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# Ultrasonic Vibration-Assisted Adhesive Bonding between CFRP and Aluminum alloy

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## ABSTRACT

This study investigates ultrasonic vibration-assisted adhesive bonding between carbon fiber reinforced polymer (CFRP) and aluminum (Al) alloys using a two-component epoxy adhesive to enhance bonding strength. The effects of ultrasonic application, bonding temperature, adhesive layer thickness, and the position of ultrasonic application on joint performance are evaluated. Experimental results reveal that ultrasonic vibration significantly improves bonding strength, especially at lower curing temperatures, by promoting adhesive penetration and mechanical interlocking at the CFRP–adhesive interface, resulting in mixed failure modes instead of interfacial failure. The maximum bonding strength (21.46 MPa) was achieved when ultrasound was applied from the CFRP side at 333 K with a controlled adhesive thickness of 200 μm. This approach demonstrates potential for improving bond reliability in lightweight multi-material structures for automotive and other industries.

## 1. INTRODUCTION

Ultrasonic-assisted adhesive bonding is gaining attention as an advanced technique for enhancing the performance of adhesive joints. By introducing ultrasonic vibrations into the bonding process, improved adhesive flow, infiltration, and mechanical interlocking can be achieved—benefits not typically attainable through conventional methods.

Hui Wang et al. reported a 29% increase in shear strength for adhesive joints between CFRP and aluminium alloy plates using film adhesives with ultrasonic application. They attributed this improvement to enhanced adhesive penetration into the aluminium surface and the filling of surface irregularities, resulting in stronger mechanical bonding. However, the use of film adhesives often requires heating equipment for curing, leading to increased costs and limited applicability for heat-sensitive materials. In their study, bonding was performed at 453 K, which may not be suitable for such substrates.

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This study aims to improve the adhesive bonding performance between CFRP and Al alloy using a two-part epoxy adhesive and ultrasonic application. Tensile tests and fracture surface analysis were conducted to evaluate the improvement in bond strength. Furthermore, the effects of bonding temperature on ultrasonic-assisted bonding were investigated.

### 2.1. MATERIALS

A5052 aluminum alloy (hereinafter referred to as Al alloy) and woven CFRP composed of Toray T300 continuous carbon fibers in an epoxy resin matrix were used as base materials. The adhesive used was a two-part epoxy resin (manufactured by Three Bond Fine Chemical Co., Ltd.). The curing conditions were 24 hours at room temperature or 1 hour at 333 K.

### 2.2. Ultrasonic Adhesive Bonding Conditions and Method.

Figure 1 presents a schematic of the ultrasonic bonding setup. Equal amounts (0.5 g) of the epoxy base and hardener were mixed with 0.02 g of a powdered coloring agent to aid fracture surface analysis. A total of 0.1 g of adhesive was applied evenly to the bonding area. Overlap joints were prepared according to the JIS K6850 Single Lap Joint (SLJ) standard, clamped, and set on a heater. The temperature was increased to the target level, and ultrasonic vibration was applied for 30 seconds using a Shimada Rika Kogyo USG-302W-2A ultrasonic generator (3 kW, 18 kHz). Bonding was completed by maintaining the set temperature.

### 2.3. Ultrasonic Sound Pressure Distribution Simulation Method

To investigate sound pressure distribution and wave propagation characteristics, simulations were conducted using Equation (1). Due to the thin adhesive layer, separate meshes were used: 1 mm for the base materials and 0.04 mm for the adhesive.

$$p = \rho c v_0 \left| 2sin\frac{\pi}{\Lambda}\left(\sqrt{x^2 + a^2} - x\right)\right| \tag{1}$$

Where:

