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Fatigue Strength Evaluation of Multi-Point Self-Piercing Riveted Joints of Al6061 and Cold-Rolled Steel Sheets

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ABSTRACT

Self-piercing riveting (SPR) is considered an environmentally friendly joining method with high static and fatigue strengths. This study aimed to assess the static and fatigue strengths of SPR joints with different numbers of rivets. The experiment utilized Al-6061 plates as the upper plate and cold-rolled steel sheet as the lower plate. In terms of static strength, the maximum loads for the SPR joints were measured as 4,211.9N, 14,128.1N, and 18,908.4N for the 1-point, 3-point, and 5-point tensile-shear specimens, respectively. To evaluate fatigue strength, a fatigue limit based on 1 million cycles was assumed. The fatigue limits of the tensile-shear specimens with 1, 3, and 5 points were found to be approximately 31.7%, 21.1%, and 17.7% of their respective static strengths. Interestingly, regardless of the number of rivets, the fatigue lifetimes of the SPR joint specimens could be accurately determined using the von-Mises stress criterion.

Key words: SPR joint (SPR), multi-point, fatigue strength, von-Mises stress

INTRODUCTION

To address the recent regulations on automobile fuel efficiency and emissions, automotive manufacturers are seeking to reduce the weight of vehicle bodies. To achieve this goal while maintaining the necessary strength and stiffness, it is necessary to join dissimilar material plates, such as aluminum and magnesium alloy plates, to a steel frame [1]. Traditional spot welding is commonly used for vehicle body joining, but it becomes challenging when joining with dissimilar materials due to their differing melting points.

To overcome this challenge, automotive manufacturers have turned to the SPR method. SPR is a mechanical joining technique that provides a permanent joint between dissimilar materials. One major advantage of SPR is that it is a non-heat-treated joining method, allowing for environmentally friendly joining without damaging the appearance or plating of the materials. Moreover, SPR offers ease of automation in production and helps reduce overall production costs [2].

Numerous studies [3-8] have been conducted to investigate the static and fatigue strengths of SPR joints using various materials. These studies have primarily focused on evaluating the joining strengths of SPR joints by considering different process variables such as rivets, dies, materials, and punch loads. For instance, Miyashita et al. examined the fatigue strength of two types of hybrid SPR joints, where AM50 magnesium alloy was joined by incorporating an adhesive bonding in addition to the conventional SPR joint [5]. The study revealed that the hybrid SPR joints with adhesive bonding exhibited improved static and fatigue strengths compared to general SPR joints. Furthermore, they observed that controlling the adhesive joint gap, which occurs due to plate deformation during the SPR process, can enhance the strength of the joint. In another study by Kang et al., the fatigue strength and lifetime of SPR joints using Al-5052 plates were evaluated using coach-peel, cross-tension, and tensile-shear specimens [8]. They found that the effective stress intensity factor, commonly employed to predict the lifetime of spot-welded joints, was also applicable for predicting the lifetime of SPR joints.

These studies, along with others in the field, contribute to a better understanding of the static and fatigue behavior of SPR joints, providing valuable insights for optimizing the joining process and improving the overall performance of SPR joints in various applications. The majority of studies conducted on SPR joints have focused on evaluating the static and fatigue strengths of single-point SPR joints. Typically, fatigue strength evaluations of SPR joints have been conducted using a load amplitude as a parameter. However, it becomes challenging to predict the static and fatigue strengths when there are variations in SPR processing conditions, such as rivet shape and size, or variations in plate thickness. Therefore, there is a need for a fatigue lifetime parameter that can accurately predict the fatigue strength of SPR joints under different conditions.

In this particular study, the fatigue strength of multi-point SPR joints was evaluated using a tensile-shear specimen. The experimental setup involved joining an upper plate made of Al6061 and a lower plate made of cold-rolled steel using SPR. Both static strength and fatigue strength tests were conducted on these joints to assess their respective static and fatigue strengths. To derive a suitable parameter for evaluating the fatigue strength of multi-point SPR specimens, structural analysis was performed, taking into consideration the maximum principal stress, maximum principal strain, and von-Mises stress. By incorporating these analyses and parameters, this study aims to provide a comprehensive understanding of the fatigue behavior of multi-point SPR joints. The derived parameter has the potential to improve the prediction and assessment of fatigue strength in SPR joints under a range of processing conditions, enhancing the reliability and efficiency of SPR joining in practical applications.

