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Research Article

Cold Expansion Strengthening of 7050 Aluminum Alloy Hole: Structure, Residual Stress, and Fatigue Life

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The 7050 aluminum alloy orifice plate is extruded and strengthened by the cold expansion process of slotted bushing holes. A three-dimensional finite element model was established for cold expansion strengthening of holes, and the residual stress distribution of 7050 aluminum alloy orifice plates is studied after cold expansion. The influence of different relative extrusion amounts and different sample thicknesses on the residual stress around the sample hole was analyzed, and the relationship between the extrusion amounts and the thicknesses of the substrate and the residual stress was obtained by analysis. The research results indicate that the cold expansion process of slotted bushing holes can enhance the residual stress distribution around the hole and form a strong residual stress layer. As the amounts of extrusion increase, the residual stress tends to increase, reaching the maximum when the amounts of extrusion are 4%. The residual stress on the surface of the extrusion inlet increases with the increase in the thickness of the substrate. Within the range of 3%-4% of the extrusion amounts, with the continuous increase of the extrusion amounts, the fatigue life has been substantially enhanced, and the number of fatigue life is more than 3 times that of the empty plate fatigue test.

1. Introduction

With the rapid development of the aerospace industry, the fatigue resistance of materials and components has become particularly important. Particularly in aircraft components, most components are mechanically connected by riveting, bolts, and positioning pins [1]. For this kind of mechanical joints, they are usually subjected to various loads, which makes the connecting holes more prone to fatigue cracks due to stress concentration, which seriously affects the safety and reliability of aircraft components. In order to meet the requirements of long life, high reliability, and easy maintenance of aircraft components, improving the fatigue resistance of connecting holes has become an indispensable link in aircraft manufacturing [2, 3]. In order to make up for this characteristic of the connecting hole, various technologies have been proposed to improve its fatigue life. In the book *Riveted Lap Joints in Aircraft Fuselage: Design, Analysis and Performance* [4], Skorupa A and Skorupa M have mainly studied and analyzed the fatigue problems of riveted lap joints between aluminum alloy sheets.

As a technology to improve the fatigue strength of connecting holes, the cold expansion strengthening [5] is currently the most widely used method of increasing the fatigue life of aerospace parts in the world [6–8]. Matos et al. [9] employed 2D, 2D axisymmetric, and 3D models to predict the resulting residual stress fields. According to research [10], under the condition of good technology, the fatigue life of pore structure can be increased by more than 3 times. The cold expansion strengthening can be divided into direct extrusion and slotted bushing extrusion according to the contact type. The cold expansion strengthening technology for slotted bushing holes is to introduce a layer of slotted steel bushing between the extrusion tool and the hole wall, and the radial force of the extrusion tool is transmitted to the hole wall through the bushing to make the hole plastically expand, and the residual compressive stress strengthening layer is formed near the hole. The local stress distribution of the hole structure under external load is improved, and the fatigue strength, stress corrosion resistance, and corrosion fatigue resistance of the connecting hole are greatly improved. It has the advantages of not

Table 1: Chemical composition of 7050-T7451 aluminum alloy.

Elements	Si	Fe	Cu	Mn	Mg	Cr	Zr	Zn	Al
Contents	0.03	0.11	2.04	0.003	2.31	0.009	0.1	6.02	Bal.

Table 2: Mechanical properties of 7050-T7451 aluminum alloy.

Density ρ (kg/m^3)	Young's modulus E (GPa)	Poisson's ratio ν	Tensile strength σ_b (MPa)	Yield strength $\sigma_{p0.2}$ (MPa)	Elongation A (%)	Fracture toughness K_{IC} ($MPa\bullet m^{1/2}$)
2830	70.3	0.33	564.7	479.4	13.3	30

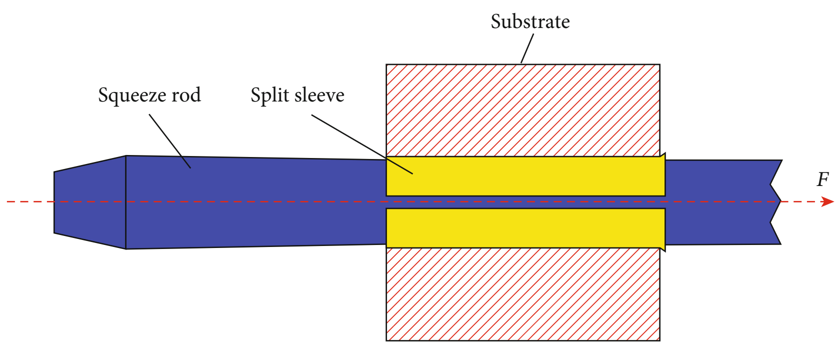


Figure 1: Cold expansion process of split sleeve.

changing the material, not changing the structure design, not increasing the weight of the aircraft, low cost, obvious strengthening effect, and wide application aperture.

Since the residual stress value introduced in the process of extrusion strengthening is the main factor that affects the strengthening effect, a lot of research is carried out on the residual stress field after strengthening [11–16]. Nigrelli and Pasta [17] conducted a three-dimensional finite element simulation for the cold expansion process of the slotted bushing hole in order to determine the residual stress field around the hole. The results show that the residual stress field obtained by this method agrees well with the analytical solution. At the same time, the influence of plate thickness on the residual stress field is also studied. Su et al. [18] analyzed the influence of cold expansion on the fatigue life of 6082-T6 aluminum alloy through a combination of experiment and numerical simulation. In addition, studies have been carried out on secondary extrusion, and the results show that secondary extrusion can fully improve the fatigue life of the material. Based on continuous damage mechanics and finite element numerical simulation, Zhao et al. [19] conducted experimental and numerical studies on the residual stress around the cold-extruded hole of ultra-high-strength steel. Sun et al. [20] studied the fatigue damage evolution of holes in the plate. The beneficial effect of cold expansion on improving the fatigue life of fastener holes is not only the maximum stress but also the change in the fatigue damage evolution at the critical location. Giglio and Lodi [21] introduced a method to determine the optimal radial interference and the optimal mandrel shape of the cold expansion bushing hole connection commonly used in aerospace structures to obtain the ideal value of the residual stress on the hole surface. This method can reduce the area of the hole surface that bears negligible residual radial stress and obtain compressive residual circumferential stress on the entire hole surface.

Kang et al. [22] conducted a three-dimensional finite element numerical simulation on the cold expansion process of 7050-T7451 aluminum alloy. Studies have shown that the residual stress field around the hole has a three-dimensional nature, and the residual stresses of different thickness sections have significant differences. Liu J et al. [23] established a finite element model and analyzed the fatigue life and fracture morphology of the direct mandrel cold expansion. The results show that the residual stress around the hole is unevenly distributed along the thickness direction, and cracks always appear first near the squeezed surface. Ayatollahi and Nik [24] used two-dimensional finite element simulation to study the influence of hole edge margin on the residual stress distribution around the hole. Research shows that when $E/d < 3$ (where E is the distance from the hole edge to the hole center and d is the initial hole diameter), the hole edge margin has a considerable influence on the residual stress profile. Cold expansion with a relatively small margin will cause considerable residual tensile stress at the free edge and reduce fatigue life. Zhao et al. [25] studied the cold expansion process of 7050-T7451 aluminum alloy hole. The results show that residual stress will be generated during the cold expansion of the hole. The maximum values of radial residual compressive stresses locate the middle of the inner wall of the hole and residual compressive stresses extend radially up to one diameter from the edge of the hole. Axial residual compressive stresses distribute near the exit. Kim C et al. [26] modeled and

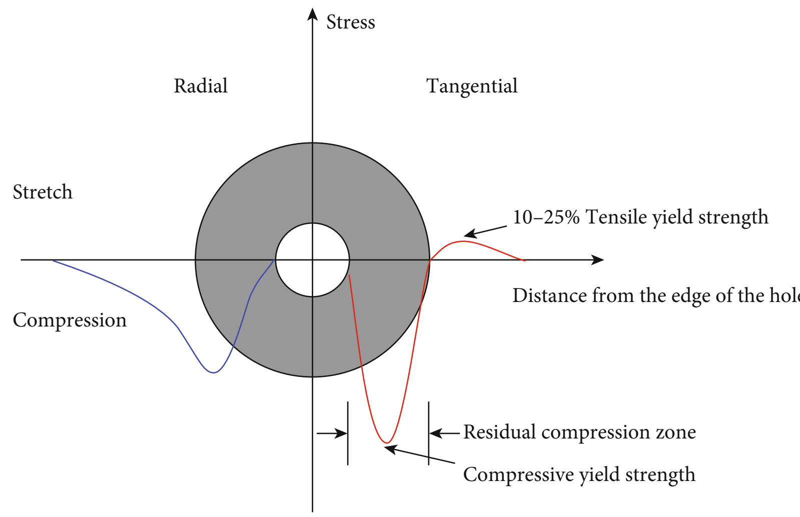


Figure 2: Residual stress distribution after extrusion.

