

## Article

# Mechanical Properties of CFRP/2024 Al Alloy Joints Fabricated by Transverse Ultrasonic-Vibration-Assisted Riveting

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## Abstract

The mechanical performance of CFRP/2024 Al alloy hybrid laminates joined by transverse ultrasonic vibration-assisted riveting (TUVAR) was investigated. The experiments were conducted on a self-developed ultrasonic riveting system with a power of 3000 W and a vibration frequency of 19.8 kHz, covering ultrasonic amplitudes from 0 to 24  $\mu\text{m}$ . Test specimens were fabricated from T300/CFRP laminates, 2024 Al alloy sheets, and 2A10 Al alloy rivets. The influences of ultrasonic amplitudes (12  $\mu\text{m}$ , 16  $\mu\text{m}$ , 20  $\mu\text{m}$ , and 24  $\mu\text{m}$ ) on riveting load, driven head geometry, interference, static tensile strength, and cyclic loading behavior were systematically analyzed. The results showed that TUVAR reduced the riveting force and promoted rivet deformation. As the amplitude increased, the driven head diameter increased, and the driven head height decreased, with a maximum reduction of 6.62%. The mean interference generally increased up to 20  $\mu\text{m}$  and then decreased slightly at 24  $\mu\text{m}$ ; the relative interference variance coefficient ranged from 0.070 to 0.155 under TUVAR. Static tensile tests showed that the joint strength first increased and then decreased with increasing amplitude, with the highest mean static tensile load obtained at 20  $\mu\text{m}$ . Cyclic tensile tests indicated that load-bearing capacity was improved with increasing amplitude, while the maximum deviation was maintained within 3.5%. These findings demonstrate that TUVAR can enhance both the forming quality and the mechanical performance of CFRP/2024 Al alloy riveted joints, and provide a useful reference for the high-performance joining of composite-metal hybrid structures in aerospace applications.

**Keywords:** ultrasonic vibration-assisted riveting; CFRP/2024 Al alloy; amplitude; interference; mechanical properties



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## 1. Introduction

In the aerospace field, composite/metal laminates are increasingly used in critical joints because of their high strength-to-weight ratio, favorable fatigue performance, and corrosion resistance [1–3]. Composite/metal laminates are increasingly used in critical joints because of their high strength-to-weight ratio, favorable fatigue performance, and corrosion resistance [4,5]. In conventional riveting (CR), fiber fracture, matrix damage, and interfacial stress concentration are induced on the composite side, which makes it difficult for the strength and stiffness of the laminate interface to reach their theoretical values. Meanwhile, deformation and heat-dissipation issues on the metallic side also generate local residual stresses and promote the accumulation of microcracks around the

rivet, thereby impairing structural integrity [6]. To address these challenges, an effective riveting strategy should suppress damage in the CFRP, promote controlled deformation of the rivet, and improve the interfacial contact conditions. Ultrasonic vibration-assisted riveting (UVAR) has attracted attention because ultrasonic vibration can regulate material plasticity, flow behavior, and contact conditions, thereby providing a potential process route for overcoming the above limitations in dissimilar-material riveting [7].

Recent studies on the effect of ultrasonic vibration (UV) on the riveting process have shown that the ultrasonic energy field (UEF) can modify plastic flow behavior, reduce the peak rivet-forming load and residual stress, and promote material filling and interfacial bonding quality in the driven head and hole edge areas [8,9]. For dissimilar-material combinations, such as CFRP and aluminum alloys, the mechanism of UV becomes more complex, because the material softening effect, heat-input distribution, and flow behavior are decisively influenced by the microstructural characteristics and interfacial bonding properties on the composite side [10,11]. Fatyukhin et al. [12] found that UV facilitated the formation of a more uniform residual compressive stress distribution through the joint thickness and reduced the load required for riveting. Sundukov [13] found that UV changed the deformation path of the rivet, allowing the rivet to fill the voids and improve the shear bearing capacity of the joint. Xie et al. [14] found that UV reduced the forming force and contact friction, and promoted rivet material flow. Zhang et al. [15] found in riveting experiments on 2A10 Al alloy that UV not only reduced the riveting force, but also improved the surface quality of the driven head, enhanced interference uniformity, and increased the shear strength. Shao et al. [16] demonstrated that UV reduced the flow stress and improved the overall deformation uniformity. Zhang et al. [17] reported that UV induced transient softening and residual hardening in the rivet, accompanied by an increase in low-angle grain boundaries and grain refinement. In addition, Zhang et al. [7] also found that the height of the driven head decreases and the diameter increases as the ultrasonic amplitude increases, and there is an optimal amplitude process window for joint shear and cross tensile properties in the Ti-45Nb riveting experiment. It is worth noting that similar effects were observed in low-frequency vibration-assisted riveting of dissimilar CFRP/Al alloy joints. Zhuang et al. [18] and Shao et al. [19] found that low-frequency vibration improved rivet deformability through vibration-induced softening and interfacial friction reduction, thereby enhancing the shear strength and fatigue life of the joints. In addition, ultrasonic treatment has also been applied to other process-assisted joining and interface-performance regulation. Previous studies reported that ultrasonic treatment could regulate microstructural evolution and improve the mechanical properties of Sn-based solder materials and joints [20,21]. These studies suggest that vibration-assisted strengthening may be applicable to a range of dissimilar-material riveting systems. Existing research has achieved preliminary results in improving riveting quality, improving driven head formation, and interference distribution. However, the process windows under different amplitudes and different material systems, the evolution of mechanical properties, and their impact on fatigue properties under long-term load need to be revealed.

Moreover, previous research has shown that UVAR has shown consistent potential for improving riveting quality. It usually reduces the riveting force requirement, increases the amount of rivet interference, and improves the forming quality of the driven head, thereby improving the interface bonding strength and cyclic bearing capacity to a certain extent as the amplitude increases [14,22]. Wang et al. [4] proposed the TUVAR process for CFRP riveted lap joints. The results showed that amplitude, vibration duration, and surface roughness jointly affected the interference distribution. However, the selection of amplitude and process parameters must consider the coupling effect between the thermodynamic behavior of the material, the interface bonding mechanism, and the mechanical properties. In

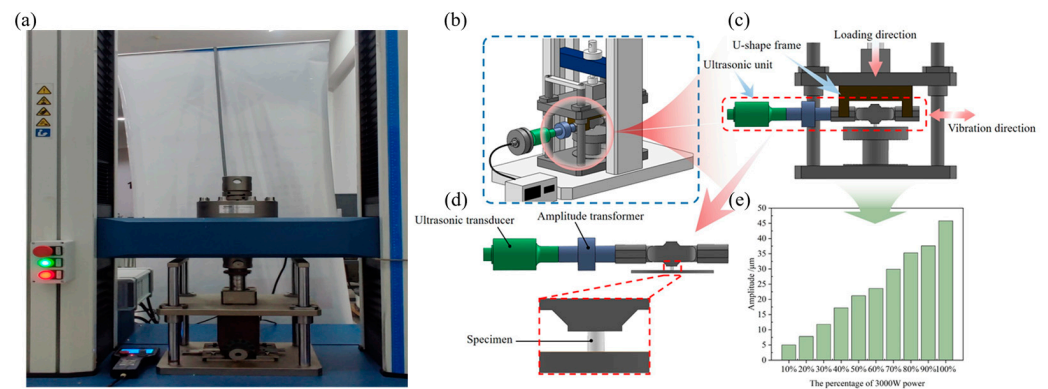
particular, stress transfer at the interface, the heat input distribution, and the local softening of the material can significantly affect the mechanical properties and long-term stability of the joint in dissimilar laminated materials [23,24]. In the CFRP/Al alloy laminate system, the driven head size and height, interference amount, and distribution characteristics of the rivet joint directly determine the compactness of the connection surface and the interface stress transfer capability [25]. Wang et al. [26] found that interlayer delamination, matrix cracking, and fiber fracture during pressure riveting were suppressed by adjusting the pore diameter. Zhang et al. [27] found that ultrasonic amplitude had a greater influence on interference and static tensile performance than riveting speed, and the driven head forming side changed the failure mode and mechanical response of the joint significantly in CFRP/TC4 riveting experiments. Jiang et al. [28,29] pointed out that joint fatigue failure was mainly related to wear in the rivet/aluminum plate contact area and crack initiation at the aluminum plate hole edge. In addition, the choice of rivet material, the prefabrication tolerance of rivet holes, and the loading path during the riveting process also affect the plastic deformation and interface bond strength of the riveting area [30]. Jin et al. [31] demonstrated that the rivet structural design can affect the interfacial bonding strength. By introducing transverse UV into the riveting process, local softening can be produced in the rivet shank, driven head, and the material adjacent to the rivet hole. Consequently, the contact condition and interfacial stress distribution were changed, thereby reducing contact friction and mitigating local stress concentration. As a result, the uniformity of interference was improved, and the yield load of the joint was increased.

