Approach to Interference Riveting Process Control of Aircraft Automatic Drilling and Riveting

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Abstract: Interference fit riveting is an effective way to improve the fatigue life of aircraft. The accurate control of riveting interference of aircraft automatic drilling and riveting equipment is achieved by process parameters including upsetting force and upset head height. It is valuable for aircraft manufacturing engineering. An approach to interference riveting process control based on the analysis of interference riveting stress field is proposed. According to assembly structure, the upsetting force is calculated by the material property and interference fit level, and the upset head height is deduced by the upsetting force. The experimental result shows that the interference fit level can be controlled accurately by the upsetting force and upset head height, and then, the quality of aircraft automatic riveting can be improved. The proposed approach is verified by the good match between the predicted result and the experimental result.

Key words: aircraft assembly; interference fit; automatic drilling and riveting; upsetting force; interference riveting

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Nomenclature

E_1/GPa	Elastic modulus of rivet
μ_1	Poisson ratio of rivet
σ_{s1}/MPa	Yield strength of rivet
D_0/mm	Initial diameter of rivet
D/mm	Diameter of final bond.
L_0/mm	Initial length of rivet except head
L_1/mm	Length of rivet when no clearance
H/mm	Head height
λ_1	Deformation curve coefficient in the quasi-linear form
σ/MPa	Stress
q/MPa	Squeezing pressure intensity
σ_i/MPa	Stress intensity
σ_z/MPa	Squeezing axial compressive stress
K/MPa	Strength coefficient
E_2/GPa	Elastic modulus of panels
μ_2	Poisson ratio of panels
σ_{s2}/MPa	Yield strength of panels
D_1/mm	Initial diameter of initial hole
r_s/mm	Radius of plastic zone
B/mm	Thickness of panels
H_1/mm	Protrusion length of rivet when no clearance, $H_1 = L_1 - B$
D_h/mm	Diameter of head
Δ/%	Interference-fit quantity
U/mm	Displacement
q_1/MPa	Residual squeezing pressure intensity
ε_i	Quantity of strain
F_{sq}/kN	Riveting force
n	Strain hardening exponent
σ_b/MPa	Ultimate strength

1 Introduction

As a way to permanently fasten two thin-walled sheet-metal parts, riveting is regarded as an important joint method in aircraft assembly for its simple process, stable and reliable quality, easy quality control, and applicability to different material joining.

Interference fit riveting means to produce

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certain interference fit between hole and rivet shank within the whole lamination thickness through certain process control. Thus, it can produce residual compressive stress around the hole of fastener, reduce the peak stress subject to fatigue load, and effectively improve the fatigue life of an aircraft. Automatic assembly and interference riveting is widely used in commercial aircraft assembly such as C919. For example, automatic drilling and riveting machine is deployed in the automatic drilling and interference riveting process of large aircraft panels. To assure the aircraft assembly quality and increase the fatigue life of C919, some effective control methods of process parameters involving riveting force and head height is required for the automatic drilling and riveting process.

Solid aluminum alloy rivets are widely used in the joints of aircraft structures. Basically, riveting is a process containing rivet shank squeezed with large plastic deformations to form driven rivet head. Many variables influence the response of rivet joints, such as the geometry of joints, the material parameters of joining parts, the clearance of the assembly, etc. The dimensions of the driven rivet head (diameter D and height H) depend on the applied squeeze load. High squeeze loads can improve the fatigue properties of riveted joints.

A method for calculating the contact pressure in durable rivet bonds subject to the force of rivet and the result of unloading is presented by Shishkin[1]. The method was to determine the radius of the plastic zone in sheets and calculate the values of residual stresses in panels.

The relation between squeeze load and the rivet head dimensions was studied by de Rijck, et al[2]. Extensive test series were conducted with several configurations of different rivet materials, rivet diameters and sheet materials. An equation was developed regarding squeeze load and rivet head dimensions under an assumption that there was no or little changing of rivet during plastic deformation. The two material constants in the equations were empirically determined for the rivet materials. A satisfactory correlation was obtained[2].

