Cell wall fracture mechanism in ultrasonic-assisted cutting of honeycomb materials

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Abstract
Revealing the ultrasonic cutting mechanism of honeycomb composite is important for determining the acoustic parameters of the ultrasonic system and selecting the parameters of the cutting process. Understanding more details of the stress on the cell wall from ultrasonic vibrating tool and the conditions for cell wall breakage is essential to study the machining mechanism. According to the evolution of contact state between the straight edge cutter and the honeycomb cell wall in a cycle, the cutting force acting on the cell wall is divided into three stages: transverse cutting load action, longitudinal cutting load action, and no cutting load action. The cell wall deflection and stress equations under transverse cutting load were established by applying elastic thin plate small deflection theory. The deformation and fracture characteristics of the honeycomb cell wall were analyzed by combining the analytical and the finite element model. The results showed that the ultrasonic vibration of the cutter greatly improved the stiffening effect of the cell wall and its fracture was caused by the deflection under the transverse cutting load, which exceeded the maximum allowable deformation after local stiffening. In addition, with only longitudinal cutting load, it was difficult to break the critical buckling state that leads to cell wall fracture.

Keywords Ultrasonic cutting · Honeycomb composites · Thin plate theory · Fracture characteristic

1 Introduction
Ultrasonic-assisted machining is a non-traditional method that applies ultrasonic vibrations to the tool or workpiece along a certain direction during the machining process. It reduces the cutting force and cutting heat, improves the surface processing quality of the workpiece and enhances the processing efficiency.

The absorbing honeycomb material is prepared from regular hexagonal aramid paper used as the matrix, followed by impregnating the cell wall with resin mixed with acetylene carbon black as the absorbent [1]. It has all the characteristics and advantages of the aramid honeycomb material, such as lightweight, high strength-to-density ratio, high stiffness-to-density ratio, good self-extinguishing performance, and excellent insulation. In addition, the thicker impregnated layer could absorb wave to achieve stealth. Now the absorbing honeycomb materials have led to the widespread use in aerospace and other fields, and the scope of its application is still continuously progressing.

Conventional high-speed milling aramid honeycomb material has several drawbacks, including rough surface quality, low processing efficiency, and related health issues due to the dust chips. Recently, ultrasonic vibration-assisted (UVA) processing has been considered more efficient for aramid honeycomb composites because of high surface precision, less tool and lower surface defects [2]. A lot of studies on the ultrasonic cutting of aramid honeycomb materials have been reported. Hu et al. [3] established the cutting force theoretical model and verified that vibration amplitude influences greatly on cutting force and surface quality with theory and applied the fracture mechanics theory to study the micro-fracture process in honeycomb composites during ultrasonic cutting. Wang et al. [4] discussed the relative motion relationship between the straight edge cutter and the cell wall of the Nomex honeycomb material and established the dynamic force model of ultrasonic cutting based on brittle fracture mechanics. Similarly, following the characteristics of ultrasonic cutting with a straight edge cutter, Xiang et al. [5] studied the effects of cutting parameters on machined surface quality of honeycomb core
the applications of the ultrasonic machining technology for absorbing honeycomb materials and observed the morphology of the materials, and studied the influence of process parameters of the straight edge cutter on the damaged morphology. Kang et al. [7] analyzed the influence of processing parameters on cutting and surface quality based on the theoretical model and optimized the processing parameters via experimental investigations. Under the conditions of different amplitudes, the cutting damage of the material has two forms: discontinuous and continuous; the relative magnitude of the ultrasonic amplitude and the critical elastic deformation of the material determine the interaction form of the tool and the material [4]. The effect of different process parameters on the cutting force has proved that ultrasonic-assisted cutting can effectively reduce the cutting force [8].

However, the components and thickness of the impregnation layer of the absorbing honeycomb material are different from that of the aramid honeycomb composites, and ultrasonic processing makes the absorbing honeycomb different defects such as significant breakage or even partial peeling appear in the cell wall. The ultrasonic cutting process parameters suitable for the aramid honeycomb materials do not apply to cutting the absorbing honeycomb materials. Fewer reports on the mechanism of ultrasonic cutting for absorbing honeycomb materials considering the material properties exist, and the studies on the fracture process of the materials during ultrasonic cutting are also rare. A thorough understanding of the ultrasonic machining mechanism in the absorbing honeycomb materials would help to optimize the process parameters and promote the application of the ultrasonic cutting technology to other similar materials.

