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Yoshihiko Uematsu

`uematsu.yoshihiko.z3@f.gifu-u.ac.jp`

Gifu University: Gifu Daigaku <https://orcid.org/0000-0003-4161-3738>

Taisuke Sato

Gifu University: Gifu Daigaku

Nobuki Hirooka

Fudow Co. Ltd.

Asami Nakai

Gifu University: Gifu Daigaku

Akio Ohtani

Kyoto Institute of Technology: Kyoto Kogei Sen'i Daigaku

Daisuke Ogawa

Gifu Prefectural Industrial Technology Center

Yoshiki Mizutani

Gifu Prefectural Industrial Technology Center

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CFRP/Al dissimilar friction stir spot welding assisted by steel mesh sheets and evaluation of fatigue properties

Yoshihiko Uematsu^{1*}, Taisuke Sato², Nobuki Hirooka³, Asami Nakai¹, Akio Ohtani⁴,
Daisuke Ogawa⁵, Yoshiki Mizutani⁵

1 Department of Mechanical Engineering, Gifu University, 1-1 Yanagido, Gifu 501-1193, Japan

2 Graduate School of Natural Science and Technology, Gifu University, 1-1 Yanagido, Gifu 501-1193, Japan

3 Fudow Co. Ltd., 2-15-16 Shin-Yokohama, Kohoku-ku, Yokohama-City, Kanagawa 222-0033, Japan

4 Department of Advanced Fibro-Science, Kyoto Institute of Technology, Matsugasaki, Sakyo-ku, Kyoto 606-8585, Japan

5 Gifu Prefectural Industrial Technology Center, 1288 Oze, Seki-shi, Gifu 501-3265, Japan

*Corresponding author: Yoshihiko Uematsu

Department of Mechanical Engineering
Gifu University,

1-1 Yanagido, Gifu 501-1193, Japan

Tel: +81-58-293-2501

E-mail: uematsu.yoshihiko.z3@f.gifu-u.ac.jp

Abstract

Lap joints between A6061 aluminum (Al) alloy and CFRP plates were fabricated using a friction stir spot welding (FSSW) technique. A stainless steel wire mesh sheet was hot pressed on the CFRP plate before joining as an assisting interlayer. Al alloy plate was successfully joined to CFRP plate through steel wire mesh, because Al and Fe easily formed intermetallic compound as a bonding layer. Three kinds of meshes, Type316L single layer mesh (316SL), Type316L double layer mesh (316DL) and Type329J1 single layer mesh (329SL), were used to optimize joint strength. Tensile shear tests and fatigue tests were conducted using the fabricated CFRP/Al joints. By using steel mesh sheets, the tensile strengths were nearly doubled compared to the direct joining between CFRP and Al. The tensile shear strengths depended on the mesh strengths, where 316DL showed the highest strength. However, all of the three joints exhibited comparable fatigue strengths in spite of the different static properties of steel meshes. Fractographic and cross-sectional analyses revealed that both static and fatigue fractures initiated within the CFRP adjacent to the interface prior to the fracture of the steel mesh. The matrix resin within about 200 μm of the interface was thermally degraded by the welding heat input, and the fracture occurred along the thermally damaged zone containing voids.

Keywords: Friction stir spot weld, Dissimilar joint, CFRP, Aluminum alloy, Fatigue

1. Introduction

In recent years, there has been a strong demand for reducing the weight of transportation vehicles and mechanical parts in order to reduce greenhouse gas

emissions and energy consumption. Therefore, non-ferrous metals such as aluminum (Al) alloys and polymer materials such as carbon-fiber-reinforced plastics (CFRP) are being used in various industrial fields in place of steel materials [1,2]. Considering the different costs and properties of these different materials, it is effective to apply them partially to the areas where their properties are appropriate, that is, to use the right materials in the right places. Achievement of such multi-material structures requires joining between different materials. In particular, it is difficult to directly join metallic and non-metallic materials such as Al alloys and CFRP. Currently, mechanical fastening using bolts and rivets, or adhesive bonding is the major joining method between Al alloy and CFRP [3,4]. However, mechanical fastening requires large fastening loads and causes a weight increase, while adhesive bonding needs long curing times. To overcome these problems, various welding-based joining processes have also been investigated for metal/CFRP and metal/thermoplastic hybrid structures [5–10]. In the present study, friction stir spot welding (FSSW), which is a solid-state welding process [11,12] and has been put into practical use mainly for Al alloy plates [13–16], was applied to the joining between Al alloy and CFRP plates. Because FSSW is suitable for the joining between dissimilar metals, it has also been applied to Mg alloys [17], to steels [18], and to the dissimilar joining between Al and steel sheets [19–23]. Furthermore, FSSW does not require large applied load and can weld in a shorter time than adhesive bonding. There are a few studies in which FSSW was applied to the joining between Al and CFRP [24,25]. Ogawa et al. [24] successfully joined A6061-T6 and CFRP, and reported that hydrogen bonding between Al and CFRP surfaces is the major mechanism of the joining. Therefore, joint strength was dependent on the surface conditions of polymers [24,25]. For example, joint strength between Al and PPS (polyphenylene sulfide) is

smaller than that between Al and PP (polypropylene) because the hydroxyl group, which induces hydrogen bonding, is less abundant on the PPS surface. To obtain good joint strength, special surface treatment should be applied to PPS to increase the hydroxyl group on the surface. In contrast, the joining between Al and steel by FSSW is much easier and has been widely succeeded because Al and Fe can easily form intermetallic compounds, which act as a bonding layer [19–23,26]. In the present study, therefore, we proposed a newly-developed joining process between CFRP and Al with the assistance of the steel wire mesh.

In general, it is important to understand the fatigue behavior of the joints, because stress concentration at the welded part results in the fatigue failure of weld structures. The fatigue behaviors of FSSW joints have been reported for similar Al alloy joints [27] and dissimilar metal joints such as Al alloy/steel [28–30]. However, there are few reports on the fatigue behavior of dissimilar FSSW joints between CFRP and Al alloys [24,25]. Therefore, in the present study, we fabricated a lap joint of CFRP and A6061-T6 plates using FSSW. At that time, we attempted to improve the joint strength by hot-pressing a steel wire mesh on the surface of the CFRP plate and joining it to the Al alloy plate through the steel wire mesh. Furthermore, the fatigue properties of the lap joints were investigated.

