Research on the Joint Strength of 6061 Aluminum Alloy/CFRP Multi-layer Laminate Made by Stamping-Joining Integrated Process

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Abstract. Automobile lightening is a direct and effective measure to realize energy saving and emission reduction. Using aluminum alloy and carbon fiber reinforced polymers (CFRP) composite materials to manufacture automobile parts can greatly reduce weight while enhance the overall strength and balance the overall toughness of the composite materials, and obtain high impact energy absorption capacity. In order to explore the feasibility of stamping-joining by hot stamping process for aluminum alloy and CFRP, using peeling test, the effects of different surface treatments of the aluminum alloy, different holding time and pressures in stamping-bonding stage on the strength of 6061 aluminum alloy/CFRP composite joints were studied. The results indicated that the joint shear strength after grinding, alkali washing and pickling the aluminum alloy's surface was 2.5 MPa, 4.3 MPa and 4.6 MPa respectively, which were increased by 155.4%, 338.77% and 369.38%, respectively. In the stamping-joining stage, when the holding time was less than 60 s, the joint shear strength increased rapidly to about 4.90 MPa, whereas the holding time is more than 60 s, the joint shear strength decreased and kept stable, remaining in the range of 3.92 to 4.34 MPa. When holding pressure was 1.0 MPa, the maximum shear strength was 4.90 MP; however, increasing the holding pressure may lead to resin overflowing.

Keywords: 6061 aluminum alloy · CFRP · Hot stamping · Shear strength · Joint

1 Introduction

Studies show that 10% reduction in automobile weight can save 6–8% on fuel and reduce emissions by 4% [1]. Therefore, automobile lightweight is the most direct and effective measure for energy-saving and emission reduction. There are about 40–50% and 50–75% weight reduction potential in automobile using aluminum alloy and carbon fiber reinforced polymers (CFRP) parts, respectively [2]. Therefore, manufacturing automobile parts with aluminum alloy and CFRP will greatly reduce the weight of the

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car body while maintaining the stiffness and strength [3]. Aluminum alloy has high specific strength, good impact energy absorption capacity and high corrosion resistance [4, 5]. CFRP is a composite material composed of polymers as matrix and carbon fiber (CF) as reinforced material. And CFRP has high specific strength, fatigue resistance, high specific modulus, and corrosion resistance, etc. [6–9]. However, CFRP only has about 1–2% elastic strain before failure [10]. Therefore, if aluminum alloy is used as the substrate and CFRP is used for strengthening, it can not only enhance the overall strength but also balance the overall toughness of composite materials, and has high impact energy absorption capacity [11, 12].

Carbon fiber reinforced epoxy matrix composites (CF/EP) are widely used in the fields of aerospace and transportation [13]. CF/EP prepreg is a sheet formed by impregnating CF in EP under certain conditions, and it is an intermediate product for manufacturing CF/EP composites. In order to study the feasibility of stamping-joining integrated process with aluminum alloy and CFRP, the CF/EP prepreg material is laid on the surface of the 6061 aluminum alloy sheet and then put them into warm tools to complete the stamping-joining process. The two materials are joined under the action of temperature and pressure, realizing forming process while completing the connection of the two materials. Finally, the aluminum alloy/CFRP composite component underwent an aging-curing synchronous process.

2 Materials and Experiments

2.1 Materials

6061 aluminum alloy was used in the investigation and its dimensions are 100 mm $\times$ 25 mm $\times$ 1.5 mm. The thermosetting prepreg (Preimpregnated Materials) of carbon fiber reinforced epoxy matrix composites was used in this study and the prepreg was unidirectional. The performance parameters of CFRP are shown in Table 1 and 2. The prepreg was cut into 100 mm $\times$ 25 mm.

Table 1. Performance parameters of the carbon fiber.

Type	Tensile strength	Elasticity modulus	Line density	Carbon content	Diameter
T700	4900 MPa	230 GPa	800 g/Km	93%	7 μm

Table 2. Performance parameters of the prepreg.