Previous TUVAR research mainly examined the coupled effects of ultrasonic amplitude, vibration duration, and surface roughness on interference distribution. Based on a self-developed TUVAR system, the present study maintains other riveting parameters constant and systematically investigates four ultrasonic amplitudes of 12, 16, 20, and 24  $\mu\text{m}$  for CFRP/2024 Al alloy riveted joints. First, the influence mechanism of TUVAR on the mechanical behavior of 2A10 rivets and the riveting mechanical response is clarified, with particular attention to the characteristics of the load–displacement curves. Second, the parameters of the driven head, including diameter and height, and their evolution with displacement under different amplitudes, are analyzed. Third, the variation trends of interference and its relative variance under different amplitude conditions are quantitatively evaluated, and the relationship between UV and the dimensional uniformity of rivet hole fit, as well as the interfacial coupling strength, is discussed. Fourth, static tensile and stepwise cyclic loading tests are conducted to compare the static load-bearing capacity and the joint response under the adopted cyclic loading protocol. These results provide an experimental basis for ultrasonic-amplitude selection in the TUVAR of CFRP/2024 Al alloy joints.

## 2. Experimental Materials and Methods

### 2.1. Transverse Ultrasonic Vibration-Assisted Riveting

As shown in Figure 1, the self-designed TUVAR test platform was established with the ultrasonic loading direction perpendicular to the riveting direction. The power of the ultrasonic generator was 3000 W. The amplitude in the riveting zone of the driven head was measured by a dial indicator under different power levels, and the ultrasonic amplitude ranged from 0  $\mu\text{m}$  to 24  $\mu\text{m}$ .

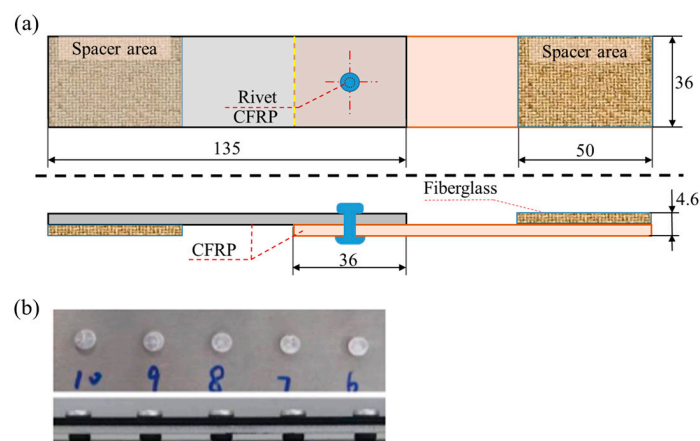


**Figure 1.** Schematic of the TUVAR platform. (a) Riveting experimental equipment; (b) model of experimental equipment; (c) main structure of the TUVAR; (d) transverse ultrasonic vibration auxiliary unit and the compressed specimen; (e) correspondence between power and amplitude.

## 2.2. Materials and Specimen Preparation

TUVAR tests on CFRP/2024 Al alloy specimens were carried out using the experimental setup, as shown in Figure 1. The main process parameters considered during riveting were amplitude, riveting force, and vibration duration. The equipment parameters were fixed at a riveting duration of 2 s, a riveting force of 16,000 N, and an ultrasonic vibration frequency of 19.8 kHz.

As shown in Figure 2, the schematic dimensions of the riveted specimen are presented. The dimensions of the T300/CFRP plate and the 2024 Al alloy plate were 135 mm  $\times$  25 mm, and their thicknesses were 2.3 mm and 2.0 mm, respectively. The fiber lay-up sequence of the CFRP laminate was [0/90/45/-45/-45/45/45/90/0]<sub>2s</sub>. Rivet holes were prepared using a 4.1 mm drill, and 2A10 Al alloy rivets with a shank diameter of 4 mm and a length of 9 mm were employed. During the riveting tests, the loading conditions for TUVAR were set as follows: the riveting speed was 0.5 mm/s, the riveting force was 16 kN, and the ultrasonic amplitudes were 12  $\mu\text{m}$ , 16  $\mu\text{m}$ , 20  $\mu\text{m}$ , and 24  $\mu\text{m}$ .

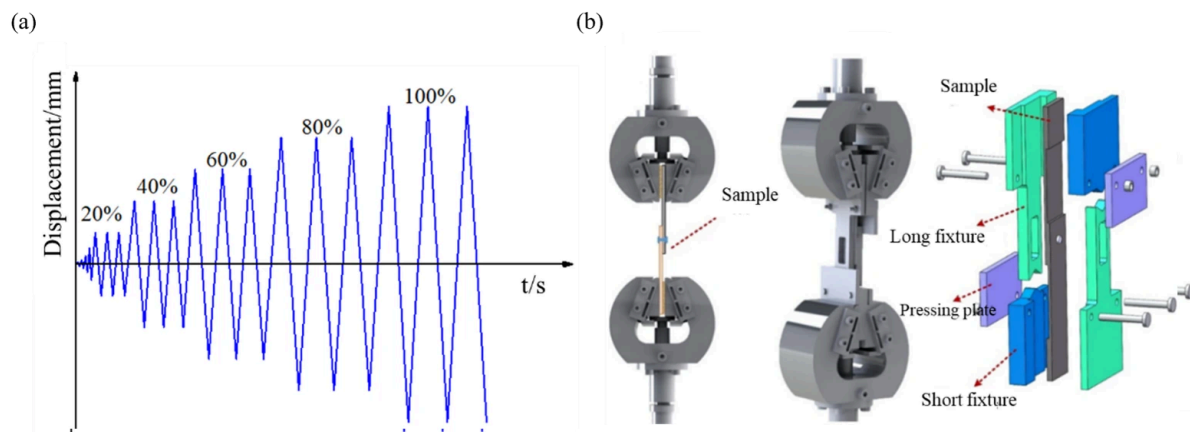


**Figure 2.** Geometry and driven head morphology of the riveted specimens: (a) dimensions of riveted specimens; (b) rivet driven head of TUVAR.