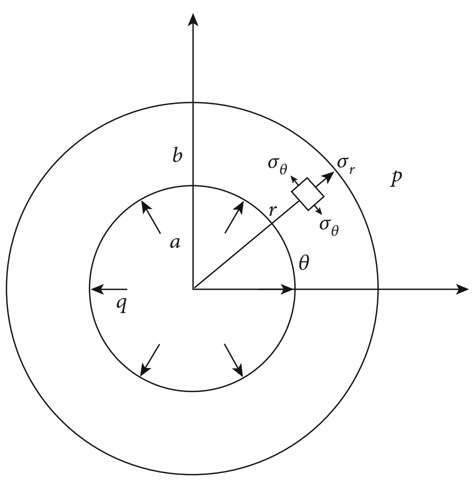


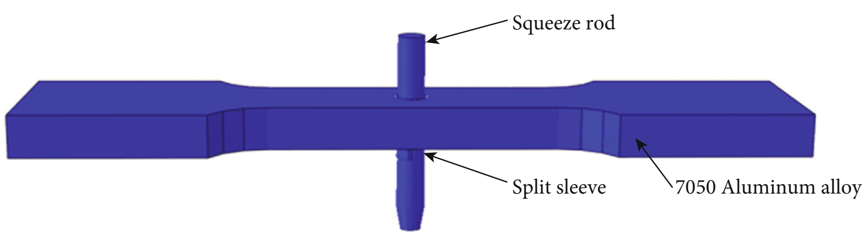
Figure 3: Schematic diagram of hole wall subjected to internal pressure.

simulated the residual stress caused by the cold expansion of two adjacent holes: simultaneous cold expansion and continuous cold expansion. Wang et al. [27] studied the effect of hole cold expansion on the fatigue behavior of AA6016-T6 fastener holes. The results show that the fatigue life of cold bulge specimens is 2.47 times longer than that of noncold bulge (NCE) specimens. The fatigue starting point of all cold bulge specimens is at the corner of the hole on the entrance side of the mandrel. Residual compressive stress can effectively slow the growth rate of fatigue cracks. The grain boundary and the angle of favored slipping planes of neighboring grains evidently affected the fatigue crack propagation path. Fernandes et al. and Bastos et al. [28, 29] studied the effect of residual stress on fatigue life. Gopalakrishna et al. [30] introduced the experimental results of the fatigue life improvement of Al 2024 (a widely used aerospace alloy) and the residual stress around the cold reaming. Faghih et al. [31] studied the hardening process of cold expansion of AZ31B plate. Residual stress measurements confirmed variations through the thickness, with the highest value being at the exit side of the sheet. The fatigue properties of the cold-expanded samples show that different degrees of cold expansion will lead to different degrees of life increase. It was found that the optimal degree of expansion was 5%, and compared with the original situation, the fatigue life was increased by 3 times.

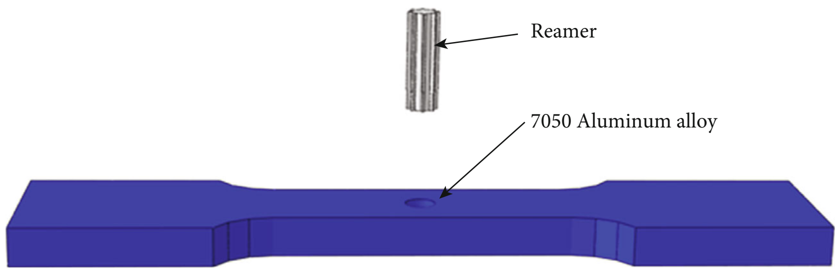
The 7050 aluminum alloy has the advantages of high strength, light weight, and high fracture toughness. This article focused on the 7050 aluminum alloy orifice plate, which is widely used in aircraft structural parts, to study the cold expansion strengthening technology of the slotted bushing hole. Mainly from the point of view of the process factors that affect the hole cold expansion strengthening, the effect of different processes on the residual stress of the hole edge is studied. Different squeezing amounts are used to strengthen the hole extrusion, and the residual stress around the hole is detected by comparing the different strengthening effects, and the relationship between the squeezing amount and the residual stress is obtained, and the influence of the thickness of the sample on the residual stress distribution is analyzed. At the same time, the ABAQUS finite element software is used to carry out a three-dimensional finite element simulation study on the cold expansion process of the hole, and the residual stress distribution law of the hole edge after extrusion is obtained. Combining the results of residual stress finite element simulation and fatigue test, the strengthening mechanism and effect of cold expansion are discussed.

2. Numerical Simulation

Cold expansion hardening of slotted bushing holes is a complex process of elastoplastic change. After extrusion, an uneven distribution of residual stress will be generated around the hole. At present, the approximate distribution of residual stress is predominantly studied by the finite element simulation method. In this paper, ABAQUS software is used to simulate the cold expansion process of 7050-



(a) Finite element model of hole cold expansion



(b) Reaming model

Figure 4: Finite element model.

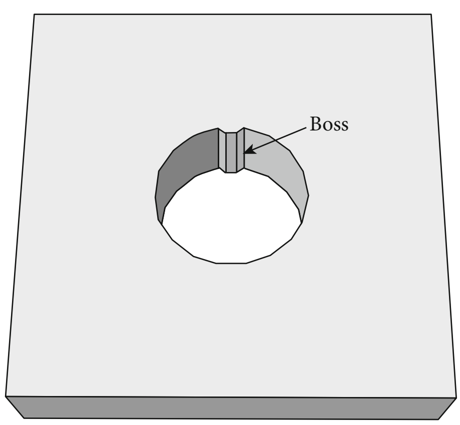


Figure 5: Boss formed by extrusion.

T7451 aluminum alloy orifice plate slotted bushing holes, and the distribution of von Mises stress and residual stress around the hole after extrusion is obtained.

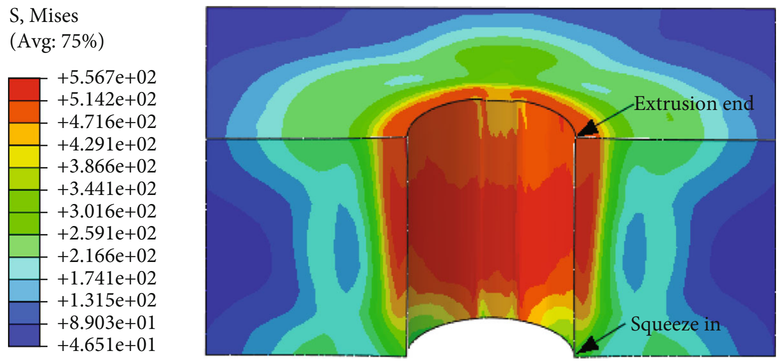
2.1. Material Used. The experimental material in this paper is 7050-T7451 aluminum alloy; its chemical composition and main mechanical properties are shown in Tables 1 and 2. In this experiment, the split sleeve provided by a domestic company was used. The split sleeve is made of 301 stainless steel, and the domestic material is 12Cr7Ni7 in GB/T3280. The thickness of the split sleeve is 0.2 mm. In order to simplify the calculation, the split sleeve material is simulated by a linear elastic material, the density is 7804 kg/m^3, the elastic modulus is 195 GPa, and Poisson's ratio is 0.3. The material properties of the extruded rod material model are the same as the high-strength steel used in the test, with a minor diameter of 6.64 mm and a major diameter of 7.084 mm.

2.2. Analysis of Residual Stress in the Extrusion Process. Cold expansion strengthening technology for slotted bushing holes is currently the most widely used fatigue strengthening method. The strengthening method is principally to use a high-strength extruded rod and add a split sleeve to the outer diameter of its working section. As shown in Figure 1, the overall diameter is moderately larger than the diameter of the squeezed hole of the substrate, and it is compelled to pass through the preprocessed hole wall under the action of external load. In the expansion process, due to the greater rigidity of the extruded rod and the slotted bushing, in the elastic-plastic stress analysis, it is assumed that the extruded rod and the slotted bushing only undergo elastic deformation. Figure 2 [32] shows the circumferential residual stress and radial residual stress distribution at the edge of the hole.

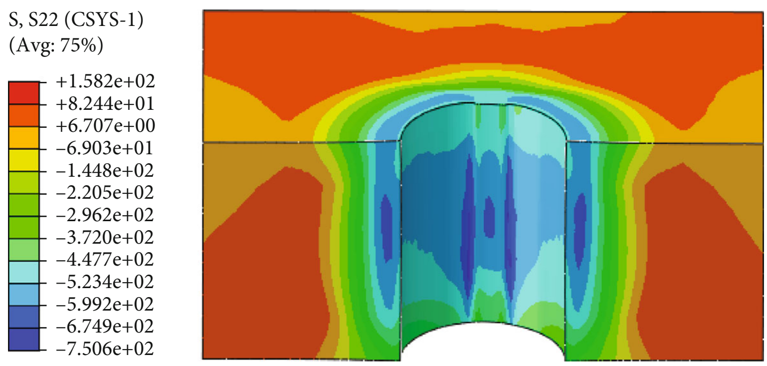
When the extrusion rod squeezes the inner wall of the slotted bushing, the slotted bushing expands outward to extrude the hole wall of the substrate, and the area close to the hole wall is plastically deformed, and the area far away from the hole wall is elastically deformed. A simplified diagram of the pressure on the hole wall is shown in Figure 3 (using a cylindrical coordinate system), where the initial hole radius is a and the outer diameter is b.