Thickness	Resin content	Curing temperature	Curing time	Glass transition temperature
0.08 mm	48–60%	160–180 ℃	180 min	225–235 ℃

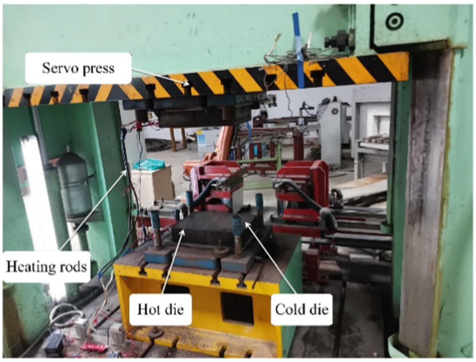

Fig. 1. The press, dies and heating system.

2.2 Experiments

2.2.1 Stamping-Joining Process

The servo press and dies with a heating system were used in the experiments, and they are shown in Fig. 1. The holding pressure and holding time in this servo press can be adjusted and the dies' temperature can be adjusted from room temperature to 400 ºC.

The stamping-joining integrated process of aluminum alloy and CFRP is as follows:

- The surface of the aluminum alloy was pretreated.
- Put the aluminum alloy into the heating furnace with a temperature of 550 ºC for solution treatment for 10 min and then transferred it quickly to the hot flat die (Fig. 2) with a temperature of 90 ºC; the press went down, then the aluminum alloy sheet was stamped and quenched with a holding time of 20 s.
- Up the press, laid four layers of prepreg on the aluminum alloy. The laying direction was 0º/90º/0º/90º (0º direction was the length direction of the aluminum alloy sheet). The bonding size of aluminum alloy and CFRP in the length direction was 12.5 mm (Fig. 2).
- The press went down again and the dies closed, then the aluminum alloy and CFRP was joined by cementing.
- The press went up again, and took out the aluminum alloy/CFRP composite component; then put it into the heating furnace with a temperature of 180 ºC for 3h for synchronous aging/curing process.

2.2.2 Experimental Design

In order to study the influence of different aluminum alloy surface pretreatment process, different holding time and holding pressure in stamping-joining stage on the joint strength of aluminum alloy/CFRP composite component, the above processing methods or parameters were changed respectively, and then the joint strength was evaluated by the peeling test (ASTM D1002). Details are as follows:

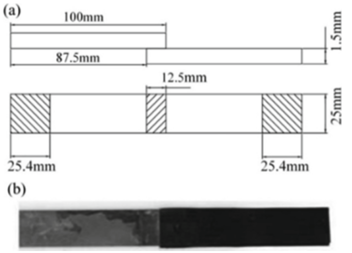

Fig. 2. The samples and dimensions for peeling test: (a) samples' dimensions, (b) the sample.

(1) Different surface pretreatment processes of aluminum alloys. No. 1: no pretreatment as control subject. No. 2: just grind for 5 min. No. 3: grind for 5 min and wash the surface with 5% sodium hydroxide solution for 5min. No. 4: grind for 5 min and wash the surface with 5% phosphoric acid solution for 5min. Then all the samples were washed with absolute alcohol and complete the stamping-joining integrated process as mentioned above. In the stamping-joining stage, the holding pressure and time were 1 MPa and 60 s, respectively.

(2) Different holding time in stamping-joining stage. The aluminum alloy was grinded for 5 min and washed the surface with 5% phosphoric acid solution for 5min. The holding time were 10 s, 20 s, 30 s, 60 s, 180 s, 300 s, 600 s and the holding pressure was 1 MPa.

(3) Different holding pressure in stamping-joining stage. The aluminum alloy was grinded for 5 min and washed the surface with 5% phosphoric acid solution for 5min. The holding pressure were 0.5 MPa, 1 MPa, 10 MPa and the holding time was 60 s.

