Stability analysis and experimental research on ultrasonic cutting of wave-absorbing honeycomb material with disc cutter

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Abstract
To address the problem of the poor stability of ultrasonic machining of wave-absorbing honeycomb material, this study takes ultrasonic cutting of wave-absorbing honeycomb material with a disc cutter as the research object and establishes a multi-degree-of-freedom mathematical model of the cutting system based on the relative positions of the tool, the wave-absorbing honeycomb material, and the motion characteristics of the tool. On this basis, modal analysis of the disc cutter and the honeycomb cell wall plate is carried out to draw the Lobe diagram of ultrasonic cutting stability, the process experimental parameters are determined to accord to the solved stability Lobe diagram, and machining stability verification experiments are carried out. The experimental results show that the machining parameters in the stable zone of the Lobe diagram result in a neat and clean surface, less fibre pullout, a complete outer substrate, and less tool wear than those in the critical and unstable zones, thus verifying the correctness of the theoretical model and the stability Lobe diagram.

Keywords Cutting stability analysis · Ultrasonic cutting · Wave-absorbing honeycomb material · Disc cutter

1 Introduction
Wave-absorbing honeycomb material is a structural wave-absorbing material developed based on an aramid honeycomb [1], which is based on a hexagonal aramid honeycomb and impregnated with the resin mixed with an acetylene carbon black honeycomb absorbing substance on honeycomb walls. Due to the excellent properties of low density, lightweight, heat resistance and corrosion resistance, and high impact resistance [2], wave-absorbing honeycomb materials are widely used in military, aerospace, and other fields with special requirements [3].

CNC milling is a common method for machining honeycomb materials [4, 5], but this method of machining produces a large amount of dust and leaves a large number of burrs on the surface of the workpiece [6]. In addition, the lateral force of the spindle during tool feeding causes a short deformation of the workpiece material, which affects the surface quality and dimensional accuracy of the workpiece [7]. There are almost no chips produced in the process of removing excess material by ultrasonic cutting, and the cutting force is very small [8]. Compared with traditional milling, ultrasonic cutting has higher machining efficiency, higher machining quality, lower machining cost, and better environmental friendliness [9].

In the cutting process of wave-absorbing honeycomb materials, the local cutting area is similar to thin-walled plate processing. If the process parameters are not selected properly, the machining state is prone to destabilization and chattering, which leads to fibre pull-out, outer substrate deformation, and coating peeling on the machined surface [10], which seriously affects the surface quality of the workpiece after moulding. Due to the special hexagonal structure of wave-absorbing honeycomb materials, the hexagonal hole lattice structure of the honeycomb is usually regarded as a thin-walled structure of the tube in the processing study of wave-absorbing honeycomb material [11]. During the processing of the thin-walled structure of the parts, chattering and processing stability are problems that cannot be ignored during the processing [12]. To improve the stability of the machining process of thin-walled parts, Bravo et al. [13] assumed thin-walled parts and tools as elastomers, analysed the three-dimensional stability leaflet diagrams of different machining stages by finite elements, and compared the cutting conditions by finite elements, and compared the
cutting conditions with the critical conditions in the leaflet diagrams to derive the optimal machining conditions for low stiffness parts. Thevenot et al. [14] after considering the vibration generated in the milling of thin-walled parts based on the assumption that the thin-walled part is an elastomer and the tool is a rigid body, established a three-dimensional stability Lobe diagram using modal analysis and finite element simulation. It was shown how to use the stability Lobe diagram to determine the changes in the dynamic characteristics of the thin-walled workpiece. Zhang et al. [15] used the matrix ingestion method to predict the dynamic modalities of the workpiece during high-speed milling on the basis of the finite element analysis model and proposed that the material during the removal process, dynamic modal changes have an important effect on the whole cutting system. Mancisidor et al. [16] proposed a method for calculating the dynamic behaviour based on the fixed boundary of the tool to obtain chatter-free machining conditions with a dynamic transfer function at the tool tip and performed experimental calculations of the frequency response function considering various combinations of tool and machine tool machining parameters. Zhang et al. [17] established a three-dimensional milling dynamics model for thin-walled materials with low stiffness, simulated and verified the critical axial chatter depth of cut versus tool speed using the fully discrete analytical method, and plotted the stability Lobe diagram. Zhu [18] investigated the vibration stability of thin-walled parts in longitudinal torsional ultrasonic vibration machining by establishing a two-dimensional milling model of a double-flexible body and studied the effect of different cutting parameters on the chattering stability in depth by finite element simulation. Due to discontinuous cutting [8], dynamic cutting forces periodically excite the relative vibration of the tool and workpiece, resulting in regenerative chatter. The chatter not only affects machining quality, tool life, but can also be dangerous for production [19]. Therefore, the stability of the process is important. The unique hexagonal thin-walled structure of wave-absorbing honeycomb materials causes the material to be difficult to achieve a stable state in ultrasonic processing, and chattering occurs during processing, which seriously affects the surface quality of the parts [20]. By plotting the response-stabilized Lobe diagram, parameters for stable machining of wave-absorbing honeycomb materials can be determined to obtain high surface quality and extend the life of ultrasonic disc cutter.

