Study on the Law of Ultrasonic Vibration-Assisted Adhesive Bonding of CFRP-to-Aluminum Joints

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Abstract. A novel ultrasonic vibration-assisted adhesion method for CFRP-to-aluminum joints is proposed. Extra force caused by ultrasonic vibration is introduced to reinforce the process of CFRP adhesion, which can overcome shortcomings in passive adhesion enhancement methods. The relationship between each ultrasonic vibration factor is explored, and the optimal ultrasonic vibration frequency, 15 KHz, is found. Through orthogonal experiment optimizing adhesive bonding process, it is found that the order of the influence of the factors on the adhesion strength is: vibration time > vibration amplitude > vibration pressure > vibration position, and the optimal ultrasonic vibration-assisted adhesive bonding of CFRP-to-aluminum joints (vibration time is 8s, vibration pressure is 0.40MPa, vibration position is 30mm and vibration amplitude is 56 µm) can improve adhesion strength by 40.14% and improve consistency of adhesion strength by 58.29%. This study provides a feasible and effective method for CFRP component adhesion.

Introduction

CFRP (Carbon fiber reinforced plastic/polymer) is a kind of excellent light-weight material that has been applied to some spheres such as automobile and airplane[1], since it has several advantages of high specific strength and stiffness, corrosion resistance and so on. As is virtually impossible to make a whole structure as a single body, many structures are therefore manufactured in various parts that are connected through joints later. Adhesive bonding is an important joining method for carbon fiber composite and other composites because of its excellent properties, such as shock absorption, reducing parts amounts, fatigue-resistance, smooth surface, and etc. [2]. To improve the joint strength and stability of carbon fiber composite, some researchers investigated the structure and physical parameters of carbon fiber composite adhesive bonding [3-4]. And some researchers have improved the interfacial wettability of carbon fiber composite with previous bonding surface treatment by methods of chemistry and physics [5-6].

The main function of ultrasonic is acoustic cavitation and acoustic streaming. Rozina et al.[7] found that ultrasonic vibration can promote gap-filling of liquid. Mohammadian et al. [8] found that ultrasonic vibration can enhance solid-to-liquid interfacial wetting. Therefore, the main scope of this paper is to introduce ultrasonic vibration to composite-to-metal adhesive bonding, taking active enhancement to effectively intervene the process of adhesive bonding with CFRP, and improving the way, adopted by many researchers use now, taking passive enforcement like physical or chemical ways to enhance interfacial adhesion of CFRP.
The Platform of Adhesive Bonding of CFRP-to-aluminum Joints

Equipment

The structure of ultrasonic workbench is shown in Figure 1. Its working principle is listed as follows: The ultrasonic generator converts the city electric power into high-frequency electric signal matching with the ultrasonic transducer; The ultrasonic transducer is drove by high-frequency electric signal, thus converting high-frequency electric signal into ultrasonic vibration; The amplitude of ultrasonic vibration (mechanical vibration) is amplified by amplitude transformer and then transmitted to the ultrasonic tool; With the cylinder pressure already set up, the ultrasonic vibration tool is made descend. When the ultrasonic tool approaches the surface of CFRP or other nonmetal experimental material fixed to the fixture, ultrasonic vibration is transmitted to the CFRP. Through this medium, vibration can have effect on adhesive in the CFRP-to-aluminum adhesive bonded gap. In this study, we used the MAXWIDE® ME-1800 ultrasonic table.

![Figure 1. The structure of ultrasonic workbench.](image1)

![Figure 2. The fixture of adhesive bonding of CFRP joints.](image2)

Figure 1. The structure of ultrasonic workbench.  
Figure 2. The fixture of adhesive bonding of CFRP joints.