PREPERATION AND TEST METHOD OF THE SPECIMEN

Fabrication of the SPR test specimen

For the purposes of this study, static and fatigue strength test specimens were fabricated using 1.5mm thick Al6061 and cold-rolled steel (SPCC) plates. The mechanical properties of these materials are summarized in Table 1. Fig. 1 illustrates the configuration of the tensile-shear specimen, which consisted of 1, 3, and 5 SPR joints. The dimensions of the specimen can be found in Table 2. To join the specimen, carbon steel rivets (0.35 wt.%) provided by Henrob Co. were utilized. These rivets had dimensions of 5mm in length and 5.3mm in shank diameter.

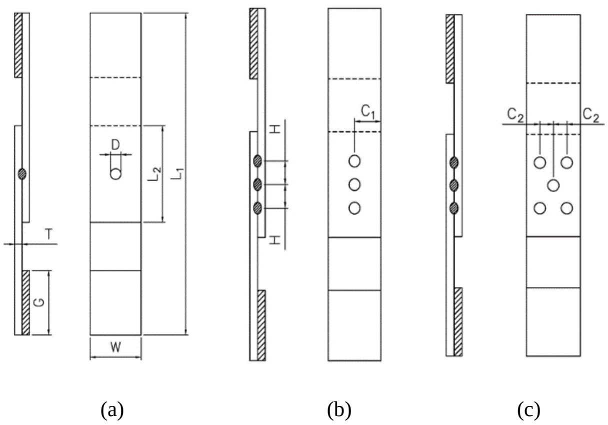


Fig. 1 Geometric and dimensions of three SPR tensile-shear test specimens with; (a) 1 point, (b) 3 points, and (c) 5 points

Table 2 Dimensions of tensile-shear test specimens

Items	Dimension (mm)
W	48
L_1	300
L_2	90
T	1.5
D	7.7
G(grip)	60
H	20
C_1	24
C_2	12

The method of fatigue test

The SPR joints were tested for static and fatigue strengths using a servo hydraulic universal testing machine (Instron 8516) with a 10-ton capacity. The fatigue tests were conducted at a frequency of 4 Hz, employing a sinusoidal waveform with a stress ratio R (=P_{min}/P_{max}) of 0.1. The infinite lifetime was defined as 1 million cycles.

Structural analysis modeling

To conduct the structural analysis of the SPR joints in this study, a modeling process was undertaken. The joints consisted of an upper plate, a lower plate, and a rivet. Initially, the cross-section of the SPR joint was cut, and this cross-section was then drawn using AutoCAD. Subsequently, 3D modeling was performed using HyperMesh to create the Finite Element Analysis (FEA) model, as depicted in Fig. 2.

The structural analysis was carried out using ABAQUS explicit, employing C3D6 and C3D8R elements for the analysis. The load was applied to the upper plate, while the lower plate was fixed. A friction coefficient of 0.2 was assigned to the interface between the rivet and the plate, and a coefficient of 0.15 was set for the interface between the plates. By applying these modeling and analysis techniques, the structural behavior of the SPR joints could be investigated, providing valuable insights into their performance and potential failure modes under various loading conditions.

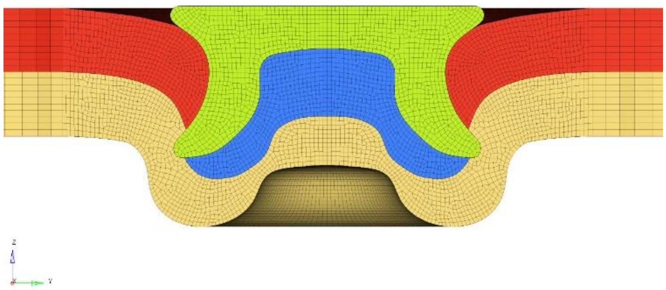


Fig. 2 3D FEA model of a SPR joint of the tensile-shear specimens

TEST RESULTS AND DISCUSSION

Optimal punch force for SPR joining

The strength of an SPR joint is influenced by several factors, including the punch force applied during the joining process, the size and shape of the rivet, and the thickness of the plate materials. To determine the maximum strength of the SPR joint, the optimal punch force was identified based on the static strength of the specimen. By utilizing the tensile-shear specimen with a single-point SPR joint, the punch force was varied, and the maximum static strength was measured. Fig. 3 illustrates the relationship between the punch force and the maximum static strength of the specimen.