In this paper, we investigate the stability processing of wave-absorbing honeycomb materials by ultrasonic cutting technology with disc cutter. First, the theoretical analysis of ultrasonic cutting of wave-absorbing honeycomb materials with a disc cutter is carried out, including establishing a multi-degree-of-freedom stability mathematical model of the cutting system and the modal analysis of the disc cutter and the cell wall [21] plate using finite element software to obtain the dynamic parameters of the tool and the cell wall plate. Then, the Lobe diagram of the disc cutter machining process stability is drawn. Second, ultrasonic cutting experiments of the disc cutter are carried out, and the correctness of the multi-degree-of-freedom stability mathematical model is verified by examining the surface morphology of the workpiece formed by cutting under each process parameter and the wear condition of the disc cutter.

2 Theoretical analysis of ultrasonic cutting wave-absorbing honeycomb materials by disc cutter

2.1 Development of a multi-degree-of-freedom stability model for ultrasonic cutting systems

An ultrasonic cutting system is a cutting system with the rotary motion of the disc cutter itself and high-frequency ultrasonic vibration as the main forms of motion. According to the relative position of the tool, the wave-absorbing honeycomb materials, and the motion characteristics of the tool, a three-dimensional coordinate system is established, as shown in Fig. 1b.

As show in Fig. 1, the feed direction is defined as Z-axis, the ultrasonic vibration direction is defined as Y-axis, and the cutting width is defined as X-axis. The honeycomb is cut in the XZ plane with the feed of the tool in the Z-direction of the coordinate axis. The rotational speed of the disc cutter is n, the feed speed is $V_f$, the motion displacement is $S'$, and the cutting time is $t$ ($0 < t < 0.4$ s)

$$S'_x = R \cdot \left(1 - \cos \frac{2\pi n}{60} t\right) \quad (1)$$

![Fig.1 a Schematic diagram of wave-absorbing honeycomb material structure and b schematic diagram of ultrasonic cutting of wave-absorbing honeycomb material by disc cutter](image-url)
\[ V_x' = \frac{2\pi n R}{60} \cdot \sin \frac{2\pi n}{60} t \]  
\[ a_x' = \left( \frac{2\pi n}{60} \right)^2 R \cdot \cos \frac{2\pi n}{60} t \]  

In the Y-direction, there is only ultrasonic vibration of the cutter, and the equations of motion are

\[ S_y' = A \cdot \sin(2\pi ft) \]
\[ V_y' = 2\pi fA \cdot \cos(2\pi ft) \]
\[ a_y' = -(2\pi f)^2 A \cdot \sin(2\pi ft) \]

In the Z-direction, the motion of the cutter includes the sub-motion of feed motion and rotary motion, and the equations of motion are

\[ S_z' = R \cdot \sin \frac{2\pi n}{60} t + V_f t \]
\[ V_z' = V_f + \frac{2\pi n R}{60} \cdot \cos \frac{2\pi n}{60} t \]
\[ a_z' = -(2\pi f)^2 R \cdot \sin \frac{2\pi n}{60} t \]

In the XOZ plane of the coordinate system, this ultrasonic cutting system can be simplified to a two-degree-of-freedom cutting system, as shown in Fig. 2, so that the dynamic equation of this ultrasonic cutting system can be obtained as.

