Experimental Evaluation for the Interference-fit Electromagnetic Riveting Joint with Headless Rivet

Danlong Song*, Xiangyang Zhang, Kai Liu, Yanchao Zhang and Zhenchao Yang
School of Mechanical and Precision Instrument Engineering, Xi'an University of Technology, Xi'an 710048, China
*E-mail: songdanlong@xaut.edu.cn

Abstract. Electromagnetic riveting (EMR) technology as a relatively new mechanical joining process has many advantages compared to traditional riveting methods. However, it needs to be investigated whether the traditional pressing riveting can be replaced by EMR process in aerospace manufacturing engineering. Therefore, in this paper, the differences of riveting quality between automatic riveting and handheld EMR were compared by riveting and mechanical experiments including the uniformity of interference fit, shear and pull-off strength and fatigue life of the joints respectively. It was observed that the interference fit of the riveting joint using EMR is more uniform along the axial direction of rivet than that of automatic riveting. In addition, the overhang of the rivet was difficult to control by handheld EMR, so the quality of rivets for EMR was poorer than that of automatic riveting. Thus, the shear and pull-off strength and fatigue life of EMR joints were affected by the quality of rivets, and a longer rivet is needed for the EMR.

Keywords: Interference fit, Electromagnetic riveting, Experiment, Mechanical evaluation;

1. Introduction
In advanced engineering fields, the reliability and safety of aircraft and vehicle is significantly important. Under service load, fatigue cracks are easily initiation and propagation in the structures, especially at the joints, more than 60% of failures occur at the joints [1]. A variety of fastening technologies are applied in manufacturing industry, such as welding, bolting, bonding and riveting. Riveting process which is a kind of interference-fit joint technology can improve the bearing capacity and sealing performance, which has proved that interference-fit joint of metal structure can enhance the fatigue life and strength in assembly of aircraft and automobile parts[2, 3]. It has been increasingly applied in many manufacturing industries[4, 5].

There are three kinds of riveting process such as pressing riveting, pneumatic riveting and electromagnetic riveting (EMR)[6]. It is proved that the quality of pressing riveting is very good. But the operating space should be open. The rivet deforms un-uniformly by pneumatic riveting. The structure skin may be scratched which will cause fatigue crack. As a new interference-fit riveting technology, the EMR, also known as stress-wave riveting, is an advanced electromagnetic rivet forming process, which act very fast [7, 8]. Usually, the rivet is formed within 1 ms, so the mechanical behavior of the material in high strain rate forming is entirely different with that of traditional pressing
riveting process. The metal deforms by the mode of homogeneous slip in quasi-static riveting, while shear mode in EMR[9].

The residual stress distribution of EMR interference-fit joint was predicted by a theoretical model which provide scientific guidance for the process parameter design and riveting setup optimization in engineering application [10]. The pressing riveting and tension processes were investigated experimentally and numerically, and three kinds of failure modes including pull through, shank breaking, and head breaking were observed[11]. Newman et al.[12] explored microstructure in the rivet cross section of the riveted sample with countersunk rivets, and found that the cracks initiated and grew from the faying surface. The differences of riveting quality between pneumatic riveting and EMR were compared by experiments including interference quantity uniformity, shear and pull-off strength of the riveting, and the EMR quality was better [13, 14]. In addition, the microstructures and mechanical properties of the pressing riveting and EMR processes were analyzed by optical microscopy and tensile testing machine respectively [15]. But the geometric dimension analysis was ignored, and the rivet is one side formed by EMR.

Therefore, the mechanical property and geometric dimension of structures with headless rivet by EMR is not clear. It needs to be investigated whether the traditional pressing riveting process can be replaced by EMR technology in aerospace manufacturing engineering. So the contrastive research of EMR and pressing riveting is conducted in this paper. The aluminum alloy skin is fastened by headless rivet with EMR gun and automatic riveting machine which employs pressing riveting technology. Then the geometrical dimension, strength and fatigue life with various riveting voltages are investigated.

2. Riveting experiments of headless rivet

Based on the technical requirements, the material and dimensions of the rivet, the riveting test was conduct by the HH503 handheld EMR gun and G86 automatic riveting machine produced by Electroimpact and GEMCOR Inc. respectively shown in Figure 1. G86 automatic riveting machine which employs pressing riveting technology is widely used in aircraft assembly process. It is proved that the riveting quality of G86 is competent for engineering requirement. The EMR gun system, which consists of driver, gun body and handle shroud, is suitable for the rivets made of aluminum alloy and titanium alloy.