In the present study, the fracture mechanism of ultrasonic cutting of the absorbing honeycomb material was studied by investigating its cell wall. Firstly, based on the analysis of the relative motion and contact force between the cutter and the material in a cycle, it was proposed that the cutting fracture in the cell wall might be caused either by the transverse cutting force or the longitudinal cutting force. Then, targeting the effect of the transverse cutting force, the deflection and stress equations for the honeycomb cell wall were established based on the theory of thin plate fracture mechanics. Also, the conditions that resulted in cell wall fracture were analyzed. The effect of the longitudinal cutting force on the cell wall stability was derived from the buckling theory. Finally, the feasibility of analyzing the cutting mechanism based on the small-deflection thin plate theory was discussed theoretically as well through simulations. The entire study was done on AC-AHM absorbing honeycomb material. This research provides theoretical guidance for expanding the applications of the ultrasonic machining technology for similar materials and expeditiously determining the plausible cutting process parameters.

2 Ultrasonic cutting process of the honeycomb cell wall with a straight edge cutter

2.1 Motion analysis of the straight edge cutter in ultrasonic cutting

The length, height, and width of the honeycomb materials were taken along the X, Y, and Z-axis, respectively. The straight edge cutter cut the honeycomb material with a feed speed of $V_z$ along the Z-axis. In the meantime, the cutter vibrated ultrasonically along the axial direction. The relative position of the cutter and the material is given in Fig. 1.

To improve the holding stability and processing efficiency of the honeycomb material during processing, the central plane of the cutter was deflected relative to the YOZ plane, forming a cutter deflection angle $\alpha$. In the meantime, the cutter axis was rotated within the central plane, resulting in a cutter inclination angle $\theta$ between the cutter axis and the direction of the speed. When the central plane of the cutter was further deflected at an angle of $\alpha$ relative to the YOZ plane in one feed, a V-shaped chip was formed. This cutting method is called V-shaped cutting. Besides, the rectangular cutting method is commonly used to simplify numerical control programming further. Specifically, the deflection angle of the straight edge cutter was set at $\alpha = \theta^\circ$. Once the cutter made cuts for two times with a specific spacing, the cutting disc then also cut the bottom, thereby forming the rectangular chip. Figure 2 displays the relative position of the straight edge cutter and honeycomb cell wall in the rectangular cutting.

As mentioned above, in absorbing honeycomb material, the impregnated layer consists of a resin mixed with the acetylene carbon black absorbent. Therefore, its out-of-plane stiffness is much greater than that of the Nomex honeycomb material. Hence, for the same vertical cutting depth,
V-shaped cutting exerts more surface pressure on the straight edge cutter and has greater contact friction than rectangular cutting, thereby making the cutter more susceptible to wear or even fracture. Thus, rectangular cutting is more suitable for the processing of absorbing honeycomb materials.

In the process of ultrasonic cutting, the cutting motion of the straight edge cutter relative to the cell wall results from the longitudinal ultrasonic vibration of the cutter along the cutter axis and its feed motion along the Z direction. The cutting displacement and the speed in the three coordinate directions are given by Eqs. (1) and (2):

\[
\begin{cases}
S_x = 0 \\
S_y = A \sin \theta \cdot \sin(2\pi ft) \\
S_z = A \cos \theta \cdot \sin(2\pi ft) + V_e t 
\end{cases} \tag{1}
\]

\[
\begin{cases}
V_x = 0 \\
V_y = A \sin \theta \cdot 2\pi f \cdot \cos(2\pi ft) \\
V_z = A \cos \theta \cdot 2\pi f \cdot \cos(2\pi ft) + V_e 
\end{cases} \tag{2}
\]

where \(A\) is the amplitude of the ultrasonic wave, \(f\) is the ultrasonic frequency, \(S\) is the motion displacement of the cutter, \(V\) is the cutter speed, and \(V_e\) is the speed along the feed direction of the cutter.