Assume that the hole wall $r = a$ is subjected to the uniform pressure q $(q > 0)$ transmitted by the outer wall of the slotted bushing. Assuming that the virtual boundary radius of the elastic-plastic deformation zone is r_p $(a < r_p < b)$, the corresponding pressure value is p_p. According to Lame's solution [33], the stress component of the elastic zone $(r_p < r < b)$ is

$$\sigma_r = -\frac{b^2/r^2 - 1}{b^2/{r_p}^2 - 1} p_p, \quad (1)$$



(a) Von Mises stress distribution cloud diagram



(b) Cloud map of tangential residual stress distribution

Figure 6: Von Mises stress cloud diagram and tangential residual stress cloud diagram.

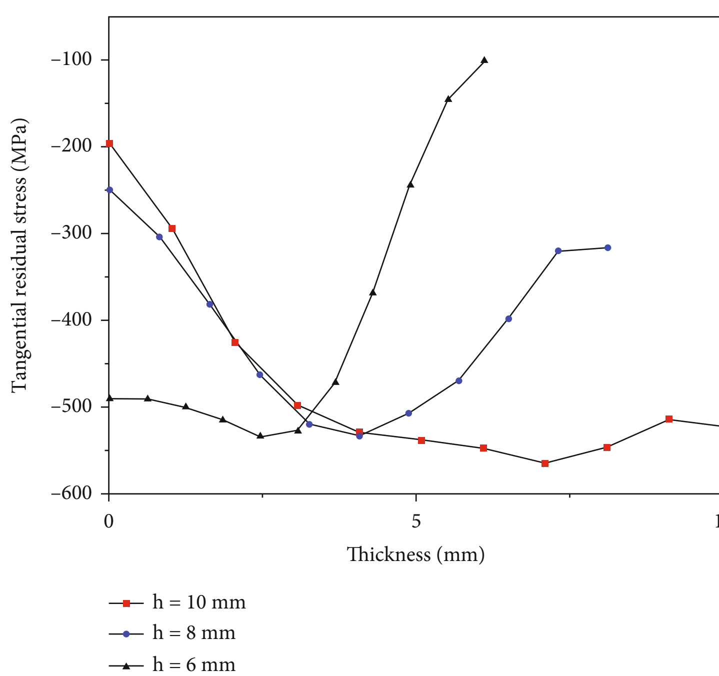
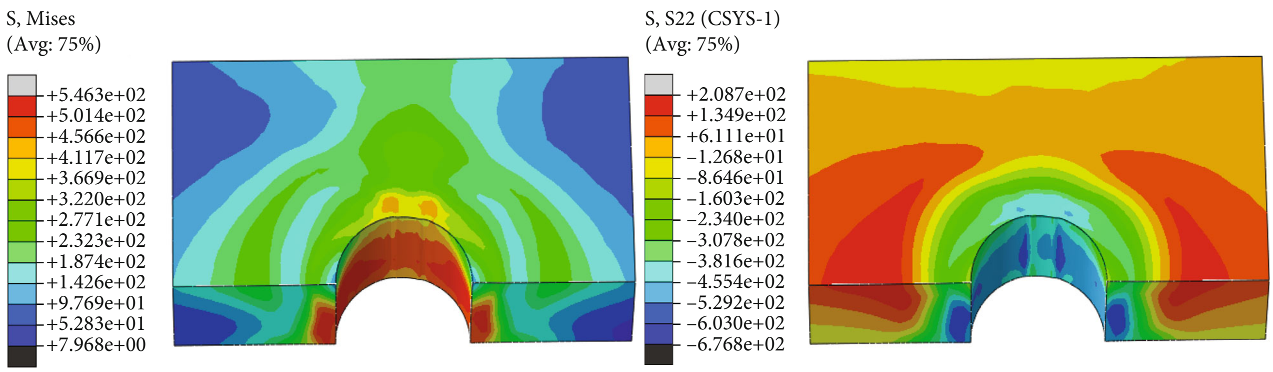
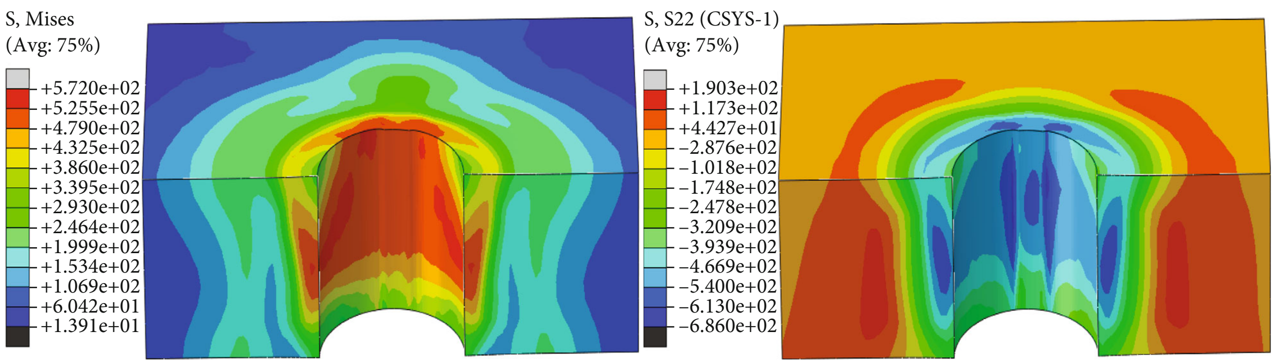


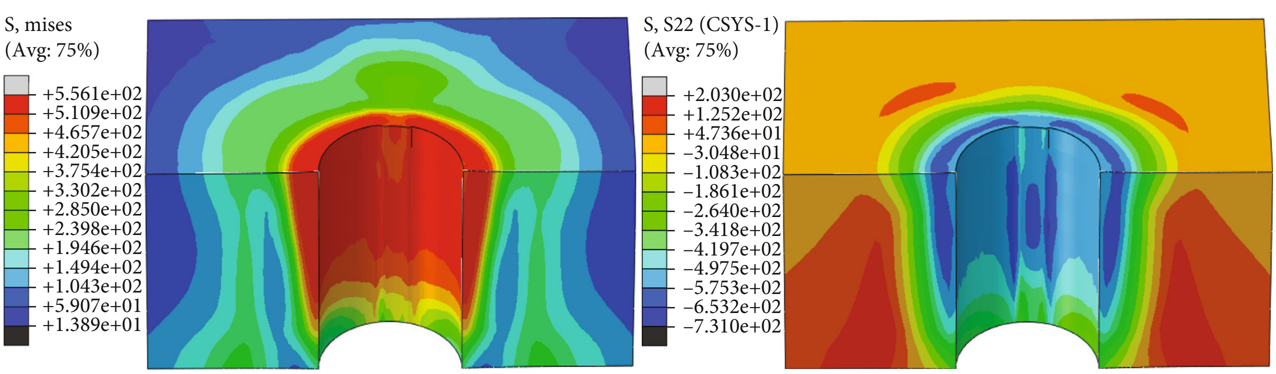
Figure 7: The tangential residual stress varies with the thickness of the substrate under different thicknesses.



(a) When the thickness is 6 mm, von Mises stress distribution cloud diagram and tangential residual stress distribution cloud diagram



(b) When the thickness is 8 mm, von Mises stress distribution cloud diagram and tangential residual stress distribution cloud diagram



(c) When the thickness is 10 mm, von Mises stress distribution cloud diagram and tangential residual stress distribution cloud diagram

Figure 8: Von Mises stress and tangential residual stress distribution cloud diagram under different thicknesses.

$$\sigma_\theta = \frac{b^2/r^2 + 1}{b^2/{r_p}^2 - 1} p_p. \quad (2)$$

The effective definition in the plastic zone ($a < r < r_p$) is

$$\sigma = \sqrt{{\sigma_r}^2 + {\sigma_\theta}^2 - \frac{2R}{1+R}\sigma_r\sigma_\theta}. \quad (3)$$

In the formula, R is the conversion ratio of plane plastic strain to three-dimensional plastic strain. When $R = 1$, it represents isotropy.

According to the material yield criterion,

$$\sigma = \sigma_y. \quad (4)$$

In the formula, σ_y is the initial yield stress.