2. Experimental procedures

2.1 Materials

The test materials were Al alloy, A6061-T6, and CFRP plates with the thickness of 2 mm. To fabricate CFRP plate, prepreg of TEPEX dynalite 207-C200 (Bondlaminates) with thermoplastic PPS matrix was used. 12 prepregs were hot pressed to form 2 mm thick plate. As schematically shown in Fig. 1(a), steel wire mesh was set on the outermost layer during the hot press process to form hybrid structure of CFRP and steel mesh. Figure 1(b) is a cross-sectional view of the hybrid structure, showing a steel wire mesh on the CFRP plate. The materials for the steel wire mesh were austenitic stainless steel Type316L and duplex stainless steel Type329J1. In terms of the material properties according to JIS (Japan Industrial Standard), duplex stainless steel Type329J1 has higher strength. The mesh has a steel wire diameter of 0.1 mm and a linear density of 100 steel wires per inch. Two types of Type316L meshes were tried, namely one has single-layered mesh and the other has double-layered mesh. Each material is hereinafter referred to as 316SL (single mesh), 316DL (double mesh), and 329SL. For comparison, we also prepared samples that were directly joined without using a steel wire mesh, and a total of four types of test samples were used.

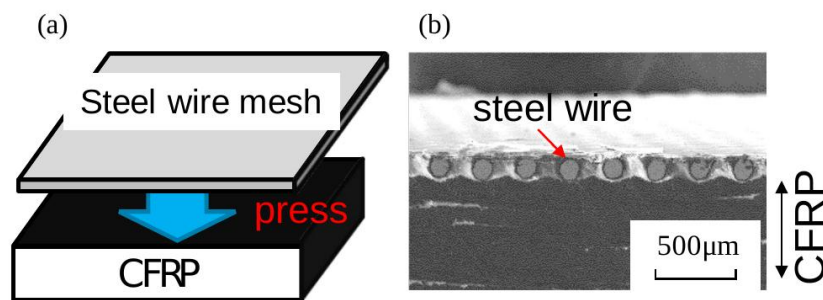


Fig. 1 (a) Schematic illustration of the hot pressing process of the steel wire mesh on the CFRP plate, (b) cross-sectional view of the CFRP/mesh hybrid structure.

2.2 Welding conditions

The FSSW tool geometry is shown in Fig. 2. The tool shoulder has a diameter of 10 mm and a concave flat shape without probe. This tool is a modified version of a scroll grooved tool without probe, which was proposed for FSSW of Al sheets [15]. The joining parameters were optimized by preliminary tests, and the tool rotational speed was 2000 rpm, the hold time was 5 s, and the penetration depth was 1.2 mm. The tensile and fatigue test specimen geometry is shown in Fig. 3. The plates with the width of 30 mm and the length of 110 mm were cut from each base plate of A6061-T6 and CFRP. Subsequently, Al and CFRP plates were put on the upper and lower sides, respectively, with the overlapping area of 30 mm $\times$ 40 mm. FSSW was performed at the center of the overlapping area. To estimate the strength of the steel wire meshes themselves, specimens with the configuration shown in Fig. 4 were cut from the steel wire meshes and subjected to tensile tests. An optical microscope (OM) and a scanning electron microscope (SEM) were used to observe the fracture surfaces. In addition, chemical composition analyses were performed at the joining area by an SEM equipped with an electron probe micro analyzer (EPMA) device.



Fig. 2 Geometry of the FSSW tool.

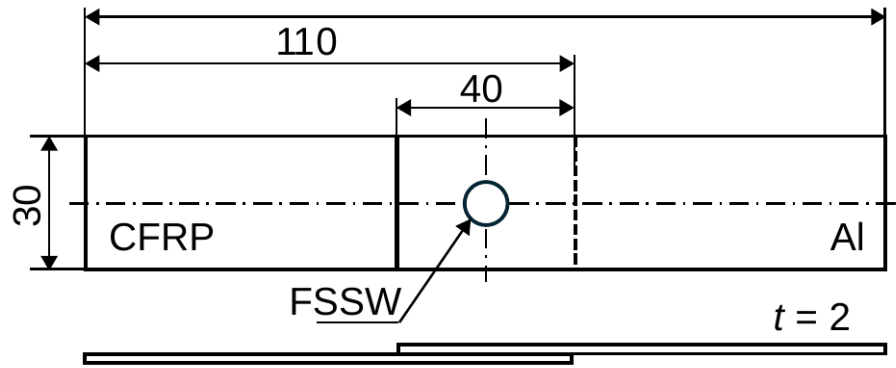


Fig. 3 Configuration of the tensile shear and fatigue test specimen.

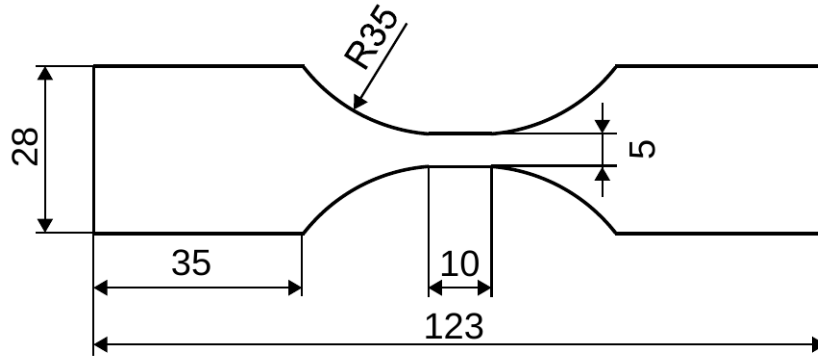


Fig. 4 Configuration of the tensile test specimen of the steel wire mesh.

2.3 Test procedures

Tensile and fatigue tests were performed using a Shimadzu electro-hydraulic servo fatigue testing machine. The load waveform for the fatigue test was a sine wave with a stress ratio of $R = 0.1$ and a frequency of $f = 20$ Hz.

