Study on Self-piercing Rivet and Mechanical Properties of Aluminum Alloy Joint

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Abstract. In this work, the self-piercing rivet (SPR) experiments were carried out and the mechanical properties tests under different SPR process were taken. The effects of SPR process on the geometric characteristics and strength of the joint were studied. It was found that the SPR joint under displacement-controlled process had larger interlocking value, higher mechanical properties, more stable geometric characteristics, and better mechanical properties. The failure mode of SPR joints was mainly pull-off failure. And the mechanical properties of SPR joints decreased with the increase of head height of SPR, while the residual thickness has no significant effect on the mechanical properties. The mechanical properties of SPR joints were significantly improved when structural adhesive was added into SPR joints, in which the failure mode was transformed into joint drawing failure. In addition, the fatigue behavior of SPR joint was studied. It was found that there was no significant difference between displacement-control process and energy-control process in fatigue performance of SPR joint. Moreover, cracks were initiated on the surface, which meet the surface initiation mechanism.

1. Introduction

The improvement on vehicle performance, such as economy, acceleration and environmental protection, is always the most important important goals for car manufacturers. Some studies have shown that the fuel economy will be increased by 3.8 % if the vehicle quality is reduced by 10 %. Besides, the acceleration time will be reduced by 8 %, the CO emission will be reduced by 4.5 % and the braking distance will be reduced by 5 %, the tire life will be increased by 7 %, and the steering power will be reduced by 6 %[1]. It can be fond that reducing the vehicle weight is one of the most effective technical methods to improve the vehicle economy, acceleration performance and reduce emissions. The most direct way to reduce vehicle weight is to use a large number of light materials such as aluminium alloy, composite material and so on. However, the use of these lightweight materials gave rise to great challenges to the joining processes[2,3].

In recent years, self-piercing rivet (SPR) technology has gradually developed, which is an efficient mechanical connection technology of aluminum alloy[4-10]. Comparing with resistance spot welding, it consumes a lot of energy and produces a lot of heat. In addition, there are quality problems of strength reduction due to the voids generated in the welding process. In addition, flue gas and welding spatter also cause safety and health problems to the working environment. Self-piercing riveting technology is relatively low noise, clean and fast, can be operated automatically, and requires less power, and does not transmit heat to the car body. This technology can not only be used to connect aluminium, magnesium and steel components, but also meet the requirements of various surface states such as pre-processing,
pre-coating, bonding and sealing parts. Self-piercing riveting technology can be combined with bonding technology to become a composite connection technology and is widely used in parts requiring high strength and stiffness.

Since SPR technology has been applied in vehicle manufacturing recently, which is still immature, and its technological theory and practical experience are deficient[11]. At present, there is no systematic study on the influence of SPR process parameters on joint quality, and there is no theoretical basis for riveting process design and joint quality evaluation[12-15]. In this paper, the influence of the process parameters on the geometric characteristics and comprehensive properties for aluminium alloy SPR joint was studied.

2. Experimental methods
Aluminium alloy 5182/T4 with thickness of 0.9 mm and 6016/T4 with thickness of 1.2 mm were used. The main chemical composition and mechanical properties are shown in Table 1 and Table 2. The SRP rivets coated with zinc were used for the riveting test. The rivet sketch is shown in Figure 1, in which K means the head height, a means the interlock value of joint and tmin means the bottom thickness of SPR joint.

![Figure 1. Sketch map of SPR joint.](image)

After riveting, Axio Imager 2 optical microscope (Zeiss, Germany) was used to measure the geometric characteristics of riveting. The measurement parameters are shown in Figure 1. The interlocking value and residual thickness are calculated as follows:

$$a = \frac{1}{2} (a_1 + a_2)$$  \hspace{1cm} (1)

$$t_{\text{min}} = \frac{1}{2} (t_{\text{min1}} + t_{\text{min2}})$$  \hspace{1cm} (2)
The shear test, tensile test and T-peeling test of riveted joints were carried out by E45 105 Tensile testing machine (MTS, USA) and the tensile rate was set as 2 mm/min. The test schematic diagram is shown in Figure 2.

![Figure 2. Schematic of mechanical properties tests.](image)

3. Experimental results and analysis

The typical geometric morphology of the joint is shown in Figure 3. SPR experiments were carried out under different head heights to analyze the relationship between geometric characteristics and process parameters. The head heights were set as 0.3 mm, 0.2 mm, 0 mm, -0.3 mm and -0.4 mm, respectively. The corresponding geometric characteristics are shown in Table 3.

![Figure 3. The typical cross-sections of SPR joint.](image)

| Head height settings | Geometric characteristics (mm) |
|----------------------|--------------------------------|
|                      | Head height | Interlock value | Minimum bottom thickness |
| -0.5                 | -0.49       | 0.54           | 0.27                   |
| -0.4                 | -0.41       | 0.48           | 0.31                   |
| 0                    | 0.02        | 0.38           | 0.37                   |
| 0.2                  | 0.21        | 0.31           | 0.39                   |
| 0.3                  | 0.31        | 0.36           | 0.36                   |

It can be found from Table 3 that the interlocking value increased with the decrease of SPR head height gradually. However, the minimum bottom thickness decreased with the decrease of head height. Usually there is a greater risk of floor penetration when the minimum bottom thickness is less than 0.2 mm. And the interlock value must be more than 0.3 mm to meet the mechanical properties requirements. It also can be found that there was a risk that the interlocking value does not meet the requirements when the head height was 0.3 mm.

In order to study the effects of different nailing methods on the mechanical properties of SPR joints, the shear, tensile and T-peeling tests on SPR joint were carried out on to study the effect of head height conditions on mechanical properties. Each group of parameters was tested three times and the average value was obtained. The typical failure morphology of SPR joint in tests are shown in Figure 4 to Figure 6. The failure modes of all SPR joints are self-locking failure. It can be found that all joint failures are pull-out failures, indicating that the head height is set as -0.5 to 0.3 mm, which can effectively avoid the phenomenon of SPR puncture and joint drawing failure.
Figure 4. The typical failure morphology of SPR joint in lap-shear test.

Figure 5. The typical failure morphology of SPR joint in cross-tensile test.

Figure 6. The typical failure morphology of SPR joint in T-peel test.

Table 4. Mechanical properties of SPR joints.

| Head height (mm) | Shear strength (kN) | Tensile strength (kN) | T-peel strength (kN) |
|------------------|----------------------|-----------------------|----------------------|
| -0.5             | 2030                 | 1096                  | 616                  |
| -0.4             | 1998                 | 1089                  | 621                  |
| 0                | 1932                 | 1046                  | 598                  |
| 0.2              | 1896                 | 1021                  | 586                  |
| 0.3              | 1832                 | 998                   | 576                  |
The mechanical properties of the joints are shown in Table 4 and Figure 7. It can be found that the joint head height is negatively correlated with the tensile-shear strength. The tensile-shear strength decreases with the increase of the head height gradually. This may be due to the decrease of interlocking value with the increase of head height, which results in the decrease of tensile and shear strength [16]. There is no obvious correspondence between the residual thickness and the tensile-shear strength.

4. Summary
In this paper, the mechanical properties of SPR joints under different process conditions were analyzed. The main conclusions are as follows:
(1) SPR riveting of Aluminium alloy 5182/T4 with thickness of 0.9 mm and 6016/T4 with thickness of 1.2 mm can obtain stable interlocking value and mechanical properties of joints.
(2) The main failure mode of SPR joint is pull-out failure, and its mechanical properties decrease with the increase of head height, which has no obvious relationship with the residual thickness.

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