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Fatigue Strength Evaluation of Adhesive-Bonded and Self-Piercing Riveted Joints of Al-5052 and Cold Rolled Steel Sheets

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ABSTRACT

Self-piercing riveting (SPR) is a mechanical joining method that can reduce damage caused by processing to materials and save time by reducing processing steps. This research used SPCC as the lower plate and Al-5052 as the upper plate to form a tensile-shear specimen. After applying an adhesive between the upper plate and the lower plate to improve the bonding strength, static and fatigue strengths were evaluated. The average value of the static strength was derived after three tests. P_{max} was found to be 5,572N, and the fracture mode was shown to be separated into the upper and lower plates by pulling out the rivet after the adhesive initially failed. The load amplitude corresponding to the fatigue limit is P_{amp} = 1,213.6N. Compared to earlier results on SPR test specimens, it was found that the static strength increased and the fatigue strength decreased. In addition, one of the reasons for the lower fatigue strength is that the depth of the rivet is not applicable with regard to the thickness of the adhesive.

Key words: SPR joint (SPR), adhesive, tensile strength, fatigue strength, tensile shear

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INTRODUCTION

Recently, the problem of reduced fuel efficiency due to the increased weights of automobiles is drawing attention. Therefore, weight-focused research to increase fuel efficiency rates is becoming more important [1]. Bolting, spot welding, and self-piercing riveting (SPR) are used to join lightweight parts [2]. SPR is a simple mechanical joining method [3] capable of reducing material damage and the joining time, and it can be used to join different materials that cannot be spot-welded. On the other hand, the static and fatigue strengths of SPR joints differ depending on the changes in the material. Many studies of SPR joining with an adhesive have been being actively conducted. For example, Sun et al. manufactured tensile-shear and cross-tension-shaped specimens using Al alloys and steels and compared fatigue strengths after changing the order of the upper and lower plates, the thickness, and in the presence and absence of an adhesive [4]. Their study confirmed that an additional adhesive applied to a SPR joint specimen had an effect on the overall improvement of the fatigue strength. In addition, SPR showed improved fatigue strength compared to spot-welding. Wu et al. evaluated the fatigue strengths of SPR-bonded, adhesive bonded, and SPR-adhesive specimens using the AA6111-T4 material [5], finding that the SPR-bonded specimen showed the best fatigue strength. In addition, cracks occurred at some distance near the rivets of most test specimens and grew, and for the tensile-shear specimens, fractures near the rivet other than adhesive fractures were not observed. Based on their test results, in the case of SPR-bonding when using the J-integral, an appropriate correlation of the fatigue life could be obtained from the specimen. Kim et al. evaluated the fatigue strength of a hybrid SPR joint specimen with a SPR joint and an adhesive using SPRC 440 and Al-5J32 [6], finding that the hybrid SPR joint specimen showed static strength greater by more than 20% compared to the SPR joint specimen. In addition, the fatigue strength showed an excellent improvement of more than 160%. Miyashita et al. evaluated the fatigue strength of the SPR method in tensile-shear specimens and in SPR joint specimen to which an adhesive was applied using an AM50 magnesium alloy [7]. They found that SPR with the adhesive applied showed a static strength nearly 200% better than that of the SPR alone. The fatigue strength was reduced by approximately about 40%. In this case, the fatigue strength was low because the adhesive thickness was not uniform when the specimen was manufactured, and a suitable thickness with high strength was not applied. They concluded that the adhesive should be uniformly and appropriately applied.

Many studies have been conducted while focusing on SPR thus far, but not many have sought to determine the fatigue strength capabilities of hybrid SPR specimens to which adhesives are applied to various materials. Here, Al-5052 as the upper plate and a SPCC material as the lower plate were used in conjunction with a tensile-shear specimen. In addition, the effects of the adhesive on the fatigue and static strength levels of the specimen were evaluated by applying an adhesive between the SPR joints. The test results of this study were compared to the results from a SPR joint alone [8] and it was found that a difference arose when the adhesive was applied.

PREPERATION AND TEST METHOD OF THE SPECIMEN

Fabrication of the SPR test specimen

The specimen used in this study, a tensile-shear specimen, is shown in Fig. 1. Given that there is no official specification for the specimen, the specimen specifications were determined to evaluate the bonding strength of spot welding [9]. The applied materials were Al-5052, with t = 1.5 mm for the upper plate and with SPCC on the lower plate, again with t = 1.5 mm. In addition, Huntman's two-liquid epoxy was applied between the upper and lower plates. The rivet used is the C5040 type manufactured by Henrob, with a diameter and length of about 5 mm and made of carbon steel (0.35 wt.%). The punching load during the riveting process was 37 kN, which considered appropriate considering a trade-off between the deformation of the upper plate and the bonding strength [8]. However, on the top of the rivet, the thickness of the adhesive is not uniform due to deformation, as shown in Fig. 2. Therefore, to apply the adhesive to a uniform thickness, it was fixed as shown in Fig. 3 and hardened for 24 hours. At this time, the thickness of the adhesive was ensured to be 0.1 mm, as that value showed the best joining during the tensile-shearing process [10].