$\rho$：Density = CFRP：1.8 g/cm$^3$, Al alloy：2.68g/cm$^3$, Adhesive：1.14g/cm$^3$

a：Horn Trip Radius = 1.25 cm, Λ：Wavelength =25.6 cm,

c：Wave Propagation Speed = CFRP：300×10$^3$ cm/s, Al alloy：313×10$^3$ cm/s

Adhesive：307×10$^3$ cm/s

x：Distance from Generator, $v_0$：Horn Vibration Speed = 63 cm/s

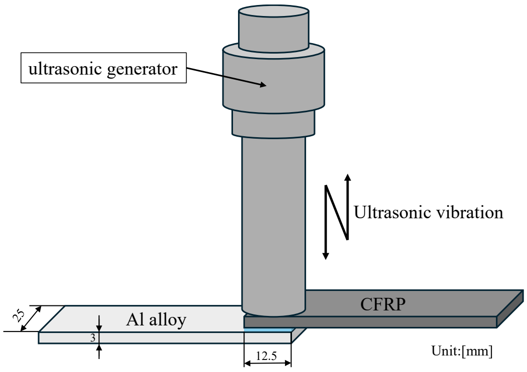


Fig. 1 Schematic diagram of ultrasonic vibration-assisted adhesive bonding

## 3. RESULTS AND DISCUSSION

### 3.1 Sound Pressure Distribution Simulation Results

The simulation results for the sound pressure distribution in materials with ultrasonic application from the CFRP and Al sides are presented. The unit is MPa. From Fig. 2, for the material with ultrasonic application from the CFRP side, the sound pressure from CFRP to the adhesive was 0.82 MPa, and from the adhesive to Al was 0.70 MPa. Furthermore, from Fig. 3, for the material with ultrasonic application from the Al side, the sound pressure from Al to the adhesive was 1.20 MPa, and from the adhesive to CFRP was 1.05 MPa. When ultrasonic waves were applied from the Al side, the overall sound pressure was 0.35 MPa higher than when applied from the CFRP side.

### 3.2 Ultrasonic Application from CFRP Side

#### 3.2.1 Bond Strength at Room Temperature (298 K)

Bond strength at 298 K was compared with and without ultrasonic application. As shown in Table 1 and Fig. 4, ultrasonic treatment resulted in a 35% increase in strength. Fracture surface observations (Fig. 5) revealed interfacial failure in untreated samples and mixed failure in ultrasonically treated ones. This improvement is attributed to ultrasonic-induced adhesive infiltration into surface irregularities, enhancing mechanical interlocking.

