# Electronic supplementary materials

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# High-efficiency ultrasonic assisted drilling of CFRP/Ti stacks under non-separation type and dry conditions

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## S1 Longitudinal vibration transducer

The longitudinal vibration transducer used in this experiment is depicted in Fig.S1a. It consists of the following structures: piezoceramics stacks, front cover, back cover, chuck and twist drill, as shown in Fig.S2b. The piezo actuator (PZT) used is type C213, and the transducer is made of 42CrMo material. A 3D model of the transducer is built and the modal analysis is carried out in ANSYS software. Modal analysis can predict the possible vibration modes and resonant frequencies of the structure. To provide a more direct visualization of the transducer vibration node positions, the modal analysis in this study does not consider fixed boundary conditions or other constraints. Since the influence of preload on the material's mechanical properties can be disregarded, it is also neglected in the modal analysis. For mesh division, special attention is given to subdividing the front cover and cutting tool, which are crucial for deformation. The simulation outcomes reveal that the first-order longitudinal resonant frequency of the oscillator model is 20.955 kHz with an error rate of 4.67% when compared to the design value of 20.020 kHz. At the first-order longitudinal resonant frequency, the displacement nephogram of the ultrasonic oscillator in the $x/y/z$ direction can be obtained through ANSYS post-processing, as illustrated in Fig.S3c. It can be seen from the nephogram that the displacement of the tool is axial, consistent with the direction of the ultrasonic vibration. In addition, in the free vibration mode, the vibration of the flange position is the smallest and is just at the vibration node position, which is convenient for the assembly of the main body of the tool holder. The displacement and deformation are mainly concentrated on the tool at the oscillator's output end, indicating that the oscillator has a positive mode. In the ANSYS analysis, the focus is to determine the vibration mode and resonance frequency of the structure, so the amplitude is not thoroughly analyzed. During the experiment, we adjusted the ultrasonic amplitude by varying the output power of the power supply.

