Numerical study on the ideal interference of aircraft riveting joints

S Sun1,2,3
1AVIC China Aero-Polytechnology Establishment, No.7 Jingshun Road, Beijing, China
2Key Laboratory of Quality Infrastructure Efficacy Research, AQSIQ, Beijing, China
E-mail: Sunsheng369@126.com

Abstract. The interference is the main parameter affecting the fatigue lifetime of the interference-fit joints. In this paper, the numerical simulation method of the interference-fit riveting process was studied for the object of the aluminum alloy joint commonly used in aircraft. On this basis, the influence of different interferences on the joint life was calculated and determined, which can provide a basis for determining the ideal riveting interference. The numerical simulation results show that the model built in this paper can well describe the whole forming process of the rivet including the overall upsetting and local upsetting. With the increase of the interference, the fatigue lifetime of the joint increases first and then decreases. For the joint structure given in this paper, when the interference is between 2.9% and 3.23%, a higher life increment can be obtained, which is basically consistent with the ideal interference obtained by experiments.

1. Introduction
Due to its characteristics such as wide application range, stable quality and low cost, the riveting is still the most important connection method for metal structures in current aircraft manufacturing. The life and reliability of the joint play a vital role in aviation safety. Because of the high cost and long cycle of the life test for the riveting joint, the optimization design method based on numerical simulation method has been gradually applied. Langrand, Blanchot, Repetto et al used different methods to establish the finite element analysis model of the riveting process, which provided ideas for the numerical simulation method of the strength of the riveting joint [1-3]. Chakherlo carried out simulated fatigue tests on the riveted structure and obtained the relationship between the interference and the fatigue life [4]. Zeng studied the effect of residual stress due to interference-fit on the fatigue behavior [5]. Abdelal investigated the dimensional growth of aircraft panels while being riveted with stiffeners based on numerical and experimental methods, he found that a higher degree of predictability of the riveting process are obtained using explicit FE models [6]. Li studied the influence of riveting dies with different angles on the electromagnetic riveting quality and provided ideas for the application of numerical simulation in the research of electromagnetic riveting technology [7]. Moreover, the structural analysis methods of composite joints were studied by Cao, Dean and Yoo [8-10].

On the basis of previous studies, the effect of the interference on the fatigue lifetime of the electromagnetic riveting joint was studied by means of numerical simulation method in this paper, which can help to select the reasonable interference in the engineering application of interference-fit
strengthening technology.

2. Numerical simulation of the forming process of the interference fit riveting joint

Compared with ordinary riveting, electromagnetic riveting technology can achieve relatively uniform interference fit when the clearance between the rivet and hole is relatively large or the interlayer thickness is relatively large. Therefore, the electromagnetic riveting joint is taken as the research object in this paper.

The electromagnetic riveting joint consists of riveting die, rivet and sandwich plates, and their geometric relationship is shown in figure 1. In this structure, the rivet diameter is 4 mm, rivet length is 9.5 mm, width of the sandwich plate is 24 mm and the thickness of each sandwich plate is 3 mm. The riveting joint is an axisymmetric structure as a whole. For improving the calculation efficiency, a 1/2 symmetry model is established by ABAQUS as shown in figure 2. Because the rigidity of the riveting die is much larger than that of the rivet and sandwich plates, it is treated as a rigid body, that is, its deformation is not considered in the analysis process. The R3D4 elements are used for the die’s mesh generation, and the rivet and sandwich plates are divided by the C3D8RT elements which can consider the temperature.

![Figure 1. Structure schematic of the riveting joint.](image1)

![Figure 2. The 1/2 symmetry model of the riveting joint.](image2)

As a rigid body, the deformation of the riveting die does not be considered. So only the parameters of the rivet and the sandwich plates need to be set. In this paper, the material of the rivet is 2A10 aluminum alloy, and the sandwich plates uses 2024 aluminum alloy. The material performance parameters are shown in table 1.

| Material | Elasticity modulus (GPa) | Poisson's ratio | Density (kg·m⁻³) | Thermoconductivity (W·m⁻¹·K⁻¹) | Specific heat (J·kg⁻¹·K⁻¹) | Thermal expansivity (m·m⁻¹·°C⁻¹) |
|----------|-------------------------|----------------|------------------|---------------------------------|-----------------------------|---------------------------------|
| 2024     | 71                      | 0.33           | 2750             | 154                             | 880                         | 2.56e-5                         |
| 2A10     | 73.1                    | 0.33           | 2770             | 121                             | 875                         | 2.47e-5                         |