2.2.3 Peeling Test

In this paper, ASTM D1002 standard was used to test the shear strength of the aluminum alloy/CFRP composite component's joint. The dimensions of the samples are shown in Fig. 2. In the peeling test (Zwick/Roell Z020 universal tensile testing machine), the both end of the samples were clamped with a length of 25.4 mm, and the tensile speed was 2 mm/min. The maximum shear strength S_{max} (MPa) was used to evaluate the joint strength. $S_{max} = P_{max}/A$, where P_{max} is the maximum load (N) applied by tensile testing machine during the experiment, and A is the contact area (mm^2) between aluminum alloy sheet and CFRP.

3 Results and Discussion

3.1 The Effect of Surface Pretreatment Processes of Aluminum Alloys on the Joint Strength

Figure 3 shows the shear strength-displacement curves of lap joints with different surface treatments. The joint strength of the unground sample in Fig. 3 increased slowly at the beginning. When the displacement reached 0.3 mm, the strength curve became steeper, and the shear strength increased to 0.98 MPa; then the joint failed step by step. The joint strength of the sample with only surface grinding increased slowly after loading, and the strength also increased rapidly when the displacement was about 0.3 mm. When the displacement reached 0.6 mm, the maximum shear strength of the joint reached 2.5 MPa. Then the joint failed step by step when the displacement continued to increase. For the sample which was ground and washed by sodium hydroxide solution, the trend of strength curve at the initial stage was consistent with that of No. 2 sample. When the displacement reached 0.68 mm, the shear strength of the joint reached the maximum value, i.e. 4.3 MPa, and then the joint failed step by step. For the sample which was ground and washed by phosphoric acid solution, the joint strength increased quickly when the displacement was 0.25 mm. When the displacement reached 4.5 mm, the joint shear strength reached the maximum value 4.6 MPa, and then the joint failed step by step. Compared with the untreated sample, the joint strength of the pretreatment samples was obviously improved. The joint strength of the sample which was only ground was increased by 155.4%. The joint strength of the sample which underwent grinding and alkaline cleaning increased by 338.7%. For the sample treated by grinding and acid cleaning, its joint strength increased by 369.4%.

Figure 4 shows the morphology of microstructure under different surface treatments. The black area at the bonding interface was epoxy resin and the gray strip were carbon fibers. As shown in Fig. 4(a), the surface of the aluminum alloy was not treated, and thus the surface of the aluminum alloy was smooth without obvious fluctuation, and the contact area between the epoxy resin and aluminum alloy was small. After the surface of aluminum alloy was ground, the surface was rough (Fig. 4(b)), and the resin embedded in the groove of the aluminum alloy. After grinding, the surface area of aluminum alloy increased, and the contact area between the epoxy resin and aluminum alloy also increased, thus the shear strength of the joint was improved. After grinding and cleaning with 5% sodium hydroxide, the concave holes on the surface of aluminum alloy were deeper (Fig. 4(c)). It was because that the surface of the aluminum alloy was etched after alkali washing [15], making the groves on the surface of aluminum alloy deeper, and the contact area between aluminum alloy and epoxy resin was larger. As a result, the shear strength of the joint increased compared with the samples which were not treated or only ground. In Fig. 4(d), the surface of aluminum alloy was ground and then cleaned with 5% phosphoric acid, and periodic grooves on the surface of the aluminum alloy formed [16]. As a result, the resin filled these grooves, increasing the contact area between aluminum alloy and epoxy resin. Therefore, the shear strength of the composite joint increased. Proper treatment of the surface of aluminum alloy before joining with CFRP is beneficial to improve the bonding performance of the joints. During chemical etching, grooves form on the aluminum surface, increasing the bonding area of aluminum alloy and epoxy resin, thus increasing the shear strength of the joint.

3.2 The Effect of Holding Time in Stamping-Joining Stage on the Joint Strength

Figure 5 and Fig. 6 show the strength-displacement curves and the maximum strength of lap joints under different holding time. When the holding time increased from 10 s to 30 s, the maximum shear strength of the joint increased rapidly from 1.88 MPa to 4.48 MPa. The maximum shear strength increased from 4.48 MPa to 4.90 MPa when the pressure holding time increased from 30 s to 60 s, and the increasing speed decreased.

