Finite Element Simulation of Residual Stress around Split Sleeve Cold Expanded Hole for AA7075

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Abstract. Split sleeve hole cold expansion strengthening technology is one of the most commonly used fatigue resistance technology for metal structures. The residual stress field of the hole cold extrusion strengthening structure needs to be analysed, which is an important part of the fatigue life study. Finite element analysis for the 7075 aluminum alloy cold extrusion strengthening plate is carried out in this paper. The effects of split sleeve and reaming process are considered in the analysis process, and the residual stress field at the hole edge is obtained. The numerical results are verified by the experimental results, which show that the two are in good agreement. It is show that the residual stress is the compressive stress near the extrusion hole while the tensile stress far away from the extrusion hole. Additionally, the compressive stress value is the largest in the middle layer, the smallest in the squeeze layer, and the value in the extrude layer is between the two.

Keywords: Split sleeve hole cold expansion; Aluminum alloy; Plate specimen with central hole; Finite element simulation.

1. Introduction

Cold extrusion strengthening technology is widely used for connecting holes at present. By using the tool with higher hardness to extrude the hole wall, hole angle and other parts, the increment of fatigue life for the fastening hole can be improved by more than three times [1]. At present, split sleeve cold expansion is the most widely used code extrusion technology, as depicted in Figure 1 [2].

Figure 1. Split sleeve cold extrusion process
Residual stress field around the hole needs to be analysed accurately, which is the key to study fatigue properties of the structure strengthened by cold extrusion technology. Among them, the finite element method (FEM) analysis is the most commonly used method to analyse the residual stress field. For example, Liu et al. [3] investigated extrusion interference effects on the distribution of residual compressive stress based on finite element simulation; Ayatollahi [4] and Liu [5] studied the influence of hole margin on residual compressive stress with finite element method. However, the influence of split sleeve and reaming process are often ignored in the finite element analysis of cold extrusion structure, which affects the analysis accuracy.

Therefore, the influence of sleeve and reaming process is considered, and the residual stress of cold extrusion hole edge is analyzed by using the finite element method in this paper.

2. Modelling

The simulation object herein is the 7075-T651 aluminum alloy material specimen with the center hole cold extruded, and its dimension parameters are shown in Figure 2. The designed relative extrusion amount is 4%. The split sleeve with a thickness of 0.152 mm is adopted. Diameter of working section for extrusion mandrel is 5.664 mm. The diameter of the central hole before cold extrusion (initial hole) is 5.738 mm, while the theoretical hole diameter is 5.968 mm after extrusion (before reaming of the final hole). Finally, the diameter of the target final hole after reaming is 6 ± 0.01 mm.

![Figure 2. configuration and dimension parameters of specimen](image)

A full-scale three-dimensional finite element model was established in this paper, as presented in Figure 3.

![Figure 3. 3D finite element model for cold extrusion of aluminum alloy plate with central hole](image)
were limited to move along the positive z-axis, while the mandrel was allowed to move along the z-direction; the friction coefficient $\mu$ between mandrel and the inner wall of split sleeve was 0.1, and it was assumed that there was no friction between the sleeve and the hole wall; the mandrel moved in the z-axis direction, passing through the sleeve. The mandrel enabled the sleeve and the specimen to be extruded during the movement of it. The simulation flow of hole cold extrusion process as shown in Figure 4.

![Diagram](image)

**Figure 4.** Basic flow and engineering application of finite element numerical simulation for holes cold extrusion process

### 3. Determination of the Relative Position of the Articulated Interface in FE Modelling

The simulation for the hinge final hole is critical, which is the key link in the whole simulation process. In this paper, the method of removing the element layer is chosen to simulate the process of final hole hinge. This requires the setting of the interface between the articulated element layer and the substrate material element during the pretreatment phase. After the mandrel extrusion simulation, the mandrel withdrawal and sleeve are completed, the element in the hinge layer is directly removed to realize the simulation of the hinge final hole.

According to the method in reference [6], the position of the hinge interface in finite element modelling is determined. Firstly, the displacement variation of the cold-extruded aluminum alloy specimens with holes was solved. The calculated radial displacement variation of the extrusion process, unloading process and the superposition of the two processes is shown in Figure 5.