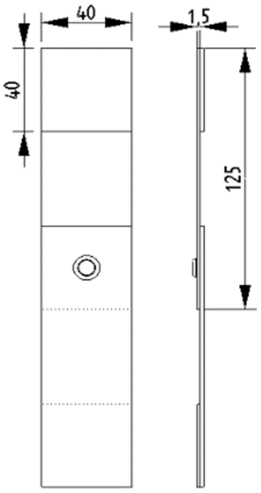


Fig. 1 Geometric and dimensions of the tensile-shear SPR specimen

Fig. 2 Lower joint part shape of after riveting

Fig. 3 Jig for fixing and adhesive hardening of the tensile-shear specimen

The method of fatigue test

A five-ton fatigue testing machine was used to evaluate the static and fatigue strengths of the tensile-shear SPR specimen. The direction of the load applied to the specimen is shown in Fig. 4. Regarding the static strength, the evaluation was conducted at a rate of 3mm/min, and for the fatigue strength, a stress ratio (R=P_{min}/P_{max}) of 0.1, a sine wave, and a frequency of 2-5 Hz were utilized, with 10^6 cycles defined as an infinite lifetime.

Fig. 4 Force direction of the static and fatigue test of the tensile-shear specimen

TEST RESULTS

Static strength of tensile-shear specimens

The static strength evaluation was conducted, and the average maximum load was P_{max} = 5,572N. According to Kim's study [9], the static strength of a SPR joint specimen of the identical material and shape was found to be P_{max} = 4,300N. Compared to this study, the adhesive-aided SPR joint shows improved static strength by 22.8%. It was also observed that the maximum load was very well dispersed due to the adhesive.

For the static strength graph in Fig. 5, the static strength is highest before the adhesive failed, and after the adhesive failed, the static strength decreased rapidly, with the load gradually increased and then failing to the SPR bonding function. It was also noted that the load is dispersed and the bonding strength increases due to the effect of surface adhesion by the adhesive, whereas after the adhesive failed, the load became concentrated on the rivet and the strength was lower than that of the surface adhesion. In addition, the reason for the difference in the static strength for each test is that the shape and rivet joint position varied slightly each time when riveting the specimen. Therefore, for the above reasons, it was found that the deformation on the upper plate slightly varies for each specimen, that the thickness of the adhesive varies slightly, and that the thickness of the adhesive is uneven on all sides, thus affecting the static strength.