1) Air pump; 2) Air cylinder; 3) Cylindrical guide; 4) Amplitude transformer; 5) Experiment table; 6) Cylinder piston; 7) Ultrasonic generator; 8) Ultrasonic transducer; 9) Ultrasonic vibration tool; 10) CFRP plate; 11) stop block 1; 12) bottom plate; 13) backing plate; 14) aluminum plate; 15) stop block 2;

Fixture

Adhesive bonding joints consist of several types, but the lap joint is an essential type and also the most widely used one. Therefore, the research object of this study bases on the single-lap joints. The simple fixture used for ultrasonic vibration-assisted adhesive bonding of CFRP-to-metal joints is shown in Figure 2. This fixture includes four parts, which are machined by laser cutting and bonded with adhesive.

![Figure 3. Size of the CFRP-to-aluminum joints.](image3)

Figure 3. Size of the CFRP-to-aluminum joints.

Materials

In this study, the adhesive bonding specimens of CFRP laminate and aluminum plate and the size of adhesive regions are based on Standard Test Method for Lap Shear Adhesion for Fiber Reinforced Plastic (FRP) Bonding (ASTM D5868-01). As shown in Figure 3, the size of the CFRP laminate is 101.6×25.4×2.5mm. The CFRP laminate is made of the 3K twill glossy CFRP (Toray™ T700). The size of the aluminum plate is 101.6×25.4×1.5mm. Laser cutting is used to manufacture the 7075 aluminum alloy plate. The size of the adhesive regions is 25.4×25.4×0.76mm. A backing plate is needed to be bonded respectively at each end of CFRP laminate and aluminum plate, so the bending
moment won’t affect the adhesive regions in tensile process when performing tensile tests on the CFRP-to-aluminum joints.

The adhesive selected is a 3M™ Scotch-Weld™ epoxy adhesive DP460, equipped with adhesive gun and 1:2 AB glue combining nozzle. The surface of CFRP laminate and aluminum plate are ground with alumina red abrasive paper.

**Test**

Shear strength is adopted in this study to evaluate the adhesion strength of CFRP-to-aluminum joints. The shear strength is based on the following functions:

\[
\tau = \frac{P}{B \times L}
\]

(1)

\(P\) (N) represents the maximum load when tensile failure initiates in adhesive bonding specimens of CFRP-to-aluminum joints; \(B \times L\) (mm\(^2\)) represents the adhesive regions area; \(\tau\) (MPa) represents shear strength. MTS810 ceramic testing system is selected to measure the maximum load when tensile failure initiates in specimens.

**Ultrasonic Vibration-Assisted Adhesive Bonding Process of CFRP-to-aluminum Joints**

When ultrasonic vibration assists adhesive bonding of CFRP-to-aluminum joints, surface treatment needs to be done firstly: Using abrasive paper to grind the bonding region of CFRP and aluminum plate respectively and uniformly along length direction of the plate. Next, using detergent with emulsification, water and acetone to degrease the grinded bonding region of CFRP and aluminum plate successively. Then it’s time for location: on the one hand, according to vibration frequency of the experimental scheme, install the transducer, amplitude transformer and vibrating tool; on the other hand, adjust the position of the fixture on the basis of the position after ultrasonic vibration tool descending and the position when ultrasonic vibration tool exerts vibration on CFRP as the experimental scheme given. And fix the fixture on ultrasonic vibration experimental table. Secondly, apply a certain amount of adhesive uniformly on CFRP according to the room size of the bonding gap and put aluminum plate in fixture slowly to assure that CFRP lamination and aluminum plate are overlapped to the designed size of joint. Then, push down the ultrasonic vibration tool and adjust the vibration pressure and amplitude. Exert intermittent vibration on CFRP to the given vibration time. Finally, lift the ultrasonic vibration tool and loosen the fixture to have the CFRP-to-aluminum bonding joint kept in the fixture to cure the adhesive completely at 20\(^\circ\). After the solidification, remove the bonded joint from the fixture and bond corresponding stop blocks at each end of the CFRP lamination and aluminum plate respectively as shown in Figure 3.