3. Results and discussion

3.1 Microstructures

Figure 5 shows the cross-sectional structure of the weld (nugget) of 316SL material. Tool indentation marks can be seen on the Al plate (upper side). It can also be seen that a steel wire mesh is present at the interface between the Al plate and CFRP. Fiber bundles can also be seen on the CFRP side. Figure 6 shows the interface between the steel wire and Al at high magnification, and analyzing the Fe and Al components with EPMA. A region of about 1 μm in which both Fe and Al were detected was confirmed at the interface. This means that it is believed that an intermetallic compound layer of Fe and Al has formed at the interface, bonding the steel wire mesh to the Al [26]. Meanwhile, it is believed that the interface between the steel wire mesh and CFRP is mechanically bonded, with the steel wire embedded in the matrix resin during hot pressing.

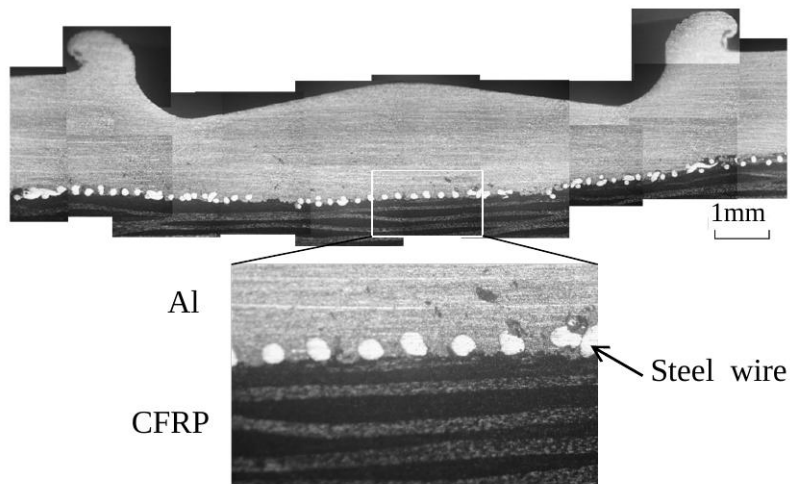


Fig. 5 Cross section of the nugget of the 316SL joint.

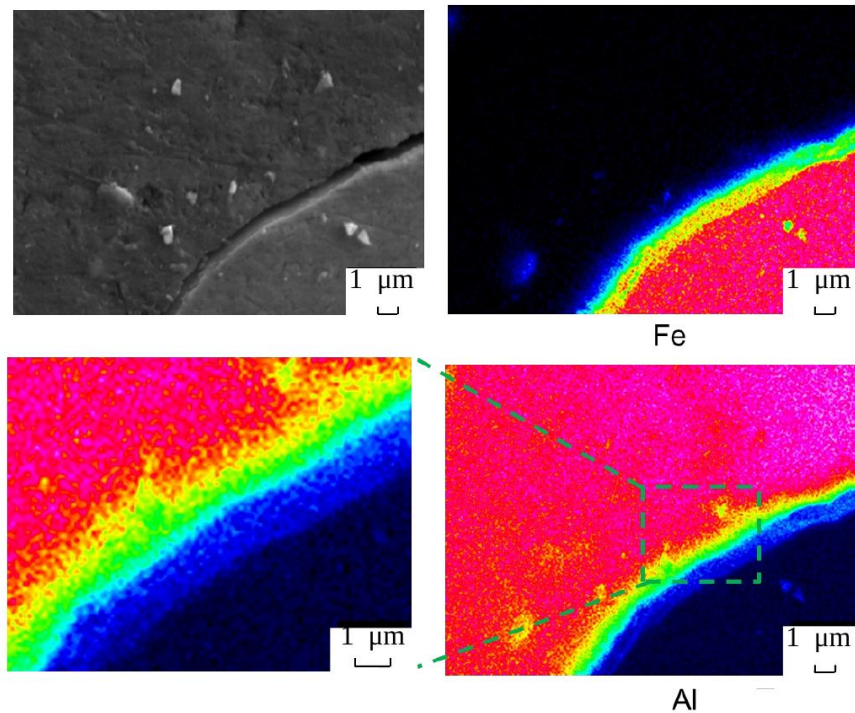


Fig. 6 SEM micrograph and EPMA analyses of Fe and Al at the interface between the steel wire and the Al plate.

3.2 Tensile tests

Figure 7 shows the load-crosshead displacement curves in a tensile test of a single steel wire mesh. The final breaking loads were 52, 93, and 100 N for 316SL, 316DL, and 329SL materials, respectively. When comparing single meshes, Type329J1 is stronger than Type316L, and the strength of the material is reflected in the mesh strength. When the material is the same Type316L, the breaking load of the double mesh is about twice that of the single mesh, and it also has greater elongation. With double mesh, the single meshes are layered with a 45° phase difference, which is thought to be why not only the breaking load but also the elongation is larger.

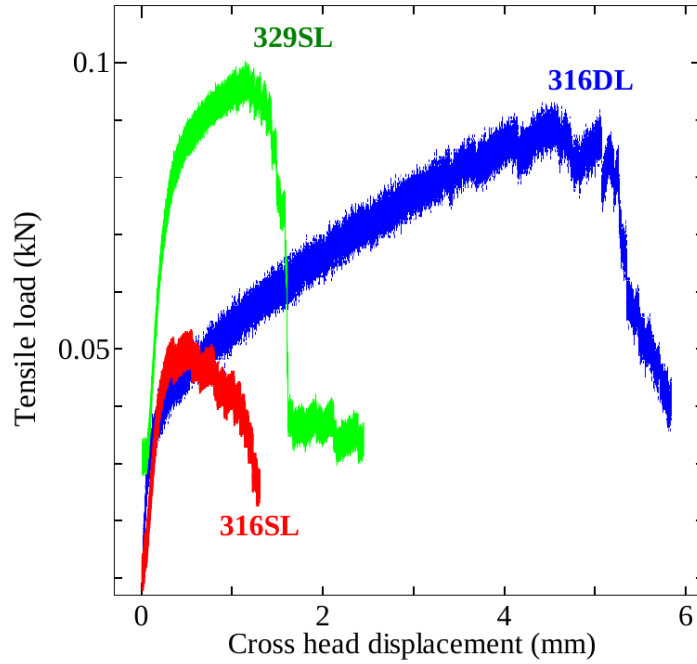


Fig. 7 Load–crosshead displacement curves of the steel wire mesh specimens.