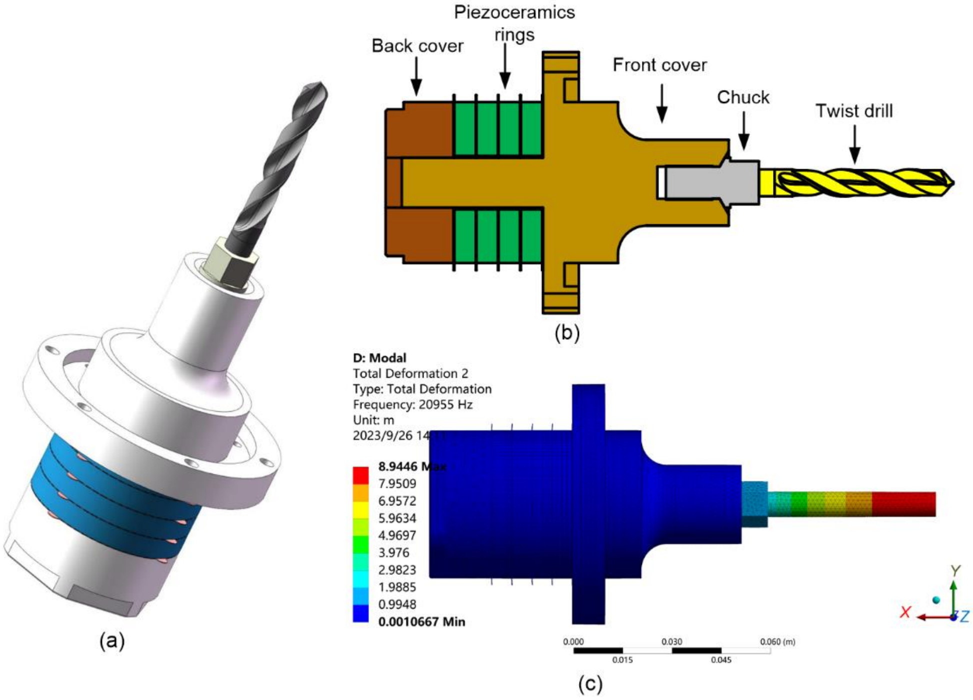
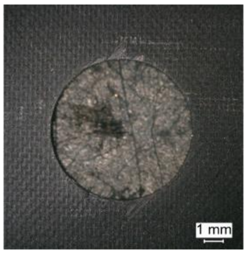
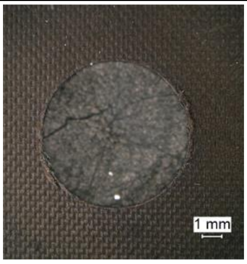
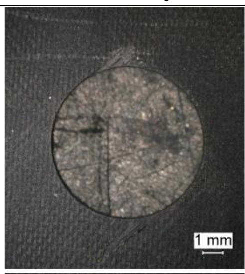
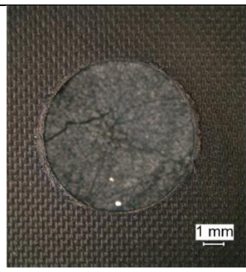
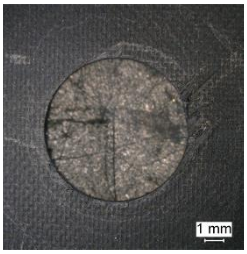
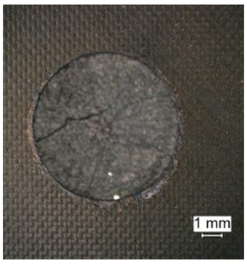
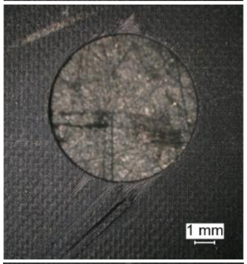
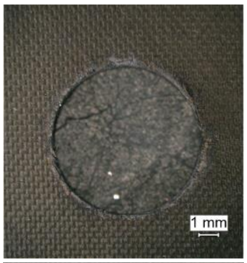
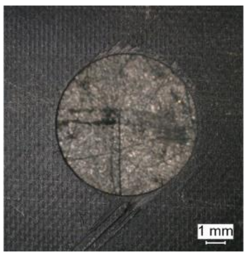
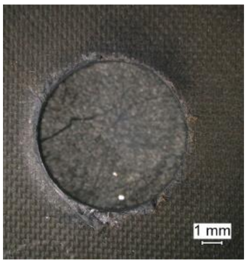
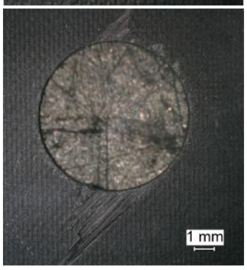
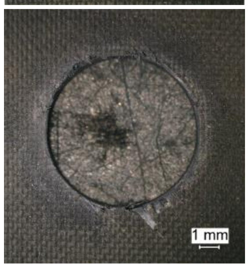
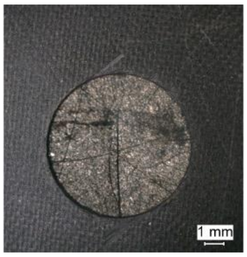
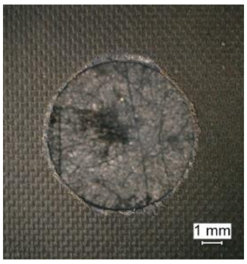
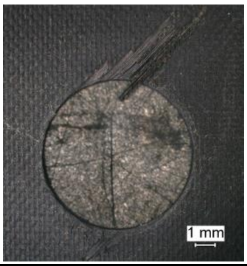
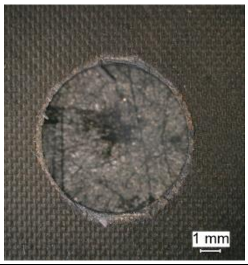