## 2.3. Data Processing Method

The relevant information of the riveted specimens is provided in Section 2. The standard requirements for the mechanical property tests of the riveted specimens were as follows. The loading procedure for the static tensile test was based on ASTM D5961 [32], and the tensile rate was 5 mm/min. The stepwise displacement-controlled cyclic loading test was conducted with reference to ISO 16670 [33]. As shown in Figure 3a, the mean

maximum displacement obtained from the corresponding static tensile tests was defined as  $\bar{u}_{\max}$ . The prescribed displacement levels were set to 1.25%, 2.5%, 5%, 10%, 20%, 40%, 60%, 80%, and 100% of  $\bar{u}_{\max}$ . The test was conducted at a loading speed of 0.1 mm/s, and each displacement level from 20%  $\bar{u}_{\max}$  onward was repeated three times. After completing the 100%  $\bar{u}_{\max}$  loading level, the specimen was continuously loaded until final tensile failure. This normalized stepwise loading sequence was adopted to progressively evaluate the joint response from small deformation to near-failure conditions. As shown in Figure 3b, the gripping configuration for the cyclic tensile and static tensile tests is presented. The experimental parameters of the ultrasonic system, riveting process, specimens, and rivets are summarized in Table 1.



**Figure 3.** Schematic diagram of mechanical property test: (a) cyclic loading mode; (b) sample clamping mode.

**Table 1.** Materials and experimental parameters used in the CR and TUVAR tests.

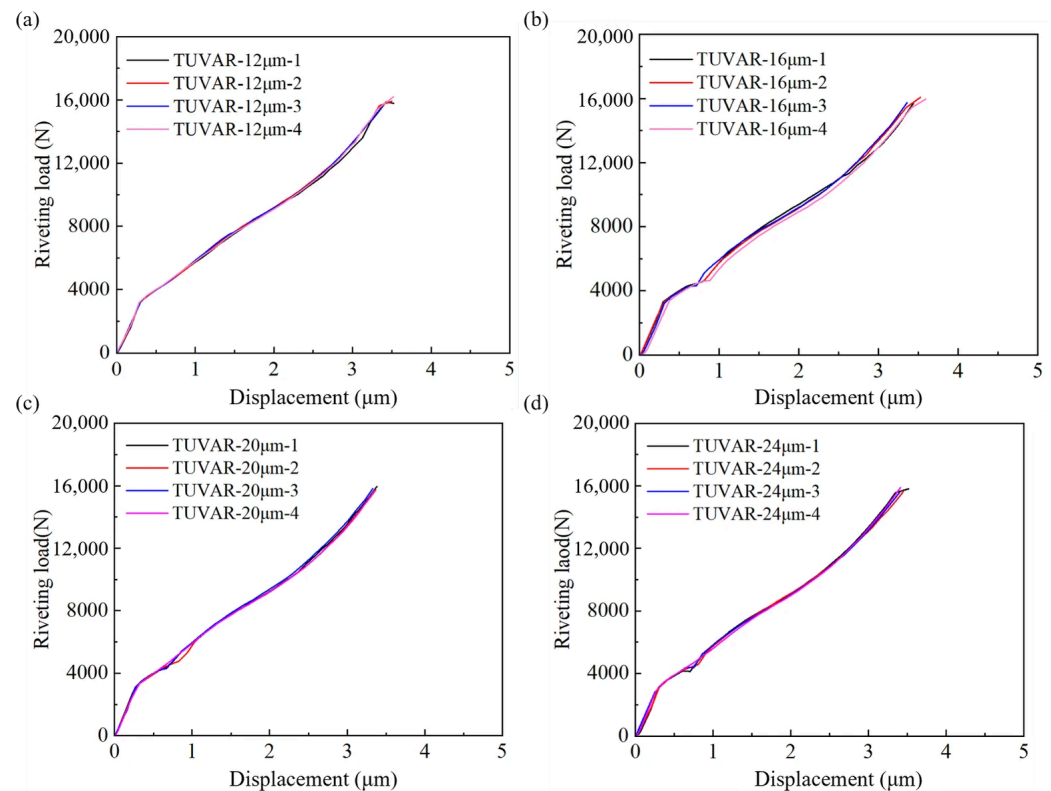
| Category          | Parameter                     | Value                                       |
|-------------------|-------------------------------|---------------------------------------------|
| Ultrasonic system | Ultrasonic generator power    | 3000 W                                      |
| Ultrasonic system | Ultrasonic frequency          | 19.8 kHz                                    |
| Ultrasonic system | Ultrasonic amplitude          | 0, 12, 16, 20, and 24 $\mu\text{m}$         |
| Ultrasonic system | Vibration direction           | Perpendicular to the riveting direction     |
| Riveting process  | Riveting force                | 16 kN                                       |
| Riveting process  | Riveting speed                | 0.5 mm/s                                    |
| Riveting process  | Ultrasonic vibration duration | 2 s                                         |
| CFRP laminate     | Material                      | T300/CFRP                                   |
| CFRP laminate     | Dimensions                    | 135 mm $\times$ 25 mm $\times$ 2.3 mm       |
| CFRP laminate     | Stacking sequence             | [0/90/45/−45/−45/45/45/90/0] <sub>2</sub> s |
| Aluminum sheet    | Material                      | 2024 Al alloy                               |
| Aluminum sheet    | Dimensions                    | 135 mm $\times$ 25 mm $\times$ 2.0 mm       |
| Rivet hole        | Nominal drill diameter        | 4.1 mm                                      |
| Rivet             | Material                      | 2A10 Al alloy                               |
| Rivet             | Shank diameter                | 4.0 mm                                      |
| Rivet             | Length                        | 9.0 mm                                      |

### 3. Results and Discussion

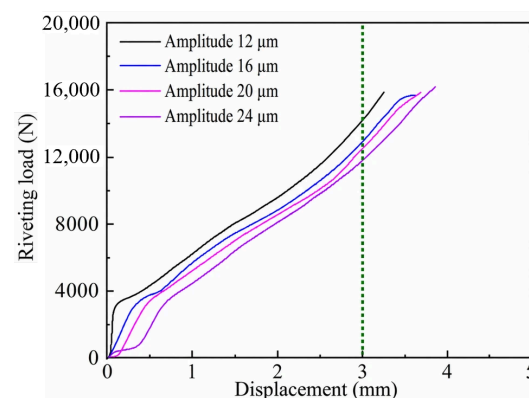
#### 3.1. Analysis of Riveting Force in TUVAR

Repeated TUVAR tests were carried out, four riveting trials were conducted at each amplitude, and the relationships between displacement and riveting load were obtained, as shown in Figure 4. The repeated riveting curves of 2A10 Al alloy under different amplitudes exhibited high overlap, indicating good experimental reliability. To directly

compare the riveting loads under the same deformation condition, a displacement of 3 mm was selected as a common reference point, as shown in Figure 5. The riveting loads were  $13,890 \pm 163$  N,  $12,975 \pm 222$  N,  $12,576 \pm 152$  N, and  $11,825 \pm 173$  N at amplitudes of 12, 16, 20, and 24  $\mu\text{m}$ , respectively. Therefore, the decrease in riveting load with increasing amplitude indicated enhanced deformation of the 2A10 Al alloy rivet under TUVAR. However, the present results cannot distinguish the respective contributions of vibration-induced material softening, interfacial friction reduction, changes in contact conditions, and local heat generation.



**Figure 4.** Force-displacement curves of 2A10 Al alloy at different amplitudes: (a) 12  $\mu\text{m}$ ; (b) 16  $\mu\text{m}$ ; (c) 20  $\mu\text{m}$ ; (d) 24  $\mu\text{m}$ .