When \(V_e < A \cos \theta \cdot 2\pi f\), the straight edge cutter and the material meet intermittently along the feed direction [9], which is consistent with the ultrasonic-assisted cutting of the honeycomb by the straight edge cutter. Under the intermittent contact process, based on Eqs. (1) and (2), the movement trajectory of the straight edge cutter is obtained, it is shown in Fig. 3. At time \(t_1\), the composite speed of the straight edge cutter is zero, and the straight edge cutter cuts into the deepest part of the material. At time \(t_2\), the straight edge cutter is in contact with the material again. From time \(t_1\) to time \(t_3\), the straight edge cutter gradually penetrates into the material. At time \(t_3\), the composite speed is zero, and the straight edge cutter cuts to the next deepest part. The cutting process further repeats from \(t_1\) to \(t_3\).
2.2 Evolution of the cutting force exerted on the honeycomb cell wall

Figure 4 shows the evolution of the contact state between the cutter and the honeycomb cell wall. It can be seen from the figure that the contact state between the straight edge cutter and the cell wall has gone through the following process: the first time the straight edge cutter cuts into the material — the straight edge cutter leaves the material for the first time — the straight edge cutter cuts into the material a second time and gradually penetrates the material — the straight edge cutter leaves the material for the second time — the straight edge cutter cuts in the second time to the position of the second exit and continues to cut the material until the cell wall fractured.

The displacement trajectory of the cutting edge during the process is shown in Fig. 5. The variation of the cutting force acting on honeycomb cell wall with the time $t$ for the straight edge cutter in one cycle is explained as below:

1. $0 < t < t_1$: The straight edge cutter exerts pressure on the honeycomb cell wall in both the Z and Y directions, resulting in the transverse cutting load $F_z$ and the longitudinal cutting load $F_y$. However, during this extremely short period, the deformation of the cell wall due to $F_y$ along the Y-direction is very small, thus, the impact of the longitudinal cutting load $F_y$ can be neglected.

2. $t_1 < t < 3T/4$: The direction of the motion of the straight edge cutter along the Z-axis is opposite the feed direction, without exerting the transverse cutting load on the cell wall. However, the cutter presses against the cell wall in the Y direction, causing a pressing effect due to the longitudinal cutting load $F_y$. Also, with the increase in the displacement of the cutter along the Y-direction, the corresponding load on the cell wall grows accordingly.

3. $3T/4 < t < t_2$: Between this interval, the straight edge cutter moves away from the material in the Y direction and closer to the cell wall in the Z direction, although it does not reach the deepest position of the previous cycle. Now, the cutter does not exert any cutting force on the cell wall in either direction.

4. $t_2 < t < t_1 + T$: At this point, the cell wall and the straight edge cutter once again make a contact only in the Z direction, thereby repeating the process of Eq. (1).
The above observations indicated that the cell wall encountered three different situations in one ultrasonic vibration cycle: single Z-direction cutting load, single Y-direction cutting load, and no cutting load in any direction. This further analyzes the possibility of the fracture in the cell wall resulting from the single transverse or longitudinal cutting load.

3 Fracture of the honeycomb cell wall under the influence of the transverse cutting load $F_z$

The cell wall of the AC-AHM absorbing honeycomb material is a three-layered plate structure of absorbing resin–aramid paper–absorbing resin. The aramid matrix as the core layer is very thin relative to the whole cell wall and the cutting quality should be such that the three-layer structure remains intact or breaks as a whole without spalling off the absorbing impregnation layer. In order to determine the finite element simulation model that most accurately reflects the constitutive characteristics of honeycomb material, the single-layer integral model, the double-layers glue model and three-layers integral model are respectively adopted. Combined with the actual ultrasonic machining experiment, the comparative study was carried out from the perspectives of cutting force, deformation damage process of aramid honeycomb material and time consumption of simulation. It can be seen that the three-layer integral model is more suitable than the single-layer integral model and the double-layer glue model [10]. Therefore, the three-layer structure is regarded as an equally thick and homogeneous thin plate without considering the laminating effect of the cell wall. The cell structure of the absorbing honeycomb is shown in Fig. 6 and the corresponding length ($l$) and cell wall thickness ($\delta$) are equal to 2.75 mm and 0.2 mm, respectively.