\[ [M_{k'}][\gamma_{k'}(t)] + [C_{k'}][\gamma_{k'}(t)] + [k_{k'}][\gamma_{k'}(t)] = \{F_k'(t)\} \]

where \([M_{k'}],[C_{k'}],\) and \([k_{k'}]\) are the 2×2 order mass, damping, and stiffness matrices of the disc cutter-cell element wall plate system, and \(\{\gamma_{k'}(t)\}, \{\gamma_{k'}(t)\}\) and \(\{F_k'(t)\}\) are the acceleration, velocity, displacement, and cutting force vectors.

When the tool is ultrasonically cutting, the cutting force gradually increases with increasing cutting thickness, and the cutter vibrates when cutting the honeycomb cell wall plate. Thus, the structural mode of the whole cutting system is self-excited and produces unstable chattering. The cutting system is excited by the cutting force in the X-direction and the Z-direction to produce dynamic displacement, and the dynamic displacement of the cutting thickness caused by the vibration between the disc cutter and the honeycomb cell wall plate is

\[ s_k = x_k \cdot \sin \phi \cdot \sin \zeta + z_k \cdot \cos \phi \cdot \sin \zeta \]

where \(\phi\) is the radial contact angle of the disc cutter, as shown in Fig. 3a when the tool spindle speed is \(n, \phi = n\pi t/30; \zeta\) is the axial immersion angle, where \(\zeta = \pi/2; x_k, z_k\) is the dynamic displacement of the cutting edge.

During the ultrasonic cutting process, as shown in Fig. 3b, when ultrasonic vibration is applied to the disc cutter, as shown in Fig. 3c, the surface of the wave-absorbing honeycomb materials is wavy in the microscopic state, as shown in Fig. 3d. With the rotation of the tool spindle, the radial contact angle of the tool changes with time, causing the chip thickness to change with time. At this time, the chip thickness includes the static chip thickness caused by the rigid body motion of the tool and the dynamic chip thickness caused by the vibration of two adjacent cycles of the cutting edge, which can be expressed as

\[ \delta_k(\phi) = [c_k \cdot \sin \phi + (s_{k-1} - s_k)] \cdot g_k(\phi) \]

where \(c\) is the cutting-edge feed, \(s_{k-1} - s_k\) is the difference of the displacement of the disc cutter in two adjacent cycles, \(g_k(\phi)\) is the unit step function used to determine whether the disc cutter is cutting, and the value of \(g_k(\phi)\) is related to whether the radial contact angle \(\phi\) is between the entrance angle \(\phi_{in}\) and exit angle \(\phi_{out}\), expressed as

\[ \begin{cases} \phi_{in} < \phi < \phi_{out} & g_k(\phi) = 1 \\ \phi_{out} < \phi < \phi_{in} & g_k(\phi) = 0 \end{cases} \]

Since the static part of the cutting thickness has no influence on the stability of the system, only the dynamic part of the chip thickness is obtained.

\[ \delta_k(\phi) = [\Delta z_{k} \cdot \sin \phi + \Delta x_{k} \cdot \cos \phi] \cdot g_k(\phi) \]

where \(\Delta x_{k} = x(t) - x(t - T), \Delta z_{k} = z_{k}(t) - z_{k}(t - T)\) in which \(t\) is the current time and \(T\) is the tool rotation period. \((x_{k}(t), z_{k}(t))\) and \((x_{k}(t - T), z_{k}(t - T))\) denote the relative
dynamic displacement between the cell wall plate and the tool in adjacent cycles, respectively.