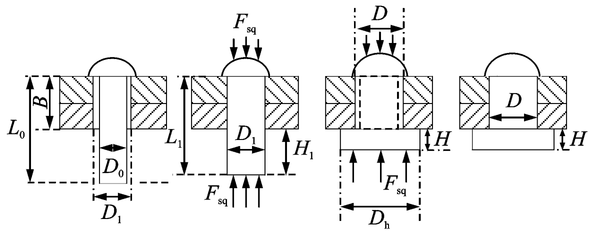
The riveting process modeling and simulating for more accurately deformation analysis of thin-walled sheet-metal parts was investigated by Zhang Kaifu, et al[3]. The results obtained by the mathematical and mechanical model were compared with those by finite element method (FEM). FEM is a more frequently-used method to study riveting process. A finite element numerical model was developed and experimentally validated by Chen Nanjiang, et al. [4] for analysis and optimization of riveting process. FEM model was constructed in three-dimensions with modeling non-axisymmetric layouts of riveting and testing of the joint strength. The effects of different parameters involved in riveting process, including squeeze force, clearance, rivet length and clamping angle in the stress field of joints, were explored by numerical models. These models aimed at obtaining an accurate stress-strain field in the most stressed zone including the residual stress in the holes. The influence of riveting parameters on fatigue strength was evaluated for optimization purposes[5]. Cheraghi[6] also presented a study of the effect of the aforementioned riveting parameters on quality of a formed rivet using finite element simulation.

The above analysis implies that in spite of the wide application of riveting technology, few researches are conducted on the rivet formation quality based on parameters in automatic drilling and riveting process. Most researches focus on the fields of fatigue life prediction, crack initiation and propagation, residual stress analysis and load distribution around riveted joints.

Although FEM is widely used in predicating rivet deformation, it is very hard to apply to an engineering locale. Therefore, we put forward an interference riveting process control approach to analyze the stress field of interference riveting structure and the process of automatic drilling and riveting. And an experiment is carried out by using the same materials as commercial airplane C919 and ARJ21-700 for validation.

2 Stress Field Analysis of Riveting Joint Structure

According to the shape variations of a rivet, the riveting formation process is divided into three phases, as shown in Fig. 1.



(a) Initial status (b) The first phase (c) The second phase (d) Spring back phase

Fig. 1 Process of interference fit riveting

The First phase: From the riveting die contacting the rivet to the rivet external surface contacting the inner wall of hole, the rivet is free upsetting without the restraint of the hole under the action of F_{sq}. This phase is prepared for interference, during which the rivet length varies from the initial L_0 to L_1, and $H_1 = L_1 - B$.

The second phase: From the rivet external surface contacting the inner wall of hole to the completion of the rivet head formation, the rivet is upsetting under the action of F_{sq} and the restraint of the hole. In this phase, the panels are deformed elastically and even plastically and the hole diameter expands in radial direction from D_1 to D_0.

The last phase: The riveting force is unloaded, and the elastic deformation of the rivet and the panel springs back. Since the elastic deformation is far less than plasticity deformation, the experiment focuses on stress variation and ignores the dimensional one.

2.1 Stress field analysis of panel after shaped

According to the elastic-plastic theory[7-8], when interference riveting or the second phase of riveting is completed, there will be a plastic zone around the hole. Based on the boundary condition shown in Eq. (1), the stress field of panel is achieved, shown in Eqs. (2—4)

$$(U)_{\rho=D/2} = \frac{D - D_1}{2}$$
$$(\sigma_\rho)_{\rho=r_s} \quad \text{stress continuity} \tag{1}$$

$$r_s = \sqrt{\frac{2r(r-r_1)E_2}{\sqrt{3}\sigma_{s2}}} = r_1\sqrt{\frac{2\Delta(1+\Delta)E_2}{\sqrt{3}\sigma_{s2}}} \tag{2}$$