Assuming that $1/80 < \delta l < 1/5$ and also, the height of the honeycomb core workpiece is typically far larger than the cell wall thickness, hence the cell wall can be considered equivalent to a thin plate. The stress–strain curve obtained by Roy et al. [11] from the tensile test of the matrix cell wall material showed that the honeycomb cell wall exhibits strict linear elastic behavior before failure. Compared with the assuming condition in Timoshenko’s book [12] the bending theory of an elastic thin plate with small deflection can be used to analyze the stress deformation and fracture in the absorbing honeycomb cell wall while getting cut with a straight edge cutter.

3.1 Cell wall deformation under the influence of transverse cutting load

Figure 7 shows the simplified thin plate structure of the absorbing honeycomb cell wall. $b$ is the length of the thin plate, corresponding to the height of the cut part of the cell wall of the honeycomb material, $l$ represents the width of the thin plate, i.e., the side length of the cell, and $\delta$ is the thin plate thickness, implying the cell wall thickness.

When the absorbing honeycomb material was processed with ultrasonic cutting, the bottom of the material was fixed on the work table with a strong double-sided adhesive tape. Thus, the bottom of the cell wall can be considered as a fixed boundary. The two sides of the honeycomb cell wall were then supported by the two cell walls of the adjacent cells. When the stiffness of the honeycomb cell is sufficient, the two sides of the cell wall can be simply considered as the supported boundaries. Besides, the top of the cell wall is a free boundary, which is impacted by the cutter load during the process of cutting.

Considering the middle plane of the thin plate as the XY plane, the Z-direction deflection of the thin plate $w(x, y)$ satisfies the following boundary conditions:

---

Fig. 6 The cell structure of the absorbing honeycomb material

Fig. 7 Simplified thin plate structure of the absorbing honeycomb cell wall
According to the Rayleigh–Ritz method, the deflection satisfying the boundary conditions can be expressed as:

$$\omega = C_1 \left( \frac{y}{b} \right)^2 \sin \frac{\pi x}{l}$$  \hspace{1cm} (5)

where $C_1$ is an unknown quantity that needs to be solved.

Based on the principle of virtual displacement, the bending strain energy acting on the thin plate is given by Eq. (6):

$$U = \int_0^b \int_0^l \frac{D}{2} \left( \left( \frac{\partial^2 \omega}{\partial x^2} + \frac{\partial^2 \omega}{\partial y^2} \right)^2 - 2(1 - \mu) \left[ \frac{\partial^2 \omega}{\partial x^2} \cdot \frac{\partial^2 \omega}{\partial y^2} - \left( \frac{\partial^2 \omega}{\partial x \partial y} \right)^2 \right] \right) \, dx \, dy$$ \hspace{1cm} (6)

where $D$ is the bending stiffness of the thin plate with a theoretical value of $D = \frac{E \delta}{12(1-\mu^2)}$, $E$ is the elasticity modulus of the thin plate, and $\mu$ is the Poisson's ratio.

Substituting Eq. (5) into Eq. (6), gives Eq. (7),

$$U = C_1 \cdot H$$ \hspace{1cm} (7)

where $H = \frac{D}{2} \left( \frac{2l^4}{30} + \frac{b^4 \delta^4}{1920} + \frac{4\pi^2 - 4\pi^4 \mu}{36l} \right)$.

When the transversely uniform force $q$ acts on the thin plate, the bending deformation occurs in the $Z$ direction, and the work done is given by Eq. (8):

$$W_z = \int q \omega \, dx \, dy$$ \hspace{1cm} (8)

When the cutting load $F_z$ concentrated in the $Z$-direction acts on the cell wall at point $(x_0, y_0)$, the transverse load can be replaced by the uniform load, $\frac{F_z}{dx \, dy}$ around the differential area of $dx \, dy$. Then, the differential area of $q$ in Eq. (8) is equal to zero except at $(x_0, y_0)$ where the differential area is equal to $\frac{F_z}{dx \, dy}$. Consequently, Eq. (8) can be rewritten as,

$$W_z = F_z \omega(x_0, y_0)$$ \hspace{1cm} (9)

Putting Eq. (5) into Eq. (9), gives the following Eq. (10),

$$W_z = F_z \frac{y_0^2 \sin \left( \frac{\pi x_0}{l} \right) C_1}{b^2}$$ \hspace{1cm} (10)