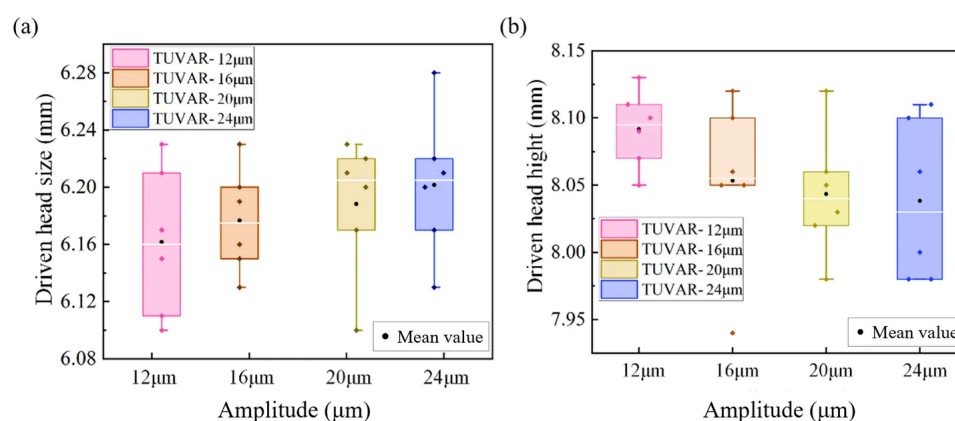


**Figure 5.** Comparison of force-displacement curves under different amplitudes.

### 3.2. Dimensional Analysis of the Driven Head in CFRP/2024 Al Alloy Riveted Laminates

For each condition, the driven head dimensions were measured seven times in different directions on the same specimen, and the mean values were used for analysis. For the CR specimen, the mean driven head diameter and rivet driven head height after riveting were 6.08 mm and 8.61 mm, respectively. As shown in Figure 6a, the mean driven head

diameters of the CFRP/2024 Al alloy riveted laminates at ultrasonic amplitudes of 12, 16, 20, and 24  $\mu\text{m}$  were 6.16, 6.18, 6.19, and 6.20 mm, respectively. Compared with CR, the driven head diameter under TUVAR increased by 1.32%, 1.64%, 1.81%, and 1.97%, respectively. The driven head diameter increased uniformly with increasing amplitude. As shown in Figure 6b, the corresponding driven head heights were 8.09, 8.05, 8.04, and 8.04 mm, respectively. Compared with CR, the compression increased by 6.03%, 6.50%, 6.62%, and 6.62%, respectively. Therefore, the driven head height decreased with increasing amplitude, and the reduction trend remained relatively uniform. In comparison with CR, UEF showed a significant effect on reducing the driven head height. In particular, the driven head height was reduced by 6.62% relative to CR at amplitudes of 20 and 24  $\mu\text{m}$ . A comparison of the driven head height and diameter under different amplitudes indicated that increasing ultrasonic amplitude promoted deformation of the 2A10 Al alloy in the driven-head region, thereby facilitating driven-head formation and affecting the fit dimensions in the riveting zone.



**Figure 6.** Driven head dimensions of CFRP/2024 Al alloy riveted joints at different ultrasonic amplitudes: (a) driven head diameter; (b) driven head height.

### 3.3. Analysis of Interference in CFRP/2024 Al Alloy Laminated Riveting

The interference ( $I_i$ ) was calculated using Equation (1), and the relative interference variance coefficient ( $I_{CV}$ ) was calculated using Equation (2). Accordingly, the uniformity of interference was evaluated.

$$I_i = [(D - D_0) / D_0] \times 100\% \quad (1)$$

where  $D$  and  $D_0$  represent the rivet shank diameter after riveting and the predrilled rivet hole diameter, respectively.

$$I_{CV} = \sqrt{\frac{1}{N} \sum_{i=1}^N \left( I_i - \frac{1}{N} \sum_{i=1}^N I_i \right)^2} / \left( \frac{1}{N} \sum_{i=1}^N I_i \right) \quad (2)$$

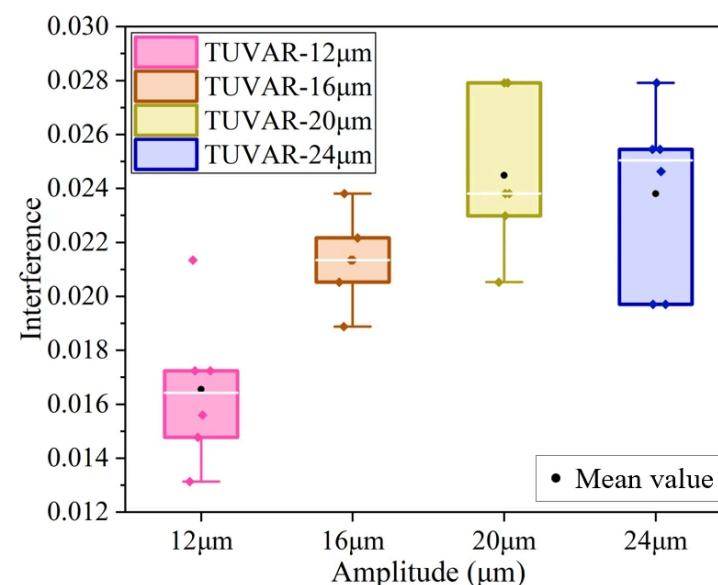
where  $I_{CV}$  is the relative interference variance coefficient, which is used as an evaluation index for interference uniformity. The more uniform the interference, the smaller the  $I_{CV}$ .  $I_i$  denotes the relative interference dimension at different measurement locations. The holes were drilled using a 4.1 mm twist drill, and the mean diameter of the predrilled rivet hole was about 4.06 mm.

Table 2 corresponds to the interference measurement experiment after riveting. At each ultrasonic amplitude, two riveted specimens were examined. Three positions, denoted as P1, P2, and P3, were measured on each specimen, and three repeated diameter measurements were performed at each position. According to Equation (1), the CR showed an

interference of 1.43%. In comparison, the interference of the TUVAR specimens increased to 1.66%, 2.13%, 2.45%, and 2.38% at amplitudes of 12, 16, 20, and 24  $\mu\text{m}$ , respectively. Numerical analysis, combined with Figure 7, indicates that the interference generally increased from 12  $\mu\text{m}$  to 20  $\mu\text{m}$  and then decreased slightly at 24  $\mu\text{m}$ . Therefore, the introduction of ultrasonic amplitude during riveting was effective in increasing rivet interference within the 12–20  $\mu\text{m}$  range. This result showed that increasing ultrasonic amplitude enhanced the interference. The marked increase in interference may be associated with the enhanced deformability of the 2A10 Al alloy rivet under ultrasonic vibration, while possible contributions from interfacial friction reduction, changes in contact conditions, and local heat generation cannot be excluded.

