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Fatigue of aluminum/glass fiber reinforced polymer composite assembly joined by self-piercing riveting

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Abstract

Automotive manufacturers work on the vehicle weight reduction to respect the new regulation laws about CO_2 emissions. The composite material can be introduced in replacement of some metallic parts to optimize the body structure in terms of weight reduction and performance. But how to join the new composite parts with the traditional metallic parts in accordance with the body in white process requirements? The self-piercing riveting (SPR) can be an innovative method to join thermoplastic composite with metal. The SPR is easy and convenient to implement because it does not require a pre-drilled hole. Fatigue tests were carried out to validate the fatigue performance of a Glass Fibre reinforced Polyamide 6.6 (PA6.6-GF) /Aluminium joint by SPR. The influence of process parameters and environmental factors on the fatigue joint performances were investigated. This study shows that the rivet shape have less influence on the joint fatigue strength than the parameters that impact the composite resistance such as the composite type and the test temperature.

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Keywords: Fatigue; Self-piercing riveting; Joint; Glass-fiber reinforced polymer; Aluminium

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1. Introduction

The new environmental laws decrees that the vehicle CO_2 emissions have to be lower. Automotive manufacturers work on the vehicle weight reduction to respect these regulation laws. The composite material can achieve a higher stiffness to weight ratio than metals. They can be introduced in replacement of some metallic parts to get lighter structures. The combination of composite and metal materials can be useful to optimize the body structure in terms of weight reduction and performance. But how to join the new composite parts with the traditional metallic parts in accordance with the body in white process requirements?

Adhesive bonding is a multi-material joining technology that requires a long processing time due to surface preparation and curing time. It is difficult to sustain the structure during the curing before the adhesive acquires its mechanical properties. The mechanical fasteners like rivets or bolts are another way to join materials of different nature. But they involve a pre-drilled hole which increases the production cycle time and causes geometry issues.

The self-piercing riveting (SPR) is an alternative technology for multi-material joining. It does not require surface pre-treatment or pre-drilled hole allowing short production time, cost savings and no geometry issue.

This technology is used for years in the automotive industry [1] to join different type of metals [2] such as steel [3], aluminium [4-6] magnesium [7]… The self-piercing riveting as used for years to join metals because experimental results prove the SPR joints have higher peel strength than Resistance Spot Weld (RSW) joints [8] and higher static shear strength than clinch joints [9]. Moreover, this joining technic is known to have good fatigue results [10].

As the Self-Piercing Riveting is multi-material joining method, a new application emerges, the SPR composite-metal joints. Process parameters influence the joint quality. For instance, combined material joints exhibit substrate defect regardless of die profile [11]. Another optimized process parameter is the distance between two rivets [12]. The static performances of the single lap joint were investigated for different thermosets composite-metal combinations by [13-16].

During the joint manufacturing, the SPR pierced the composite and creates damages such as fibre cutting and delamination. This damage may spread when the joint is loaded under fatigue cyclic stresses and eventually it may cause premature joint failure by composite rupture.

The objective of this paper is to measure the fatigue strength of the thermoplastic composite-aluminium joints by self-piercing riveting. The experimental results will be useful to integrate the SPR technology to join thermoplastic composite with metal in the traditional automotive process. This study also investigates the impact of parameters such as the rivet shape the composite material type and the testing temperature on the joint fatigue performances.

2. Materials and method

2.1. Joint configuration

The joint were manufactured by a Tucker riveter whose maximum load is 80 kN. The self-piercing rivets are provided by Böllhoff. The rivet shank has a diameter of 5 mm. A domed head self-piercing rivet and a countersunk head self-piercing rivet are investigated as shown on Figure 1.

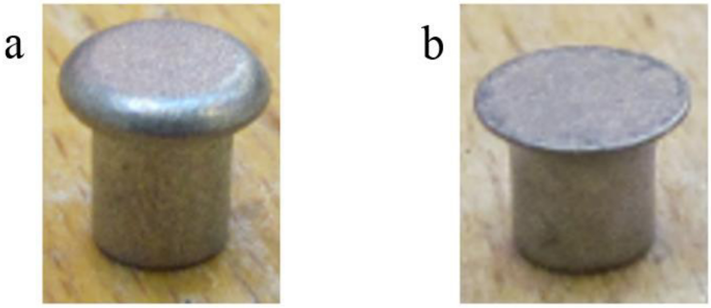

Fig. 1. (a) Domed head self-piercing rivet; (b) Countersunk head self-piercing rivet.

The material which has the higher deformation capacity is put on the forming die. So, the bottom sheet is in aluminum alloy whereas the joint top sheet is the composite plate. The single lap shear joint configuration is shown on Figure 2.