The total potential energy of the cell wall is $U = W$. Taking advantage of the principle of least total potential energy $\frac{\partial U}{\partial C_1} = 0$, $C_1$ is obtained as:

$$C_1 = \frac{F_z y_0^2 \sin \left( \frac{\pi x_0}{l} \right)}{2Hb^2}$$ \hspace{1cm} (11)

By substituting $C_1$ into Eq. (5), the deflection formula for the wall cell is obtained as:

$$\omega = \frac{F_z y_0^2 \sin \left( \frac{\pi x_0}{l} \right)}{2Hb^2} \left( \frac{y}{b} \right)^2 \sin \frac{\pi x}{l}$$  \hspace{1cm} (12)

3.2 Cell wall fracture analysis under the influence of transverse cutting load

3.2.1 Cutting fracture based on stress intensity

According to the relationship between the stress and deflection of the thin plate along with the application of the transverse cutting load, the stresses $\sigma_x$, $\sigma_y$, and $\tau_{xy}$ for each point within the surface of the wall with thickness $\delta$ can be expressed as:

$$\sigma_x = \frac{EC_1 \sin \left( \frac{x_0}{l} \right)}{b^2 \varphi(1 - \mu^2)} \left( \pi^2 y^2 - 2\mu \pi^2 \right)$$ \hspace{1cm} (13)

$$\sigma_y = \frac{EC_1 \sin \left( \frac{x_0}{l} \right)}{b^2 \varphi(1 - \mu^2)} \left( \pi^2 y^2 \mu - 2\pi^2 \right)$$ \hspace{1cm} (14)

$$\tau_{xy} = \frac{EC_1 \cos \left( \frac{x_0}{l} \right)}{b^2 \varphi(1 + \mu)} (-2\pi y)$$ \hspace{1cm} (15)

While deducing the above Equations, it is assumed that the straight edge cutter starts ultrasonic cutting by contacting the cell wall at a point in the middle of its upper edge $(\frac{l}{2}, b)$. As observed from Eq. (12), the deflection at this point is maximum on the whole cell wall, and is given by Eq. (16),

$$\omega' = \frac{F_z}{2H}$$ \hspace{1cm} (16)

The in-plane stress on the cell wall is directly related to the deflection. The point $(\frac{l}{2}, b)$ has the largest deflection and thus the maximum in-plane stress.

On comparing the stresses of the point, it was found that $\sigma_x > \sigma_y$, $\tau_{xy} = 0$. Substituting Eq. (12) into Eq. (13) gives the principal stress of the point as,

$$\sigma_{\text{max}} = \frac{E \delta}{2(1 - \mu^2)} \frac{\pi^2 b^2 - 2\mu \pi^2}{b^2 \varphi} \frac{F_z}{2H}$$ \hspace{1cm} (17)
This is also the maximum principal stress applied on the entire cell wall. When the maximum principal stress of a certain point in the thin plate reaches its threshold value, the thin plate fractures.

3.2.2 Cutting fracture based on deformation deflection

From the macroscopic point of view, when the deformation of the brittle and elastic honeycomb cell wall under the cutting force reaches its critical elastic deformation, the cell wall gets fractured.

Due to the thin-walled structure, the cell wall is prone to stress stiffening. Lin et al. [13] proposed that the higher the stress, the more significant is the stiffening effect. The in-plane stress varies at different positions of the cell wall. The point \((\frac{l}{2}, b)\) demonstrates the largest local stiffness on the entire cell wall, as the in-plane stress is largest at this position. The local stiffness \(D_0\) and the theoretical bending stiffness \(D\) are interrelated, and Xie et al. [14] expressed the relation as: \(D = kD_0 (0 < k < 1)\) where \(k\) is the scaling factor.

Based on the theory of brittle fracture mechanics, when the amplitude along the feed direction of the straight edge cutter satisfies the condition of \(Acos\theta > \frac{b}{2}\), the cutter will cut the material intermittently, and the dynamic transverse cutting force of the cell wall would be given by Eq. (18):

\[
F_z(t) = D_0 \left[ Acos\theta \cdot sin\sin(2\pi ft) + V_f t - (Acos\theta - \lambda_0) \right]
\]  

(18)

where \(D_0\) is the local stiffness of the cell wall, and \(\lambda_0\) is the critical elastic deformation of the cell wall.