**Optimization of Adhesive Bonding of CFRP-to-aluminum Joints**

**Relationship between the Ultrasonic Vibration Parameters**

Ultrasonic vibration adopts the process of external force intervening the CFRP-to-aluminum bonding, which adds several factors such as vibration frequency, vibration amplitude, vibration stress, vibration time, vibration and so on. The adjustment of ultrasonic vibration pressure can be achieved by changing the air pressure of the cylinder following with regulation of pre-pressing force of the ultrasonic vibration tool. The adjustment of vibration time can be achieved by adjusting control time on the control panel of ultrasonic generator (manual mode). The vibration position can be adjusted by changing the ultrasonic vibration tool’s loading position on CFRP with the translation of fixture on experimental platform. The adjustments of vibration stress, vibration time and vibration position are independent.

Through the replacements of parts of the ultrasonic workbench can generate different ultrasonic vibration frequencies. The amplitude under different frequencies can be changed by adjusting the
amplitude percentage (50%-100% infinitely variable control) on the panel, which is a relevant value. Additionally, with the increase of ultrasonic vibration frequency, the absolute value of amplitude under the same percentage will decrease and its variation range gets small. The ultrasonic vibration frequency is correlated with the amplitude, and the relationship between the both is shown in Table 1 by measuring the amplitude percentage under different frequencies with dial indicator.

**Optimization of Ultrasonic Vibration Frequency**

It is indicated that negative correlation but not a simple linear one exists between the ultrasonic vibration frequency and amplitude. And the variation ranges of amplitude under different ultrasonic vibration frequencies overlap a little, which means that the maximum amplitude under high frequency may be lower than the minimum amplitude under low frequency. Therefore, when conducting researches on the ultrasonic vibration-assisted adhesive bonding process of CFRP-to-aluminum under different frequencies, the chosen amplitude may not be acquired under a certain frequency and amplitude percentage. So the most premium vibration frequency is essential before optimizing adhesive bonding process of CFRP-to-aluminum.

For this reason, five different vibration amplitudes are selected under different vibration frequencies to study the effects that different frequencies and amplitudes of ultrasonic vibration have on the CFRP-to-aluminum adhesive bonding process. Vibration stress, vibration time and vibration position should stay the same. And vibration stress is 0.24MPa; vibration time is 12s; vibration position (the shortest distance between the ultrasonic vibration tool and the aluminum plate along the CFRP direction) is 30mm. For the purpose of experimental accuracy, repetitive experiments were conducted. The experimental data in Table 1 indicate that the adhesion strength of specimens of CFRP-to-aluminum joints to each amplitude as the vibration frequency is 15 KHz is prior to the one when the vibration frequency is 20 KHz and 25 KHz. So the most premium ultrasonic vibration frequency is 15 KHz.

Table 1. Experimental schemes and results of vibration frequency and amplitude’s influence on adhesive joints.

| No | Frequency (KHz) | Amplitude percentage | amplitudes (µm) | Maximum tensile load (N) | Mean(N) | Adhesion strength (Mpa) |
|----|----------------|----------------------|----------------|-------------------------|---------|------------------------|
| 1  | 15             | 52%                  | 24             | 6101 5351              | 5726    | 8.875                  |
| 2  | 66%            | 32                   | 5772 6134      | 5953                    | 9.227   |
| 3  | 70%            | 40                   | 5316 5948      | 5632                    | 8.730   |
| 4  | 75%            | 48                   | 5401 5121      | 5261                    | 8.155   |
| 5  | 80%            | 56                   | 6538 5938      | 6238                    | 9.669   |
| 6  | 52%            | 17                   | 6016 4996      | 5506                    | 8.534   |
| 7  | 70%            | 20                   | 4496 5034      | 4765                    | 7.386   |
| 8  | 75%            | 23                   | 5848 4542      | 5195                    | 8.052   |
| 9  | 83%            | 26                   | 3929 5489      | 4709                    | 7.299   |
| 10 | 88%            | 29                   | 6098 5194      | 5646                    | 8.751   |
| 11 | 52%            | 15                   | 5056 4462      | 4759                    | 7.376   |
| 12 | 66%            | 17                   | 5705 4807      | 5256                    | 8.147   |
| 13 | 75%            | 19                   | 4795 5319      | 5057                    | 7.838   |
| 14 | 88%            | 21                   | 4768 5608      | 5188                    | 8.041   |
| 15 | 100%           | 23                   | 5792 4644      | 5218                    | 8.088   |

