, (c) 45°, and (d) 90°.

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5. Conclusions

Multi-objective optimization of a feeder chamber was performed by using the RSM and PSO. Moreover, the hot extrusion process of 7075 Al was experimentally studied using a flat die with the optimal feeder chamber. The main conclusions are summarized as follows.

1. Using the RSM method, three variables of F, W, and L were selected to represent the key dimensions of the feeder chamber, and 17 simulated schemes were designed. According to the simulation results, three high-quality fitting functions of SDV, Dis, and F in terms of F, W, and L were established. Using the PSO algorithm, the optimal R, W, L values for the feeder chamber were determined as 16, 18, and 60 mm, respectively.

2. After optimization, the SDV value in the cross section of the extruded plate decreased from 0.827 to 0.499 mm/s. The Dis value was approximately 0.041 mm, exhibiting a 22.0% reduction from the initial value of 0.050 mm. The F value was reduced from 905.49 to 868.79 tons. The results indicate that the optimization of the feeder chamber simultaneously improved the homogeneity of the flow velocity and reduced the die displacement and extrusion load.

3. The extruded plate had a typical fibrous structure, and the average grain sizes of the center and edge areas were refined to 5.59 and 5.88 μm because of the severe plastic deformation. DRV and partial DRX occurred during the hot extrusion of 7075 Al, and DRV was the primary restoration mechanism. The DRX degree was higher in the edge area of the plate than in the center area.

4. The texture components of Brass, S, and Copper were formed in the extruded 7075 Al plate owing to the severe plastic deformation, and the Cube component was also observed, because of the DRX. However, the fractions of these texture components varied significantly between the center and edge areas.

5. The hardness of the extruded plate was greatly enhanced compared with the homogenized billet. The plate center had higher hardness, lower elongation, and lower ultimate tensile strength than the edge area. The tensile properties at 0°, 45°, and 90° exhibited differences, indicating that anisotropy existed for the extruded Al-Zn-Mg plate.

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Fig. 18 shows the fracture morphology of the tensile test specimens. Overall, a cleavage-like structure can be observed from the low magnification images. Moreover, some dimples with non-uniform size and different depth exist in all specimens. This phenomenon can be identified as a mixture of ductile and brittle fractures mode [30]. As shown in Figs. 18(b) and (d), the big and deep dimples can be observed, which indicates the better plasticity of 0°-edge and 90° specimens. However, a very smooth fracture plane and river pattern can be clearly observed in Fig. 18(c), and a few micro voids appear in the fracture plane, which means that the 45° specimen has the feature of quasi-cleavage fracture. The less dimples and smooth fracture plane also indicate that the brittle fracture is dominated in 45° specimen, and thus the worst plasticity was observed. The above analysis agrees well with the tensile test results shown in Fig. 17, and it again proves the obvious anisotropy of the extruded plate. Finally, it should be pointed out that the heat treatments such as solution and aging are sometimes performed on the extruded Al alloys. The type, size and distribution of the precipitations formed during aging greatly affect the mechanical properties. Moreover, the residual stress is also an important issue, since it can affect the instability phenomenon such as chatter during the subsequent machining [31]. The present study mainly focus on the hot extrusion process, and the heat treatment will be a future topic.
Data availability

The raw/processed data required to reproduce these findings cannot be shared at this time due to technical or time limitations.

Conflicts of interest

The authors declare no conflicts of interest.

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