Radial and tangential cutting forces on unit arc length $F_r, F_t$ with $a_p$ (axial depth of cut), the $\delta_k(\phi)$. The following relationship exists:

$$\begin{cases} F_r = K_r a_p \cdot \delta_k(\phi) \\ F_t = K_t a_p \cdot \delta_k(\phi) \end{cases}$$

(15)

In formula (15), $K_r$ and $K_t$ is the radial cutting force coefficient and tangential cutting force coefficient. The radial and tangential cutting forces are decomposed to

$$[N(t)] = [N_0] = \frac{1}{4} \left[ \begin{array}{cc} (-K_r \sin 2\phi + 2K_t \phi + K_t \cos 2\phi)/\phi_{\text{in}} & (K_r \cos 2\phi - 2K_t \phi + K_t \sin 2\phi)/\phi_{\text{in}} \\ (-K_r \cos 2\phi + 2K_t \phi - K_t \sin 2\phi)/\phi_{\text{in}} & (K_r \sin 2\phi - 2K_t \phi - K_t \cos 2\phi)/\phi_{\text{in}} \end{array} \right]$$

(20)

obtain the X-directional and Z-directional cutting forces, which is expressed in the matrix as

$$\begin{bmatrix} F^X \\ F^Z \end{bmatrix} = \begin{bmatrix} \sin \phi - \cos \phi \\ -\cos \phi \sin \phi \end{bmatrix} \begin{bmatrix} F_r \\ F_t \end{bmatrix}$$

(16)

Substituting (14) and (15) into (16) to obtain the relationship between the cutting force and displacement as

$$\begin{bmatrix} F^X \\ F^Z \end{bmatrix} = a_p [N] \begin{bmatrix} \Delta x_k \\ \Delta z_k \end{bmatrix}$$

(17)

where $[N]$ is the time-varying dynamic ultrasonic cutting force coefficient, which is a $2 \times 2$ order matrix, and the individual elements of the matrix are

$$[N] = \begin{bmatrix} n_{xx} n_{xz} \\ n_{xz} n_{zz} \end{bmatrix} = g_k(\phi) \begin{bmatrix} -\sin \phi - \cos \phi \\ -\cos \phi \sin \phi \end{bmatrix} \begin{bmatrix} K_r \\ K_t \end{bmatrix} \begin{bmatrix} \sin \phi \cos \phi \end{bmatrix}$$

(18)

Equation (8) is expressed in the time domain in the form of a matrix as

$$\begin{bmatrix} F^X(t) \\ F^Z(t) \end{bmatrix} = a_p [N(t)] \{ \Delta(t) \}$$

(19)

where the matrix $\{ F^X(t) \}$ represents the dynamic cutting force in the X- and Z-directions; the disc cutter then rotates clockwise when the disc cutter enters the cutting state.

The matrix $\{ \Delta(t) \}$ represents the dynamic displacement in the X- and Z-directions and is expressed in terms of the transfer function matrix of the cutter-cell wall plate as

$$\{ \Delta(t) \} = (1 - e^{-j\omega_{c^t} t}) [H(s)] \{ F^X(t) \}$$

(21)

where $\omega_{c^t}$ is the chattering frequency; the transfer function matrix $[H(s)]$ is the transfer function matrix of the disc cutter $[H_c^c(s)]$, and the transfer function matrix of the cell wall plate $[H_w(s)]$ is the sum of:

$$[H(s)] = \begin{bmatrix} H_c^c_{xx}(s) + H_{Wxx}(s)H_c^c_{xz}(s) + H_{Wxz}(s) \\ H_c^c_{xz}(s) + H_{Wxz}(s)H_c^c_{zz}(s) + H_{Wzz}(s) \end{bmatrix}$$

(22)
The chattering stability of the system is determined by the characteristic equation of the two-dimensional dynamic ultrasonic cutting system and is given by the following equation.

\[
\text{det}([I] + \Lambda \cdot [\Phi]) = 0
\]  

(23)

where \([I]\) is the unit matrix; \([\Phi] = [N_0][H(s)]\) is the directional transfer function matrix; The complex eigenvalue is \(\Lambda = -\alpha_p (1 - e^{-i\omega_c T});\) if the value of cutting force coefficient, \(K_c\), and \(K_t\), are given, solves for the complex eigenvalue as

\[
a_2 \Lambda^2 + a_1 \Lambda + 1 = 0
\]  

(24)

According to Euler’s formula, we have \(e^{-i\omega_c T} = \cos\omega_c T - i\sin\omega_c T\) and substitute into \(\Lambda\).

\[
\Lambda = -\alpha_p (1 - \cos\omega_c T + i\sin\omega_c T) = \Lambda_R + i\Lambda_I
\]  