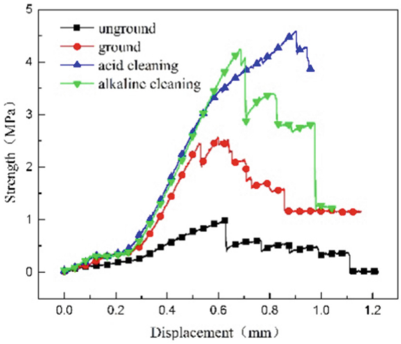

Fig. 3. Strength-displacement curves of lap joints with different surface treatments.

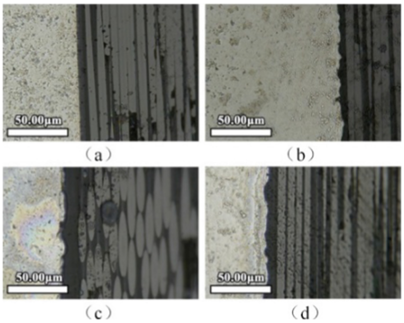

Fig. 4. Morphology of microstructure under different surface treatments (x2000): (a) untreated; (b) grinding; (c) grinding + 5% NaOH; (d) grinding + 5% H_3PO_4.

With the increase of the holding time, the maximum shear strength of the joint decreased from 4.90 MPa to 3.94 MPa. The shear strength of the joint did not change significantly when the holding time increased from 180 s to 600 s, and the shear strength of the joint remained at about 4 MPa. On the whole, when the holding time was less than 60 s, the shear strength of the joint increased rapidly to about 4.90 MPa with the increase of the holding time. When the holding time exceeded 60 s, the shear strength of the joint showed a decreasing trend with the increasing of the holding time. When the holding time exceeded 180 s, the shear strength of the joint remained at about 3.92–4.34 MPa.

With the increase of the holding time, more and more epoxy resins were push into the grooves on the surface of the aluminum alloy, and the binding force between resins and aluminum alloy increased. As a result, the shear strength of the joint increased rapidly. However, when the holding time was more than 60 s, due to the limited number and area of grooves, increasing the holding time did not increase the contact area between epoxy resin and aluminum alloy. Therefore, the shear strength of the joint was almost constant.

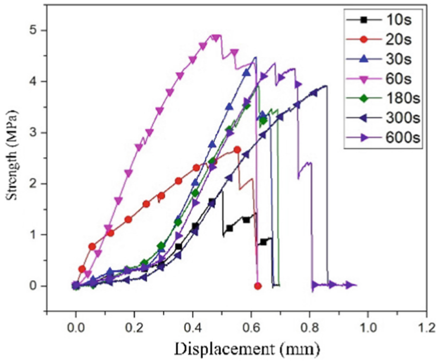

Fig. 5. Strength-displacement curves of lap joints under different holding time.

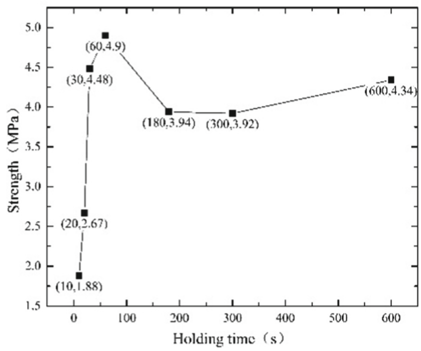

Fig. 6. The maximum strength of lap joints under different holding time.