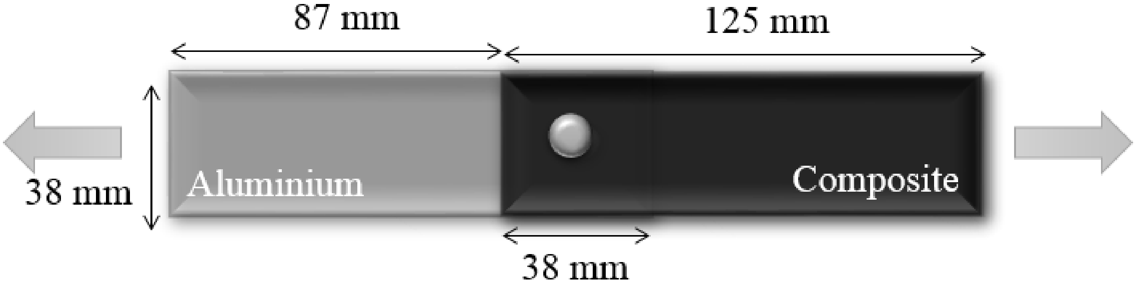

Fig. 2. Single lap joint configuration.

The material properties are presented in Table 1 for aluminium, composite 1 and composite 2.

Table 1. Materials properties.

Properties	Aluminum	Composite 1	Composite 2
Material	5182-O	PA6.6-GF50	PA6.6-GF63
Thickness	2 mm	2 mm	1.5 mm
Young Modulus	71 GPa	31,2 GPa	17,7 GPa
Tensile strength	255 MPa	880 MPa	303 MPa
Poisson's ratio	0.33	0.17	0.17

Six joint configurations are tested under cyclic fatigue tests. All the joint configurations are listed in Table 2 with different top thicknesses, two rivet shapes and different temperature.

Table 2. Summary of the joint configuration studied.

Top material	Top thickness	Bottom material	Rivet shape	Test temperature
PA6.6-GF50	2 mm	AA 5182-O	Domed	23°C
PA6.6-GF50	2 mm	AA 5182-O	Domed	-40°C
PA6.6-GF50	2 mm	AA 5182-O	Domed	50°C
PA6.6-GF50	2 mm	AA 5182-O	Domed	90°C
PA6.6-GF63	1.5 mm	AA 5182-O	Domed	23°C
PA6.6-GF63	1.5 mm	AA 5182-O	Countersunk	23°C

2.2. Experimental fatigue test procedure

The fatigue tests were performed on INSTRON or MTS testing machine. The minimum versus maximum load ratio was chosen equal to 0.1. With the frequency of 10 Hz, the joint self-heating was lower than 3°C.

To evaluate the stop criteria, displacement of the actuator has been recorded as shown in figure 3. At the beginning of the fatigue test, the displacement rapidly increased up to 1 mm and then it stabilized. The joint broke quickly (few seconds) after 3000s (30 000 cycles) corresponding to an absolute displacement between 2 and 4.5 mm as shown on Figure 3.

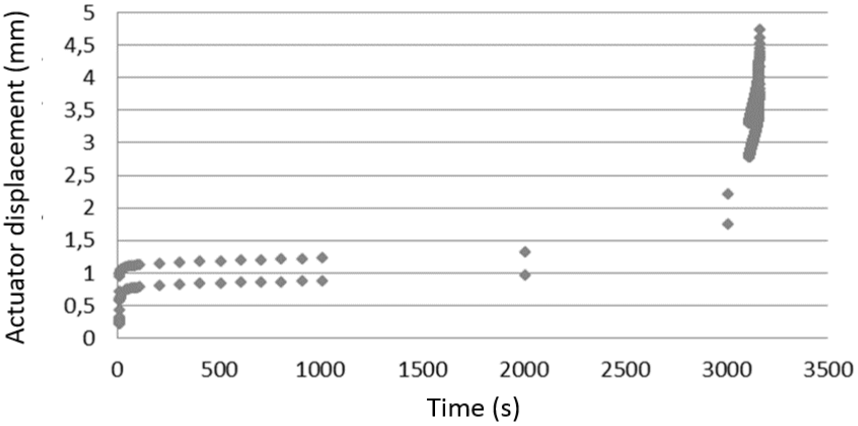

Fig. 3. Actuator displacement versus time.

It was decided that the fatigue tests were performed until an actuator displacement of 3 mm. This criterion corresponds to a total breakdown of the multi-material SPR joint. The fatigue tests were also stopped when two millions cycles were reached.