The electromagnetic riveting usually produces 30% -50% strain at the instant of several hundred microseconds to milliseconds, and its strain rate is several magnitudes higher than that of the ordinary riveting. In order to consider the influence of the loading rate and temperature rise on the flow properties of the materials, the Johnson-Cook thermo-viscoplastic constitutive model of the two materials needs to be fitted.

\[
\sigma = (A + Be^n)[1 + C\ln\varepsilon_p^*][1 - T^m]
\]

\[
\varepsilon_p^* = \frac{\varepsilon_p}{\varepsilon_0}
\]

\[
T^* = \frac{(T - T_0)}{(T_m - T_0)}
\]
Among these equations, $\varepsilon_p$ is the strain rate, $\varepsilon_0$ is the reference strain rate, $T_0$ and $T_m$ are the room temperature and melting temperature, and C and m are the strain rate sensitive coefficient and thermal softening coefficient. The other five parameters A, B, C, m, n are the intrinsic parameters of the material. A, B and n are the strain strengthening coefficients, C is the strain rate strengthening coefficient, and m is the temperature softening coefficient. The values of these five parameters can be calculated \cite{11} according to the data from the quasi-static test and Hopkinson pressure bar test. The room temperature $T_0$ is set at 20°C. The JC constitutive model parameters of the materials are shown in table 2.

**Table 2.** The JC constitutive model parameters of the materials.

| Material | A (MPa) | B (MPa) | C | n | m | $T_m$ (°C) |
|----------|---------|---------|---|---|---|------------|
| 2024     | 71      | 0.33    | 2750 | 154 | 880 | 2.56e-5 |
| 2A10     | 73.1    | 0.33    | 2770 | 121 | 875 | 2.47e-5 |

In order to guarantee the accuracy of the riveting force, the riveting force curve was measured directly through the experimental method \cite{11}. The riveting force is loaded on the surface of the riveting die, and the plastic deformation process of the rivet in the riveting process includes two parts: the overall upsetting and the local free upsetting. The forming process of the upsetting head of the rivet is shown in figure 3. When $t=0.35$ ms (figure 3(d)), the rivet head has been basically formed. At this time, the riveting force has been rapidly attenuated, and the force is not enough to continue forming, and a small amount of rebound will occur in the area of the upsetting head.

![Figure 3. The forming process of the upsetting head of the rivet.](image)

Finally, the riveting joint after forming is calculated as shown in figure 4.

![Figure 4. The final forming result of the joint.](image)

3. **Calculation of the fatigue lifetime of the interference fit riveting joint**

The fatigue failure of the riveting joint is mainly manifested by the tension failure of the sandwich plates. The fatigue failure of the sandwich plates occurred earlier than that of the rivet at the stress concentration position. Therefore, the fatigue lifetime of the sandwich plates is chosen to evaluate the
fatigue strength of the riveting joint.

3.1. Analysis of residual stress at the edge of sandwich plates hole

The residual pressure stress is generated on the surface of the part and hole by the interference fit connection to reduce the mean stress of spectrum load at the local fatigue risk point, which has a significant gain on the fatigue lifetime of the structure. Therefore, the condition of residual stress at the edge of sandwich plates hole was analyzed firstly in this paper. According to figure 5, three node paths are established. The path direction extends from the edge of the hole to the edge of the plate width side.

![Figure 5. Schematic of the three node paths.](image)

After the riveting die is unloaded and the rivet rod finishes the rebound process, the residual stresses in the x-direction of each node in the three paths are extracted. The path distance is taken as the abscissa and the residual stress is taken as the ordinate to make figure 6. It can be observed from figure 6 that the residual pressure stress is at the edge of the sandwich plates hole in the interference fit connection. It can reduce the average stress of the spectrum load when subjected to the tension-tension cyclic external load, which has a beneficial effect on improving fatigue lifetime of the riveting joint. When the distance from the edge of the hole is far (more than 6 mm), the residual stress of each path approaches to 0. Observe the path-1 curve, at the position of 1 mm from the edge of the hole, the residual stress on the side of the upsetting head becomes the tensile stress, and the generation of the residual tensile stress will have an adverse effect on the fatigue strength of the area. Based on the above analysis, the riveting interference fit has an obvious strengthening effect on the edge of the hole, but has little effect on the area far from the hole, and even may have an adverse effect on some areas.