**Optimization of Ultrasonic Vibration-Assisted Adhesive Bonding of CFRP Joints**

Orthogonal experimental design is an efficient way to work out the optimal horizontal combination, and usually used for studying multi-factor. The experimental objective is to enhance adhesion strength of CFRP-to-aluminum single-lap joint, and the higher the adhesion strength is, the better the
joint is. The designed orthogonal experiment scheme is shown in Table 2, which is designed by the Minitab software. To reduce operating errors, the orthogonal experiment is carried out repeatedly.

As is shown in Table 3, the experimental data is obtained after performing tensile testing on specimens that have been ultrasonic vibration according to the orthogonal experimental schemes. And control groups data are shown in Table 5. The mean response obtained is shown in Table 4 through visual analysis of orthogonal experiment, and the main effects is shown in Figure 4.

### Table 2. The factors and levels for the orthogonal experiments.

| Level | Vibration time (s) | Vibration pressure (MPa) | Vibration position (mm) | Vibration amplitude (µm) |
|-------|--------------------|--------------------------|-------------------------|--------------------------|
| 1     | 8                  | 0.08                     | 10                      | 24                       |
| 2     | 16                 | 0.16                     | 20                      | 32                       |
| 3     | 24                 | 0.24                     | 30                      | 40                       |
| 4     | 32                 | 0.32                     | 40                      | 48                       |
| 5     | 40                 | 0.40                     | 50                      | 56                       |

### Table 3. Orthogonal experiment schemes and experimental data.

| No. | Vibration time (s) | Vibration pressure (MPa) | Vibration position (mm) | Vibration position (mm) | Records(N) | Mean(N) | Adhesion strength (MPa) |
|-----|--------------------|--------------------------|-------------------------|-------------------------|------------|---------|------------------------|
| 1   | 4                  | 0.08                     | 10                      | 24                      | 5009       | 4419    | 4714 7.307             |
| 2   | 4                  | 0.16                     | 20                      | 32                      | 5217       | 6072    | 5644.5 8.749           |
| 3   | 4                  | 0.24                     | 30                      | 40                      | 5179       | 4844    | 5011.5 7.768           |
| 4   | 4                  | 0.32                     | 40                      | 48                      | 4404       | 4708    | 4556 7.062             |
| 5   | 4                  | 0.4                      | 50                      | 56                      | 6072       | 6251    | 6161.5 9.550           |
| 6   | 8                  | 0.08                     | 20                      | 40                      | 4799       | 4915    | 4857 7.528             |
| 7   | 8                  | 0.16                     | 30                      | 48                      | 5466       | 5967    | 5716.5 8.861           |
| 8   | 8                  | 0.24                     | 40                      | 56                      | 6136       | 5877    | 6006.5 9.310           |
| 9   | 8                  | 0.32                     | 50                      | 24                      | 5315       | 4623    | 4969 7.702             |
| 10  | 8                  | 0.4                      | 10                      | 32                      | 4877       | 5226    | 5051.5 7.830           |
| 11  | 12                 | 0.08                     | 30                      | 56                      | 6229       | 6071    | 6150 9.533             |
| 12  | 12                 | 0.16                     | 40                      | 24                      | 5449       | 5788    | 5618.5 8.709           |
| 13  | 12                 | 0.24                     | 50                      | 32                      | 6789       | 6591    | 6690 10.370            |
| 14  | 12                 | 0.32                     | 10                      | 40                      | 5645       | 6004    | 5824.5 9.028           |
| 15  | 12                 | 0.4                      | 20                      | 48                      | 6298       | 6867    | 6582.5 10.203          |
| 16  | 16                 | 0.08                     | 40                      | 32                      | 4892       | 4175    | 4533.5 7.027           |
| 17  | 16                 | 0.16                     | 50                      | 40                      | 5464       | 6126    | 5795 8.982             |
| 18  | 16                 | 0.24                     | 10                      | 48                      | 4569       | 4686    | 4627.5 7.173           |
| 19  | 16                 | 0.32                     | 20                      | 56                      | 5891       | 5689    | 5790 8.975             |
| 20  | 16                 | 0.4                      | 30                      | 24                      | 6274       | 5892    | 6083 9.429             |
| 21  | 20                 | 0.08                     | 50                      | 48                      | 5678       | 4979    | 5328.5 8.259           |
| 22  | 20                 | 0.16                     | 10                      | 56                      | 5878       | 6179    | 6028.5 9.344           |
| 23  | 20                 | 0.24                     | 20                      | 24                      | 4411       | 5103    | 4757 7.373             |
| 24  | 20                 | 0.32                     | 30                      | 32                      | 6321       | 6719    | 6520 10.106            |
| 25  | 20                 | 0.4                      | 40                      | 40                      | 5393       | 5886    | 5639.5 8.741           |