$$q = \frac{2\sigma_{s2}}{\sqrt{3}}\ln\frac{r_s}{r} + \frac{\sigma_{s2}}{\sqrt{3}} = \frac{2\sigma_{s2}}{\sqrt{3}}\ln\sqrt{\frac{2\Delta E_2}{(1+\Delta)\sqrt{3}\sigma_{s2}}} + \frac{\sigma_{s2}}{\sqrt{3}} \tag{3}$$

$$\left.\begin{aligned}(\sigma_\rho)_{\rho=r} &= -q\\ (\sigma_\varphi)_{\rho=r} &= \frac{2\sigma_{s2}}{\sqrt{3}} - q\end{aligned}\right\} \tag{4}$$

2.2 Stress field analysis of rivet after shaped

When interference riveting or the second phase of riveting is completed, $(\sigma_\rho)_{\rho=0}$ will be a finite number and $(\sigma_\rho)_{\rho=r} = -q$, according to the boundary condition. And the stress filed of rivet can be arrived at

$$\sigma_\rho = \sigma_\varphi = -q \tag{5}$$

According to stress-strain relationship of Eq. (6) and Eqs. (2, 3), the relationship of the axial compressive stress σ_z and interference-fit volumn can be reached

$$\sigma_z = -(\sigma_i + q) = -[\lambda_1 \cdot \sigma_{s1} + E_1 \cdot (1-\lambda_1) \cdot \varepsilon_i + q]$$

where $$\varepsilon_i = \Delta + \frac{(D_1 - D_0)}{D} \tag{6}$$

2.3 Residual stress field analysis after springing back

After riveting force is unloaded, the elastic deformation of rivet and panel springs back. The radial displacement of joint hole surface U_1 is equal to that of rivet surface U_2[1]

$$U_1 = \frac{\mu_1\sigma_z + (q-q_1)(1-\mu_1)}{E_1} \cdot \frac{D}{2} = U_2 = -\frac{(q-q_1)(1+\mu_2)}{E_2} \cdot \frac{D}{2} \tag{7}$$

The residual squeezing pressure intensity of rivet and hole q_1 can be got through Eqs. (6,7)

$$q_1 = q - (q + \sigma_i)\frac{\mu_1}{(1-\mu_1) + (1+\mu_2)\dfrac{E_1}{E_2}} \tag{8}$$

3 Interference Riveting Process Control

During the virtual producing process, interference-fit volume is mainly affected by the riveting process parameters. Based on the automatic drilling and riveting system, the process control model used in this paper adopts parameters of upsetting force and upset head height to precisely control riveting interference-fit volume.

3.1 Ascertaining upsetting force

Eqs. (3,6) are used to calculate the relationship between Δ and σ_z caused by upsetting force. And the upsetting force can then be achieved through Eq. (9) in which D_h is the head diameter.

$$F_{sq} = \sigma_z \pi D_h^2 / 4 \tag{9}$$

What need be noted is that the head is not cylinder-shaped but drum-shaped, so it cannot be calculated simply. The head diameter of the section contacting the riveting die is used as D_h value, and a modification factor m is also introduced into the calculating process. m is equal to the square root of $2H/H_1$ and it corresponds to the value measured in the experiment. Therefore, D_h can be obtained at through Eq. (10), where H_1 is the protrusion length of rivet when there is no clearance between the rivet and the hole

$$D_h = m \cdot \sqrt{\frac{(D_0^2 L_0 - D^2 B)}{H}} = \sqrt{\frac{2(D_0^2 L_0 - D^2 B)}{H_1}} \tag{10}$$

On the basis of volume constant principle, it can be obtained through Eq. (11)

$$H_1 = L_1 - B = D_0^2 L_0 / D^2 - B \tag{11}$$

It is interesting to note that the calculation of D_h is irrelevant with head height H after introducing the modification factor m, and therefore H can be omitted when figuring out the upsetting force. In this way, the calculating process is in fact simplified rather than complicated.

3.2 Ascertaining head height

If neglecting the gap of the rivet and the hole, the relationship between upsetting force and head height can be achieved through the formula offered by de Rijck, et al[2].