When the cell wall is constantly under the influence of the transverse cutting load between time \(0\) to \(t_f\), the averaged transverse cutting force can be expressed as:

\[
F_z = D_0 \left[ \lambda_0 - Acos\theta + \frac{V_f t_f}{2} + \frac{Acos\theta \cdot sin\sin(\pi ft_f)}{\pi ft_f} \right]
\]  

(19)

The deflection \(\omega'\) caused by the transverse load \(F_z\) is the elastic deformation of the cell wall. If it reaches the critical elastic deformation, i.e., \(\omega' \geq \lambda_0\), the cell wall will experience a fracture. If the amplitude in the feed direction is equal to \(Acos\theta\), the critical elastic deformation \(\lambda_{\text{emax}}\) when the cell wall will be cut intermittently is taken as \(2Acos\theta\).

Based on the above analysis, we could say that the cell wall undergoes a fracture under the influence of the transverse cutting force when,

\[
\sigma_{\text{emax}} > [\sigma], \omega \geq 2Acos\theta
\]

4 Fracture of the honeycomb cell wall under the influence of the longitudinal cutting load \(F_y\)

The small-deflection bending theory of the elastic thin plate was also used to analyze the fracture mechanism of the cell wall under the longitudinal cutting load \(F_y\).

4.1 Critical longitudinal cutting force on the cell wall

The longitudinal cutting force \(F_y\) in the Y-direction buckles the cell wall and generates the mid-plane internal force \(F_{Ty}\). The work done by the mid-plane force is given as:

\[
W_y = -\int_0^b \int_0^{l_f} \frac{1}{2} F_{Ty} (\frac{\partial \omega}{\partial y})^2 \, dx \, dy
\]

(20)

Since the cell wall is very thin, the longitudinal cutting load acting on the free boundary of the cell wall only generates the stress parallel to the middle plane, i.e., the plane stress \(\sigma_y\) under the influence of the longitudinal cutting load is equal to:

\[
\sigma_y' = -\frac{\int_0^{l_f} \frac{F_y}{b} \, dx}{d} = -\frac{F_y}{d}
\]

(21)

where \(d\) is the cell wall thickness. The plane stress on the unit width of the cell wall results in the mid-plane internal force:

\[
F_{Ty} = \delta \sigma_y'
\]  

(22)

On comparing Eqs. (21) and (22), we obtained \(F_{Ty} = -F_y\).

Besides, the amount of work done when the concentrated longitudinal cutting load \(F_{y}'\) acts on the point \((x,y)\) of the cell wall is given as,

\[
W_y = \left( \int_0^b \int_0^{l_f} \frac{1}{2} F_{y}' \left( \frac{\partial \omega'}{\partial y} \right)^2 \, dx \, dy \right)_{(x,y)} = F_{y}' \left( 2sin^2 \left( \frac{\pi x}{2l} \right) \right) C_1
\]

(23)

Similarly, by using the principle of least total potential energy, the critical longitudinal cutting load \(F_{y}'\) required to bend the cell wall is obtained as:

\[
F_{y}' = \frac{3bH}{2sin^2 \left( \frac{\pi x}{2l} \right)}
\]

(24)

4.2 The analysis of the cell wall fracture under the influence of longitudinal cutting load

The critical longitudinal cutting load required for bending at the middle point of the upper edge of the cell wall is given by Eq. (25),
During this period, a friction component exists along the Z-direction between the straight edge cutter and the cell wall. In the case of a critical buckling state, even if the transverse force is very small, it is easy to break the equilibrium state, resulting in cell wall instability and fracture.

Therefore, for the cell wall experiencing the longitudinal cutting force \( F_y \), if the condition \( F_y > F_y' \) is satisfied, the cell wall will fracture during the application of the longitudinal cutting load.

### 5 Empirical study of the mechanism of ultrasonic-assisted cutting method

The absorbing honeycomb material is subjected to flat tension experiment, flat pressing experiment, shear experiment and density testing experiment to obtain the mechanical properties parameters such as strength, modulus and density of the absorbing honeycomb material. Calculated according to the well-known theory from Gibson and Ashby [2], and revised by means of the approaches of virtual testing recommended by Seeman et al. [15]. The relevant parameters of the thin plate equivalent to the cell wall of the AC-AHM absorbing honeycomb are shown in Table 1.