From Table 4 and Figure 4, it is found that the order of the influence of the factors on the adhesion strength is: Vibration time > Vibration amplitude > Vibration pressure > Vibration position. By analyzing the Figure 4, the optimal ultrasonic vibration-assisted adhesive bonding of
CFRP-to-aluminum joints is the vibration time of 8s, the vibration pressure of 0.40MPa, the vibration position of 30mm and the vibration amplitude of 56 μm.

Because the optimal scheme of ultrasonic vibration-assisted adhesive bonding of CFRP-to-aluminum joints is not included in the orthogonal experimental schemes in Table 3, verification experiments on the optimal process are carried out repeatedly, and the results are shown in Table 5 (Experimental group). Comparing the data of the control group (the test results of specimens without ultrasonic vibration-assisted adhesive bonding) in Table 5, we found that the ultrasonic vibration can improve the adhesion strength and stability by 40.14% and 58.29%.

| No. | Maximum tensile load(N) | Adhesion strength (MPa) |
|-----|------------------------|-------------------------|
|     | Control group          | Experimental group       | Control group | Experimental group |
| 1   | 6017                   | 6504                    | 9.326         | 10.081             |
| 2   | 3421                   | 6917                    | 5.303         | 10.721             |
| 3   | 3932                   | 6751                    | 6.095         | 10.464             |
| 4   | 5407                   | 7054                    | 8.381         | 10.934             |
| 5   | 4531                   | 5875                    | 7.023         | 9.106              |
| 6   | 5036                   | 7213                    | 7.806         | 11.180             |
| Mean| 4724                   | 6719                    | 7.322         | 10.414             |

Table 4. The mean response.

| Level | Vibration time | Vibration pressure | Vibration position | Vibration amplitude |
|-------|----------------|--------------------|--------------------|--------------------|
| 1     | 8.087          | 7.931              | 8.136              | 8.104              |
| 2     | 8.246          | 8.929              | 8.566              | 8.816              |
| 3     | 9.569          | 8.399              | 9.139              | 8.409              |
| 4     | 8.317          | 8.575              | 8.17               | 8.312              |
| 5     | 8.765          | 9.151              | 8.973              | 9.342              |
| Delta | 1.481          | 1.22               | 1.003              | 1.238              |
| Rank  | 1              | 3                  | 4                  | 2                  |

Table 5. The experimental results of verification experiments.

Figure 4. Main effects plot for means.

**Conclusions**

An experiment platform of ultrasonic is established and the law of ultrasonic vibration-assisted adhesive bonding of CFRP-to-aluminum joints is studied. Studies show that:
a. There exists nonlinear negative relationship between the ultrasonic vibration frequency and amplitude, and the premium ultrasonic vibration frequency is 15 KHz.

b. The order of the influence of the four processing factors on the adhesion strength is: vibration time > vibration amplitude > vibration pressure > vibration position.

c. The optimal ultrasonic vibration-assisted CFRP-to-aluminum bonding method (vibration time is 8s, vibration stress is 0.40MPa, vibration position is 30mm, and vibration amplitude is 56 \( \mu m \) ) can improve the adhesion strength and the stability of it by 40.14\% and 58.29\% respectively.

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