**Fig. S4　Longitudinal vibration transducer: (a) 3D model; (b) composition; (c) displacement nephogram**

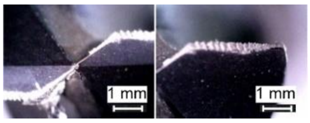
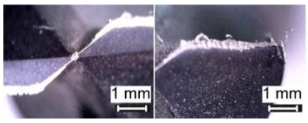
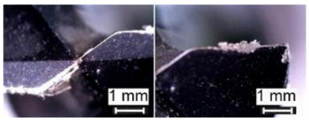
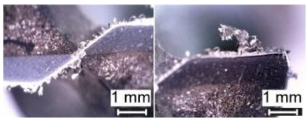
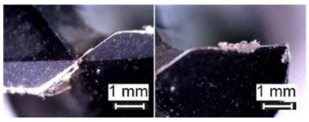
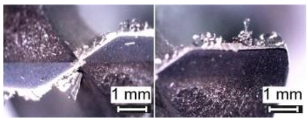
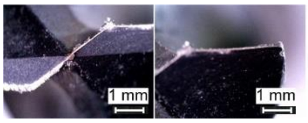
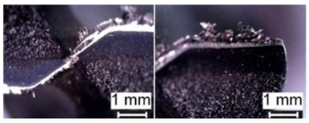
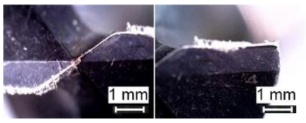
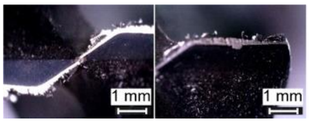
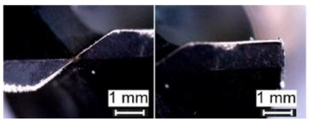
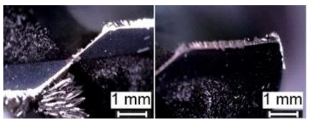
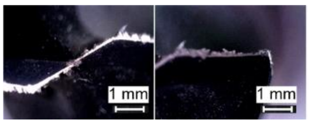
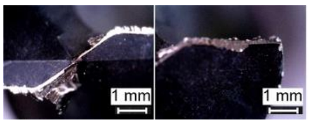
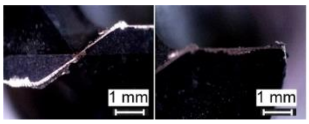
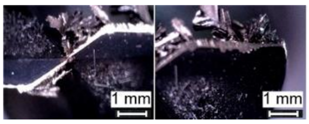
**Table S1　Morphology of entry and exit of CFRP holes**

| Experiment parameter | UAD | | CD | |
|---|---|---|---|---|
| | Hole entry | Hole exit | Hole entry | Hole exit |
| 25 m/min; 10 μm/r |  |  |  |  |
| 25 m/min; 30 μm/r |  |  |  |  |
| 25 m/min; 50 μm/r |  |  |  |  |

| | | | | |
|---|---|---|---|---|
| 25 m/min;<br>70 μm/r |  |  |  |  |

From the entrance morphology in Table S1, an obvious delamination in terms of tearing phenomenon of surface material can be seen. The appearance of the entry tear is mainly because the bit-cutting is insufficient, resulting in part of the fiber at the entrance being not cut off. Then that uncut fiber contacts with the spiral groove of the bit to generate an upward peeling force, which expands continuously in the process of cutting-tool feed, and produces the phenomenon of the surface fiber and the woven layer peeling off the material when the cutting tool leaves the workpiece and forming an entry tearing morphology (Girot et al., 2017).

**Table S2 Tool wear images with the number of holes**

| No. | UAD | CD |
|---|---|---|
| 2 |  |  |
| 5 |  |  |
| 10 |  |  |
| 20 |  |  |
| 30 |  |  |
| 40 |  |  |
| 50 |  |  |
| 60 |  |  |

From the initial wear stage (2 holes), much titanium alloy adhesion occurs on the cutting edge in CD, while the adhesion extent is significantly less in UAD. With the increase of the number of holes, the difference of titanium alloy adhesion is more obvious. For ultrasonic vibration drilling, the adhesion of titanium alloy is more uniform. The adhesive titanium alloy is mainly concentrated in the middle of the cutting edge. As for CD, a large volume of titanium alloy chips and debris adhered to the surface of the tool; the chisel edge and cutting edge are adhered with titanium alloy. Meanwhile, the width of the wear band on the back tool surface increases with the increase of the number of holes and so the sharpness of the cutting edge of CD decreases obviously compared with UAD. This is due to the variable cutting thickness characteristics of UAD effectively reducing the continuous adhesion of titanium alloy.

## Reference

Girot F, Dau F, Gutiérrez-Orrantia ME, 2017. New analytical model for delamination of CFRP during drilling. *Journal of Materials Processing Technology*, 240:332-343. https://doi.org/10.1016/j.jmatprotec.2016.10.007