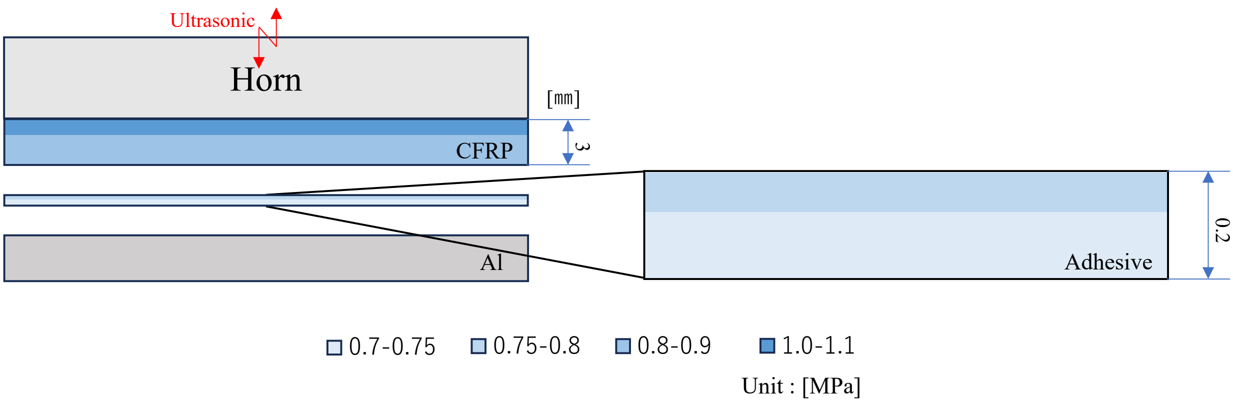


Fig. 2 Sound pressure distribution simulation from the CFRP side

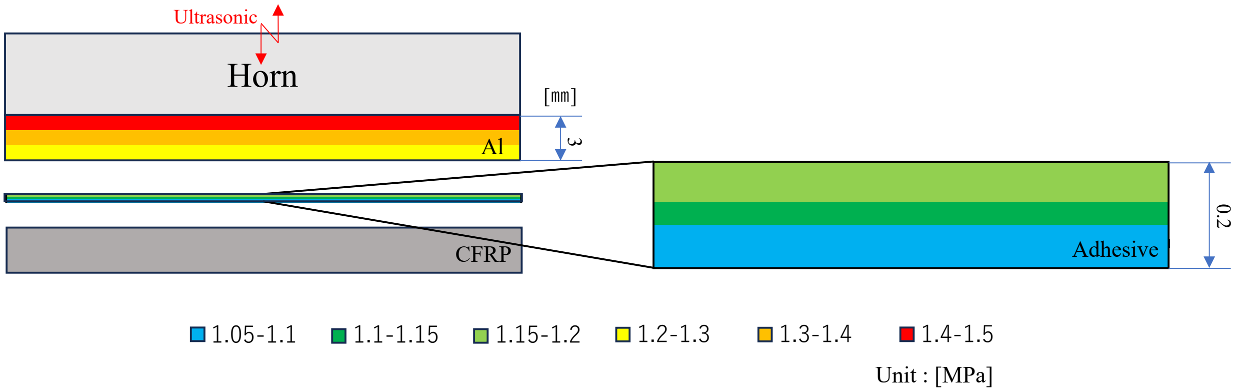


Fig. 3 Sound pressure distribution simulation from the Al side

Table. 1 Adhesive bond strength at 298K with and without ultrasonic application

| Ultrasonic Application | Adhesive Bond strength, $\tau$ [MPa] | | | Average Bond strength, $\tau$ Ave. [MPa] |
|---|---|---|---|---|
| ○ | 14.57 | 11.75 | 11.42 | 12.58 |
| - | 8.92 | 8.67 | 6.98 | 8.19 |

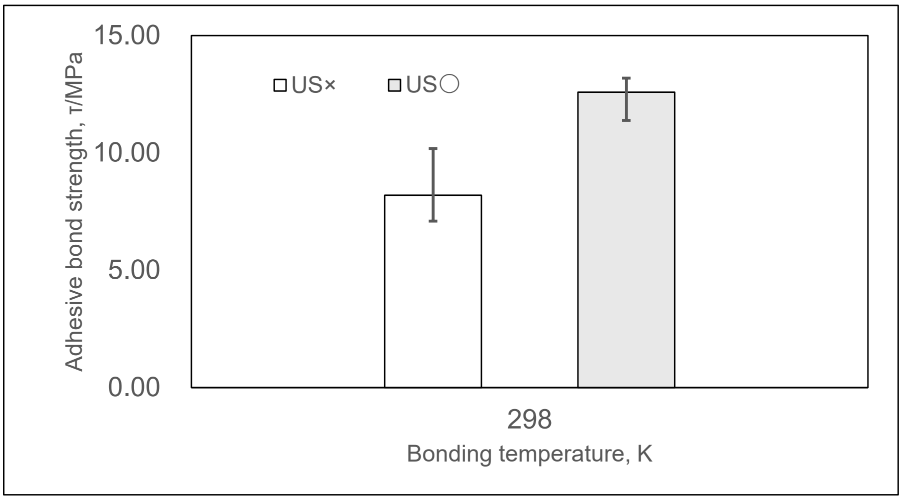


Fig. 4 Graph of Adhesive bond strength at 298K with and without ultrasonic application