The alignment of load paths were ensured by shims.

3. Results and discussion

Figure 4 presents the fatigue results for the joint configuration with the PA6.6-GF50 composite plate on the aluminum AA 5182-O sheet joined by a domed head self-piercing rivet. The Basquin model is used for the results exploitation.

The average curve is obtained by the Basquin equation:

$$Log(N) = \log(C) - m.\log(\Delta F) \qquad (1)$$

N is the number of cycles to failure, ΔF is the amplitude of the range load, C and m are two constants.

To evaluate the fatigue characteristics quantitatively, fatigue results are evaluated according to statistical method. First of all, for a 50% survival probability level, a mean fitting curve is obtained considering a least square linear regression as equation (1) with the fatigue data considering $log\ N$ as a function of ΔF (only the failed fatigue tested samples are considered); m is the slope of the curve in log-log.

Using ISO 12107 standard, a design curve at 95% survival probability levels and 90% confidence interval is also calculated; the equation (1) becomes (2):

$$log\ (N) = \overline{\log(N)} - k(p = 95\%; (1-\alpha) = 90\%; n = 27).S_{\log(N)} \qquad (k = 2.08) \qquad (2)$$

Figure 4 presents the fatigue results with mean and design curves for the joint configuration with the PA6.6-GF50 composite plate on the aluminum AA 5182-O sheet joined by a domed head self-piercing rivet.

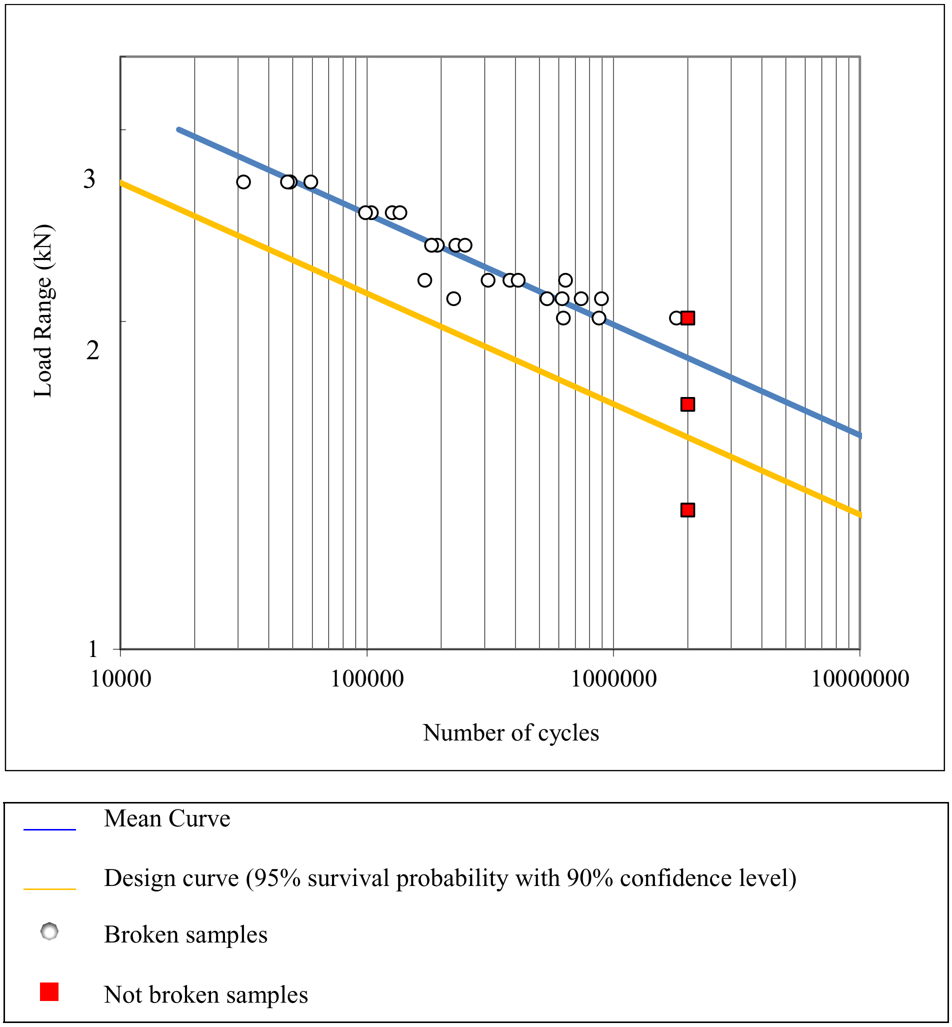

Fig. 4. Fatigue curve of the PA6.6-GF50/AA5182 joint by domed head SPR at 23°C.