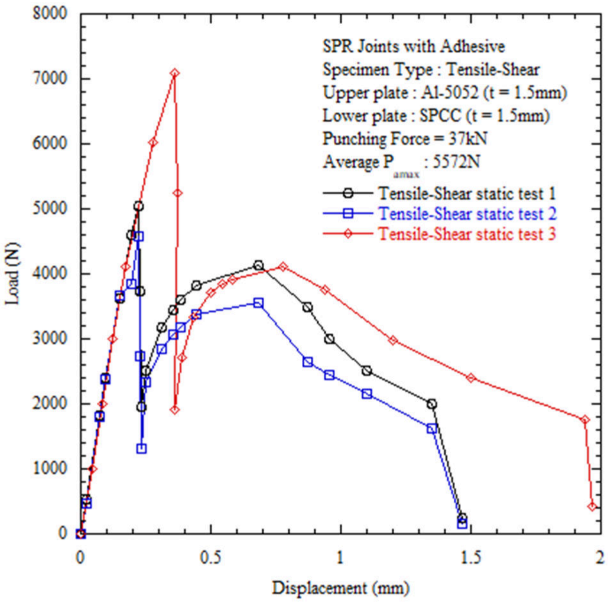


Fig. 5 Static load versus displacement curves for tensile-shear SPR specimen

Evaluation of fatigue life of tensile-shear specimens

Table 1 summarizes the results of the fatigue lifetime for the load amplitude in consideration of the fracture criteria of the specimen in this study. In addition, the relationship between the load amplitude (P_{amp}) and the fatigue life (N_f) is shown in Figure 6. The fatigue endurance limit of the tensile-shear specimen is based on 10^6 cycles, and the fatigue limit load amplitude is P_{amp} = 1,213.6N. In addition, the relationship between the load amplitude and fatigue life was found to be $P_{amp} = 9534.1{N_f}^{-0.1492}$. According to Kim's study [9], the fatigue limit for SPR joint specimens using the identical shapes and materials used here is based on 10^6 cycles, and the fatigue limit load amplitude is P_{amp} = 1,530N. When comparing the fatigue strength of the adhesive-aided SPR joint specimen and the SPR joint specimen, the result of the former was reduced by about 20%. Hence, when an adhesive is applied and the specimens are riveted during the manufacturing process, the depth of the rivet does allow the rivet to reach the level of thickness of the adhesive, as shown in Fig. 7. As a result, when the load is concentrated on the rivet after the adhesive joint fails during the fatigue test, the rivet depth does not match that of the SPR joint specimen and it does not function. Moreover, the limit of the load the rivet can withstand is reduced. In addition, during the fatigue test, it was observed that the rivet could easily be pulled out before the material is damaged, and the fatigue limit is reduced.

Table 1 Summarized fatigue test results

Spec. Num.	P_{amp} (N)	N_f (cycles)
1	1,666	186,706
2	1,560	229,221
3	1,504	201,051
4	1,449	333,830
5	1,389	460,637
6	1,300	468,328
7	1,281	497,688
8	1,254	695,683
9	1,243	550,434
10	1,226	1,357,541
11	1,111	>2,071,893

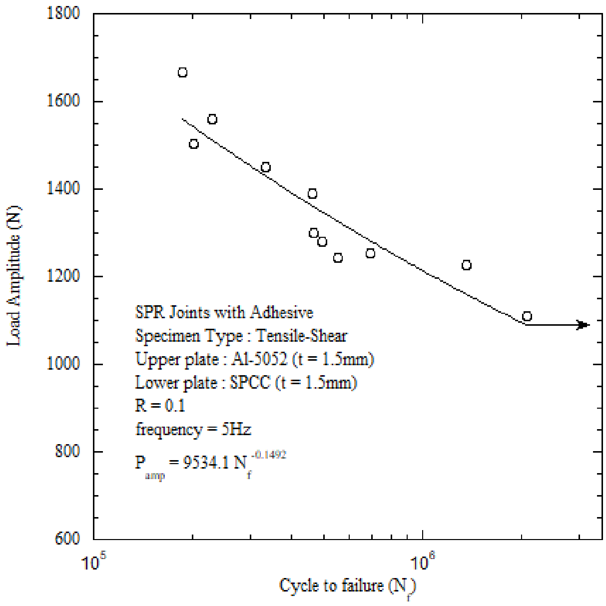
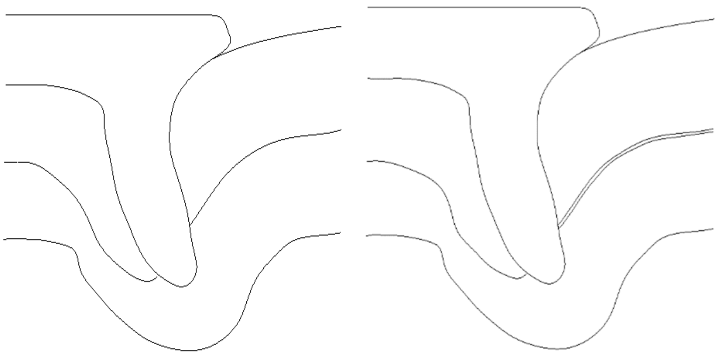


Fig. 6 Load amplitude against the number of fatigue cycles for the tensile-shear specimen



(a) **(b)**

Fig. 7 Cross-section of the SPR joint: (a) SPR and (b) adhesive-aided SPR

Fatigue fracture surfaces analysis

For the tensile-shear specimen, it was observed that the upper plate and lower plate were separated via a fracture. The fracture of the tensile-shear specimen was defined as a fracture when the upper plate and lower plate were separated. First, it was observed that the adhesive surface on one side was fractured, as shown in Fig. 2, at around 30,000 to 40,000 cycles during the fatigue test. The fractured part is the part where the deformation of the upper plate that occurs after riveting during the manufacturing of the specimens becomes hardened when using the adhesive and a jig, as shown in Fig. 3. However, it was also observed that it could be easily fractured due to a complex load such as spring-back or a tensile load occurring in the deformed part. In addition, after part of the adhesive surface fractured, as shown in Fig. 8, bearing stress and fretting occurred near the head of the rivet, and continuous tensile stress occurred on the opposite part, resulting in a pull-out fracture. In this study, various fatigue failure forms of the SPR joint specimen were not found, and only pull-out forms were observed. When examining the shape and process of this type of fracture, the load is dispersed due to the bonding by the adhesive, and the load received on the material is reduced. However, it was found that a pull-out fracture occurs more easily due to the fretting that occurs near the head of the rivet and the tensile stress that occurs on the opposite part. In addition, a pull-out fracture was found to occur more readily because the presence of the adhesive meant that the depth of the rivet was not as deep as that of the SPR joint specimen.