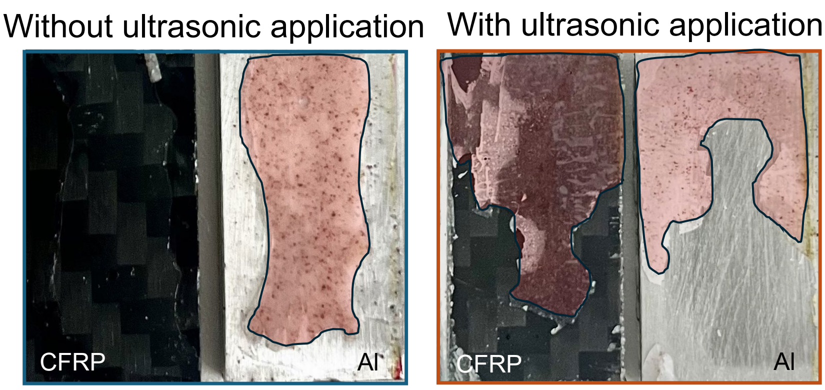


Fig. 5 Fracture surface with and without ultrasonic application at 298K

### 3.2.2 Effect of Bonding Temperature

The specified curing time for the two-part epoxy resin adhesive used in this study is 1 hour at 333K, and it is known that adhesive bond strength decreases as the bonding temperature decreases. Therefore, in this experiment, we investigated whether the decrease in bonding performance due to lower bonding temperatures could be improved by ultrasonic application. The adhesive bond strength values are shown in Table 2, and the graph in Fig. 6. The fracture surfaces are shown in Fig. 7. For materials without ultrasonic application, the adhesive bond strength decreased as the bonding temperature decreased. In contrast, under the same conditions, materials with ultrasonic application were able to maintain a higher adhesive bond strength. While the adhesive strength of non-ultrasonically applied materials decreased by 53% when comparing 333K and 298K, ultrasonically applied materials were able to limit the decrease to 27%. In fracture surface observations, mixed failure occurred at 333K regardless of ultrasonic application, resulting in high adhesive strength. For materials without ultrasonic application at 323K and 313K, interfacial failure occurred at the CFRP-adhesive interface, but for ultrasonically applied materials, mixed failure occurred, leading to higher adhesive strength. This indicates that ultrasonic application strengthened the interfacial strength between CFRP and the adhesive. As the temperature decreases, the viscosity of the adhesive increases, making it difficult for the adhesive to naturally flow into the irregularities on the CFRP surface simply by application. As a result, the contact area between the CFRP surface and the adhesive decreases, leading to a lower joint strength. On the other hand, for ultrasonically applied materials, even at lower temperatures and higher adhesive viscosity, the ultrasonic vibrations are thought to promote the penetration of the adhesive into the CFRP surface's irregularities, filling them and strengthening the mechanical interlocking (anchoring effect) at the adhesive interface, thereby improving the joint strength.

Table. 2 Adhesive bond strength at various temperature conditions

| Temperature [K] | Ultrasonic Application | | | | Non-Ultrasonic Application | | | |
|---|---|---|---|---|---|---|---|---|
| | Bond Strength, $\tau$ [MPa] | | | | Bond Strength, $\tau$ [MPa] | | | |
| RT | 14.57 | 11.75 | 11.42 | Ave.11.42 | 8.92 | 8.67 | 6.98 | Ave.8.19 |
| 313 | 8.92 | 8.67 | 6.98 | Ave.9.87 | 9.27 | 8.75 | 8.28 | Ave.8.77 |
| 323 | 15.19 | 13.16 | 12.60 | Ave.12.60 | 12.98 | 10.15 | 8.06 | Ave.10.40 |
| 333 | 18.53 | 17.61 | 15.36 | Ave.15.36 | 19.53 | 17.89 | 15.37 | Ave.17.60 |