The tensile shear load of the lap joints is shown in Fig. 8. Four tests were performed for each joint, and the average value was used. The tensile shear loads were 1.75, 2.15, and 1.70 kN for 316SL, 316DL, and 329SL materials, respectively. The strength of Type316L improved by changing the single mesh to a double mesh, but the increase was only about 23%. In addition, the joint strengths of 316SL and 329SL were similar, and no clear correlation was found between the strength of the steel wire mesh and the strength of the joint. On the other hand, when an Al plate and CFRP were directly FSSW-jointed without using a steel wire mesh and a tensile test was performed, the breaking load was 0.89 kN. In other words, the breaking load was increased by about two times by using a steel wire mesh, indicating that the presence of the steel wire mesh greatly contributes to improving the strength.

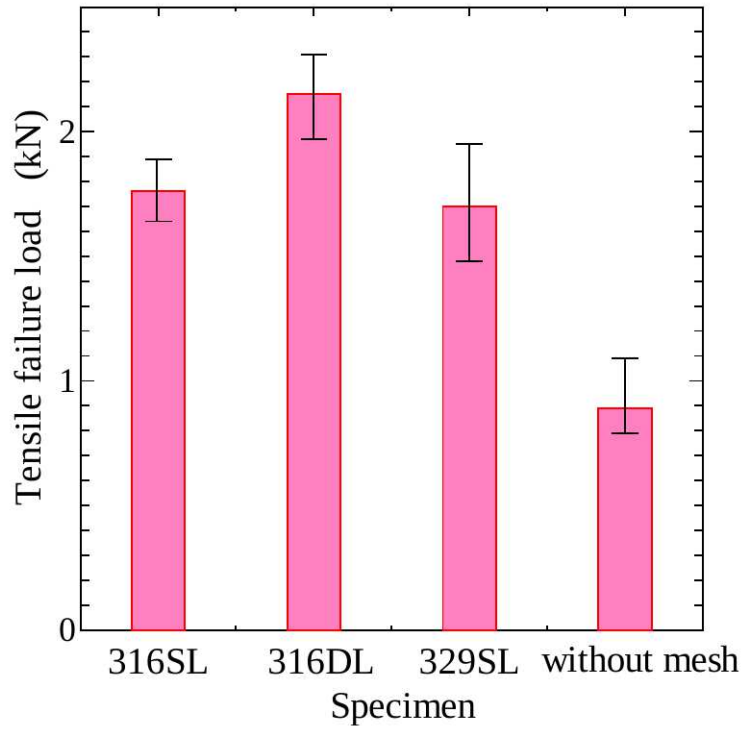


Fig. 8 Tensile shear loads of the CFRP/Al joints.

Figure 9 shows examples of fracture surfaces of 316SL material after tensile tests. Figures 9a and 9b show the results of observations on the Al side and the CFRP side, respectively. It should be noted that the fractured steel wire mesh and CFRP remain on the fracture surface of the Al side, and the corresponding parts on the CFRP side are hollowed out. In other words, as shown in Fig. 10, the steel wire mesh and Al plate remain joined at the nugget part, and the upper and lower plates are finally separated due to the fracture inside the CFRP and the fracture of the steel wire mesh. This fracture morphology was the same regardless of the type of steel wire mesh. From the above results, it is considered that the interface strength between Al and steel wire mesh, and between the steel wire mesh and the CFRP itself is high, but the CFRP is thermally damaged by the heat input during FSSW, and the fracture occurred at the damaged part. On the other hand, Fig. 11 shows the fracture surface appearance of an Al-CFRP directly bonded joint without the steel wire mesh. A small amount of CFRP remains on the Al side (Fig. 11a),

but its area is smaller than that in Fig. 9a. Also, as in Fig. 9b, the CFRP side (Fig. 11b) has a concave fracture surface, and it is thought that fracture occurred in the thermally damaged area of the CFRP, as in Fig. 9.

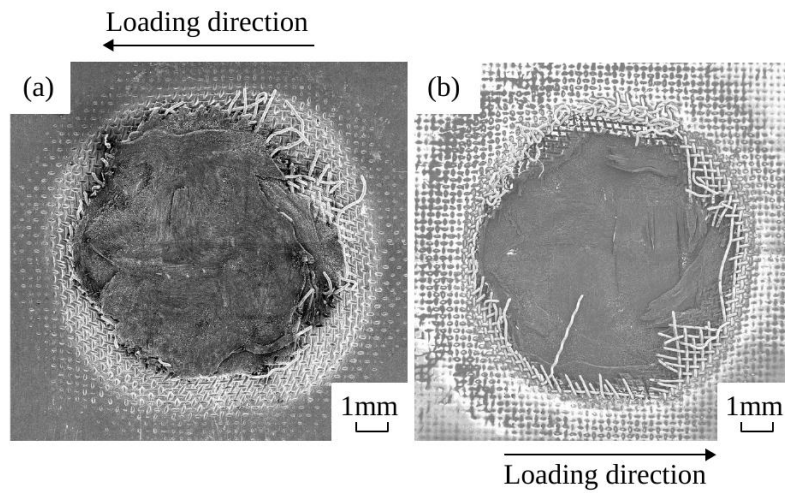


Fig. 9 Fracture surfaces of the 316SL joint after the tensile shear test: (a) Al side; (b) CFRP side.

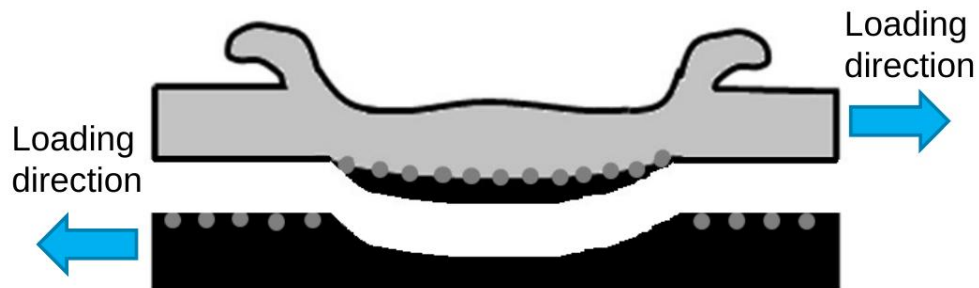


Fig. 10 Schematic illustration of the fracture path in the joint.