(25)

The formula for solving the critical depth of cut \(d_{plim}\), which is related to the depth of cut \(\omega_c\), be expression as

\[
da_{plim} = -\frac{\Lambda_R + i\Lambda_I}{1 - \cos\omega_c T + i\sin\omega_c T}
\]  

\[= -\frac{1}{2} \left(\frac{\Lambda_R (1 - \cos\omega_c T) + \Lambda_I \sin\omega_c T}{1 - \cos\omega_c T} + i \frac{\Lambda_I (1 - \cos\omega_c T) - \Lambda_R \sin\omega_c T}{1 - \cos\omega_c T}\right)
\]  

(26)

\(d_{plim}\) must be real, so Eq. (26) has only a real part and no imaginary part, giving \(\Lambda_I (1 - \cos\omega_c T) - \Lambda_R \sin\omega_c T = 0\). After simplifying by shifting the terms, we have

\[
\frac{\Lambda_I}{\Lambda_R} = \frac{\sin\omega_c T}{1 - \cos\omega_c T} = \kappa = \tan\Psi
\]  

(27)

where \(\kappa\) is the number of leaflets of the stability wavefront map, taken as an integer; \(\Psi\) is the phase shift of the eigenvalues; the dither-free axial depth of cut is obtained as

\[
da_{plim} = -\frac{\Lambda_R}{2} (1 + \kappa^2)
\]  

(28)

Therefore, after determining \(\omega_c\) and based on expression (27), the relationship between the period \(T\) and the spindle speed \(n\) and the relationship between the depth of cut and the speed of rotation, which represents the stability Lobe diagram, can be obtained as follows:

\[
\begin{align*}
\omega_c T &= \pi - 2\Psi + 2k\pi \\
\Psi &= \arctan \kappa \\
T &= \frac{\pi}{\omega_c} (\pi - 2\arctan \kappa + 2k\pi) \\
n &= \frac{1}{T}
\end{align*}
\]  

(29)

\[\text{Fig. 4} \ 5\text{th-}, 12\text{th-}, 17\text{th-}, \text{and} 30\text{th-order vibration patterns of the disc cutter}
\]
vibration patterns remains consistent at the same radius of the tool and increases monotonically along the radial direction of the tool, reaching the maximum amplitude at the cutting edge. The above vibration patterns meet the requirements of the maximum amplitude at the cutting edge of the ultrasonic tool, but the 5th-order vibration pattern also has axial bending. The 17th- and 30th-order amplitudes are more complicated and easily cause tool fracture. Meanwhile, the inherent frequency of the 12th order is consistent with the resonant characteristics of the operating frequency of the ultrasonic variable amplitude rod. In summary, the 12th-order inherent frequency and vibration pattern meet the requirements of this paper.

The three-dimensional model of the cell wall plate was established according to the actual dimensions, and its material properties [23] are shown in Table 2. The modal analysis procedure is the same as that of the disc cutter, and the first-order inherent frequency of the cell wall plate is 64,517 Hz, which is much larger than the 12th-order inherent frequency of the disc cutter.

### 2.3 Cutting force coefficient analysis

According to the mathematical stability model of the ultrasonic cutting process of the disc cutter established in a previous paper, it is known that to draw a complete stability Lobe diagram, in addition to obtaining the kinetic parameters of the disc cutter, it is also necessary to obtain the ultrasonic cutting force coefficients of the disc cutter. In the actual cutting process, the tool rotates with the spindle tangential cutting force \( P_t \) and radial cutting force \( P_r \) with the cutting depth of the tool \( a_p \) and the related cutting force coefficient \( K \) and feed \( f_z \) [24].

\[
\begin{align*}
  P_t &= K_{tc}a_p f_z + K_{te}a_p \\
  P_r &= K_{rc}a_p f_z + K_{re}a_p
\end{align*}
\]

where \( K_{tc} \) and \( K_{rc} \) are the cutting force coefficients in the Z-direction and X-direction of the disc cutter (N/mm²) and \( K_{te} \) and \( K_{re} \) are the edge force coefficients in the Z-direction and X-direction of the disc cutter (N/mm²). The edge force coefficient is related to the edge wear of the disc cutter. According to cutting experience, there is a certain degree of edge wear, and the edge is gradually rounded when the tool is cut.