#### 5.1 Local stiffening effect in ultrasonic cutting

According to the analysis done in Sect. 3.2, the maximum critical elastic deformation is given by \( \lambda_{\text{umax}} = 2\cos \theta \). Substituting this into Eqs. (19) and (16) along with the condition required for the cell wall fracture i.e., \( \omega' \geq 2\cos \theta \), the local stiffness of the cell wall at the position can be obtained as:

\[
D_0 \geq \frac{8\pi AH\cos \theta \cdot t_1}{2\pi f V_e \cdot t_1 + \pi f V_e \cdot t_1^2 + 2\cos \theta \cdot \sin(\pi f t_1)^2}
\]

(26)

The corresponding process parameters of the ultrasonic cutting of AC-AHM absorbing honeycomb material are given in Table 2. Assuming that the honeycomb height or the panel length \( b \) is 20 mm, \( D_0 \) was calculated nearly \( 1.97 \times 103 \) N/m. In the static case, the stiffness, \( D \) of the cell wall was about \( 4 \times 10^4 \) N/m. Due to the dimensions of \( D \) and \( do \) are different, it is impossible to directly compare \( D_0 \) and \( D \). Using the dimensional normalization method to put these two quantities in a system for evaluation and comparison [6], it is obtained that the local stiffness \( D_0 \) is better than the cell wall stiffness \( D \). It’s indicating that the ultrasonic vibration had a significant stiffening effect on the material.

#### 5.2 Calculation and subsequent verification of panel fracture

Between time 0 to \( t_1 \), the transverse cutting force increases with the increase in time. At \( t_1 \), the cutter exhibits the largest displacement in the feed direction. Besides, the cell wall also experiences maximum deflection and stress. The maximum principal stress and deflection of the cell wall under different cutting process parameters can be obtained from Eqs. (3), (16), (17), and (19). The compared values of the strength limit and the maximum critical elastic deformation are shown in Table 3.

### Table 1 Relevant parameters of the equivalent thin plate

| Width (mm) | Length (mm) | Thickness (mm) | Elasticity modulus (Mpa) | Tensile strength (Mpa) | Density (kg/m^3) | Poisson’s ratio |
|------------|-------------|----------------|--------------------------|-----------------------|-----------------|----------------|
| 2.75       | 20          | 0.2            | 544                      | 12.2                  | 739.4           | 0.3            |

### Table 2 Process parameters in ultrasonic cutting with a straight edge cutter

| Amplitude \( A \) (\( \mu m \)) | Frequency \( f \) (kHz) | Cutter inclination angle \( \theta \) (°) | Cutter deflection angle \( \alpha \) (°) | Feed speed \( V_e \) (m/min) | Cutting depth \( a_p \) (mm) |
|---------------------------------|-------------------------|--------------------------------------|--------------------------------------|--------------------------|-----------------|
| 30                              | 20                      | 70                                   | 0                                    | 5                        | 10              |

### Table 3 Stress and deflection values of the cell wall under different process parameters of the ultrasonic cutting

| \( A \) (m) | \( f \) (kHz) | \( \theta \) (°) | \( V_e \) (m/min) | \( \sigma_{\text{umax}} \) (Mpa) | \( |\sigma| \) (Mpa) | \( \omega' \) (\( \mu m \)) | \( \lambda_{\text{umax}} \) (\( \mu m \)) |
|------------|--------------|-----------------|-----------------|----------------------|----------------|-----------------|-----------------|
| 20         | 20           | 70              | 3               | 1.31                  | 12.2           | 16.9            | 13.7            |
| 25         | 20           | 70              | 3               | 1.64                  | 21.1           | 17.1            | 17.1            |
| 30         | 20           | 70              | 3               | 1.97                  | 25.2           | 20.52           | 20.52           |
| 30         | 30           | 70              | 3               | 1.96                  | 25.2           | 20.52           | 20.52           |
| 30         | 40           | 70              | 3               | 1.96                  | 25.2           | 20.52           | 20.52           |
| 30         | 20           | 60              | 3               | 2.87                  | 36.8           | 30              | 30              |
| 30         | 20           | 50              | 3               | 3.69                  | 47.3           | 38.6            | 38.6            |
| 30         | 20           | 70              | 5               | 1.97                  | 25.3           | 20.52           | 20.52           |
| 30         | 20           | 70              | 10              | 1.99                  | 25.6           | 20.52           | 20.52           |
| 30         | 20           | 70              | 20              | 2.03                  | 26             | 20.52           | 20.52           |
Under the influence of different ultrasonic cutting process parameters, the following condition is applicable,

\[ \sigma_{\text{max}} < [\sigma], \text{and} 2A\cos\theta = \lambda_{\text{omax}} \]