From the above formula, the stress component of the elastic zone can be obtained as

$$\sigma_r = -\sigma_y \frac{\left(b^2/r^2\right) - 1}{\sqrt{\left(2b^4/{r_p}^4\right) + 2 + (2R/1+R)\left(\left(b^4/{r_p}^4\right) - 1\right)}}, \quad (5)$$

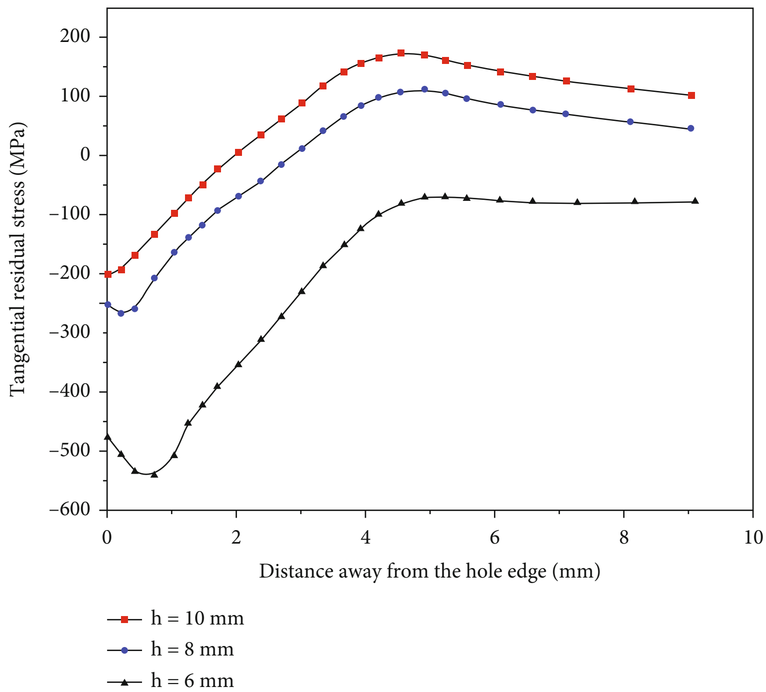


Figure 9: Changes of tangential residual stress under different substrate thicknesses.

$$\sigma_\theta = \sigma_y \frac{\left(b^2/r^2\right)+1}{\sqrt{\left(2b^4/{r_p}^4\right)+2+(2R/1+R)\left(\left(b^4/{r_p}^4\right)-1\right)}}. \quad (6)$$

Based on the key parameter α, Ball [34] gave the analytical formulas for the stress components σ_r and σ_θ in the plastic zone in the polar coordinate system:

$$\sigma_r = \frac{\sigma}{2}\sqrt{2+2R}\left[\cos\alpha - \frac{1}{\sqrt{1+2R}}\sin\alpha\right], \quad (7)$$

$$\sigma_\theta = \frac{\sigma}{2}\sqrt{2+2R}\left[\cos\alpha + \frac{1}{\sqrt{1+2R}}\sin\alpha\right]. \quad (8)$$

According to Ball's basic theory, the reverse yield criterion of the plastic zone is

$${\sigma_y}' = (1+\beta)\sigma_y + (1-\beta)\sigma. \quad (9)$$

In the formula, β is the Bauschinger effect parameter, and $0 \le \beta \le 1$.

In elastoplastic unloading, the stress component of the plastic deformation zone ($a' \le r \le {r_p}'$) is

$${\sigma_r}' = \sigma'\sqrt{\frac{1+R}{2}}\left(\cos\alpha' - \frac{1}{\sqrt{1+2R}}\sin\alpha'\right), \quad (10)$$

$${\sigma_\theta}' = \sigma'\sqrt{\frac{1+R}{2}}\left(\cos\alpha' + \frac{1}{\sqrt{1+2R}}\sin\alpha'\right). \quad (11)$$

In the formula, a' is the distance between the hole wall and the center of the connecting hole after extrusion;

During the elastoplastic unloading process, the stress component of the elastic deformation zone (${r_p}' \le r \le b$) is

$${\sigma_r}' = {\sigma_y}' \frac{\left(b^2/r^2\right)-1}{\sqrt{\left(2b^4/{r_p}'^4\right)+2+(2R/1+R)\left(\left(b^4/{r_p}'^4\right)-1\right)}}, \quad (12)$$

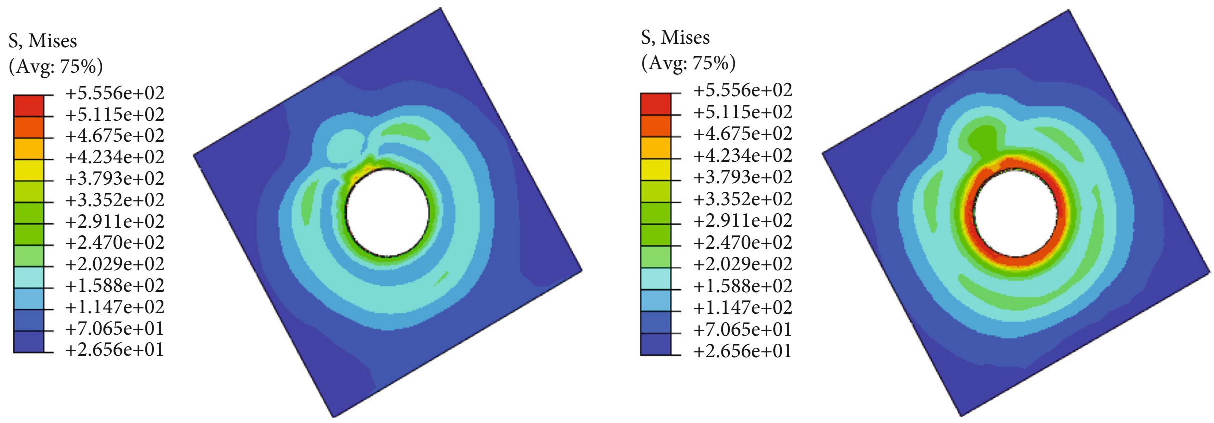
$${\sigma_\theta}' = -{\sigma_y}' \frac{\left(b^2/r^2\right)+1}{\sqrt{\left(2b^4/{r_p}'^4\right)+2+(2R/1+R)\left(\left(b^4/{r_p}'^4\right)-1\right)}}. \quad (13)$$

According to the principle of stress superposition, the residual stress during the fatigue strengthening process of cold extrusion of the entire hole is

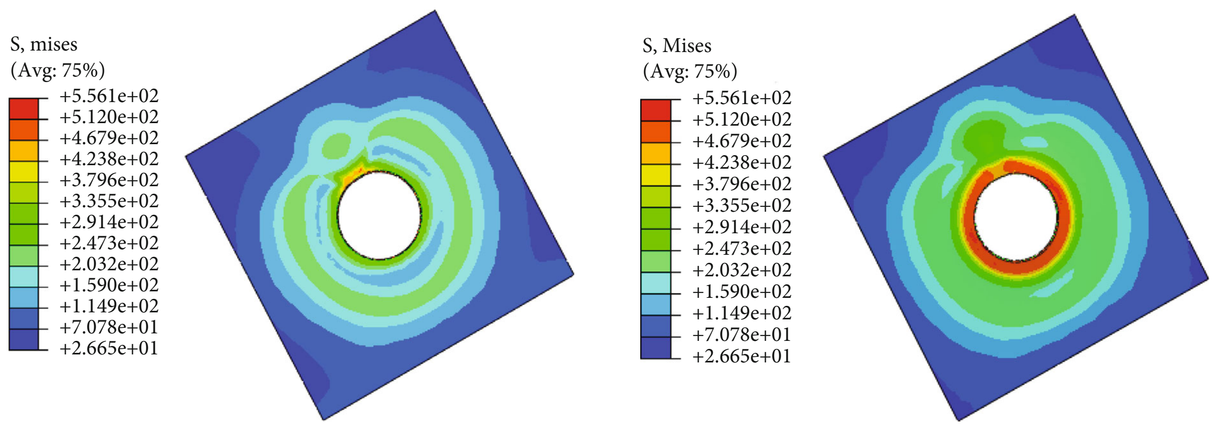
$$\Delta\sigma_r = \sigma_r + {\sigma_r}', \quad (14)$$

$$\Delta\sigma_\theta = \sigma_\theta + {\sigma_\theta}'. \quad (15)$$

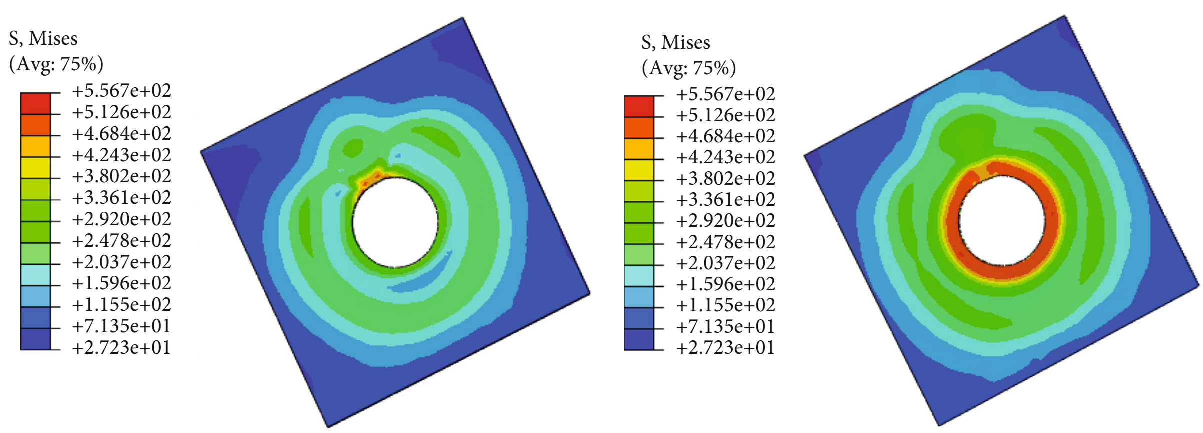
2.3. Experimental Process Simulation. In this paper, a three-dimensional finite element model of the actual hole cold expansion process is established, as shown in Figure 4. In order to simplify the 3D finite element simulation process, the main study is the 25 mm × 25 mm × 10 mm square member around the hole. The initial diameter of the hole is 7.226 mm. The amount of extrusion is 3%-4%, and the amount of extrusion can be controlled by changing the maximum diameter of the extrusion rod. For the division of the mesh, the finite element model is meshed with the C38DR