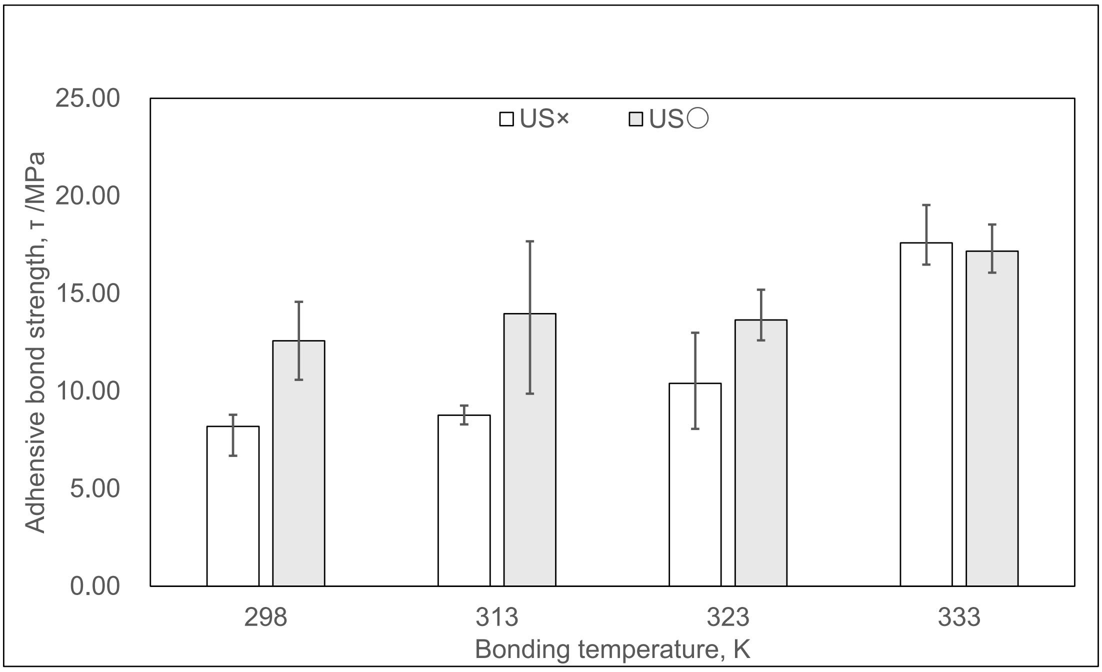


Fig. 6 Graph of Adhesive bond strength at various temperature conditions

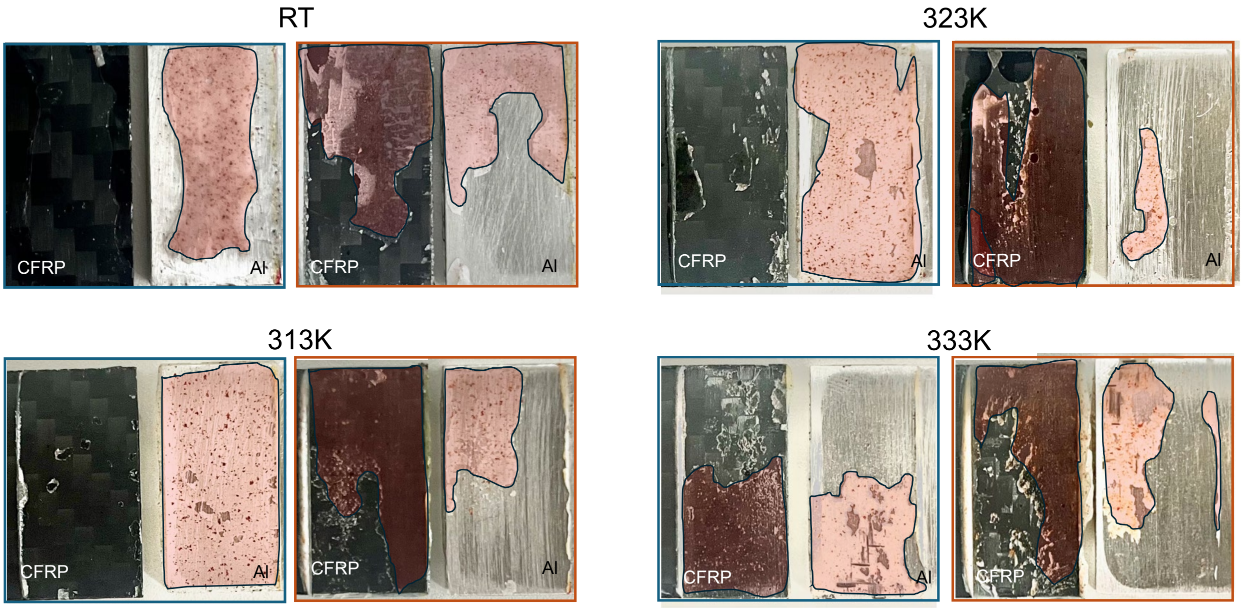


Fig. 7 Fracture surface for each temperature condition

### 3.3 Ultrasonic Application from the Al Side

#### 3.3.1 Bond Strength under Optimal Conditions

Previous experiments involved ultrasonic application from the CFRP plate side, but in the following experiments, ultrasonic application was performed from the Al alloy plate side. Furthermore, experiments were conducted under the conditions that yielded the highest adhesive bond strength in previous experiments: controlled adhesive layer thickness (200 μm) and a bonding temperature of 333K.The adhesive bond strength values for ultrasonic application from the CFRP side and the Al side are shown in Table 3, and the graph in Fig. 8. The fracture surfaces are shown in Fig. 9. The material with ultrasonic application from the CFRP side showed an adhesive bond strength that was 4.83 MPa higher. In fracture surface observations, the material with ultrasonic application from the CFRP side showed adhesive residue on both plates, indicating that mixed failure occurred. Additionally, CFRP surface fibers were adhered to the adhesive, indicating that a high adhesive bond strength was achieved. For the material with ultrasonic application from the Al side, interfacial failure occurred between the Al and the adhesive, resulting in a lower adhesive bond strength. The lower adhesive bond strength in the material with ultrasonic application from the Al side is considered to be related to the sound pressure intensity shown in 3.1. From the sound pressure distribution simulation results in 3.1, the sound pressure transmitted from the adhesive to the lower plate was 0.35 MPa higher for the material with ultrasonic application from the Al side, which promoted adhesion to the lower CFRP plate. However, the sound pressure from the upper plate, Al, to the adhesive was very high, and as a result, a strong downward sound pressure was applied to the adhesive, which is thought to have weakened the adhesion between the Al and the adhesive.

Table. 3 Adhesive bond strength with ultrasonic application from CFRP or Al

| Position of Ultrasonic Application | Adhesive Bond strength, $\tau$ [MPa] | | | Average Bond strength, $\tau$ Ave. [MPa] |
|---|---|---|---|---|
| CFRP | 22.19 | 21.98 | 20.21 | 21.46 |
| Al | 17.23 | 16.71 | 15.35 | 16.63 |