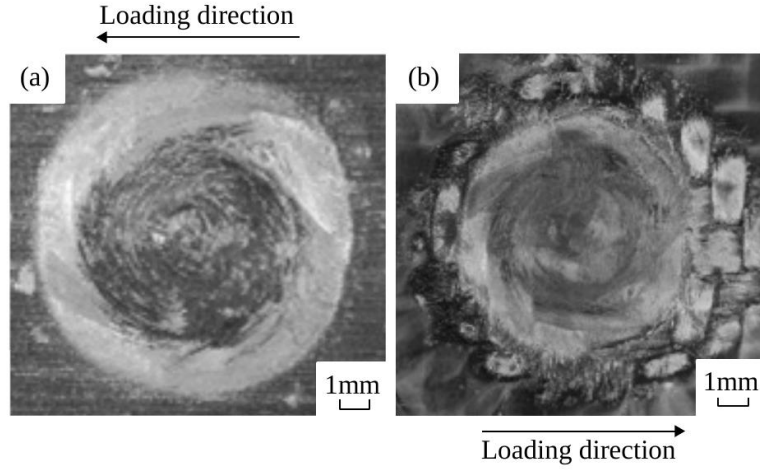


Fig. 11 Fracture surfaces of the directly joined CFRP/Al joint after the tensile shear test: (a) Al side; (b) CFRP side.

3.3 Fatigue strengths

Figure 12 shows the relationship between the maximum load $P_{\max}$ and the number of cycles to failure N_f in the fatigue test. Note that fatigue tests were not performed on Al-CFRP directly bonded joints that did not use steel wire mesh because their static strength was low. Although there was a large scatter in fatigue strength, when the fatigue limit was set at 10^7 cycles, $P_{\max}$ was approximately 0.75 kN. In static tensile tests, a clear difference in strength was observed between 316SL and 316DL. However, in fatigue tests, the static strength differences in the steel wire mesh caused by the difference in material and the use of double mesh almost disappeared, and all joints had approximately the same fatigue strength.

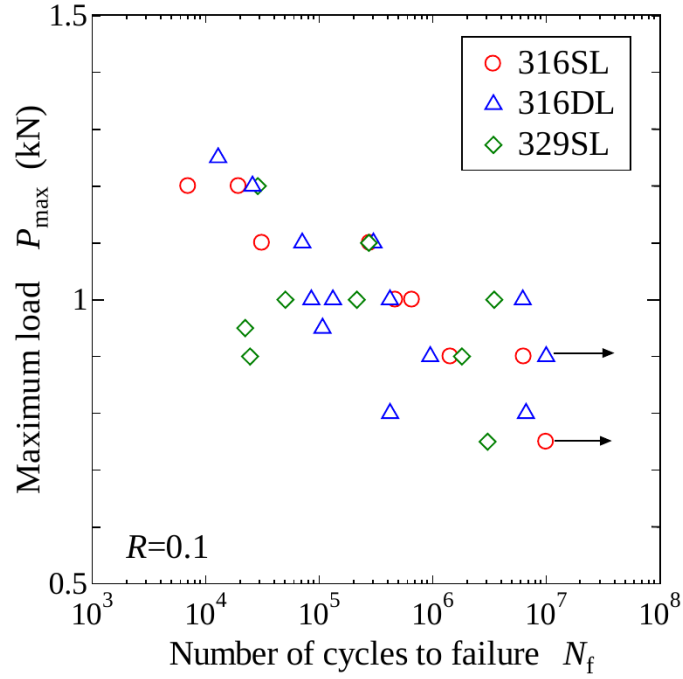


Fig. 12 Relationship between the maximum load P_{max} and the number of cycles to failure N_f of the joints.

The fatigue fracture surface appearance of the 316SL material is shown in Fig. 13. The fracture surface appearance is almost the same as the static one (Fig. 9), with the steel wire mesh and CFRP remained on the Al side (Fig. 13a), and a corresponding recess remaining on the CFRP side (Fig. 13b). In other words, the fracture path is the same for static and fatigue fracture, as shown in the schematic diagram of Fig. 10.

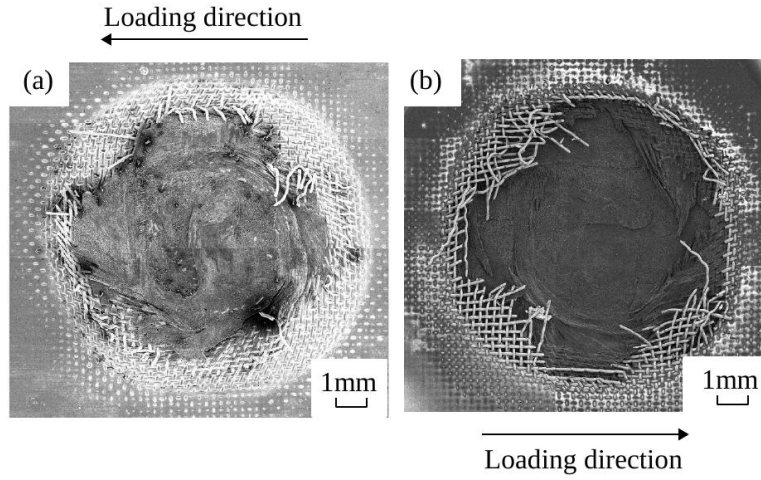


Fig. 13 Fatigue fracture surfaces of the 316SL joint: (a) Al side; (b) CFRP side. $P_{\max} = 1\text{ kN}$, $N_f = 6.6 \times 10^5$.

A fatigue interruption test was conducted to confirm the progression of fatigue fracture over time. A fatigue test was conducted with 316SL material at $P_{\max} = 1\text{ kN}$, and the test was interrupted when the load decreased to 0.94 kN. The nugget part of the interrupted test piece was cut in the longitudinal direction of the test piece to confirm the state of internal fracture. The results are shown in Fig. 14. From the figure, it can be seen that a crack had occurred in the CFRP part directly below the steel wire mesh in the nugget part. However, fracture of the steel wire mesh could not be confirmed at this point. From the above observation results, it is considered that fatigue fracture first occurs in the thermally damaged part of the CFRP in the nugget part, and then the steel wire mesh breaks, leading to the final separation of the upper and lower sheets.