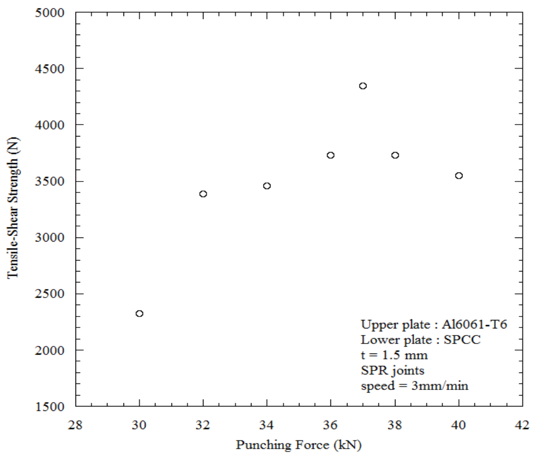


Fig. 3 Tensile strength variation with punch forces for tensile-shear SPR specimens

Observations indicated that when the punch force was set at 30 kN, it was slightly low. Consequently, the rivet head did not adhere completely to the upper plate, and the rivet was not entirely fixed to the lower plate. As the punch force increased gradually, the static strength improved, reaching its peak at a punch force of 37 kN. However, when the punch force exceeded 38 kN, excessive bending occurred on the aluminum upper plate, resulting in a decrease in static strength. Based on these findings, a punch force of 37 kN was determined to be the optimal value for SPR joining. Consequently, all static strength and fatigue strength evaluation specimens were fabricated using this punch force, ensuring consistency in the joining process and facilitating accurate comparisons and evaluations.

Static strength of SPR joints

To evaluate the static strength of the SPR joints, static strength tests were conducted three times for each tensile-shear specimen containing 1, 3, and 5 SPR joints. A punch force of 37 kN was applied for these specimens. The test results are presented in Fig. 4, illustrating the load and displacement. Based on the static strength tests conducted on the tensile-shear specimens, it was observed that the static strengths of the 1-point, 3-point, and 5-point SPR specimens were measured at 4,212N, 14,128N, and 18,908N, respectively. It was noted that the strength of the 3-point SPR specimen was approximately 3.3 times that of the 1-point SPR specimen, while the strength of the 5-point SPR specimen was approximately 4.5 times that of the 1-point SPR specimen. However, the increase in strength was not strictly proportional to the number of SPR points.

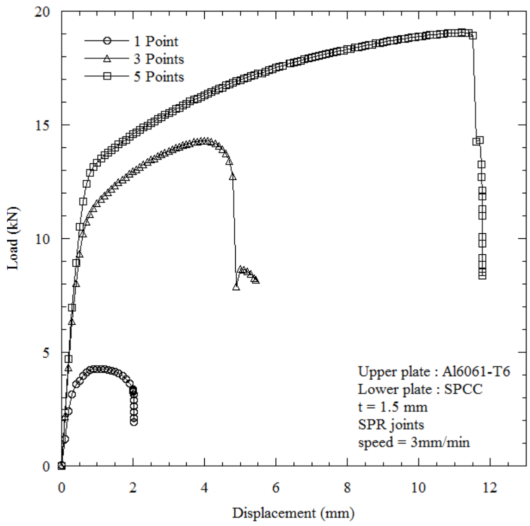


Fig. 4 Static load versus displacement curves for the three types of SPR specimens