![Figure 6. The residual stresses (x-direction) of each node.](image)

![Figure 7. The minimum fatigue life of the sandwich plate.](image)
3.2. **Calculation of the fatigue lifetime of the sandwich plate**

The stress results of the sandwich plate are substituted into the fatigue life analysis software MSC. Fatigue to calculate the fatigue lifetime of the sandwich plate. Take the tension-tension load with the stress ratio of 0.1, the stress level is 162 Mpa (about 60% of the shear strength of the joint), the length direction of the plate is chosen as the loading direction, and the load type is a sinusoidal wave. The life cloud-chart of the joint is calculated as shown in figure 7. The minimum life value is 86500 cycles (the logarithmic life is 4.94). The minimum life is not at the edge of the hole, but at a certain distance. According to the residual stress analysis results in Section 3.1, this is due to the effect of the interference fit, which produces the residual pressure stress at the edge of the hole and the residual tensile stress at the periphery of the hole.

4. **Effect of the interference on fatigue lifetime of the riveting joint**

4.1. **Control of the interference of the riveting joint model**

In order to study the influence of different interferences on the strength of the joint, it is first necessary to obtain electromagnetic riveting joint models with different interferences. The main factors affecting the interference of the joint include the clearance between the rivet and hole, the extension length of the rivet and the inclination angle of the riveting die. Compared with the clearance between the rivet and hole and the extension length, it is more convenient to control the inclination angle of the riveting die as a changing factor in the numerical simulation. Therefore, the models with different interferences are obtained by changing the inclination angle of the riveting die.

In order to obtain the electromagnetic riveting joint model with the interference in the range of 0.5%~4.5%, the numerical simulation of the riveting process was carried out by selecting the riveting dies with 180° (flat punch), 120°, 90°, 70°, 60° and 45° respectively. The calculation results of the interference respectively are 0.96%, 1.97%, 2.75%, 2.9%, 3.23%, 3.9%. It can be seen from the results that as the inclination angle of the riveting die decreases, the overall interference increases gradually.

4.2. **Effect of the interference on the residual stress of the sandwich plate**

According to the residual stress analysis method in Section 3.1, the X-direction residual stresses of the models with different interferences are analysed as shown in figure 8. It is observed from the figure that the residual pressure stress can be significantly increased with the increase of the interference, which is also the reason why the interference has a great influence on the fatigue lifetime of the structure. Comparing with the three curves, it is observed that as the interference increases, the effect range of the residual pressure stress increases, which has a positive effect on the improvement of the fatigue strength, but at the same time, it can be seen that the peak value of the residual tensile stress...
generated in the area far from the hole also increases as the interference increases, which will have an adverse effect on the life of the joint. Therefore, it can be inferred that for the interference fit riveting joint, it is not always better for larger amount of interference, but there is an optimal interference, when the interference is close to the optimal interference, the joint has the maximum fatigue life.

4.3. Determination of the ideal interference

The fatigue lifetime of the models with different interferences are analysed according to the life calculation method of the joint in Section 3.2. The fatigue lifetime of the aluminium alloy sandwich plate is calculated respectively when the inclination angle of the riveting die is 180°, 90°, 70°, 60°, and 45°. The results obtained are shown in table 3. In the table, the “Life increment” indicates the ratio of the fatigue life of riveting plates with different interferences to that of the riveting plate with 0.96% interference.

| Inclination angle(deg) | Interference(%) | Fatigue life(cycles) | Life increment |
|------------------------|-----------------|----------------------|----------------|
| 180°                   | 0.96%           | 2×10^4               | 1              |
| 90°                    | 2.5%            | 4.17×10^5            | 2.085          |
| 70°                    | 2.9%            | 7.13×10^5            | 3.565          |
| 60°                    | 3.23%           | 8.65×10^4            | 4.325          |

From the data in table 3, the interference is taken as the abscissa and the fatigue life is taken as the ordinate, and the fatigue life curve is plotted as the interference changes, as shown in figure 9.