(a) Von Mises stress distribution cloud diagram of extrusion inlet and extrusion outlet under 3%



(b) Von Mises stress distribution cloud diagram of extrusion inlet and extrusion outlet under 3.6%



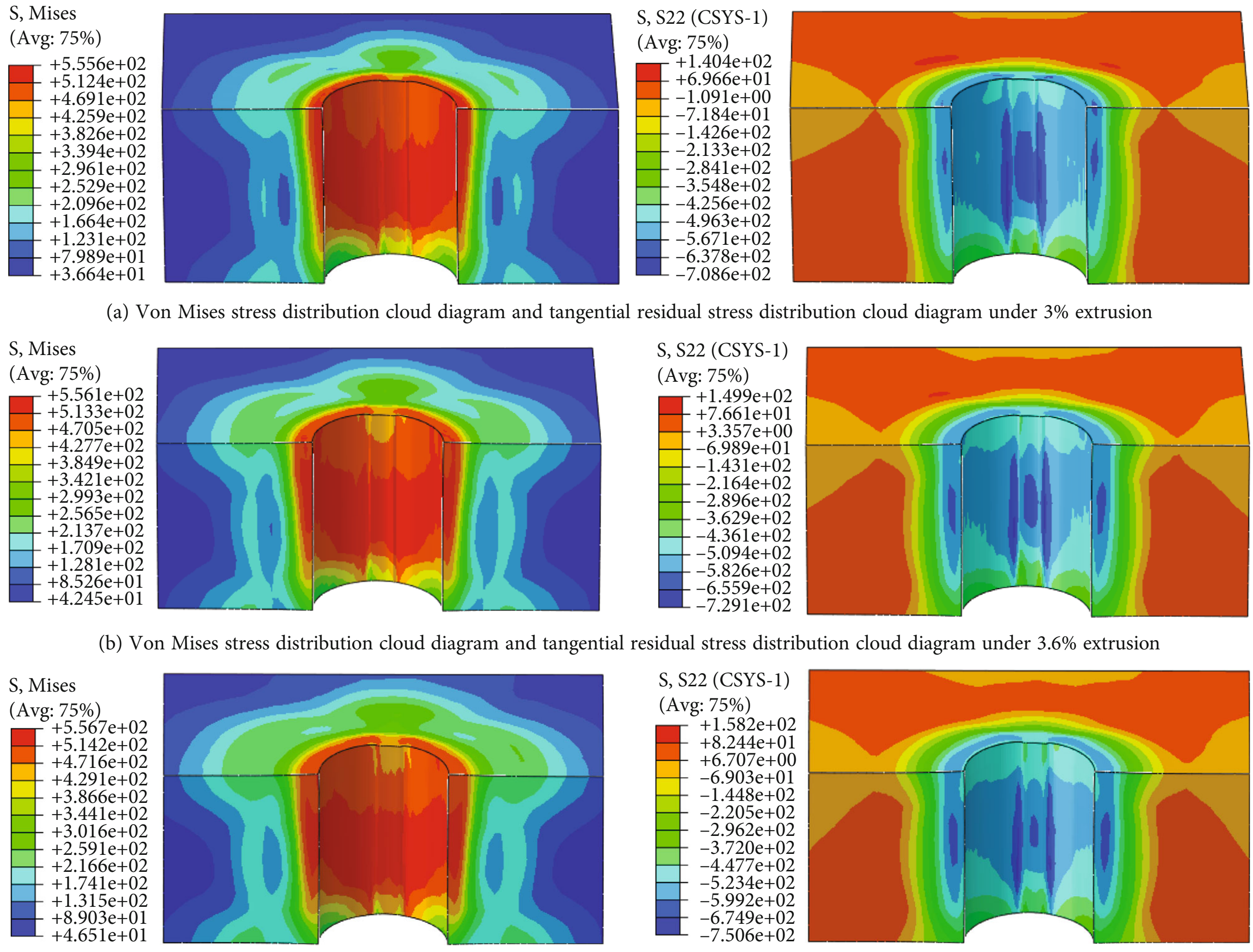
(c) Von Mises stress distribution cloud diagram of extrusion inlet and extrusion outlet under 4%

Figure 10: Von Mises stress distribution cloud diagram around the hole of the extrusion inlet and the extrusion outlet under different extrusion amounts (on the left is the extrusion inlet and on the right is the extrusion outlet).

hexahedral element in ABAQUS, and the mesh around the hole needs to be refined to ensure that the experimental phenomena can be clearly observed. The boundary conditions and constraints are set according to the actual extrusion process.

After the cold expansion through the slotted bushing hole is completed, due to the opening of the split sleeve, the base material flows to the opening of the split sleeve due to pressure during the extrusion process, and then, a boss is formed, as shown in Figure 5. The location where the boss is generated is the location where fatigue fracture is more likely to occur after the hole is strengthened by cold expansion. Therefore, after the cold expansion of the hole, the hinge pin should be added to remove the boss and micro cracks.

At the same time, the amount of extrusion directly affects the fatigue gain during hole extrusion strengthening. When the amount of extrusion is too small, the plastic strengthening layer cannot be formed, which affects the strengthening effect; when the amount of extrusion is too



(a) Von Mises stress distribution cloud diagram and tangential residual stress distribution cloud diagram under 3% extrusion

(b) Von Mises stress distribution cloud diagram and tangential residual stress distribution cloud diagram under 3.6% extrusion

(c) Von Mises stress distribution cloud diagram and tangential residual stress distribution cloud diagram under 4% extrusion

FIGURE 11: Von Mises stress cloud diagram and tangential residual stress cloud diagram under different squeezing amounts.

large, because the tangential tensile stress exceeds the stress corrosion threshold of the material, stress corrosion cracks are readily formed and fatigue life is reduced. The amount of extrusion is divided into absolute amount of extrusion E and relative amount of extrusion E_r:

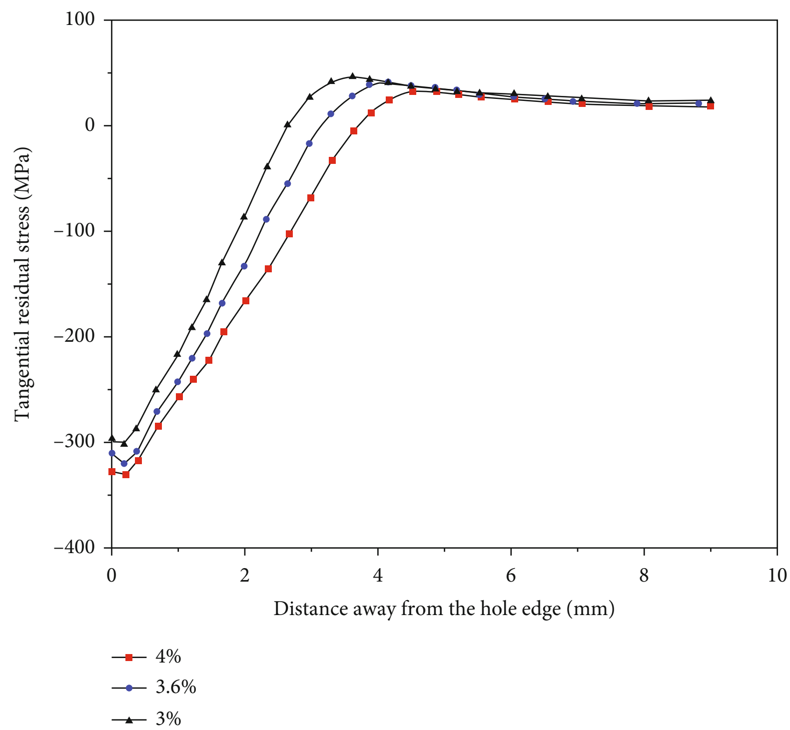
$$E_r = \frac{(D_0 + 2d) - D}{D}. \quad (16)$$

In the formula, D_0 is the diameter of the extruded rod, D is the diameter of the initial hole of the sample before extrusion, and d is the thickness of the slotted bushing.