In Fig. 4, it can be observed that the load of the 1-point SPR specimen increases with displacement until reaching a maximum static strength of approximately 4.2 kN. Subsequently, the rivet gradually separates, leading to a rapid reduction in load and eventual specimen failure. The 3-point SPR specimen exhibits a maximum static strength of around 14 kN, with the load increasing almost linearly to approximately 10 kN as the displacement increases. The rivet gradually separates, resulting in a rapid decrease in load. At this stage, the outermost rivet separates, and the rivet breaks. Further displacement application causes a slight increase in load, followed by a decrease, confirming complete separation of the upper and lower plates in the rivet joint. In the case of the 5-point SPR specimen, the maximum static strength is observed at approximately 19 kN as displacement increases. The load then increases linearly to about 12 kN and subsequently exhibits a nonlinear behavior. Afterward, the two rivets located at the outermost side in the axial direction of the load separate, followed by the separation of the remaining three rivets. Finally, the upper and lower plates of the rivet joint completely separate. These results provide insights into the static strength behavior of the SPR joints, showcasing the load-displacement relationship and the failure modes observed in different specimen configurations.

Fatigue lifetime of SPR specimens

The fatigue strength of the SPR joints was assessed by subjecting the specimens with 1, 3, and 5-point SPR joints to repeated tensile-shear load conditions. Fig. 5 presents the relationship between load amplitude and lifetime for the three specimens. For the tensile-shear specimen with a one-point SPR joint, the relationship with fatigue lifetime was determined to be $P_{amp} = 5{,}199N_f^{-0.098}$. Based on a lifetime of 1 million cycles, the load amplitude corresponding to the fatigue endurance limit was found to be 1,335 N, which corresponds to approximately 31.7% of the static strength (=4,212 N). Similarly, for the three-point SPR joint specimen, the relationship with tensile-shear fatigue lifetime was determined as $P_{amp} = 11{,}036N_f^{-0.095}$. The load amplitude corresponding to the fatigue endurance limit was 2,979 N, which corresponds to approximately 21.1% of the static strength (=14,128 N). Lastly, for the tensile-shear specimen with five-point SPR joints, the relationship with fatigue lifetime was determined as $P_{amp} = 48{,}395N_f^{-0.193}$. The load amplitude corresponding to the fatigue endurance limit was found to be 3,354 N, which corresponds to approximately 17.7% of the static strength (=18,908 N). These results highlight the load amplitudes at which the SPR joints can endure a specified number of cycles (1 million cycles in this case) before failure. It is evident that the fatigue endurance limit is a percentage of the corresponding static strength, and the relationship varies depending on the number of SPR points in the specimen configuration.

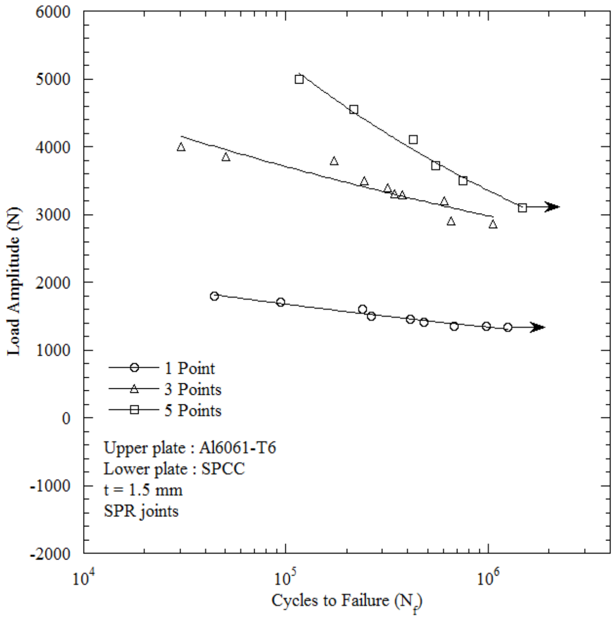
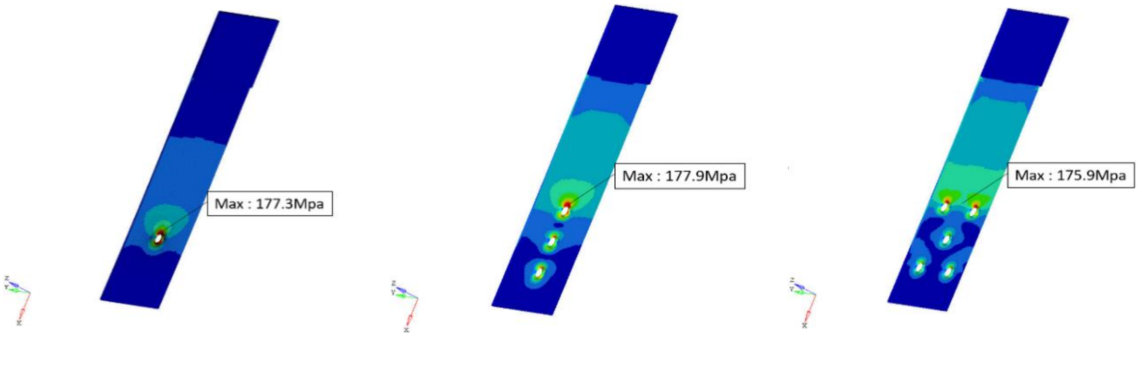