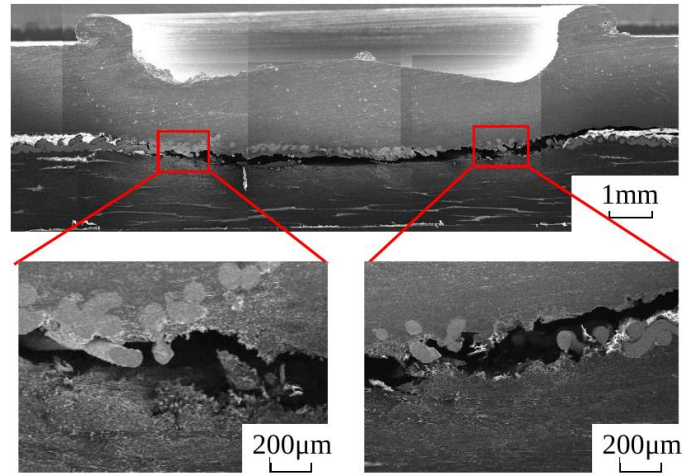


Fig. 14 Cross section of the nugget of the 316SL joint interrupted during the fatigue test at $P_{\max} = 1$ kN.

3.4 Contribution of the steel wire mesh to the joint strength

As described in section 3.2, no clear correlation was found between the strengths of the steel wire meshes themselves and the tensile shear loads of the joints. The load-carrying capacity of the mesh within the nugget can be estimated from the tensile test results of the mesh specimens. The diameter of the nugget is approximately 10 mm, corresponding to the tool shoulder diameter, and thus the effective width of the steel wire mesh which can carry the applied load is about 10 mm. Since the width of the parallel part of the mesh specimen shown in Fig. 4 is 5 mm, the load-carrying capacity of the mesh within the nugget is roughly estimated by doubling the fracture load of the mesh specimen. Table 1 summarizes the estimated load-carrying capacities of the meshes together with the tensile shear loads of the joints. The estimated capacities, 0.10, 0.19 and 0.20 kN for 316SL, 316DL and 329SL, respectively, are only 6–12% of the corresponding joint strengths. Furthermore, the increase in the tensile shear load from the directly joined joint (0.89 kN) to the mesh-assisted joints (1.70–2.15 kN) is much larger than the load-carrying capacities

of the meshes.

To quantify the effect of the steel type, the mesh load-carrying capacity and the joint strength are compared on a normalized basis. Relative to 316SL, the fracture load of the mesh itself was 79% higher for 316DL and 92% higher for 329SL, whereas the tensile shear load of the joint changed by only +23% for 316DL and −3% for 329SL. Expressed as a nominal shear strength over the nugget area (10 mm in diameter, 78.5 mm²), the single-mesh joints gave almost identical values of 22.3 MPa (316SL) and 21.7 MPa (329SL) in spite of the 92% higher mesh strength of 329SL, while the double mesh (316DL) gave a modestly higher 27.4 MPa; the directly joined joint gave only 11.3 MPa. Thus a 79–92% change in the mesh capacity produced at most a 23% change in the joint strength, which quantitatively demonstrates that the joint strength is largely decoupled from the mesh strength and is instead governed by a mesh-independent interfacial capacity of about 22 MPa that is set by the CFRP adjacent to the interface.

Table 1 Estimated load-carrying capacities of the steel wire meshes within the nugget and tensile shear loads of the joints.

Mesh type	Fracture load of mesh specimen (N)	Estimated load-carrying capacity in the nugget (kN)	Tensile shear load of the joint (kN)
316SL	52	0.10	1.75
316DL	93	0.19	2.15
329SL	100	0.20	1.70

These results indicate that the steel wire mesh improves the joint strength not by carrying the applied load itself, but by acting as a bonding interlayer between the Al plate and the CFRP. The mesh is rigidly bonded to the Al plate through the Fe–Al intermetallic compound layer, while it is mechanically interlocked with the matrix resin, being embedded during the hot pressing. The applied load is then transferred to the CFRP over the whole nugget area through the mesh. Since the fracture occurs within the CFRP near

the interface as discussed in section 3.3, the joint strength is governed primarily by the strength of the CFRP adjacent to the interface rather than by the strength of the mesh itself. This could explain why the static and fatigue strengths of the joints were insensitive to the steel type and the number of the mesh layers.

3.5 Thermal damage of CFRP induced by welding heat input

As discussed above, both static and fatigue fractures initiated within the CFRP adjacent to the interface. Figures 15, 16 and 17 show the cross sections of the CFRP plate before hot pressing, after the hot pressing of the steel wire mesh and after FSSW joining, respectively. Large defects (voids) were recognized only after FSSW (Fig. 17), revealing that the voids were induced not by the hot pressing but by the welding process. The voids became drastically smaller beyond the second ply from the interface. Since the thickness of one ply is approximately 90 μm , the fracture would occur within about 180 μm from the interface if the fracture path follows the voids. The thickness of the CFRP layer remaining on the Al side fracture surface was measured to be 100–200 μm , which is in good agreement with the above estimation. Consequently, it is concluded that the heat input during FSSW thermally degraded the matrix resin and induced voids in the CFRP near the interface, and that both static and fatigue fractures occurred along the thermally damaged zone containing the voids. It also implies that the joint strength could be further improved by reducing the heat input during welding, which is a subject for future work.

These quantitative results point to a generic design principle for mesh-assisted FSSW of CFRP: because the joint strength is set by the thermally degraded CFRP layer within about 180 μm of the interface rather than by the mesh, the most effective route to higher

strength is to reduce the welding heat input (for example, by lowering the tool rotational speed or shortening the hold time) so as to thin this degraded layer, rather than to increase the mesh strength. A systematic study in which the heat input is varied to establish the quantitative relationship between the degraded-layer depth and the joint strength would be a valuable next step.

The strength-governing thermally degraded layer can thus be quantified: the welding-induced voids and the fracture were confined to the first two plies from the interface, that is, within about 180 μm (at 90 μm per ply), which corresponds to only about 9% of the 2 mm thickness of the CFRP. In other words, the load capacity of the whole joint is controlled by a thin surface layer of the CFRP that is thermally degraded during welding.