However, if the realistic gap of rivet and hole is taken into consideration, the protrusion length H_1 of rivet need be calculated first when there is no clearance between them. Then the formula provided by de Rijck, et al.[2] can be used, as is shown in Eq. (12)

$$F_{sq} = \frac{\pi D_1^2}{4} \frac{H_1}{H} K \left[\ln\left(\frac{H_1}{H}\right) \right]^n \tag{12}$$

For the function relationship in Eq. (12) is complex, trial and error method is applied to get H from F_{sq}.

3.3 Application of interference riveting process control

The traditional process parameter is head height or head diameter owning to the limitation existing in the performance of conventional pressure riveting machine, because the upsetting force can not be controlled accurately while using the conventional pressure riveting machine. Another reason is that the head height could be measure conveniently. With the development and application of automatic drilling and riveting technology, the force and the distance can be measured online. More process parameters, including upsetting force and head height, can be used to ensure the interference riveting quality. The interference riveting can be controlled accurately though measuring and controlling the upsetting force online, because it is the direct influencing factor of riveting stress field. Wang, et al.[9] illustrated that the upsetting force could influence the fatigue of structure significantly.

Based on the above analysis, the process control model is displayed as follows:

Step 1 Figure out the upsetting force (F_{sq}) through Eq. (9) according to the material characteristics (σ_s, E, μ, etc.), initial dimensions (D_0, D_1, L_0, and B, etc.) and expectation interference fit quality (Δ).

Step 2 Calculate H through Eq. (12) on the basis of the F_{sq} value obtained from Step 1, and the material characteristics and the dimensions.

Step 3 Determine the process parameters of automatic drilling and riveting machine, based on the result from Steps 1,2. Owing to the control accuracy of the device, the parameter setting value may be a rounding value.

Step 4 Test and modify the model by applying it in engineering.

4 Experimental Verification

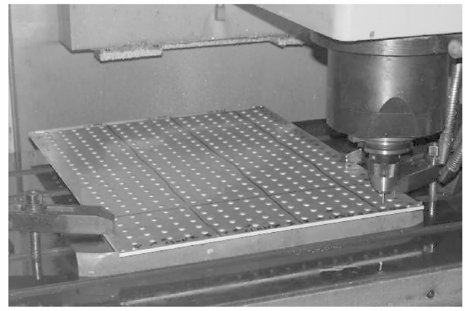
The materials used in the experiment adopt those of commercial airplane C919 and ARJ21-700. The rivets are aluminum alloy 2117-T4 (MS20426AD5-6). The panels are aluminum alloy 2024-T3. The materials properties is shown in Table 1.

Table 1 Materials trademark and properties

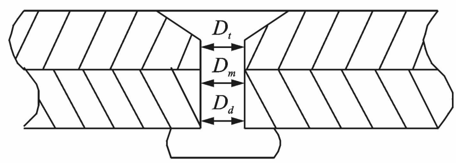
Parameter	Rivet	Panel
Material	2117-T4	2024-T3
σ_s /MPa	311.3	345
σ_b /MPa	442.9	530
E/GPa	73	71
μ	0.33	0.33
K/MPa	600	
λ	0.982	
n	0.3	
B/mm		4
D_1/mm		4.125

Calculated result: The expecting interference-fit quantity is respectively 2.30%, 1.7%, and 0.85%. The upsetting force is calculated through Eq. (9), and the head height is achieved through Eq. (12). Table 1 is the calculation result, which is rounding to be applied by automatic drilling and riveting machine. For example, to achieve interference-fit quantity of about 2.30%, the upsetting force value should be set 23 kN and head height value 1.68 mm.

Experimental result: An experiment is conducted to verify the proposed method of interference riveting process control. The materials and size of test components are in accord with those of calculation, and the interference riveting experiment is conducted on multi-panel assembly cell (MPAC)[10] automatic drilling and riveting system of Germany Brotjie Automation Co. Then the rivet is taken out to measure interference-fit level by lengthwise cutting used CNC machining center which is shown in Fig. 2(a). The diameter of final bond $D=(D_t+D_m+D_d)/3$, which is shown in Fig. 2(b).