### 3 Experimental studies

#### 3.1 Experimental platform construction

Figure 5 shows the experimental setup for ultrasonic cutting of wave-absorbing honeycomb materials with a disc cutter. The ultrasonic generator is produced by “Mingquan” company. The working frequency is 20 kHz and has the automatic frequency chasing function. The output power can be adjusted from 0 to 2 kW. The cutting force was measured by using a Kistler-9119AA2 force measuring sensor. An 8-channel charge amplifier (5080-A1080004) and a data collector (5697A1) were also used. The software of “Dynoware”, a special data acquisition and processing software developed by Kistler, was used to collect measurement data.

The processing results shown in Fig. 8 were observed by optical microscope. The microscope has the ability to observe at a magnification of 10 to 1000 times, and 100 times magnification is used for observation in this manuscript. The magnification has been calibrated with a standard plate.

**Table 2 Mechanical characteristics parameters of the cell wall plate of wave-absorbing honeycomb material**

| Materials       | Modulus of elasticity (MPa) | Shear modulus (MPa) | Poisson’s ratio | Density (kg/m³) |
|-----------------|----------------------------|---------------------|----------------|-----------------|
| Cell wall plate | 544                        | 3016                | 0.3            | 739.4           |

![Fig. 5 Ultrasonic cutting experiment device for disc cutter](image-url)

CNC Milling Machine

Machine spindle

Ultrasonic-3000 power supply

Data Acquisition System

Honeycomb material

Cutting width

Section contour of disc cutter

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The S-type tool path was used in the experiment, and the cutting distance \( S \) equals to the product of workpiece width \( M \) and reciprocation times \( n \), as shown in Fig. 6. The size of the workpiece is 100 × 80 × 60 mm. The properties of wave-absorbing honeycomb material are described in Fig. 1a and Table 3.

During the experiments, the wave-absorbing honeycomb material was fixed using gluing method. This is a common clamping method in the processing of this material [25]. A layer of transparent adhesive was first applied to the top surface of the Kistler-9119AA2 force sensor and putting 3 M VHB double-sided foam tape on the top of the transparent adhesive, then putting the honeycomb material on the foam tape. Pressure was applied on the upper surface of the workpiece and continued for a period of time to ensure the reliability of bonding.

### 3.2 Cutting force coefficient calibration

The ultrasonic amplitude was chosen to be 20 µm, and the ultrasonic frequency was 20 kHz. Disc cutting experiments with different cutting parameters were carried out to obtain the corresponding average cutting forces in the X-direction and Z-direction, as shown in Table 4.

The obtained cutting forces were imported into MATLAB for fitting to obtain the cutting force coefficients and edge force coefficients for ultrasonic cutting of wave-absorbing honeycomb material by the disc cutter, as shown in Table 5.

Substituting the stability kinetic parameters in Table 6 into Eq. (20) for the relationship between ultrasonic cutting depth of cut and rotational speed to solve for the depth of cut \( a_p \) corresponding to the spindle speed \( n \) and using MATLAB programming in the set frequency range to plot the complete \( n-a_p \) relationship plot, i.e., stability Lobe plot.

The results are shown in Fig. 7.

As shown in Fig. 7, when the axial depth of the cut was selected to be below 4 mm, the tool was in a stable state when it was cut. When the axial cutting depth is selected from 4 to 8 mm, the tool is in a critical state of stability and instability when cutting, and then the tool needs to be selected at approximately 700 r/min, 900 r/min, or 1200 r/min for stable cutting. When the cutting depth is greater than 8 mm, the cutting process is usually in a nonstable state. By looking at the whole leaf flap diagram, the right leaf flap is large and sparse, while the left leaf flap is small and dense. Therefore, to obtain stable machining process parameters
for a larger cutting depth, it is necessary to find parameters in a higher speed range.

3.3 Ultrasonic disc cutter cutting stability experiments and results analysis

To verify the accuracy of the stability Lobe diagram, the tool speed and depth of cut was selected in the stable zone, unstable zone, and critical stable zone as shown in Fig. 7 to carry out ultrasonic cutting experiments with the disc cutter, as shown in points 1–6 within Fig. 7, and the specific values are shown in Table 7.