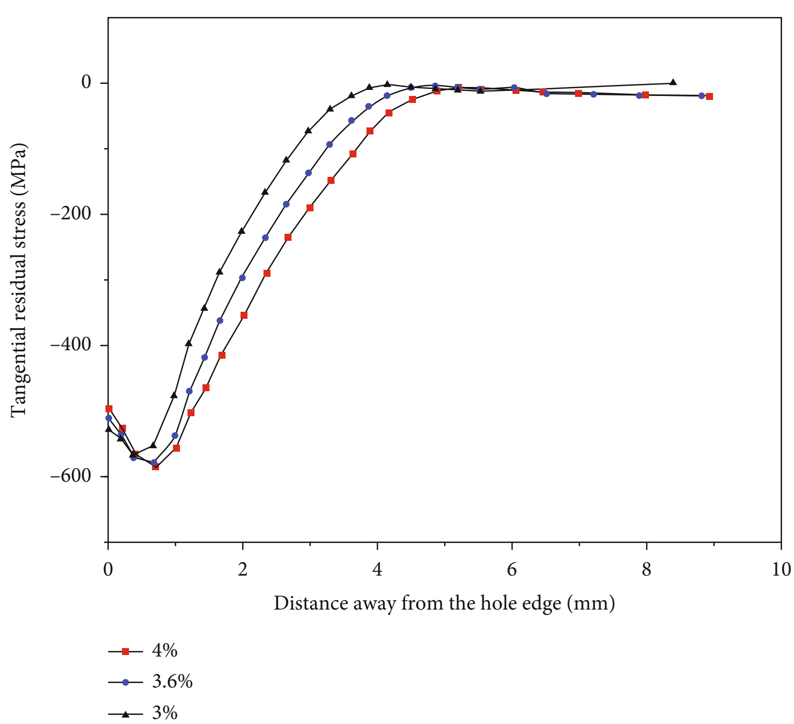
3. Results and Discussion

When the extrusion rod is pulled out of the hole, the elastically deformed material on the surface of the hole begins to rebound under the action of internal stress and forms a reverse extrusion of the plastic deformation layer, thereby forming a residual compressive stress zone within a certain range of the hole wall. The negative value is compressive stress, and the positive value is tensile stress. After the slotted bushing hole is cold-extruded, residual stresses are mainly generated in three directions. They are the radial residual stress, the tangential residual stress, and the residual stress of the substrate thickness. Because of the parts under the action of alternating loads, the tangential residual stress affects the fatigue life the most. Therefore, this article mainly focuses on the tangential residual stress of the 7050 aluminum alloy orifice plate after the cold expansion and briefly analyzes the radial residual stress.

3.1. Residual Stress Distribution. In order to obtain a clear stress cloud diagram, only a part of the area is displayed in the stress cloud diagram. Figure 6 shows the von Mises stress distribution cloud diagram, and the tangential residual stress distribution cloud diagram of 4% of the extrusion after the hole is strengthened after cold expansion. Figure 6(a) is the von Mises stress distribution cloud diagram. According to the plastic theory, the von Mises stress distribution can reflect the plastic strain of the material. It can be seen that after the hole is strengthened by cold expansion, the material undergoes uneven plastic deformation along the thickness, forming a certain degree of residual stress layer.



(a) Extrusion inlet surface



(b) Extrusion outlet surface

Figure 12: The distribution of tangential residual stress under different squeezing amounts.

Figure 6(b) is a cloud diagram of the tangential residual stress distribution in cylindrical coordinates. Due to plastic deformation near the hole wall after the hole is cold-pressed, plastic strain and material spring back will form a tangential residual compressive stress at the edge of the hole. It can be seen from the figure that after the hole is strengthened by cold expansion, a large residual compressive stress is introduced near the hole wall of the material, and the residual compressive stress reaches the maximum value near the hole wall of the extrusion end. There is a certain depth of residual tensile stress on the edge of the material squeezed into the hole. At the same time, the range of compressive residual

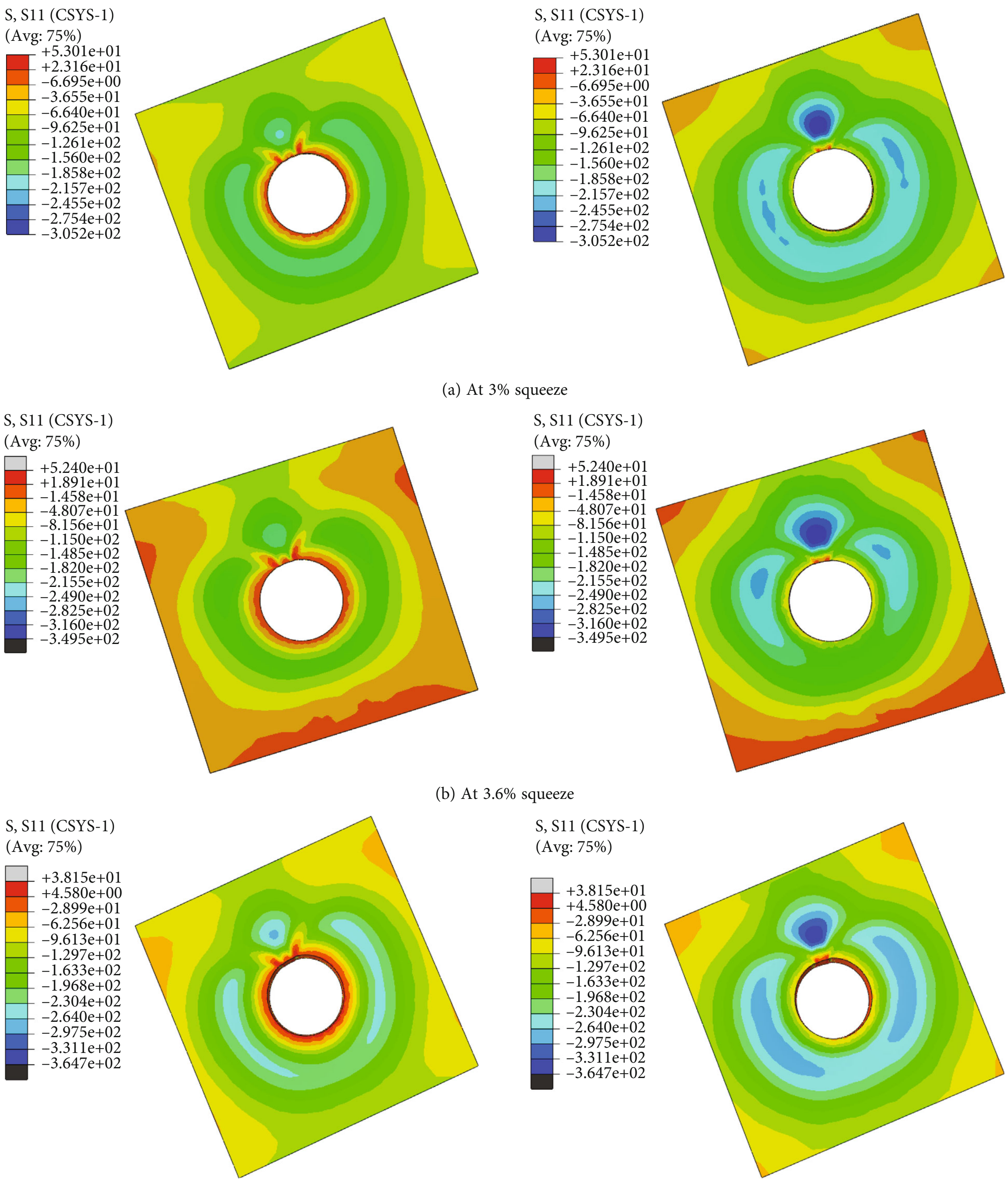
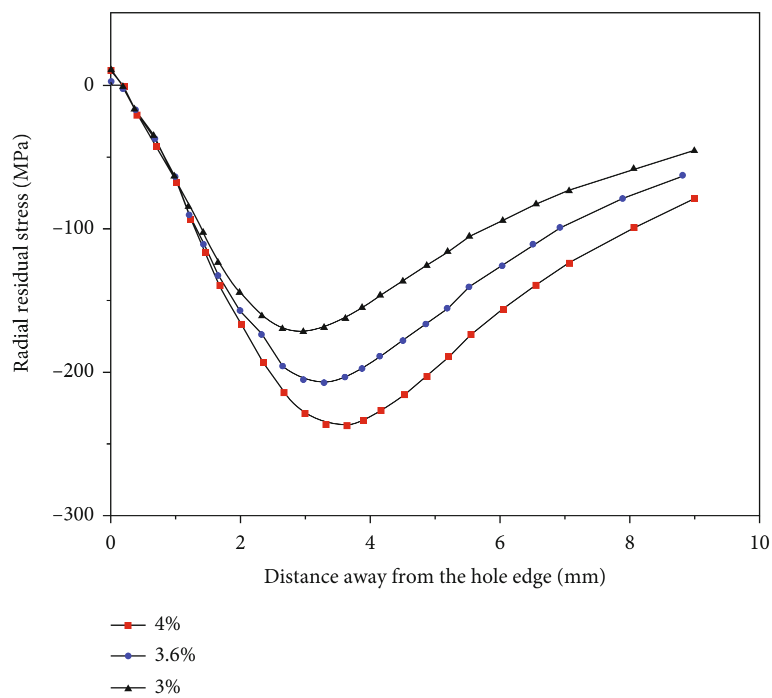