![Graph](image)

**Figure 5.** The radial displacement of the specimens with central aluminum alloy orifice during cold extrusion
Then, taking the distance between the micro element and the hole center before extrusion deformation as the abscissa and the distance between the extrusion reinforcement and the hole center as the ordinate, the corresponding relationship is established, as shown in Figure 6.

![Figure 6](imageurl)

**Figure 6.** Comparison of the distance from the center of connecting hole before and after cold extrusion

When the ordinate value is equal to the target value, the corresponding abscissa value is the distance between the boundary surface and the hole center. The distance between the hinge interface and the hole edge is 0.049mm.

4. Numerical Results

Distributions of the equivalent Mises stress, circumferential stress and radial stress at the hole edge on the central cross section were obtained through FEM analysis, as shown in Figure 7.

![Figure 7](imageurl)

(a) Equivalent Mises stress contour  
(b) Stress distribution contour in S11 direction / circumference of hole edge  
(c) Stress distribution contour in S22 direction / radial

**Figure 7.** Stress distribution at the hole edge(MPA)

In Fig. 7, it can be concluded that the residual stress is the compressive stress near the extrusion hole while the tensile stress far away from the extrusion hole. In addition, the value of the residual compressive stress is the largest in the central layer, the smallest in the squeeze layer, and the value in the extrude layer is between the two.

The residual stress distribution curve extracted from the minimum section of the central hole is shown in Figure 8.
As shown in Figure 8, the circumferential residual compressive stress of the middle layer is the largest, while the squeeze layer is the smallest.

After following the pre-processing setup, rebalance. The residual stress distribution of the extrusion layer, intermediate layer and extrusion layer extracted from the minimum section where the center hole is located is shown in Figure 9.

By comparing Figure 8 and Figure 9, after removing the element of the hinge layer, the stress distribution of the hole edge will reach a new equilibrium state. Residual stress distribution around the hole edge is affected by the hinge layer element. However, the change in residual stress distribution is insignificant.

5. Verification of Finite Element Simulation Results

X-ray diffraction method was adopted to measure the initial residual stress field, which was further used to verify the results of finite element simulation. It is measured by X-ray diffraction stress gauge of Proto-LXRD and calculated by method of sin2ψ. By comparing the calculated circumferential residual stress curve with the measured stress, the feasibility and accuracy of this method are verified. The comparison results are shown in Figure 10.
Figure 10. Comparison between the simulation results and the XRD measurements

It can be observed that the mean residual stress obtained by XRD stress measurement method is basically consistent with the residual stress trend obtained by finite element and analytical model, but there are some differences. The main reason for the difference is that the XRD measurements represent the average stress in a circular spot with a diameter of 1 mm.

6. Conclusion

In this paper, the finite element simulation analysis of 7075 aluminum alloy hole cold extrusion strengthening plate was carried out. The influence of split sleeve and reaming process were considered in the simulation process, and residual stress distributions at the hole edge were obtained. The simulation results were verified by the experimental results, which show that the two were in good agreement.

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References

[1] WANG YL, ZHU YL, CAO Q, et al. Progress and prospect of research on hole cold expansion technique[J]. Acta Aeronautica et Astronautica Sinica, 2018, 39(2): 021336(in Chinese).
[2] Fatigue Technology. Cold Expansion of Holes Using the Standard Split Sleeve System and Countersink Cold expansionTM (CsCxTM). FTI Process Specification 8101 Revision J[S]. Seattle: Fatigue Technology Inc., 2014.
[3] LIU Y S, SHAO X, LIU J, et al. Finite element method and experimental investigation on the residual stress fields and fatigue performance of cold expansion hole [J]. Materials and Design, 2010, 31(3): 1208-1215.
[4] AYATOLLAHI M R, NIK M A. Edge distance effects on residual stress distribution around a cold expanded hole in Al 2024 alloy[J]. Computational Materials Science, 2009, 45(4): 1130-1141.
[5] LIU J, WU H, YANG J, et al. Effect of edge distance ratio on residual stresses induced by cold expansion and fatigue life of TC4 plates [J]. Engineering Fracture Mechanics, 2013, 109: 130-137.
[6] DU X, ZHANG T, HE YT, et al. Determining position of reaming interface in cold expansion FEM simulation[J]. Acta Aeronautica et Astronautica Sinica, 2019, 40(4): 422674(in Chinese).