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The influence of fatigue on the stiffness and remaining static strength of self-piercing riveted aluminium joints

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ABSTRACT

Self piercing riveting (SPR) is one of the major joining technologies for aluminium structures due to its advantages over some of the more traditional joining technologies. In this paper, the mechanisms of crack initiation and growth during fatigue and the influence of fatigue on the stiffness and remaining static strengths of SPR joints in both lap shear and T peel configurations were studied. The results showed that cracks could initiate and develop from different locations on the substrate materials depending on load levels and test types. Fatigue increased the remaining static lap shear strength and stiffness of specimens due to the increased friction force at the top/bottom sheet interfaces around the tip of punched hole through fretting; however, fatigue reduced the remaining static T peel strength of specimens due to crack initiation and development; T peel fatigue at high load levels also increased the stiffness of specimens due to geometry change through large plastic deformation.

1. Introduction

To increase fuel efficiency and reduce CO_2 emission, one efficient way is to reduce the weight of body-in-white structures of a vehicle. As a result, more and more lightweight materials like Al are increasingly used in automotive body structures. SPR is one of the main joining methods for aluminium automotive body structures and is popular for the environmental advantages of a cold joining process as well as, the ability to join similar and dissimilar materials, no requirement for pre-drilled holes and alignment, low energy requirement and high static and fatigue joint strengths [1–3]. A lot of research results on SPR have been reported, as to rivetability [4,5], rivet materials [6,7], rivet coatings [8], joint strength [9,10], rivet geometry [11], and joint dimensions [12,13]. Fatigue is a common phenomenon to be considered in any dynamic structure and understandably some research has been done on the fatigue properties of SPR joints intended for automotive applications [3,13–18]. Li and Fatemi [16] studied the T peel strength of Al specimens with different thickness combinations and found that crack formation locations and growth paths were dependent on the plate thickness combinations, applied load level, and load ratio. Research from Sun et al. [3] showed that the addition of structural adhesives could increase a joint's fatigue durability. They also found that material thickness and rivet inserting direction were other factors that could affect joint fatigue strength. Fu and Mallick [15] studied the fatigue strength of AA6111T4 joints. They presented that the rivet setting pressure influenced the static failure load, but not the fatigue life, and their results also showed that the sequence of loading influenced the fatigue life. Some research activities have focused on the fretting damage of SPR joints during fatigue processes [14,17,18]. The results from Han et al. [17] showed that solid lubricant, wax, on the material surface can reduce the fretting damage and subsequently increase fatigue strength. However, the detail of crack initiation and development, in SPR joints, has not yet been reported.

Stiffness of an automotive body-in-white structure is very important as to whether a vehicle being designed will offer the required performance [19,20]. If the stiffness is insufficient, the vehicle will have large vibration on the road or have large deformation in turns or when it is loaded. As a result, the driving performance, riding comfort, and consequently customer satisfaction of the vehicle will be affected. Apart from stiffness, the remaining static strengths of vehicle structures during using stage are also important for vehicles' safety and performance. Fatigue is a common phenomenon for a vehicle, and such that understanding the influence of fatigue on joint stiffness and remaining static strengths will be crucial for understanding the influence of fatigue on vehicles' performance during using stage. However, the influence of fatigue on the performance of self-piercing riveted structures has not been publically reported.

In this paper, the crack initiation and development mechanisms of SPR joints during fatigue were analysed, and the influence of fatigue on the stiffness and remaining static strengths of SPR lap shear and T peel joints was studied.

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2. Experimental procedure

2.1. Materials

The material used in this study is commercially available 2.0 mm thick AA5754 with a standard pretreatment (PT2) and wax lubricant (AL070). The compositions of AA5754 are listed in Table 1. The AA5754 has UTS of 241 MPa, yield strength of 110 MPa and elongation of 25%.

2.2. Sample preparation

For all stacks, steel rivets with a countersunk head and mechanical zinc/tin surface coating were used. The rivets were supplied by Henrob Ltd., and all samples were produced using a Henrob servo-driven riveting equipment. A rivet/die/velocity combination, as listed in Table 2, was selected to achieve good joint quality. Joint quality of specimens was inspected through cross-sections before mechanical tests. A special fixture was used to ensure all joints were vertically cross-sectioned through the center of the rivets in transverse direction. Following sectioning, the joint features were measured and analyzed with respect to rivet head height, interlock and remaining bottom material thickness using the a4i image analysis software supplied by Aquinto.

Specimen geometries and dimensions for lap shear and T peel tests are shown in Figs. 1 and 2. During the preparation of specimens, coupons were cut from sheet such that the longitudinal direction of coupons (loading direction during following mechanical tests) coincides with the rolling direction of sheet metal. To reduce any variations of rivet position, custom designed fixtures were used to set rivets into correct positions. For each specimen, the coupon width was fixed at 48 mm, and two rivets were set with an edge distance of 11.5 mm.