(a) Handheld EMR gun (b) Automatic riveting machine

Figure 1. Riveting machines used in the experiments

The EMR tests of headless rivet require two EMR guns, the riveting mould is installed on the primary gun to punch the rivet, and the riveting die is installed on the assistant gun to support the rivet. Based on the experiential parameters, the riveting voltage ranges are 170V ~ 180V and 220V ~ 250V for the headless rivets of Φ3/16" and Φ1/4" respectively. However, lower riveting voltage causes incomplete forming of rivets, the riveting mould is filled with gap. When the riveting voltage is too high, the riveting impact force will cause overlarge interference-fit percentage which may reduce the joint strength.
The material of headless rivets is 2117-T4 aluminum alloy, and the materials of the plates are 7055-T3 aluminum alloy. The automatic riveting specimens are riveted by G86 machine. The rivet holes for EMR process are drilled by G86 machine with drill-counterbore tools made of cemented carbide. The diameters are $\Phi 4.90 \pm 0.02\text{mm}$, $\Phi 6.45 \pm 0.02\text{mm}$ for two types of rivets respectively. Then, the riveting process is implemented by handheld EMR guns. The specimens are shown in Figure 2.

(a) Automatic riveting specimens  
(b) Handheld EMR specimens

Figure 2. Specimens of two kinds of riveting tests

3. Geometrical analysis of the riveting joint

The geometrical shapes of the formed rivet are effected by many factors, such as riveting voltage, mould, material and dimension of headless rivets. The effects of riveting voltage on geometrical shapes, which include interference-fit percentage, the height and diameter of rivet head, are investigated by riveting experiments in details.

3.1. Interference-fit percentage

The interference-fit percentage, which affects the strength and fatigue life of the joint, is a very important parameter for the riveting joint in the field of aircraft assembly. The expansion percentage of the rivet hole during the EMR process is described by the interference-fit percentage which can be expressed by:

$$\Delta = \left(\frac{D - D_0}{D_0}\right) \times 100\%$$  \hspace{1cm} (1)

where $D_0$ represents the initial hole diameter, and $D$ represents the hole diameter after riveting which is equal to the rivet diameter after riveting.

The interference percentage is affected by riveting process. The riveting impact force is act on the head of the rivet during the riveting process, so the expansion of the rivet may not uniform along the axial direction of the rivet. Then, the specimens are decomposed by a saw to measure the diameter of the rivet at different location. The specimens and rivets cut by a saw are shown in Figure 3.

Figure 3. Specimens and rivets cut by a saw

To explore interference percentages of different location in the joint clearly, $D_1$ and $D_2$, the interference-fit percentages of 2 locations along the axial direction of the headless rivet, shown in Figure 4. The specimens of EMR tests are disassembled by cutting machine. The diameters of each location are measured by a digimatic micrometer.

The interference-fit percentages of the headless rivets of $\Phi 3/16"$ and $\Phi 1/4"$ are shown in Figure 5 and Figure 6 respectively. The min and max curves are the allowable minimum and maximum
interference-fit percentages respectively in engineering applications. The interference-fit percentages increase with the increasing of riveting voltage. It is proved that 180V and 210V are the optimal riveting voltages for Φ3/16" and Φ1/4" rivets respectively. However, the interference-fit percentages of Location D2 are a little larger than those of Location D1. Because the countersink of Location D1 makes for the flow of metal material.

![Figure 5](image1)

**Figure 5.** The interference-fit percentage of D1 and D2 for Φ3/16" rivets

![Figure 6](image2)

**Figure 6.** The interference-fit percentage of D1 and D2 for Φ1/4" rivets

In order to analyse the rivet deformation of EMR deeply, the average interference-fit percentages of EMR and automatic riveting are compared shown in Table 1. The results indicate that the average interference-fit percentages of EMR are larger than those of automatic riveting. Meanwhile, the interference-fit percentage along the axial direction of rivet by EMR is more uniform. The rivet completes plastic forming in one microsecond under the stress wave. From the point of the interference-fit percentage, EMR process is better than automatic riveting process.

**Table 1.** Comparison of the average interference-fit percentages

| Specimens   | Φ1/4" rivets | Φ3/16" rivets |
|-------------|--------------|---------------|
| Automatic Riveting | 1.91%        | 2.30%         |
| EMR         | 1.99%        | 2.34%         |

3.2. The height of rivet head

The height of rivet head for the headless rivets of Φ3/16" and Φ1/4" is shown in Figure 7. The Min curve is the allowable minimum height of rivet head in engineering applications. The height of rivet head decreases with the increasing of riveting voltage, because there is a positive correlation between the impact force for riveting and the riveting voltage. Besides, the height of rivet head meets the requirement of engineering applications in the range of testing voltages.