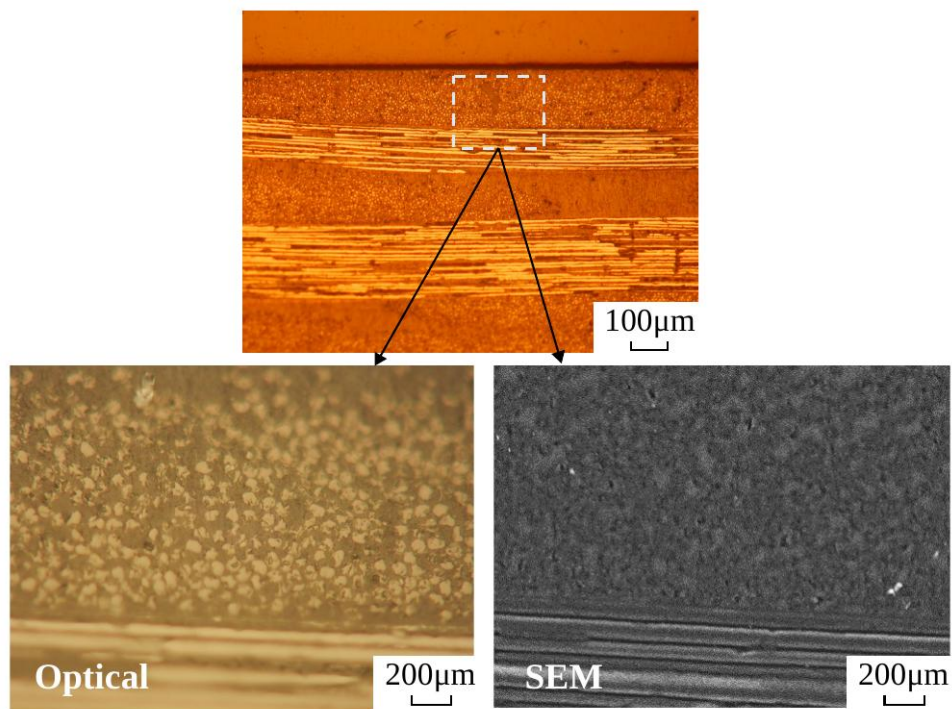


Fig. 15 Cross sections of the CFRP plate before hot pressing.

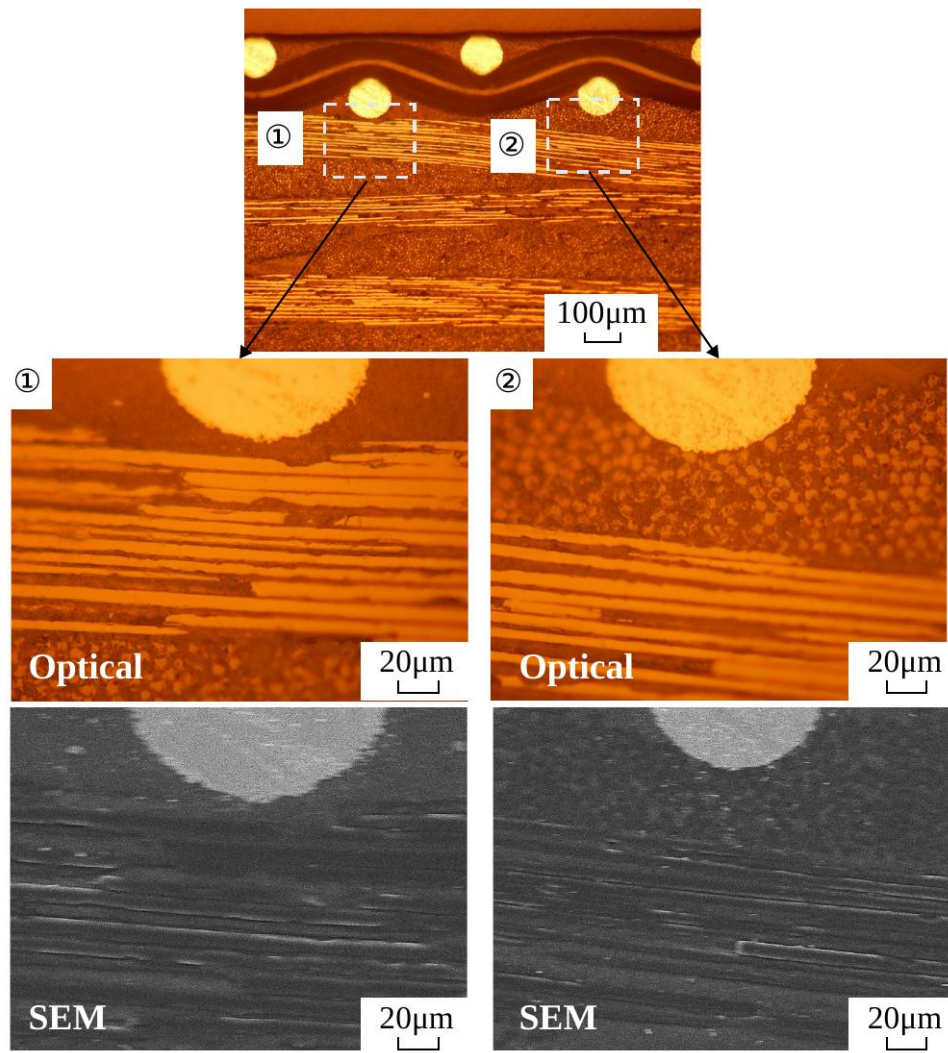


Fig. 16 Cross sections of the CFRP plate after hot pressing.