Fig. 5 Comparison of load amplitudes for the number of failure cycles of the SPR joints with different points

According to the fatigue evaluation on a one-point SPR specimen with an upper plate of Al-5052 and a lower plate of cold-rolled steel, the load amplitude corresponding to the fatigue limit of the tensile-shear specimen was determined to be 1,530 N, which is approximately 35.4% of the static strength (=4,320 N). This value is very similar to the previously mentioned fatigue ratio of 31.7% for a one-point SPR joint with the upper plate of Al-5052 and the lower plate of cold-rolled steel [9]. These findings indicate that the fatigue endurance limit of the specimen, where SPR was joined with three or five points within a certain width (=48 mm), did not increase proportionally with the number of SPR points compared to the one-point specimen. Therefore, it is crucial to establish the relationship between static strength and fatigue limit considering the number of SPR points and incorporate it into the design of automotive panels with SPR joints.

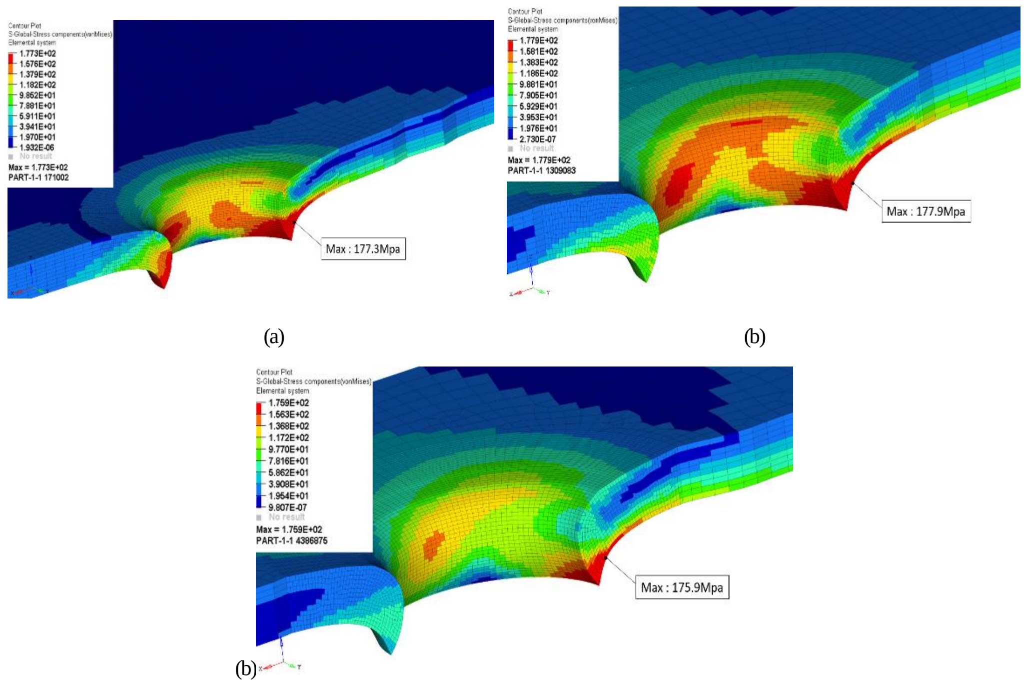
Structural analysis results of fatigue specimens