**Table 2.** Measurement of riveted diameter of P1–P3 under different ultrasonic amplitudes.

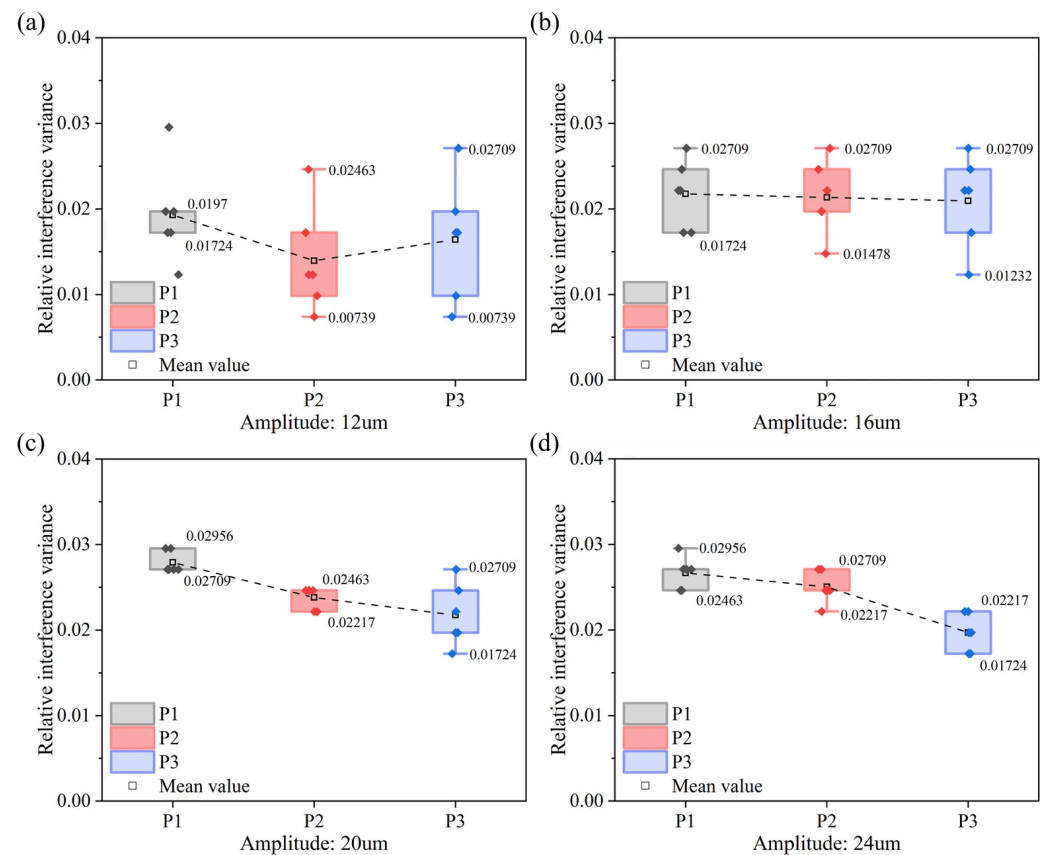
| TUVAR No.                 | P1/mm          | P2/mm          | P3/mm          |
|---------------------------|----------------|----------------|----------------|
| TUVAR-12 $\mu\text{m}$ -1 | 4.13/4.13/4.18 | 4.11/4.16/4.09 | 4.13/4.17/4.09 |
| TUVAR-12 $\mu\text{m}$ -2 | 4.11/4.14/4.14 | 4.10/4.11/4.13 | 4.14/4.10/4.13 |
| TUVAR-16 $\mu\text{m}$ -1 | 4.15/4.13/4.16 | 4.12/4.14/4.15 | 4.16/4.13/4.15 |
| TUVAR-16 $\mu\text{m}$ -2 | 4.13/4.15/4.17 | 4.17/4.14/4.16 | 4.17/4.15/4.11 |
| TUVAR-20 $\mu\text{m}$ -1 | 4.17/4.18/4.17 | 4.16/4.16/4.15 | 4.14/4.16/4.13 |
| TUVAR-20 $\mu\text{m}$ -2 | 4.17/4.18/4.17 | 4.15/4.16/4.16 | 4.14/4.15/4.17 |
| TUVAR-24 $\mu\text{m}$ -1 | 4.16/4.17/4.16 | 4.16/4.17/4.16 | 4.13/4.14/4.15 |
| TUVAR-24 $\mu\text{m}$ -2 | 4.17/4.18/4.17 | 4.16/4.15/4.17 | 4.15/4.13/4.14 |



**Figure 7.** Distribution and mean values of interference at different ultrasonic amplitudes.

As shown in Figure 8, the interference at different locations was obtained from the measurements at P1, P2, and P3 under different amplitudes. According to Equation (2) and Table 2, the CR exhibited a relative interference variance coefficient of 0.198. Under TUVAR, this coefficient decreased to 0.155, 0.070, 0.108, and 0.129 at amplitudes of 12, 16, 20, and 24  $\mu\text{m}$ , respectively. The results showed that, within the amplitude range of 12–24  $\mu\text{m}$ , the relative interference variance coefficient was lowest at 16  $\mu\text{m}$  and increased again at 20  $\mu\text{m}$  and 24  $\mu\text{m}$ . Because a lower coefficient indicates a more uniform interference distribution along the rivet shank, the coefficient indicates that interference uniformity was not monotonically improved with amplitude. Since interference is an important indicator of riveting quality, TUVAR improved the relative interference variance coefficient to CR but

did not monotonically improve it, thereby influencing the riveting quality of the CFRP/2024 Al alloy components.



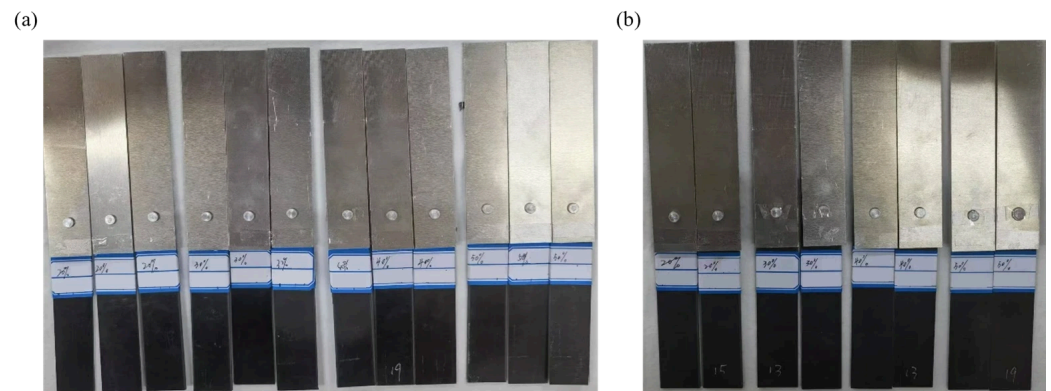
**Figure 8.** Relative interference variance coefficient at different measurement positions under different amplitudes: (a) 12  $\mu\text{m}$ ; (b) 16  $\mu\text{m}$ ; (c) 20  $\mu\text{m}$ ; (d) 24  $\mu\text{m}$ .

### 3.4. Comparative Analysis of Static Tensile Strength

Further mechanical property analyses were conducted on CFRP/2024 Al alloy riveted specimens prepared by TUVAR under different amplitudes. The grouping of the mechanical property tests is presented in Table 3. For each amplitude, three independent specimens were used for the static tensile tests presented in Figure 9a, whereas two independent specimens were used for the stepwise cyclic loading tests presented in Figure 9b.