Figure 8a, b show the machined surfaces after cutting with the process parameters at points 1 and 2 in the stable zone of the Lobe diagram, respectively. The surface of the workpiece is neat and smooth, the fibre layer fracture is flat, only a small number of positions have a slight fibre layer pulling fracture, the resin layer does not produce peeling, and only a small number of local fractures occur. Figure 8c, d show the machined surfaces after cutting with process parameters of 5 and 6 points in the critical zone of the Lobe diagram, respectively. There is a clear deformation of the fibre layer in the cell wall and a large amount of separation of the resin layer from the fibre layer in the cell wall intersection zone. Figure 8e, f show the machined surfaces after cutting with process parameters of 3 and 4 points in the unstable zone of the Lobe diagram, respectively. It can be observed that the cell wall shows severe fibre layer pulling, deformation and fracture, and the cell wall intersection zone shows the separation of the resin layer and the fibre layer on a larger scale. The analysis also shows that the damage of the fibre layer mainly occurs at the cell wall, while the damage of the resin layer, such as fracture and separation, mainly occurs at the cell wall intersection zone. According to structural mechanics, these two locations show different mechanical properties due to their different structures, with the cell wall showing higher elasticity and plasticity and the cell wall intersection zone, showing higher strength. Since the resin material has a weaker tensile capacity and more obvious brittleness compared with the fibre material, it can be introduced that the cutting force is greater in the Lobe diagram instability zone and the critical zone when selecting process parameters for processing, which leads to large-scale deformation of the cell wall; damage characteristics are mainly manifested as deformation, drawing, and fracture of the fibre layer, while the material deformation is smaller in the cell wall intersection zone, so the damage characteristics. The damage is mainly characterized by the fracture and peeling of the resin layer.

Figure 9 shows the changes in the number of notches and notch pattern of the cutting edge with cutting distance during ultrasonic cutting using the process parameters represented by points 1, 4, and 6 in Fig. 7. It can be seen from the figure that when the cutting parameters of unstable zone and critical zone are selected for machining, the cutting edge of disc cutter is broken when the cutting distance reaches 300 mm, and the edge breakages increase rapidly with the increase of cutting distance. For disc cutter cutting in unstable conditions, the number of edge notches increases rapidly, and the notch increases significantly after the cutting distance reaches 500 mm. For disc cutter cutting in the critical state, when the cutting distance reaches 1000 mm, the number of cutting-edge notches increases rapidly, the notch depth also increases significantly, and there is high-temperature smoke and burn. When the stable zone cutting parameters were selected for machining, edge breakage was found only when the cutting distance reached

### Table 5 Cutting force coefficients and edge force coefficients for ultrasonic cutting of disc cutter

| Coefficient | $K_{tc}$(N/mm²) | $K_{rc}$(N/mm²) | $K_{te}$(N/mm²) | $K_{re}$(N/mm²) |
|-------------|----------------|----------------|----------------|----------------|
| Results     | 75             | 192            | 14             | 21             |

### Table 6 Parameters required for plotting stability Lobe diagrams

| Disc cutter | $\omega_{u}$(Hz) | $\xi_{u}$ | Cell wall plate | $\omega_{n}$(Hz) | $\xi_{n}$ | $K_{nc}$(N/mm²) | $K_{rc}$(N/mm²) | $\phi_{in}$(°) | $\phi_{out}$(°) |
|-------------|-----------------|---------|----------------|-----------------|---------|----------------|----------------|--------------|----------------|
|             | 21,904          | 0.05    | 64,517         | 0.05            | 192     | 75             | 0              | 90           |                |

Fig. 7 Lobe diagram of stability of ultrasonic cutting honeycomb cell wall by the disc cutter.
800 mm; when the cutting distance reached 1500 mm, a large number of edge notches appeared; the machining process gradually destabilized, high temperature burn marks appeared on the tool surface, and the machined surface deteriorated sharply. By comparing the cutting edge notch patterns generated under different process parameters, it can be found that the cutting edge notches generated by machining with non-stable zone and critical zone cutting parameters are discrete thin strips of broken off, while the cutting edge notches generated by machining with stable zone are semi-circular broken and usually accumulate. As the machining continues, the notches will continue to increase together leading to the accumulation of poor machining condition.