In addition, the height of rivet head conducted by EMR and automatic riveting are compared in Figure 8. It is observed that the height of rivet head of EMR is about 7.8% smaller than that of
automatic riveting with the same type of rivets. There is more material of the rivet for EMR flowing into the hole than that of automatic riveting. In addition, the overhang of the rivet was difficult to control by handheld EMR. But, the height of rivet head conducted by EMR could satisfy the engineering need.

![Figure 7](image1.png)

**Figure 7.** The height of rivet head for the Φ3/16” and Φ1/4” rivets

![Figure 8](image2.png)

**Figure 8.** The height of rivet head of the EMR and automatic riveting

### 3.3. The diameter of rivet head

The diameters of rivet head for the headless rivets of Φ3/16” and Φ1/4” are shown in Figure 9. The min curve is the allowable minimum diameter of rivet head in engineering applications. The plastic forming of the headless rivet is under the condition without volume dilatation. The average diameters of rivet head conducted by EMR and automatic riveting are compared in Table 2. The average diameters of rivet head for EMR are the same as those for automatic riveting. However, the diameter of rivet head depends on the diameter of riveting die. The riveting voltage and riveting process have almost no effect on the diameter of rivet head.

![Figure 9](image3.png)

**Table 2.** Comparison of the average diameters of rivet head

|                  | Φ1/4” rivets | Φ3/16” rivets |
|------------------|--------------|--------------|
| Automatic Riveting (mm) | 9.10         | 8.05         |
| EMR (mm)          | 9.00         | 8.15         |
4. Mechanical performance of riveting joint

The geometrical shapes of EMR joint indicate the riveting quality directly. However, the mechanical performance and fatigue life of EMR joint still should be investigated by mechanical experiments in order to evaluate the engineering applicability of EMR process.

4.1. Strength of the riveting joint

The quasi-static mechanical performance experiments, such as tensile experiment and pull-out experiment, were conducted by INSTRON 2383 hydraulic universal material testing machine with the speed of 1mm/min. The specimens of tensile and pull-out experiment are shown in Figure 10. The load-displacement curves are record in real time.

The tensile experimental results of the riveting specimens is shown in Table 3. The average shear strength of the EMR specimens is 7.1% lower than that of the automatic riveting specimens. A same regularity for the pull-off strength is observed, which is shown in Table 4. The primary reason is that the height and diameter of rivet head of the EMR specimens are smaller than those of the automatic riveting specimens. But, the strength of EMR joint could satisfy the engineering need.

**Table 3. Shear strength of riveting specimens**

| Specimens      | 1     | 2     | 3     | 4     | Average |
|----------------|-------|-------|-------|-------|---------|
| Automatic Riveting (MPa) | 177.41 | 169.25 | 169.25 | 175.37 | 173.33  |
| EMR (MPa)      | 157.01 | 167.21 | 157.01 | 163.13 | 161.09  |
Table 4. Pull-off strength of riveting specimens

| Specimens | 1     | 2     | 3     | 4     | Average |
|-----------|-------|-------|-------|-------|---------|
| Automatic Riveting (MPa) | 12.4  | 13.0  | 12.6  | 12.8  | 12.7    |
| EMR (MPa)  | 12.2  | 12.1  | 11.9  | 12.3  | 12.1    |

4.2. Fatigue life of the riveting joint

The specimens of fatigue experiment are shown in Figure 11. The fatigue experiments for the joint of EMR and automatic riveting processes were conducted by INSTRON 8801 hydraulic fatigue testing machine. The maximum stress is 140 MPa and the stress ratio is 0.1. The fatigue loading frequency is 15 Hz. The fatigue experiment should be stopped when visible cracks appear or the number of loading cycles reaches $1.00 \times 10^6$.

![Fatigue experiment setup](image)

Figure 11. The dimensions of fatigue specimens

The fatigue life comparison of EMR and automatic riveting joints are shown in Table 5. It is observed that the average fatigue life of EMR joints is 34.61% smaller than that of automatic riveting joints, which is caused by that the smaller height and diameter of EMR rivet head than those of automatic riveting rivets. Therefore, the automatic riveting process is better than EMR process on the same condition. But, the fatigue of EMR joint could satisfy the engineering need.