In order to assess the fatigue strength of the multi-point self-piercing riveted (SPR) joint between Al6061 and cold rolled steel plates, the structural analysis results were examined to determine the distribution of von-Mises stress (σ_{eq}), maximum principal strain (ε_1), and maximum principal stress (σ_1) around the rivet. Fig. 6 illustrates the location where the maximum von-Mises stress occurs in the SPR joint when the maximum load (P_{max}) is applied at the load amplitude corresponding to a fatigue life of 1 million cycles for the 1, 3, and 5-point SPR specimens. The maximum von-Mises stress values were observed to be 177.3 MPa, 177.9 MPa, and 175.9 MPa for the 1, 3, and 5-point SPR specimens, respectively. Irrespective of the number of rivets, the maximum von-Mises stress value remained similar, and it was concentrated in the rear part of the upper plate where it is joined to the neck part of the rivet. Specifically, in the case of the one-point SPR specimen (Fig. 7(a)), the maximum von-Mises stress was applied at the rivet part of the upper plate. For the three-point SPR specimen, as shown in Fig. 7(b), the maximum von-Mises stress was experienced at the rivet joint located at the outermost part of the upper plate. Similarly, in the case of the five-point SPR specimen, depicted in Fig. 7(c), the maximum von-Mises stress was observed at the two rivet joints situated at the outermost part of the upper plate.



(a) (b) (c)

Fig. 6 Maximum von-Mises stress location with an applied load (P_{max}) corresponding to 10^6 cycles fatigue life for the SPR specimens with; (a) 1 point, (b) 3 points and (c) 5 points



(c)

Fig. 7 Von-Mises stress distribution under a load (P_{max}) corresponding to 10^6 cycles fatigue life for specimens; (a) 1 point, (b) 3 points and (c) 5 points

Fatigue lifetime assessment through structural analysis

To assess and compare the fatigue lifetime of the multi-point SPR specimens of Al6061 and cold rolled steel plates, the structural analysis results of the 1-point, 3-point, and 5-point SPR specimens were analyzed using parameters such as von-Mises stress (σ_{eq}), maximum principal strain (ε_1), and maximum principal stress (σ_1).

Fig. 8 presents the fatigue lifetime as a function of von-Mises stress for the 1-point, 3-point, and 5-point SPR specimens. The evaluation of these specimens resulted in a correlation coefficient (R) of 0.91, indicating a strong relationship between fatigue lifetime and von-Mises stress. Fig. 9 displays the fatigue lifetime as a function of maximum principal strain for the 1-point, 3-point, and 5-point SPR specimens. The evaluation yielded a correlation coefficient (R) of 0.86, which is relatively lower compared to the von-Mises stress. Fig. 10 illustrates the fatigue lifetime as a function of maximum principal stress for the 1-point, 3-point, and 5-point SPR specimens. The evaluation of these specimens resulted in a correlation coefficient (R) of 0.76, which is also relatively lower compared to the von-Mises stress or maximum principal strain. Therefore, to assess the fatigue lifetime of joints where Al6061 and cold rolled steel plates are joined with SPR, it is recommended to adopt von-Mises stress or maximum principal strain as parameters. Additionally, it is crucial to gather more fatigue experimental data under various material combinations and load conditions to further evaluate the effectiveness of these parameters.