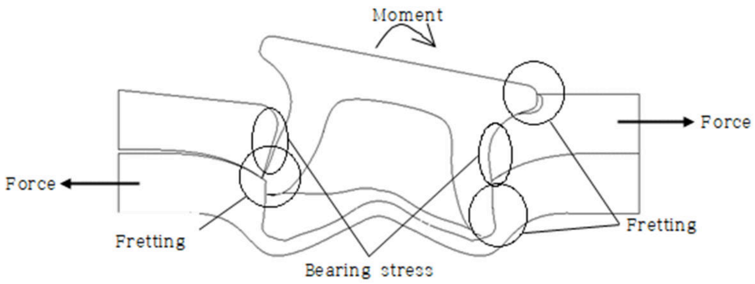
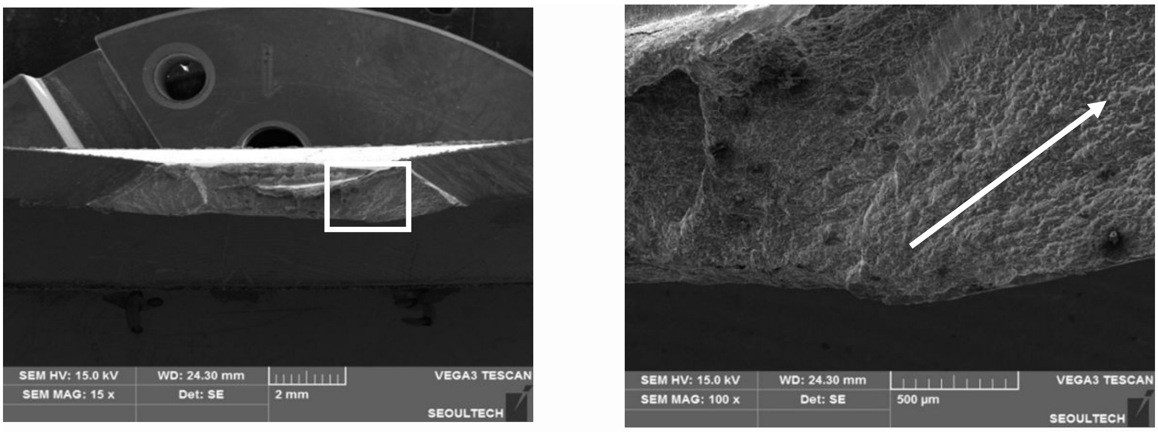


Fig. 8 Fatigue failure mode of the tensile-shear specimen

In addition, the fracture surface of the specimen was observed using a scanning electron microscope (SEM, TESCAN VEGA3). The fatigue fracture specimen was observed by applying the load amplitude P_{amp} = 1,226N, as shown in Fig. 9. Fig. 9(a) shows the overall appearance of the fracture surface, and an enlarged image of the displayed part is shown in Fig. 9(b). Here, cracks are shown to grow in the direction of the arrow shown in Fig. 9(b), and the final fracture occurs.



(a) (b)

Fig. 9 Upper plate fracture surface applied load with P_{amp} = 1,226N: (a) fracture surface view and (b) enlarged marked area

CONCLUTION

This study evaluated the fatigue strength of a SPR tension-shear joint specimen in which the upper plate is Al-5052 and the lower plate is SPCC, with an adhesive applied to the joint. The results are summarized below.

1. A static strength test found that the average maximum load was 5,572 N. In addition, the highest static strength was found before the adhesive was fractured, after which the load was concentrated on the rivet and a pull-out fracture occurred.
2. Crack generation and fractures were observed in the upper plate of Al-5052 with low strength during the fatigue test. In addition, shortly after the test, the lower part of the adhesive on the bonding surface was fractured, and the load was concentrated on the rivet and the upper adhesive. In addition, it was observed that bearing stress and fretting occurred and that cracks arose with the sample then fracturing.
3. The static strength of the SPR joint specimen was P_{max} = 4,300N and the static strength of the adhesive-aided SPR joint specimen was P_{max} = 5,572N, showing an increase of 29%. In addition, the fatigue limit of a typical SPR joint specimen was P_{amp} = 1,530N, and the fatigue limit of an adhesive-aided SPR joint specimen was P_{amp} = 1,213.6N, which was lower by 20%.
4. The reason for the reduced fatigue limit is related to the depth of the rivet, which could not be applied deeper than that of the SPR joint specimen during riveting due to the adhesive applied to the SPR joining surface. Accordingly, the fatigue limit is considered to be low. Therefore, it is considered that a bonding load considering the thickness of the adhesive is required when manufacturing SPR specimens to which an adhesive has been applied.

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