**Table 3.** Experimental grouping of the mechanical properties of TUVAR specimens at different amplitudes.

| Amplitude ( $\mu\text{m}$ ) | Process Connection | Loading Mode | Number of Specimens |
|-----------------------------|--------------------|--------------|---------------------|
| TUVAR-12 $\mu\text{m}$      | TUVAR              | Static       | 3                   |
| TUVAR-16 $\mu\text{m}$      | TUVAR              | Static       | 3                   |
| TUVAR-20 $\mu\text{m}$      | TUVAR              | Static       | 3                   |
| TUVAR-24 $\mu\text{m}$      | TUVAR              | Static       | 3                   |
| TUVAR-12 $\mu\text{m}$      | TUVAR              | Cyclic       | 2                   |
| TUVAR-16 $\mu\text{m}$      | TUVAR              | Cyclic       | 2                   |
| TUVAR-20 $\mu\text{m}$      | TUVAR              | Cyclic       | 2                   |
| TUVAR-24 $\mu\text{m}$      | TUVAR              | Cyclic       | 2                   |



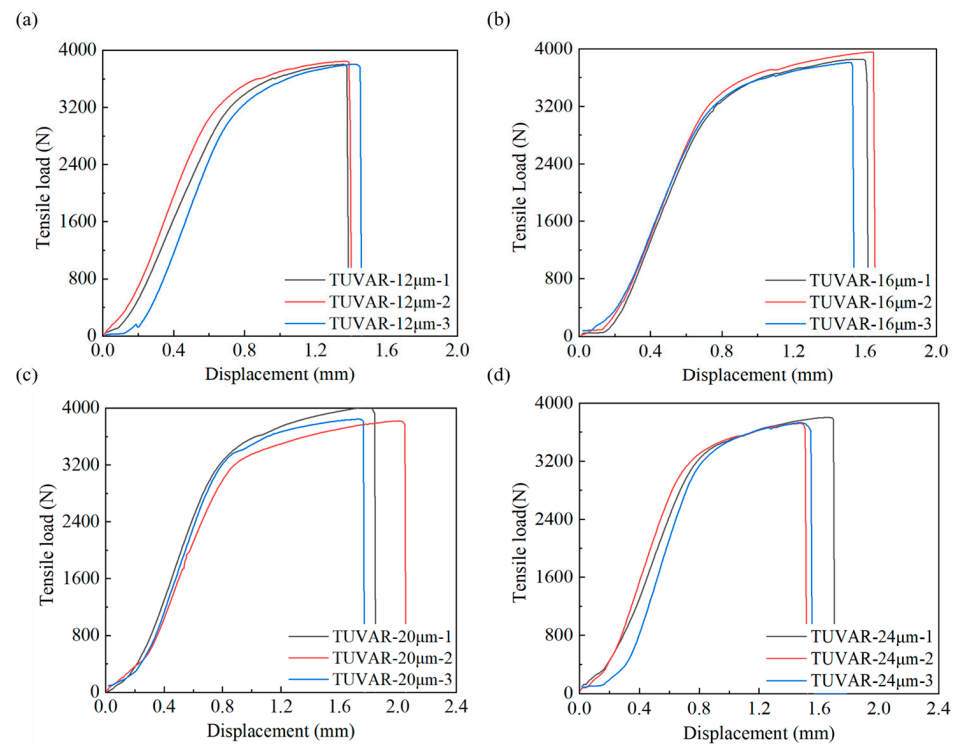
**Figure 9.** Specimens of mechanical testing under different ultrasonic amplitudes: (a) static tensile tests; (b) stepwise cyclic loading tests.

Static and cyclic tensile tests were performed using the universal tensile testing machine. The specimens after testing are shown in Figure 9. For each riveting condition, three specimens were tested under static tension, while two specimens were tested under cyclic loading.

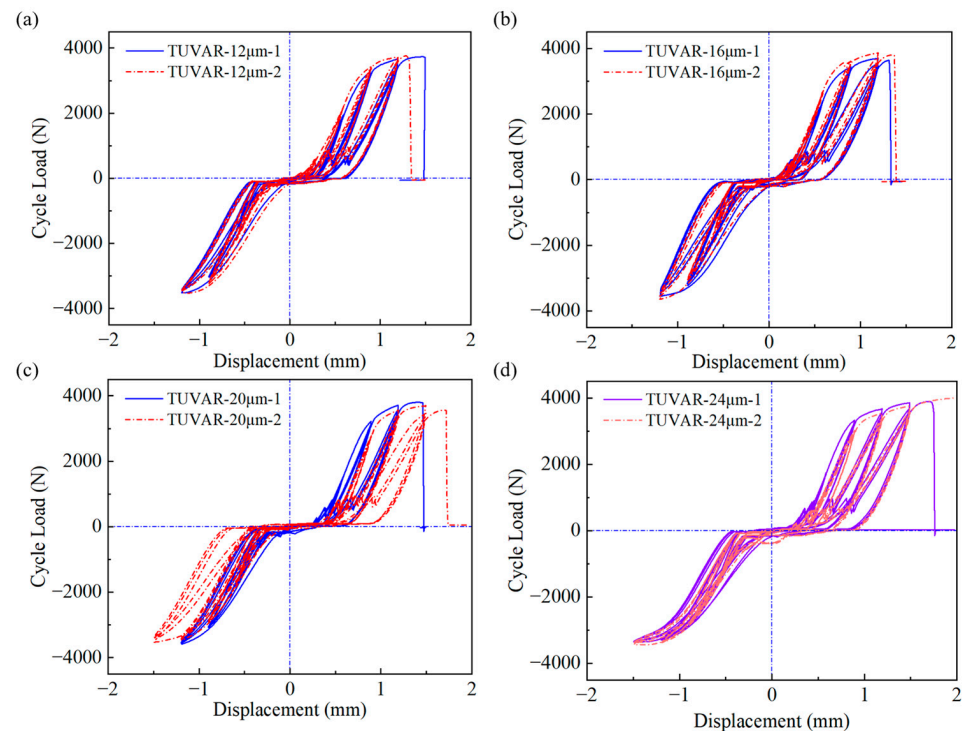
As shown in Figure 10, tensile tests were conducted on CFRP/2024 Al alloy riveted laminates prepared under different ultrasonic amplitudes. The displacement–tensile load curves indicated that the repeatability of the tensile curves under TUVAR was poorer than that under CR. Meanwhile, the displacement generally increased with amplitude. The largest displacement deviation was observed at 16  $\mu\text{m}$ , where the maximum displacement reached 2.1 mm. The maximum displacements at amplitudes of 20  $\mu\text{m}$  and 24  $\mu\text{m}$  were both approximately 1.8 mm, whereas that at an amplitude of 12  $\mu\text{m}$  was about 1.5 mm and remained below 1.6 mm. In addition, the displacement–tensile load curves showed the highest uniformity at an amplitude of 20  $\mu\text{m}$ . The mean maximum tensile load of the CR was  $3767 \pm 29$  N. The corresponding values for the TUVAR were  $3819 \pm 37$  N,  $3871 \pm 64$  N, and  $3895 \pm 73$  N at amplitudes of 12, 16, and 20  $\mu\text{m}$ , respectively, all exceeding the CR, whereas the value at 24  $\mu\text{m}$  decreased to  $3750 \pm 37$  N and became close to the CR level. Overall, TUVAR was capable of improving joint strength when appropriate parameters were adopted. Combined with Figure 7, it can be concluded that the tensile strength first increased and then decreased with increasing amplitude. This behavior was consistent with the mean interference trend, in which the mean interference increased to 2.45% at 20  $\mu\text{m}$  and then decreased slightly to 2.38% at 24  $\mu\text{m}$ . The 24  $\mu\text{m}$  condition therefore did not further improve the interference state, which may have reduced the beneficial contribution of interference to mechanical performance.

### 3.5. Effect of Amplitude on Cyclic Loading Strength

The cyclic loading curves of TUVAR specimens under different amplitudes were analyzed in Figure 11. The cyclic loading test was conducted stepwise and was followed by final tensile failure after the 100% loading level. Under the four amplitude conditions, the displacement–cyclic load curves shifted progressively with increasing amplitude at the same cyclic load level. This result indicated that the tensile resistance of the TUVAR specimens increased gradually with amplitude.



**Figure 10.** Tensile load displacement curves of the CFRP/2024 Al alloy riveted laminates at different ultrasonic amplitudes: (a) 12  $\mu\text{m}$ ; (b) 16  $\mu\text{m}$ ; (c) 20  $\mu\text{m}$ ; (d) 24  $\mu\text{m}$ .