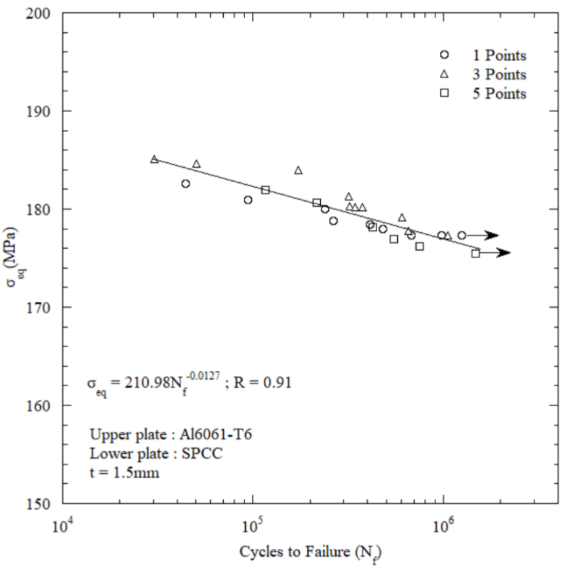


Fig. 8 Fatigue lifetimes of the SPR specimens as a function of von-Mises stress

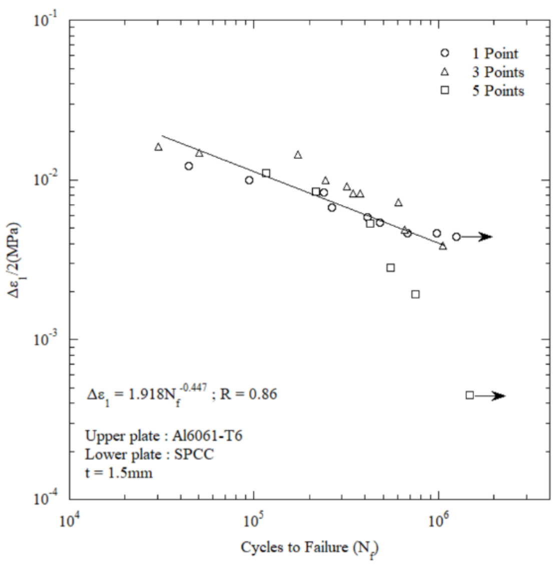


Fig. 9 Fatigue lifetimes of the SPR specimens as a function of maximum principal strain

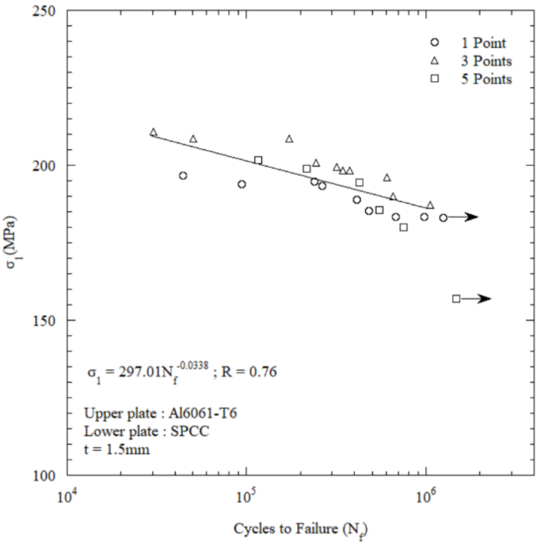


Fig. 10 Fatigue lifetimes of the SPR specimens as a function of the maximum principal stress

CONCLUTION

The static and fatigue strengths of tensile-shear multi-point SPR specimens were assessed using Al6061 and cold rolled steel plates. The static strength tests revealed maximum loads of 4.2 kN, 14.1 kN, and 18.9 kN for the 1-point, 3-point, and 5-point SPR joints, respectively. The fatigue limit, based on 1 million cycles of fatigue lifetime, was approximately 31.7% of the static strength for the one-point specimen, 21.1% for the three-point specimen, and 17.7% for the five-point specimen. Structural analysis was performed on the 1-point, 3-point, and 5-point SPR specimens using von-Mises stress, maximum principal strain, and maximum principal stress to evaluate the fatigue lifetime. The results indicated that von-Mises stress was the most suitable parameter for evaluating the fatigue lifetime. The relationship between von-Mises stress and fatigue lifetime is represented by the equation: $\sigma_{eq} = 211N_f^{-0.013}$. It is recommended to consider the von-Mises stress as a parameter for evaluating the fatigue lifetime of multi-point SPR joints in automotive panel design. Further studies are needed to gather fatigue experimental data for different material combinations and load conditions to validate the effectiveness of these parameters.

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