![Figure 9. The Variation curve of fatigue life along with interferences.](image)

It can be seen from figure 9 that as the interference increases, fatigue lifetime of the joint increases first and then decreases. When the interference is about 3%, the joint has a maximum fatigue life. Based on the analysis results of the residual stress, when the interference is less than 1%, the residual pressure stress generated by the interference fit is very small, and its maximum residual stress is only 15% of the maximum value when the interference is 3.23%, so the improvement effect of too small interference on the fatigue life is not obvious. When the interference reaches 3.9%, fatigue life has a significant downward trend. By analyzing the residual stress, when the interference increases, the effect range of the residual pressure stress will also increase, but at the same time, the peak value of the tensile stress generated in the area far from the hole will also increase. From figure 8, when the interference increases from 2.9% to 3.23%, the peak value of the residual tensile stress increases by 50%. Therefore, excessive interference will have an adverse effect on the fatigue strength of the structure. In summary, when the interference is between 2.9% and 3.23%, the joint can obtain a higher.
4.4. Comparison with experimental research conclusions
The optimum interference of aviation aluminium alloy joints with the same thickness of 6mm was studied by experimental method, and the recommended optimum interference was 3.1%, which is basically consistent with the conclusion of 2.9%~3.23% ideal interference given in this paper [12].

5. Conclusions
In this paper, we studied the relationship between interference and fatigue life of riveting joints by means of numerical simulation method, which can provide a reference for the selection of the interference in engineering applications. The main conclusions are as follows:

The numerical simulation of the forming process of the electromagnetic riveting is carried out. The finite element model established by the Johnson-Cook material constitutive model can completely describe the whole forming process of the rivet, including the overall upsetting and local upsetting.

Based on MSC. Fatigue, the calculation of the fatigue lifetime of the interference fit riveting joint is carried out. When the interference is large, the position with the minimum fatigue life does not appear at the edge of the hole, but at a certain distance. This is due to the effect of the interference fit, which produces the residual pressure stress at the edge of the hole and the residual tensile stress at the periphery of the hole.

The effect of the interference on residual stress and fatigue lifetime of riveting joint was analyzed. As the amount of interference increases, the fatigue lifetime increases first and then decreases. For the structural parameters given in this paper, when the interference is between 2.9% and 3.23%, a higher life increment can be obtained.

References
[1] Langrand B, Deletombe E, Markiewicz E and Drazetic P 2001 Riveted joint modeling for numerical analysis of airframe crashworthiness Fintet. Elem. Anal. Des 38 21-44
[2] Blanchot V and Daidie A 2006 Riveted assembly modeling: Study and numerical characterization of a riveting process J. Mater. Process. Tech 180 13-5
[3] Repetto E A, Radovitzky R, Ortiz M, Lundquist R C and Sandstrom D R 1999 A finite element study of electromagnetic riveting J. Manuf. Sci. Eng 121 61-8
[4] Chakherlou T N and Vogwell J 2010 A novel method of cold expansion which creates near-uniform compressive tangential residual stress around a fastener hole Fatig. Fract. Eng. Mater. Struct 27 343-51
[5] Zeng C, Tian W and Liao W H 2016 The effect of residual stress due to interference fit on the fatigue behavior of a fastener hole with edge cracks Eng. Fail. Anal 66 72-87
[6] Abdelal G F, Georgiou G, Cooper J, Robotham A, Levers A and Lunt P 2015 Numerical and experimental investigation of aircraft panel deformations during riveting process J. Manuf. Sci. Eng 137 011009
[7] Li Y H, Cao Z Q, Zhang Q L and Feng D G 2013 Study on the effect of riveting quality with different angles of the forming cup of riveting die Acta Aeronautica et Astronautica Sinica 34 426-33 (in Chinese)
[8] Cao Z and Cardew-Hall M 2006 Interference-fit riveting technique in fiber composite laminates Aerosp. Sci. Technol 10 327-30
[9] Dean A, Sahraee S, Reinoso J and Rolfe S R 2016 Finite deformation model for short fiber reinforced composites: Application to hybrid metal-composite clinching joints Compos. Struct 151 162-71
[10] Yoo S Y, Kim C H, Kweon, J H and Choi J H 2016 The structural analysis and strength evaluation of the rivet nut joint for composite repair Compos. Struct 136 662-8
[11] Milani A S, Dabboussi W, Nemes J A and Abeyaratne R C 2009 An improved multi-objective identification of Johnson–Cook material parameters Int. J. Impact. Eng 36 294-302
[12] Guo L Z and Xing W Z 2000 Experimental study on optimum interference-fit level of interference fit New Technology & New Process 1 14-6 (in Chinese)