Table 5. The numbers of loading cycles of fatigue specimens

| Specimens | 1     | 2     | 3     | 4     | Average |
|-----------|-------|-------|-------|-------|---------|
| Automatic Riveting (MPa) | $8.39 \times 10^5$ | $1.00 \times 10^6$ | $9.82 \times 10^5$ | $9.47 \times 10^5$ | $9.42 \times 10^5$ |
| EMR (MPa)  | $6.63 \times 10^5$ | $5.36 \times 10^5$ | $5.78 \times 10^5$ | $6.85 \times 10^5$ | $6.16 \times 10^5$ |

5. Conclusion

In allusion to the riveting process of aircraft assembly, a comparative investigation of EMR and automatic riveting processes was conducted in this paper. The geometrical dimensions and mechanical performance were discussed respectively for EMR and automatic riveting processes by riveting and mechanical experiments. It was proved that the riveting quality of EMR was lower than that of automatic riveting with the same type of rivet. But EMR as an advanced technology should be investigated deeply. Some results were in the following conclusions.

(1) The average interference-fit percentages of EMR are larger and more uniform than those of automatic riveting. But the height and diameter of EMR rivet head are smaller than those of automatic riveting rivets. Because the stress wave transmits very fast, and there is more material of the rivet for EMR flowing into the hole than that of automatic riveting.
(2) The average interference-fit percentages and diameters of rivet head increase with the riveting voltages. The optimal riveting voltages for $\Phi 3/16\"$ and $\Phi 1/4\"$ rivets are 180V and 210V respectively.

(3) The shear and pull-off strength and fatigue life of EMR joint are lower than those of automatic riveting joint on the same condition, such as the length and overhang of rivet. So a longer rivet is needed for the EMR.

Acknowledgments
This work is supported by the Project funded by China Postdoctoral Science Foundation (Program No. 2018M643815XB), the Project Supported by Natural Science Basic Research Plan in Shaanxi Province of China (Program No. 2018JQ5025), the Scientific Research Program Funded by Shaanxi Provincial Education Department (Program No. 18JK0570) and the Young Talent fund of University Association for Science and Technology in Shaanxi, China (20190416). The authors would like to greatly acknowledge the editors and the anonymous referees for their insightful comments.

References
[1] Skorupa A and Skorupa M 2012 Riveted lap joints in aircraft fuselage: design, analysis and properties (Dordrecht, Heidelberg, New York, London: Springer)

[2] Zhang K, Hu J, Zou P, Cheng Y, Luo B and Cheng H 2019 Effect of secondary bending and bolt load on damage and strength of composite single-lap interference-fit bolted structures J Compos Mater 53 4385-98

[3] Wei J, Jiao G, Jia P and Huang T 2013 The effect of interference fit size on the fatigue life of bolted joints in composite laminates Compos Part B-Eng 53 62-68

[4] Chakherlou T N and Abazadeh B 2012 Investigating clamping force variations in Al2024-T3 interference fitted bolted joints under static and cyclic loading Mater Design 37 128-36

[5] Zhang Q, Cao Z, Li H, Xiang C and Liu P 2017 Elastic fatigue enhancement mechanism of interference fit Acta Aeronautica et Astronautica Sinica 39 235-43

[6] Li G, Jiang H, Zhang X and Cui J 2017 Mechanical properties and fatigue behavior of electromagnetic riveted lap joints influenced by shear loading J Manuf Process 26 226-39

[7] Cao Z and Zuo Y 2019 Electromagnetic riveting technique and its applications Chinese J Aeronaut

[8] Psyk V, Risch D, Kinsey B, Tekkaya A and Kleiner M 2011 Electromagnetic forming - A review J Mater Process Tech 787-829

[9] Zhang X, Yu H P, Su H and Li C F 2016 Experimental evaluation on mechanical properties of a riveted structure with electromagnetic riveting Int J Adv Manuf Tech 83 2071-82

[10] Zhang X, Jiang H, Luo T, Hu L, Li G and Cui J 2019 Theoretical and experimental investigation on interference fit in electromagnetic riveting Int J Mech Sci 156 261-71

[11] Chen N, Luo H, Wan M and Chenot J 2014 Experimental and numerical studies on failure modes of riveted joints under tensile load J Mater Process Tech 214 2049-58

[12] Newman J C and Ramakrishnan R 2016 Fatigue and crack-growth analyses of riveted lap-joints in a retired aircraft Int J Fatigue 82 342-49

[13] Feng D and Cao Z 2012 Quality comparing analysis of electromagnetic riveting and pneumatic riveting Ferg & Stamp Tech 123-26

[14] Skorupa M, Machniewicz T, Skorupa A, Schijve J and Korbel A 2015 Fatigue life prediction model for riveted lap joints Eng Fail Anal 53 111-23

[15] Dong D, Sun L, Wang Q, Li G and Cui J 2019 Influence of electromagnetic riveting process on microstructures and mechanical properties of 2A10 and 6082 Al riveted structures Arch Civ Mech Eng 19 1284-94