**Figure 11.** Displacement–cyclic load curves at ultrasonic amplitude: (a) 12  $\mu\text{m}$ ; (b) 16  $\mu\text{m}$ ; (c) 20  $\mu\text{m}$ ; (d) 24  $\mu\text{m}$ .

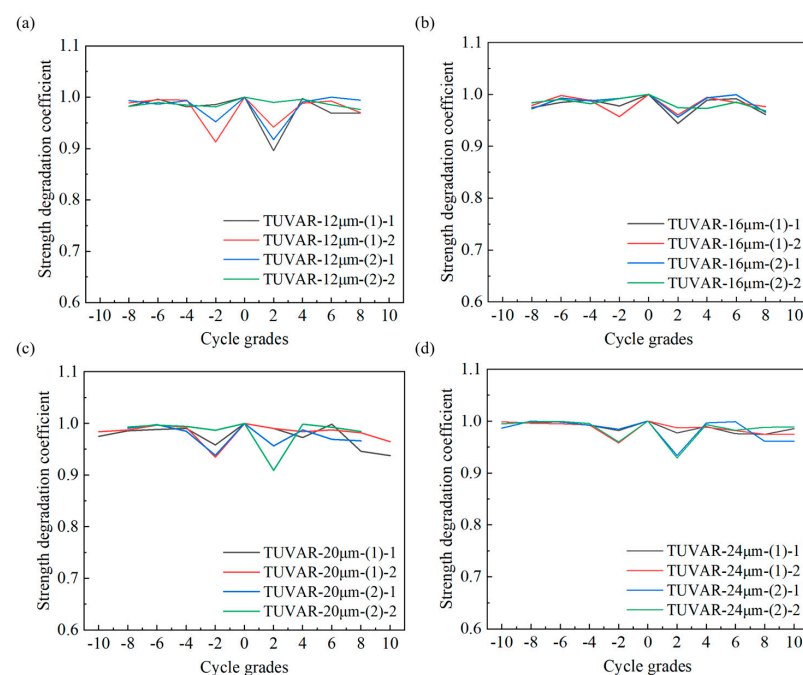
$F_{\text{max}+}$  and  $F_{\text{max}-}$  denote the positive and negative peak loads during cyclic loading, respectively, while  $F'_{\text{max}+}$  denotes the maximum load obtained during the final tensile loading to failure after completion of the cyclic loading procedure. The limit deviation was calculated as  $(1 - F_{\text{max}+}/F'_{\text{max}+}) \times 100\%$ . For the CR, the  $F_{\text{max}+}$  during cyclic loading was 3590 N, and the  $F'_{\text{max}+}$  was 3877 N. Further results for the positive peak load and negative

peak load under cyclic loading at different amplitudes are summarized in Table 4. The results show that the positive peak load,  $F_{\max+}$  was lower than the maximum tensile failure load,  $F'_{\max+}$ , which is consistent with the comparison results obtained from the tensile tests of conventional riveted specimens and TUVAR specimens. This further supports the reliability of the experiments and the beneficial effect of UEF on the mechanical properties of CFRP/2024 Al alloy riveted components. Moreover, the analysis of the limit deviation in the cyclic tensile tests showed that the limit deviations of all four amplitude groups were below 3.5%.

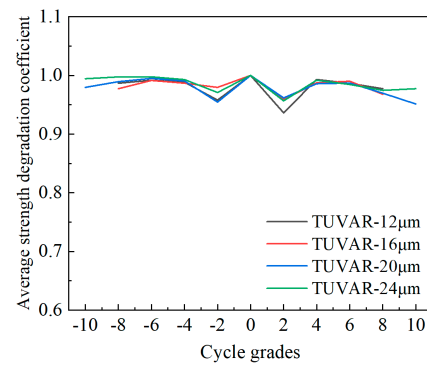
**Table 4.** Cyclic tensile test results at ultrasonic amplitude.

| Amplitude ( $\mu\text{m}$ ) | $F_{\max+}$ (N) | $F_{\max-}$ (N) | $F'_{\max+}$ (N) | Limit Deviation |
|-----------------------------|-----------------|-----------------|------------------|-----------------|
| TUVAR-12 $\mu\text{m}$      | 3668            | 3520            | 3711             | 2.7%            |
| TUVAR-16 $\mu\text{m}$      | 3692            | 3462            | 3797             | 2.8%            |
| TUVAR-20 $\mu\text{m}$      | 3696            | 3466            | 3801             | 2.8%            |
| TUVAR-24 $\mu\text{m}$      | 3746            | 3348            | 3881             | 3.5%            |

The strength degradation behavior of the TUVAR joints was further analyzed, as shown in Figures 12 and 13. The strength degradation coefficients remained generally close to 1.0 at amplitudes of 12, 16, 20, and 24  $\mu\text{m}$ , indicating that the joints retained good overall strength during cyclic loading. Local decreases were still observed at several loading levels, suggesting that degradation was concentrated at specific loading stages. The largest fluctuation occurred at 12  $\mu\text{m}$ , where marked reductions were observed near levels -2 and 2, indicating that the suppression of degradation was limited at the lower amplitude. At 16  $\mu\text{m}$ , the curves were the most stable, and the degradation coefficient remained essentially above 0.95. When the amplitude increased to 20 and 24  $\mu\text{m}$ , the overall degradation coefficient remained high, but local decreases reappeared near level 2. Overall, the effect of ultrasonic amplitude on strength degradation resistance was nonlinear. Although the cyclic peak load increased with amplitude, the 16  $\mu\text{m}$  condition showed the most stable strength degradation response during cyclic loading.

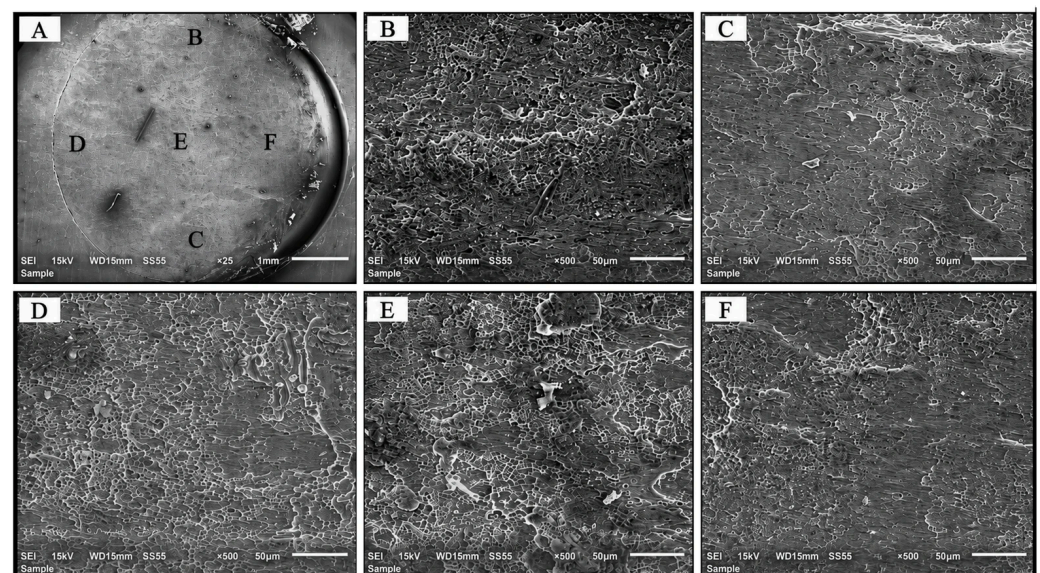


**Figure 12.** Comparative analysis of strength degradation results with different amplitudes: (a) 12  $\mu\text{m}$ ; (b) 16  $\mu\text{m}$ ; (c) 20  $\mu\text{m}$ ; (d) 24  $\mu\text{m}$ .