Table 3 lists the joint fatigue limit at 2.10^6 cycles for each configuration. By comparing the configurations with the domed head self-piercing rivet and with the countersunk self-piercing rivet, the influence of the self-piercing rivet shape on the joint fatigue strength is highlighted. The two specimens are composed of PA6.6-GF63/AA5182 joined by SPR at room temperature. The joint fatigue limit strength at 2.10^6 cycles with the domed head rivet is 22% higher than the one of the joint with the countersunk self-piercing rivet. The rivet shape may impact the composite damage during the joint manufacturing. The self-piercing rivet head shape also influences the stress concentrations around the rivet during the fatigue test.

Each joint is composed of a composite plate and an aluminium sheet. Two different composite plates are tested at room temperature. The first is the PA6.6-GF50 with a thickness of 2 mm and the second is PA6.6-GF63 with a thickness of 1.5 mm. Both are joined by a domed head self-piercing rivet. The first configuration with PA6.6-GF50 achieves higher fatigue limit strength at 2.10^6 cycles of 37% compared to the joint configuration with PA6.6-GF63. The mechanical properties of PA6.6-GF50 2 mm are higher than the mechanical properties of PA6.6-GF63 1.5 mm as shown on Table 1. The Young modulus difference is around 40%. This difference is explained by the composite weave. The PA6.6-GF63 1.5 mm weave is 2-2 twill whereas the PA6.6-GF50 2 mm weave is 8H satin.

Table 3. Summary of the joint fatigue limit and the comparison with the static strength.

Top material	Top thickness	Bottom material	Rivet shape	Test temperature	Fatigue limit at 2.10^6 cycles (Range ΔF)	% of Rm at 2.10^6 cycles
PA6.6-GF50	2 mm	AA 5182-O	Domed	23°C	1880 N	56 %
PA6.6-GF50	2 mm	AA 5182-O	Domed	-40°C	2440 N	59 %
PA6.6-GF50	2 mm	AA 5182-O	Domed	50°C	1760 N	63 %
PA6.6-GF50	2 mm	AA 5182-O	Domed	90°C	450 N	58 %
PA6.6-GF63	1.5 mm	AA 5182-O	Domed	23°C	1180 N	56 %
PA6.6-GF63	1.5 mm	AA 5182-O	Countersunk	23°C	970 N	58 %

The joint is tested under severe environment with temperature range from -40°C to 90°C. The polyamide resin of the composite is sensitive to temperature. So, the fatigue joint strength will be impacted by the temperature variation. The joint is tested in fatigue under four temperature conditions: -40°C, 23°C, 50°C and 90°C. When the temperature increases, the fatigue joint performances decrease. For instance, the joint fatigue limit strength at 2.10^6 cycles decreases of 30% when the temperature increases from -40°C to 23°C and 22% from 90°C to 23°C.

The studied parameter that has the less influence on the fatigue joint performances is the self-piercing rivet shape. Contrariwise, the type of composite material and the test temperature have a very high impact on the fatigue joint performances. These two parameters are representative of the mechanical properties of the composite material. So, the mechanical properties of the composite is the most important factor for the fatigue joint strength.

The joint fatigue limit at 2.10^6 cycles is more than the half of the joint static strength. This order of magnitude is similar to the steel limit fatigue that proves the SPR composite/aluminum joint fatigue performance is high.

4. Conclusion

This paper studies the fatigue behaviour of PA6.6-GF50-Aluminum joint by self-piercing riveting. The influence of parameters such as the rivet shape, the test temperature and the composite material type on the joint fatigue strength are investigated. The major results of this paper include:

- The rivet shape can noticeable influence the SPR joint fatigue limit strength. The domed head SPR is more favourable than the countersunk rivet. The fatigue limit strength at 2.106 cycles is higher of 22%.
- The composite materials is a determining factor for the SPR joint fatigue strength. The fatigue strength at 2.10^6 cycles varies from 37% between the two studied composite materials. The difference is due the composite mechanical properties and its thickness.
- The temperature yields different fatigue strengths. The fatigue joint performance decreases of 30 % when the temperature increases from -40°C to 23°C. This phenomena is explained by the polyamide resin sensitivity to temperature.
- The SPR joint fatigue strength at 2.10^6 cycles is more than the half of the joint static strength. This result is similar to the steel limit fatigue. The SPR composite/aluminium joint are proved to be a durable multi-materials joining method for the automotive industry.

Finally, it was shown that material and process parameters have an impact on the multi-material joint fatigue performance. Furthermore, the influences of others parameters such as the die design can be investigate in a future experimental study.

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