The above experimental results show that selecting cutting parameters in the stable zone of the Lobe diagram for machining, the machined surface has a better finish and the machining quality is much higher than the cutting parameters selected in the critical stable zone and unstable zone. Selecting process parameters in the stable zone of the Lobe diagram for machining can significantly improve the tool life, which proves that the theoretical model and stability established in the Lobe diagram in this paper can be used to guide the cutting process of wave-absorbing honeycomb material.

### Table 7 Experimental parameters for stability Lobe plot accuracy verification

| Zone serial number | Cutting depth $a_p$/mm | Tool speed /rpm | Feeding speed $V_f$/ (m/min) |
|--------------------|------------------------|-----------------|-----------------------------|
| Stable zone        | 1 2                    | 1000            | 5                           |
|                    | 2 2                    | 1600            | 5                           |
| Unstable zone      | 3 5.5                  | 1600            | 5                           |
|                    | 4 4                    | 1000            | 5                           |
| Critical stability zone | 5 7                    | 1600            | 5                           |
|                    | 6 7                    | 1000            | 5                           |

**Fig. 8** Microscopic surface profile of the wave-absorbing honeycomb material after ultrasonic cutting with a disc cutter

(a) The parameters represented by point 1 in the stable region of the Lobe diagram

(b) The parameters represented by point 2 in the stable region of the Lobe diagram

(c) The parameters represented by point 5 in the critical zone of the Lobe diagram

(d) The parameters represented by point 6 in the critical zone of the Lobe diagram

(e) The parameters represented by point 3 in the unstable zone of the Lobe diagram

(f) The parameters represented by point 4 in the unstable zone of the Lobe diagram
4 Conclusion

In this paper, by establishing a mathematical model of an ultrasonic disc cutter and honeycomb cell wall plate, using MATLAB to draw the stability Lobe diagram of the ultrasonic cutting tool, and building the ultrasonic cutting test bench of the disc cutter, ultrasonic cutting experiments were conducted on wave-absorbing honeycomb material at different rotational speeds and axial cutting depths. By observing the surface of the honeycomb after cutting and the broken state of the tool, the optimal depth of cut and spindle speed during ultrasonic cutting was analysed in combination with the stability Lobe diagram. By comparison, the following conclusions can be drawn:

1. The experimental results are consistent with the overall trend predicted by the stability Lobe diagram, which verifies the correctness of the mathematical model of the multi-degree-of-freedom stability of the ultrasonic cutting system.
2. For the ultrasonic disc tool with a diameter of 50 mm in ultrasonic cutting, the axial depth of cut is selected from 1 to 4 mm, and the spindle speed is selected from 800 to 1200 r/min to obtain the best quality of honeycomb cutting surface and long tool life. These selections lay a solid foundation for the selection of wave-absorbing honeycomb processing process parameters.
3. Due to the different structural strengths of the honeycomb cell wall and the cell wall intersection, as well as the different mechanical properties of the resin layer material and the fibre layer material, damage to the fibre layer mainly occurs at the location of the cell wall, while damage such as fracture and separation of the resin layer mainly occurs at the location of the cell wall intersection.
4. Compared with the unstable zone and the critical zone, the tool life is significantly improved by selecting the stable zone process parameters for cutting. By comparing the cutting-edge notch morphology, it can be found that the discrete, strip-shaped notches produced by selecting the unstable and critical zone process parameters are closer to the form of fatigue breakage, while the continuous, semi-circular notches produced by selecting the stable zone process parameters are closer to the form of breakage under normal operation.

Author contribution Xiaoping Hu, Baohua Yu, and Hongxian Ye planned the research. Xin Liu and Sufang Yao did the experiments. Zongfu Guo wrote the paper and analyzed the data.

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Data availability This article contains all the data gathered or analyzed during this study.

Declarations

Ethical approval None of the studies mentioned in this article contain any human participation. Also, no animals were harmed during these experiments.
Consent to participate The authors consent to participate.

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Competing interests The authors declare no competing interests.

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