**Figure 13.** Mean strength degradation results for different amplitudes.

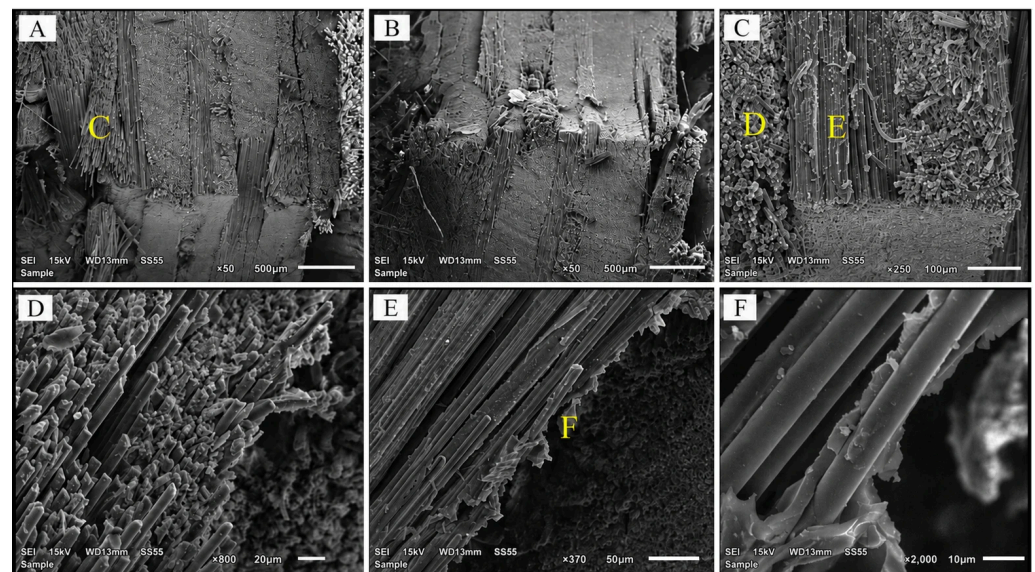
Specimens at all tested amplitudes failed by rivet shear fracture, with no pull-off failure observed. The 20  $\mu\text{m}$  condition was selected for detailed fracture-surface and CFRP hole-wall observations because it exhibited the highest mean interference and the highest mean static tensile load among the investigated amplitudes. Therefore, this condition was used to examine the failure characteristics of the joint with the best static load-bearing performance within the tested range, as shown in Figure 14. The low-magnification image in Figure 14A shows a relatively flat fracture surface, indicating that the rivet failed through a macroscopically stable fracture path. The enlarged regions in Figure 14B–F reveal numerous dimples and microvoids, which are typical features of ductile fracture in Al alloy rivets. These dimples indicate that void nucleation, growth, and coalescence occurred during rivet fracture. In addition to the dimpled morphology, several regions show elongated tearing traces and locally smooth shear surfaces. These features indicate that the rivet fracture was not governed by pure tensile rupture, but by a mixed ductile-shear failure mode. The shallow morphology of some dimples suggests that the plastic deformation capacity of the rivet material was locally constrained after TUVAR. This constraint may be related to different stress states in the plastic deformation of rivets [34].



**Figure 14.** SEM morphologies of the 2A10 Al alloy rivet fracture surface after TUVAR at 20  $\mu\text{m}$ : (A) overall fracture surface, (B–F) magnified regions B–F showing ductile dimples and local shear features.

Figure 15 shows the damage morphology of the CFRP hole wall after joint failure. The overview image in Figure 15A shows severe local damage around the rivet hole, indicating

that the CFRP side was a major damage-bearing region during tensile loading. Clear interlaminar delamination is observed in Figure 15B, indicating that the load transferred from the rivet to the laminate generated separation between adjacent CFRP layers. The magnified images further show that the CFRP damage was governed by multiple coupled failure modes. In Figure 15C, broken fiber bundles and crushed matrix fragments appear near the damaged edge, which indicates strong local stress concentration at the rivet-hole contact region. Figure 15D shows matrix spalling and exposed fibers, while Figure 15E,F show fiber breakage and fiber/matrix interfacial debonding. These observations indicate that the final failure of the CFRP/2024 Al alloy joint involved damage accumulation in the CFRP laminate, including interlaminar delamination, matrix spalling, interfacial debonding, and fiber fracture.



**Figure 15.** SEM morphologies of CFRP hole wall damage after joint failure under TUVAR at 20  $\mu\text{m}$ : (A) overall damaged hole wall; (B) interlaminar delamination; (C) localized edge damage; (D) matrix spalling; (E) fiber breakage; (F) fiber/matrix interfacial debonding.

It should be noted that detailed fracture-surface and CFRP hole-wall observations were conducted only for the 20  $\mu\text{m}$  condition. Therefore, the microscopic damage features described above are specific to this condition and should not be assumed to represent identical damage evolution at the other amplitudes.

These results indicate that no single ultrasonic amplitude was optimal for all the evaluated performance indicators. Within the investigated amplitude range, 20  $\mu\text{m}$  was preferred when mean interference and static load-bearing capacity were prioritized, whereas 16  $\mu\text{m}$  provided the best interference uniformity and the most stable load-bearing response under the adopted stepwise cyclic loading protocol. Although the cyclic peak load continued to increase up to 24  $\mu\text{m}$ , the static tensile load at this amplitude decreased to a level close to that of CR. Therefore, an amplitude range of 16–20  $\mu\text{m}$  can be considered a practical multi-objective process window, with the specific amplitude selected according to the required balance among interference uniformity, static load-bearing capacity, and cyclic-loading stability.

#### 4. Conclusions

(1) TUVAR reduced the forming load of the 2A10 Al alloy rivet under the tested amplitude range. At a riveting displacement of 3 mm, the riveting load decreased from 13,890 N at 12  $\mu\text{m}$  to 11,825 N at 24  $\mu\text{m}$ , indicating enhanced rivet deformability under TUVAR.

(2) TUVAR promoted driven head formation. Compared with CR, the driven head diameter increased under TUVAR, while the driven head height decreased. The maximum height reduction reached 6.62% at amplitudes of 20  $\mu\text{m}$  and 24  $\mu\text{m}$ .

(3) TUVAR improved the mean interference of CFRP/2024 Al alloy riveted joints, but the improvement was not monotonic for interference uniformity. The mean interference increased from 1.43% for CR to 2.45% at 20  $\mu\text{m}$ , whereas the lowest relative interference variance coefficient was obtained at 16  $\mu\text{m}$ .

(4) The static tensile load first increased and then decreased with increasing amplitude. The highest average static tensile load was obtained at 20  $\mu\text{m}$ , whereas the 24  $\mu\text{m}$  condition decreased to a level close to CR. Therefore, 20  $\mu\text{m}$  is more suitable for improving static load-bearing capacity.

(5) As the ultrasonic amplitude increased, the maximum peak load before fracture under the adopted stepwise cyclic loading increased continuously for the CFRP/2024 Al alloy riveted components. The positive peak load,  $F_{\text{max}+}$  was lower than  $F'_{\text{max}+}$ , and the limit deviation remained within 3.5%. However, the strength degradation response was most stable at 16  $\mu\text{m}$ .

(6) The failed joints mainly exhibited rivet shear fracture. The fracture morphology at 20  $\mu\text{m}$  showed ductile dimples, microvoids, and local shear features in the 2A10 Al alloy rivet, while the CFRP hole wall showed delamination, matrix spalling, interfacial debonding, and fiber fracture.

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