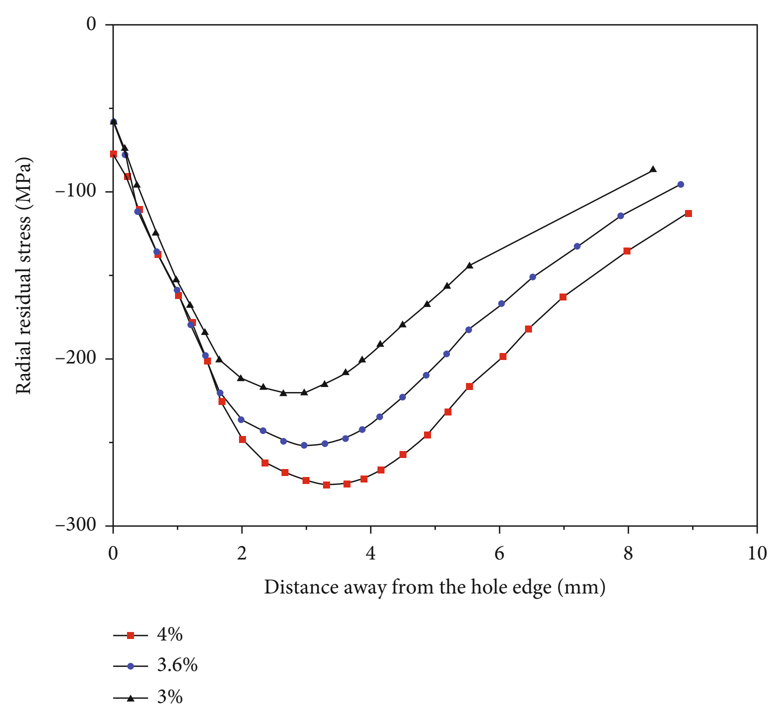
Figure 13: Radial residual stress cloud diagram under different squeezing amounts (on the left is the extrusion inlet and on the right is the extrusion outlet).

stress is much larger than the range of tensile residual stress, and the extreme value of compressive residual stress is much larger than the extreme value of residual tensile stress.

3.2. Change of Residual Stress with Substrate Thickness. Since the crack first appeared at the entrance of the extrusion, it is necessary to study the influence of the thickness of the substrate on the residual stress of the material. Research [35] shows that in the hole cold expansion strengthening process, the thickness of the substrate is generally required to be greater than or equal to 3 mm, so this paper mainly studies the residual stress distribution at 6 mm, 8 mm, and 10 mm.



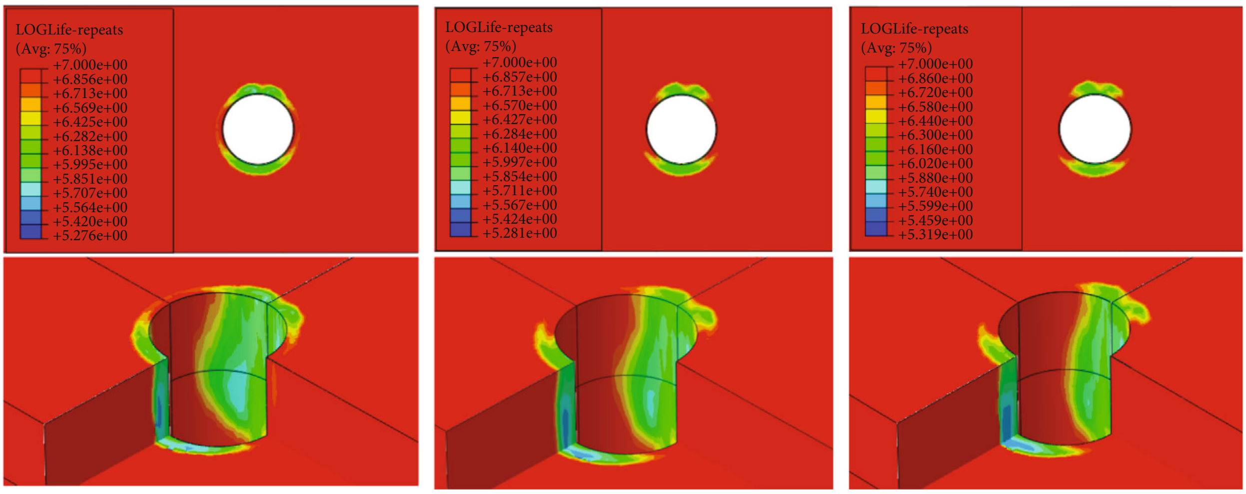
(a) Extrusion inlet surface



(b) Extrusion outlet surface

Figure 14: Radial residual stress distribution law under different squeezing amounts.

Figure 7 shows the change of the tangential residual stress with the thickness of the substrate from the extrusion inlet to the extrusion inlet when the substrate thickness is 6 mm, 8 mm, and 10 mm, respectively. It can be found that when the thickness of the substrate is 8 mm and 10 mm, the change trend of the tangential residual stress generally shows a trend of first increasing and then decreasing (here only for the residual stress value, no distinction is made between tensile stress and compressive stress). This also shows that the minimum tangential residual stress appears at the entrance of the extrusion, and the tangential residual stress reaches the maximum in the middle of the substrate. When the thickness of the substrate is 6 mm, it also shows a tendency to increase first and then decrease, but the tangential residual stress at the entrance of the extrusion is greater than that at the exit of the extrusion. Figure 8 is the



3% Extrusion 3.6% Extrusion 4% Extrusion

Figure 15: Fatigue life cloud diagram under different squeeze amounts.

von Mises stress distribution cloud diagram and the tangential residual stress distribution cloud diagram under different thicknesses, which can more clearly reflect the trend shown in Figure 7.

Figure 9 shows the variation of the tangential residual stress at the squeeze end with the distance from the hole edge under three substrate thicknesses. It can be seen from the figure that as the thickness of the substrate changes from small to large, the tangential residual stress at the extruded end gradually increases. At the same time, it can be found that when the substrate thickness is 10 mm and 8 mm, the variation range of the change trend with the thickness of the substrate is smaller. When the substrate thickness is 6 mm, the tangential residual stress at the extruded end is infinitely close to the extruded end. This is good proof that the thickness of the substrate cannot be too small.

3.3. Change of Residual Stress with Squeeze Amount. The amount of extrusion is a key parameter in the strengthening of the hole cold expansion. When the amount of extrusion is too small, the corresponding residual stress layer cannot be formed around the hole, which cannot achieve the desired effect; when the amount of extrusion is too large, there will be many deep microcracks in the boss after extrusion, which will lead to a decrease in fatigue strength. At the same time, the extrusion outlet is obviously convex. This study mainly focuses on the three extrusion rates of 3%, 3.6%, and 4% to study the strengthening effect after the hole cold expansion.

Figure 10 is a cloud diagram of von Mises stress distribution around the hole of the extrusion inlet and the extrusion outlet under different extrusion amounts.

Figure 11 is a cloud diagram of the tangential residual stress distribution under different squeezing amounts. When the extrusion amount is 3%, the residual stress layer of the material hole wall is very thin, and the residual stress mainly exists at the extrusion end of the connecting hole. When the extrusion amount reaches 3.6%, the residual stress layer expands to the subsurface layer of the hole wall. When the extrusion amount reaches 4%, the von Mises stress on the hole wall reaches the peak value except for the extrusion end, which indicates that the hole wall and the subsurface have undergone relatively severe plastic deformation. At the same time, as shown in Figure 10, the von Mises stress distribution area also appears at the outer end, which means that when the extrusion amount reaches 4%, the influence range of the residual stress extends to the edge of the specimen.

Figure 12 shows the distribution of tangential residual stress around the hole after the extrusion inlet surface and extrusion outlet surface are extruded with different extrusion amounts. It can be seen from the figure that both the extrusion inlet surface and the extrusion outlet surface have produced residual compressive stress after extrusion. It can be seen that as the distance from the hole increases, the residual compressive stresses show a trend of first increasing and then decreasing. When a certain distance is exceeded, the residual compressive stress will disappear, leaving only the residual tensile stress. At the same time, it can be found that the residual compressive stress gradually increases as the amount of extrusion increases on the surface of the extrusion inlet and reaches the maximum value when the amount of extrusion is 4%, and its value is about 330 MPa. The extrusion outlet surface also showed the same result and reached the maximum when the extrusion volume was 4%, and its value was about 580 MPa. Therefore, the simulation results show that in the process of cold expansion of 7050 aluminum alloy with slotted bushing holes, when the extrusion amount is 4%, the residual compressive stress on the specimen reaches the maximum value.