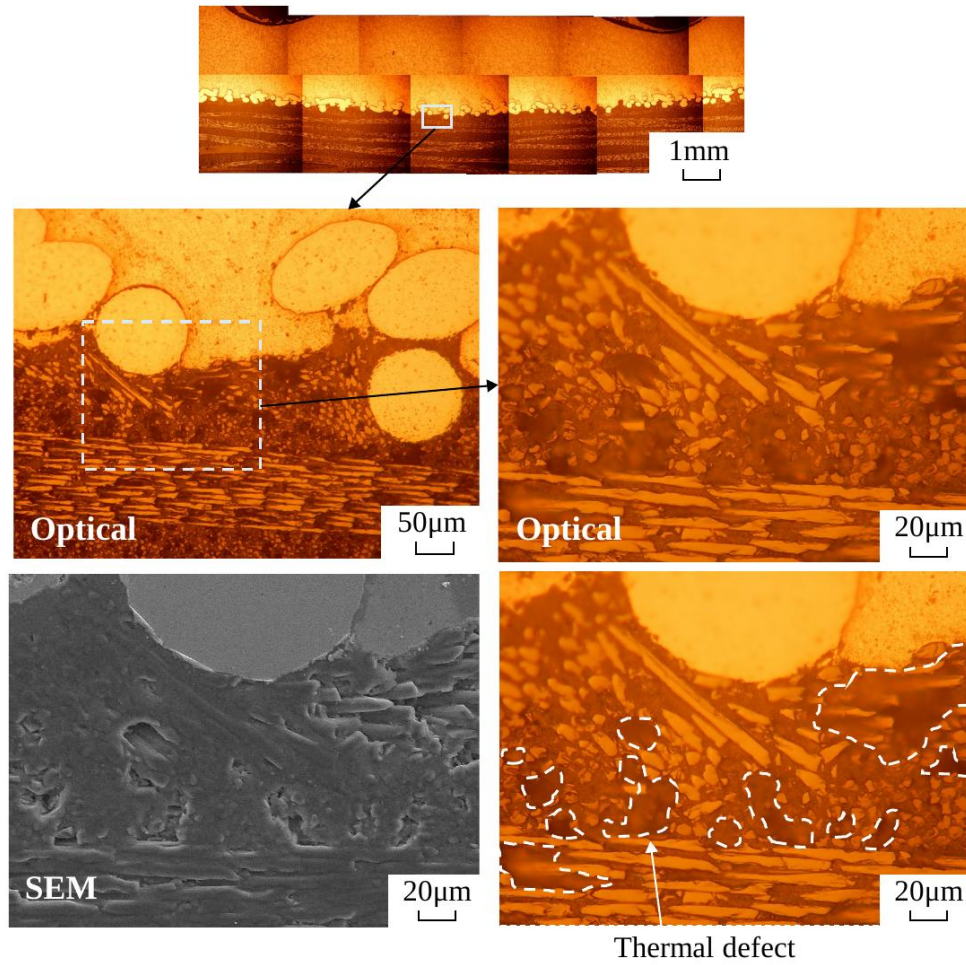


Fig. 17 Cross sections of the CFRP plate after FSSW joining.

3.6 Advantages of the proposed joining process

Finally, the advantages of the proposed mesh-assisted FSSW process are summarized. Firstly, an Al alloy plate can be joined to a CFRP plate without any special surface treatment of the CFRP. In the direct joining between Al alloys and polymers, the joint strength strongly depends on the chemical conditions of the polymer surface, and special surface treatments are required for some matrix resins such as PPS [5,24,25]. In the present process, the substantial bonding is achieved between the steel wire and the Al

plate through the Fe–Al intermetallic compound layer, and consequently the joining is possible regardless of the type of the matrix resin. Secondly, the proposed process is suitable for large structures. In this study, the steel wire mesh was hot pressed onto the entire surface of the CFRP plate. However, when the process is applied to actual structures, thin and flexible steel wire meshes could be placed only at the appropriate locations where the spot joints are required, before the press forming of a relatively large CFRP component. The weight increase due to the meshes is negligibly small, in contrast to mechanical fastening. Thirdly, since FSSW is a solid-state and short-time welding process, the proposed process requires neither the large fastening loads of mechanical fastening nor the long curing times of adhesive bonding.

4. Conclusions

In this study, spot joining of Al alloy plates and CFRP plates was performed using friction stir spot welding (FSSW). Steel plate meshes with different strength levels were sintered onto the CFRP plate by hot press forming, and the effect of the steel type on increasing the strength of the joint was evaluated. Three types of steel wire meshes were used: Type316L single mesh, double mesh, and Type329J1 single mesh. Tensile and fatigue tests were performed using the obtained lap joints. The results obtained are as follows.

1. The tensile strength of the steel wire mesh itself depends on the strength level of the steel type and the mesh structure, with Type316L single mesh having the lowest strength, and Type316L double mesh and Type329J1 single mesh both

having strength approximately twice that of Type316L single mesh.

2. The strength of the joint was nearly doubled by using steel wire mesh compared to a lap joint in which an Al alloy plate and a CFRP plate were directly joined without using steel wire mesh. The joint strength did not improve when using Type329J1 single mesh compared to Type316L single mesh. The joint strength improved slightly when using Type316L double mesh, but the strength of the steel wire mesh itself was not reflected in the joint strength.
3. The static fracture of the joint was due to fracture of the CFRP and steel wire mesh in the nugget, and the bonds between the Al alloy plate and the steel wire mesh, and between the steel wire mesh and the CFRP, were well maintained. The CFRP part had thermal damage caused by the heat input during joining, which is thought to have been the starting point of the fracture.
4. The fatigue strength was almost the same regardless of the type of steel wire mesh. The results of the fatigue interruption tests showed that fatigue cracks first occurred in the CFRP part of the nugget, and ultimately the steel wire mesh broke, leading to separation of the upper and lower sheets. The origin of fatigue fracture is also thought to be the thermally damaged part of the CFRP.
5. Quantitative comparison showed that a 79–92% change in the mesh load-carrying capacity produced at most a 23% change in the joint strength, and the single-mesh joints of SUS316 and SUS329J1 gave almost identical nominal shear strengths (22.3 and 21.7 MPa). The joint strength is therefore governed not by the mesh but by the thermally degraded CFRP layer within about 180 μm (approximately 9% of the CFRP thickness) of the interface, which identifies heat-input reduction as the key lever for further strengthening.

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Statements and Declarations

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Competing interests The authors declare that they have no competing interests.

Author contributions Yoshihiko Uematsu: conceptualization, methodology, supervision, writing – review & editing, funding acquisition. Taisuke Sato: investigation, formal analysis, writing – original draft. Nobuki Hirooka: resources, investigation. Asami Nakai: conceptualization, resources, supervision. Akio Ohtani: methodology, resources. Daisuke Ogawa: validation, investigation. Yoshiki Mizutani: resources, investigation.

Data availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Use of generative AI in the writing process During the preparation of this work the authors used a generative AI assistant to help with language editing and with formatting

of the manuscript and the reference list. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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