3.3 The Effect of Holding Pressure in Stamping-Joining Stage on the Joint Strength

Figure 7 shows the strength-displacement curves of lap joints under different holding pressure and Table 3 indicates the shear strength of lap joints under different holding pressure. As can be seen, the shear strength increased first and then decreased when the holding pressure increased from 0.5 MPa to 10 MPa. As the holding pressure increased, the volume of epoxy resins pressed into the grooves on the surface of the aluminum alloy increases, so the shear strength of the joint was improved. But as the holding pressure continued to increase, the grooves on the surface of the aluminum alloy had been filled with epoxy resin, and the resin overflowed the bonding interface, thus the joint strength no longer improved. Figure 8 shows the morphology of microstructure under different holding pressure. When the holding pressure was 1 MPa (Fig. 8(a)), there was only a small amount of clumped resin on the surface of the interface, and no obvious resin overflowing phenomenon occurred. When the holding pressure was 10 MPa (Fig. 8(b)), excessive pressure led to a large amount of resin on the interface of the joint, which reduced the resin content between CFRP layers and the contact surface, thus reducing the bond performance and interlayer performance of the joint.

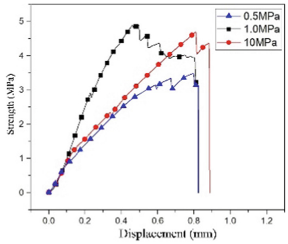

Fig. 7. Strength-displacement curves of lap joints under different holding pressure.

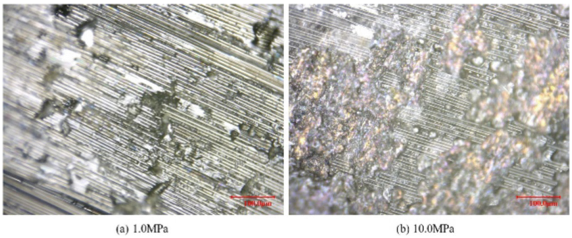

Fig. 8. Morphology of microstructure (500x) under different holding pressure: (a) 1 MPa; (b) 10 MPa.

Table 3. Shear strength of lap joints under different holding pressure.

Holding pressure	Maximum shear strength	Displacement at failure
0.5 MPa	3.48 MPa	0.79 mm
1 MPa	4.9 MPa	0.49 mm
10 MPa	4.69 MPa	0.81 mm

4 Conclusions

(1) After grinding, the surface roughness of aluminum alloy increased, and the surface micro-grooves increased. Compared with the sample without grinding, the shear strength of the joint increased from 0.98 MPa to 2.5 MPa, meaning am improvement of 155.4%. After further cleaning by sodium hydroxide or phosphoric acid, the surface micro-grooves of aluminum alloy increased, and the contact area between aluminum alloy and resin was larger. Therefore, the shear strength of the joint increased to 4.3 MPa and 4.6 MPa, respectively, improving by 338.7% and 369.4%.

(2) During stamping-joining stage, when the holding time was less than 60 s, the shear strength of the joint increased rapidly to about 4.90 MPa with the increase of the holding time. When the holding time exceeded 60 s, the shear strength of the joint showed a decreasing trend with the increasing of the holding time. When the holding time exceeded 180 s, the shear strength of the joint remained at about 3.92–4.34 MPa. With the increase of the holding time, more and more epoxy resins were

push into the grooves on the surface of the aluminum alloy, and the shear strength of the joint increased rapidly. However, when the holding time was more than 60 s, due to the limited number and area of grooves, increasing the holding time did not increase the contact area between epoxy resin and aluminum alloy. Therefore, the shear strength of the joint was almost constant.

(3) During stamping-joining stage, when the holding pressure was 0.5 MPa, 1 MPa, 10 MPa, the shear strength of the joint was 3.48 MPa, 4.9 MPa, 4.69 MPa. When the holding pressure increased from 0.5 MPa to 1.0 MPa, the shear strength of the joint increased because the increasing volume of the epoxy resin pressed into the micro-grooves on surface of the aluminum alloy due to the increasing pressure. However, when the holding pressure increased to 10.0 MPa, due to the limited volume of the micro-grooves, excessive pressure led to resin overflowing, resulting in a decrease in the shear strength of the joint.

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