Figure 13 is a graph showing the radial residual stress distribution of the extrusion inlet surface and the extrusion outlet surface under different extrusion amounts. Figure 14 shows the distribution law of radial residual stress around the hole after the extrusion inlet surface and extrusion outlet surface are extruded with different extrusion amounts. It can be found from the figure that, whether it is the extrusion inlet indication or the extrusion outlet surface, as the amount of extrusion increases, the residual compressive

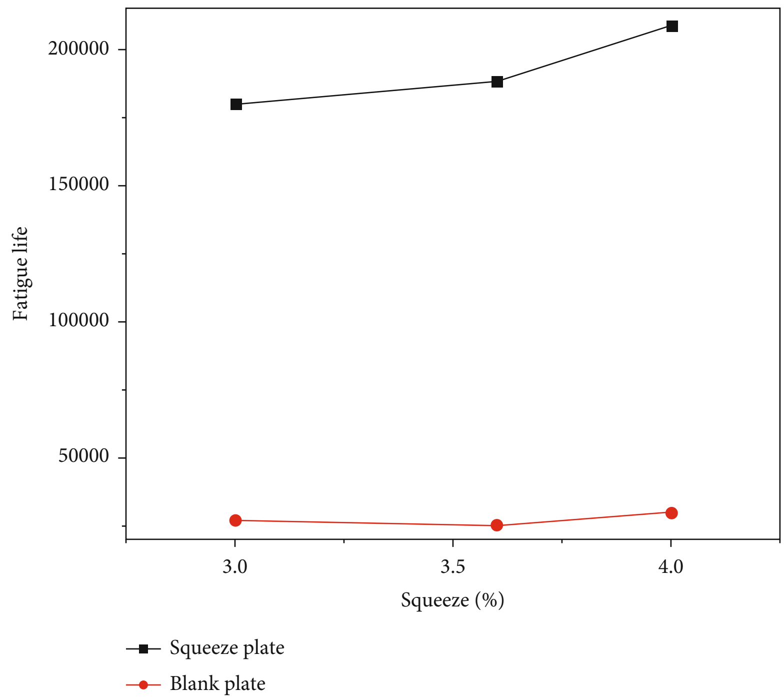


FIGURE 16: Comparison of fatigue life under different squeezing amounts.

TABLE 3: Comparison of experimental life and simulated life under different reaming amounts.

Final hole size after reaming	Experimental life	Average	Simulated life
	300941		
7.78 mm	115766	198887	168198
	179955		
	100070		
7.98 mm	129493	124789	101165
	144805		
	28306		
7.88(blank plate)	32549	33220	23919
	38806		

stress is gradually increasing. On the extrusion inlet surface, when the extrusion amount is 3%, the residual compressive stress reaches a maximum of -170 MPa at a position of about 3 mm in the radial distance. When the extrusion amount is 3.6% and 4%, the residual compressive stress reaches the maximum at a radial distance of about 3.3 mm, which is approximately -206 MPa and -235 MPa.

Therefore, within the range of 3%-4% extrusion amount, both the tangential residual stress and the radial residual stress increase with the increase of the squeeze amount, and the residual compressive stress reaches the maximum when the squeeze amount is 4%.

3.4. Fatigue Life. At least 3% extrusion should be used for aluminum alloy. At the same time, if the process is good, the fatigue life of the connecting hole can be increased by more than 3 times. If the relative extrusion is too small, the plastic deformation area is small, the residual stress is small, the action range is small, and the fatigue life gain of structural parts with holes is limited; if the relative extrusion is too large, defects such as cracks are likely to occur around the hole, which reduces the fatigue life gain [36].

Figure 15 is a cloud diagram of fatigue life under different squeeze amounts. It can be found that the crack propagation mainly occurs at the slotted bushing, and the fatigue life number is the lowest here. This is due to the fact that the residual compressive stress generated during the extrusion of the slit is small, which is prone to early crack growth, which reduces the fatigue life there. Figure 16 is a comparison chart of fatigue life under different extrusion amounts. When the extrusion amount is 3%, the fatigue life is 180054 cycles, when the extrusion amount is 3.6%, the fatigue life is 188274 cycles, and when the extrusion amount is 4%, the fatigue life is 208663 cycles. Therefore, within a certain range, as the amount of extrusion increases, the number of fatigue life increases, and the number of fatigue life is more than 3 times under the blank board fatigue test.

In this paper, for the actual measurement of fatigue life, each group is measured three times and the results are averaged. Table 3 shows the fatigue test results at different reaming amounts. It can be found that with the increase of reaming amount, the fatigue life cycle is gradually shortened.

3.5. Experimental Verification. For the extruded 7050 aluminum alloy components, the X-ray diffraction (XRD) method [37] was used to measure the residual stress on the surface of the extrusion entrance to verify the accuracy of the finite element simulation results. This experiment uses a $\mu - $X360 ray stress tester. Figure 17 is a picture of the measurement

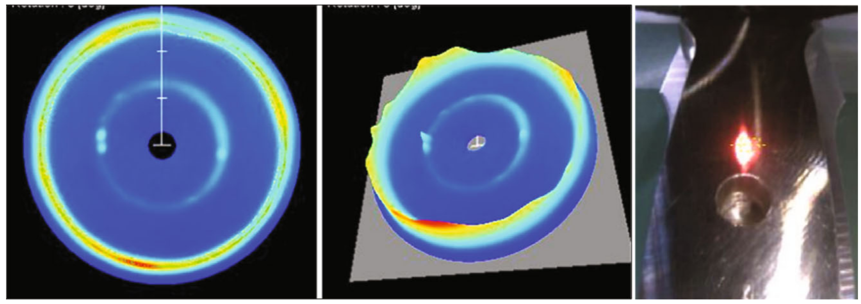


Figure 17: Debye ring and measured physical map.

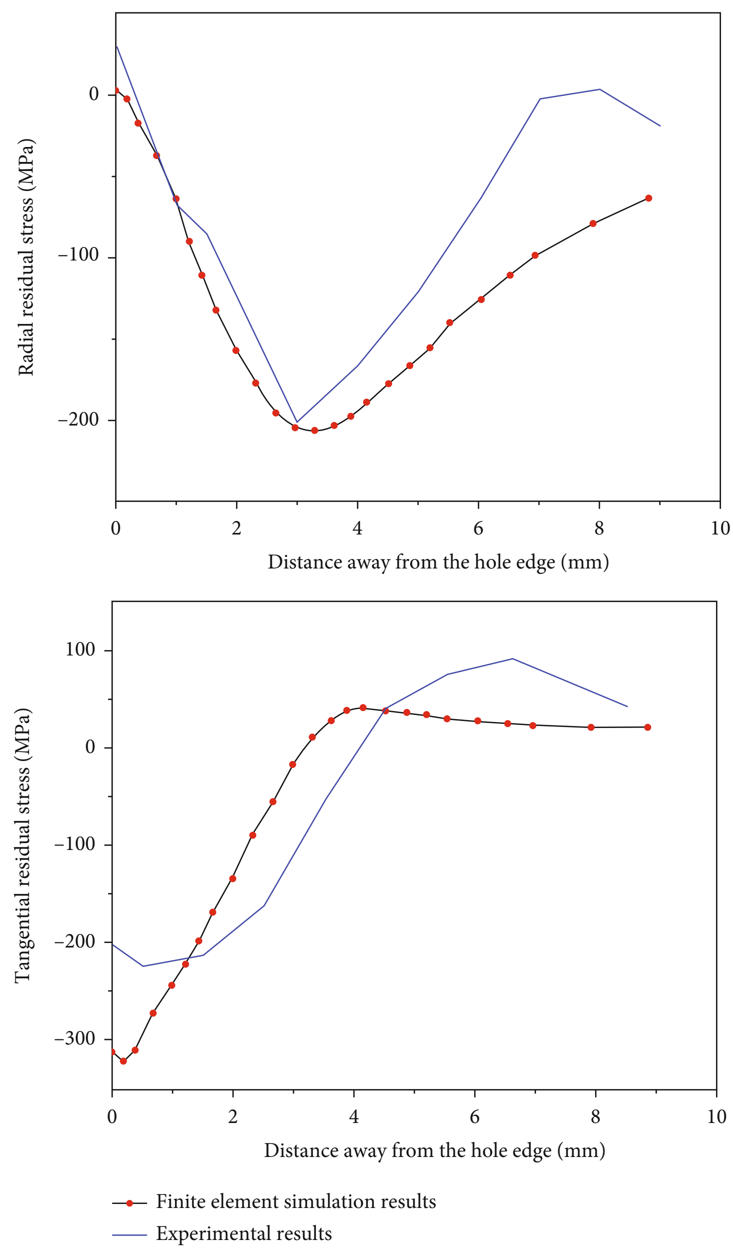


Figure 18: Experimental measurement and finite element simulation of residual stress.

process and the diffraction Debye ring used to obtain the experimental data. Figure 18 shows the comparison between the experimental results and the finite element simulation results. It can be found that the finite element numerical simulation results basically coincide with the experimental results, which verifies the correctness of the finite element numerical simulation results.

4. Conclusion

The finite element software ABAQUS was used to simulate the cold expansion strengthening process of 7050 aluminum alloy slotted bushing holes, and the residual stress distribution after cold expansion strengthening was studied. Meanwhile, the XRD method was used to measure the residual stress of 7050 aluminum alloy for verification. The following conclusions can be drawn:

(i) After the hole is strengthened by cold expansion, the residual stress on the surface of the extrusion inlet increases with the increase of the thickness of the substrate

(ii) After the hole is strengthened by cold expansion, within the range of 3%-4% of the extrusion amount, as the amount of extrusion increases, the residual stress in the periphery of the hole continues to increase and reaches the maximum when the amount of extrusion is 4%

(iii) The slotted bushing extrusion strengthening process can significantly improve the fatigue life of the 7050 aluminum alloy orifice plate structure

(iv) The XRD analysis results show that the experimental measured values are basically consistent with the finite element simulation results, which verifies the correctness of the finite element numerical simulation results

Data Availability

In this study, all data are true and reliable. All data are obtained from experimental measurements and numerical simulations.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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