(a) Test couple using CNC machining center



(b) Schematic diagram of measuring D

Fig. 2 Process of taking rivet out to measure interference-fit level

The experimental result is presented in Table 2. For example, the measured interference-fit quantity of expectation value 2.3% is 2.33%.

It should note that there is certain difference between the setting value and the measured value of process parameters. For example, in order to achieve 2.2% interference-fit quantity, the setting value is 23 kN and 1.68 mm, but the measured value is 23.7 kN and 1.64 mm.

Comparative analysis of calculation and experiment: Through the comparison between the calculation and experiment results shown in Table 2, it reveals that the deviation of the three group tests are no more than 1.2%, which confirms the accuracy of the proposed method.

The relationship between interference-fit quantity and upsetting force are achieved through Eqs. (3, 8—10), and the calculated result and the

Table 2 Calculation of process control parameters and experimental result

Group	Calculation value			Experimental result			
	Expectation Δ/%	Setting F_{sq}/kN	Setting H/mm	Measured F_{sq}/kN	Measured H/mm	Measured Δ/%	Deviation of Δ/%
1	2.30	23	1.68	23.70	1.64	2.33	1.17
2	1.70	21	1.75	21.8	1.79	1.72	1.18
3	0.85	18	2.00	17.60	2.24	0.85	0

measured result coincide very well, as is shown in Fig. 3.

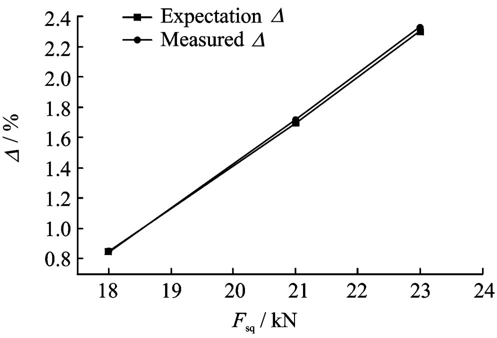


Fig. 3 Relation of F_{sq} and Δ

The relationship between head height and upsetting force are achieved through Eqs. (11, 12), and the calculated result and measured result also coincide very well, as is shown in Fig. 4.

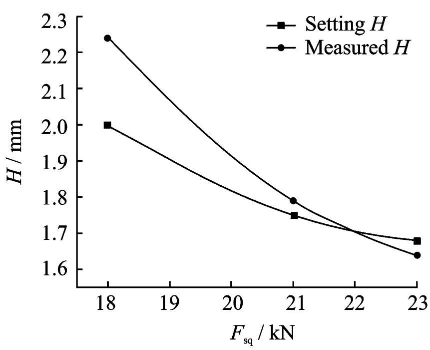


Fig. 4 Relationship of F_{sq} and H

5 Conclusions

Interference riveting is an effective method to improve the fatigue life of the aircraft assembly joint quality. The accurate control of interference riveting of aircraft automatic drilling and riveting equipment is achieved by controlling the process parameters of the upsetting force and the upset head height. An approach to interference riveting process control is presented, to provide an engineering application basis for the automatic drilling and riveting of the riveted structure.

(1) Based on the elastic-plastic theory, the solution of interference stress field is presented through simplifying the rivet deformation model and boundary conditions. These formulas describe the stress state after being shaped, so it can be quite accurate in spite of a simple form.

(2) Adopting automatic drilling and riveting technique, the interference fit quantity of assembly joint can be controlled accurately by upsetting force and upset head height. Eqs. (9,12) offer an accurate calculating method, in which deviation of calculation and test value is about 1.2%, which is far less than the precise requirement of 20% in engineering. The method can fulfill the requirements in engineering application.

(3) In theory, control of head diameter is equally effective to that of head height. However, since it is easily controlled through the stroke length of riveting die, the head height is used more often.

(4) Compared with finite element analysis, the proposed engineering solution method is easier to use and faster to calculate.

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