2.3. Mechanical tests

Mechanical tests were conducted by following company standards. Custom designed lightweight aluminium grips were used for fatigue tests to reduce inertia and increase the fatigue machine's response speed. These grips were specially designed for lap shear fatigue tests so that the gripping surfaces of the two fixed jaws from the upper and lower grips (in opposite sides) were aligned along the joint interface, with no spacers needed. When the two fixed jaws were turned to the same side, in combination with internal spacers, the same grips can also be used for T peel fatigue tests. Load-controlled fatigue tests were performed on a close-loop servo hydraulic testing machine using a sinusoidal waveform and in tension–tension mode. The ratio of the minimum load and the maximum load or *R* ratio was 0.1 and the test frequency was 15 Hz in all the tests. Three or four load levels, with different values of maximum load or load amplitude (half of the difference between a maximum load and a minimum load) were used in the tests. The maximum loads for fatigue were determined according to the maximum loads obtained previously through static tests. For lap shear, the values of the maximum loads used ranged from 30% to 80% of the maximum loads obtained from static tests. As the maximum loads that could be sustained in T peel fatigue were much lower than those in static tests, 20–50% of the maximum loads obtained from static tests were used. The failure criterion for fatigue was fracture of the specimens.

Some specimens were terminated in the middle of fatigue tests at different stages. Parts of terminated specimens were cross-sectioned for crack initiation and growth study, and the rest were tested for static strengths to see the influence of fatigue and cracks on remaining static strengths and stiffness. A bench top Instron with cross-head speed of 10 mm/min was used for the static tests, and in order to minimize coupon bending during lap-shear testing, 2 mm thick spacers were applied at both ends of the lap-shear samples. The fracture interfaces of the specimens after static tests were then analyzed using a Zeiss Sigma scanning electron microscope (SEM) to study the growth of cracks during fatigue.

Table 1
Nominal compositions and mechanical properties of AA5754.

Nominal compositions (balance Al), wt%								
Mg	Mn	Cu	Fe	Si	Ti	Cr	Zn	Others
2.6–3.6	0–0.5	0–0.1	0–0.4	0–0.4	0–0.15	0–0.3	0–0.2	0–0.15

Table 2
Optimum SPR parameters for (2 + 2)AA5754 stack-up.

Rivet	Length: 6.5 mm; type: countersunk; hardness: ~410 Hv
Die	Cavity diameter: 9 mm; cavity depth: 2 mm; type: flat bottom
Velocity	100 (Henrob unit, determining applied force)

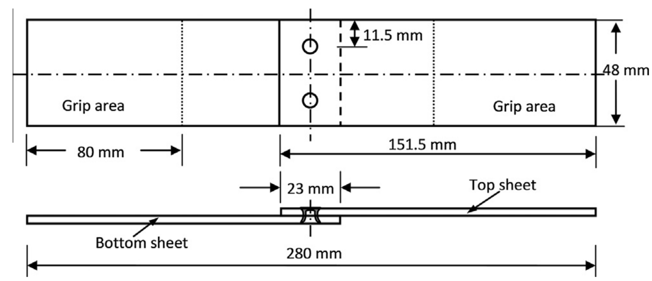

Fig. 1. Specimen geometry for lap shear tests.

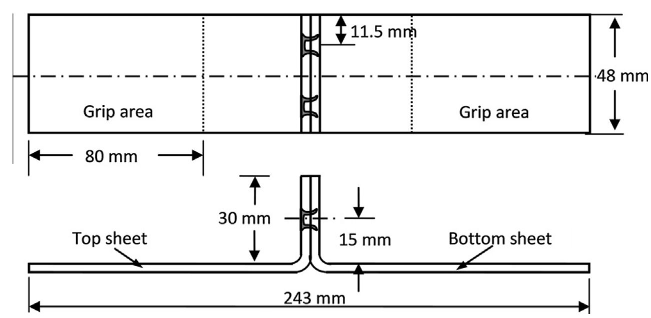

Fig. 2. Specimen geometry for T peel tests.

3. Results

3.1. SPR joint quality

Fig. 3 shows a cross section of the typical SPR joints studied in this paper. The SPR joint quality attributes have been annotated and these are rivet head height of −0.13 mm, an average interlock of 0.77 mm, and a minimum remaining bottom material thickness of 0.33 mm.

3.2. Lap shear and T peel fatigue strength of SPR joints

Fatigue results showed that the average lap shear fatigue lives of the specimens were in the order of 600,000, 90,000 and 20,000 cycles when the applied maximum loads were 3.5 kN, 5.5 kN and 8 kN, respectively and the average T peel fatigue lives