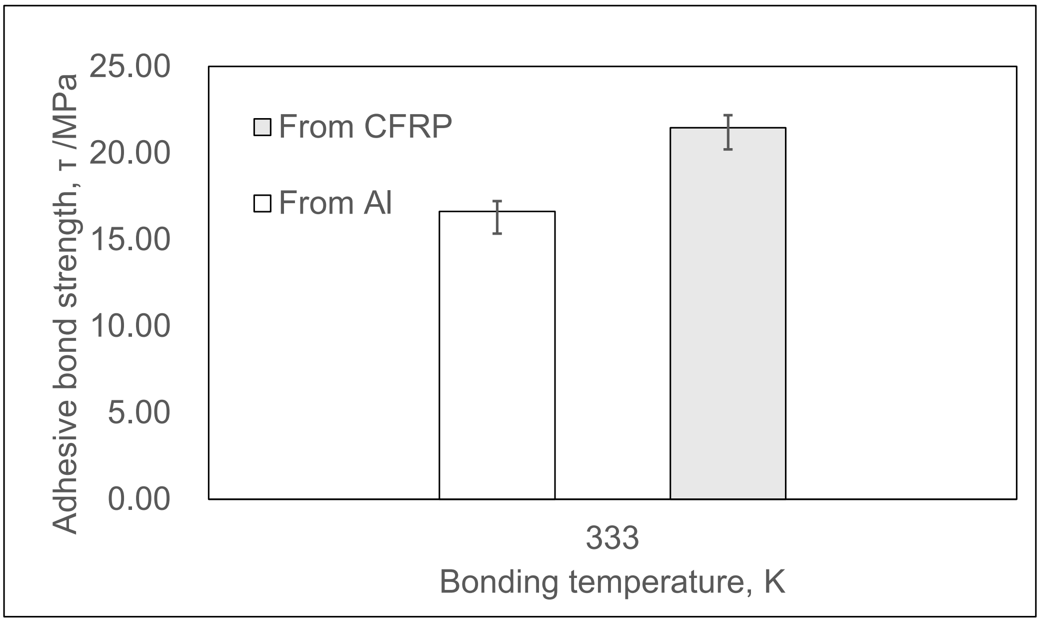


Fig. 8 Graph of Adhesive bond strength when ultrasonic waves are applied from CFRP or Al

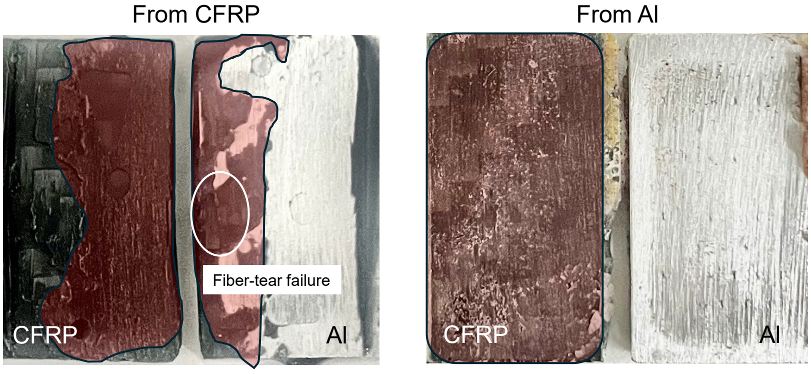


Fig. 9 Fracture surface when ultrasonic waves are applied from CFRP or Al

## 4. CONCLUSION

This study demonstrated the effectiveness of ultrasonic vibration in improving adhesive bonding between CFRP and aluminum alloy using a two-part epoxy adhesive.

1. Effect of Ultrasonic Application:
   Ultrasonic treatment at 298 K increased bond strength by 35%, shifting the failure mode from interfacial to mixed.
2. Effect of Bonding Temperature:
   Without ultrasound, bond strength decreased by 53% from 333 K to 298 K. With ultrasonic assistance, the reduction was limited to 27%, indicating improved interfacial bonding under suboptimal curing conditions.
3. Effect of Application Side:
   Ultrasonic application from the CFRP side yielded superior bonding performance, with 4.83 MPa higher strength and favorable failure modes. In contrast, application from the Al side led to interfacial failure, likely due to excessive sound pressure at the adhesive–Al interface.

Optimal bonding was achieved by applying ultrasound from the CFRP side at 333 K with a controlled adhesive thickness of 200 μm. Further enhancements may be possible through surface treatments on the Al alloy to improve interface adhesion.

## 5. REFERENCES

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