In other words, the maximum principal stress in the panel does not reach the strength limit, but the deflection caused by the transverse cutting force exceeds the maximum critical elastic deformation in intermittent cutting.

By substituting the cell wall parameters listed in Table 1 into Eq. (25), the critical longitudinal cutting load under the buckling condition was \( F_y' = 56.8N \). The honeycomb material was cut via a self-made experimental ultrasonic cutting machine by using different combinations of the process parameters [16]. Figure 8 shows the experimental ultrasonic cutting machine. The value of the cutting force measured by the Kistler-9119A 3D dynamometer was converted for a single cell wall. The corresponding longitudinal load exerted on the cell wall is shown in Table 4.

It was observed that the longitudinal load on the cell wall was less than 56.8 N under different process parameters implying that \( F_y < F_y' \). The longitudinal cutting force does not reach the critical value to destroy the buckling state of the panel, hence no fracturing of the cell wall.

The above calculations and experiments indicated that the local stiffness of the cell wall was greatly improved by the ultrasonic stiffening effect. The deflection generated by the relatively small transverse cutting force exceeds the critical elastic deformation which led to brittle fracture in the panel. At this moment, the tensile stress in the panel did not attain the strength limit, resulting in no tensile fracture. Besides, the longitudinal cutting force did not achieve the critical value required for the bending of the thin plate, not enough to cause a fracture in the cell wall.

6 Simulation studies for the fracture of the cell wall during ultrasonic cutting

6.1 Establishment of the simulation model

The ABAQUS simulation software was used to simulate the cutting of the AC-AHM absorbing honeycomb cell wall with a straight edge cutter. The initial contact point between the cutter and the cell wall was set at the midpoint of the upper edge of the cell wall. The relevant parameters of the cell wall are given in Table 1. Cemented carbide

![Fig. 8 Image of the process equipment used in the experiments](image)

![Fig. 9 Simulation model established for the cutting of the honeycomb cell wall by a straight edge cutter](image)

| Table 4 | Longitudinal load on the cell wall during ultrasonic cutting |
|---------|-------------------------------------------------------------|
| No      | A peak-to-peak value (µm) | \( \theta \) (°) | \( V_e \) (m/min) | \( F_y \) (N) |
| 1       | 20                          | 50           | 2               | 24.65           |
| 2       | 20                          | 60           | 4               | 34.95           |
| 3       | 20                          | 70           | 4.5             | 23.91           |
| 4       | 25                          | 50           | 4               | 24.73           |
| 5       | 25                          | 60           | 4.5             | 15.79           |
| 6       | 25                          | 70           | 2               | 8.09            |
| 7       | 30                          | 50           | 4.5             | 15.99           |
| 8       | 30                          | 60           | 2               | 18.52           |
| 9       | 30                          | 70           | 4               | 24.22           |

| Table 5 | Basic performance parameters of the straight edge cutter |
|---------|--------------------------------------------------------|
| Density (kg/m³) | Elasticity modulus (Mpa) | Poisson’s ratio |
| 14,500      | 400,000                                               | 0.2             |
YG6X-1 was selected for the straight edge cutter and its basic performance parameters are shown in Table 5. Ultrasonic cutting process parameters are also shown in Table 2. Figure 9 illustrates the simulation model. Free meshing and the C3D4 grid were used for the straight edge cutter, while sweep meshing and the C3D8R grid were adopted for the cell wall. The processed grid parts were assembled and oriented according to the position of the cutter and the material during the actual cutting. The load was defined by a periodic amplitude curve and expressed in the BC boundary. The boundary constraints on the cell wall were also set. In the meantime, the ultrasonic vibration cutting motion of the cutter was set by controlling the displacement and speed in the Y and Z directions, respectively. Finally, the simulations were run explicitly.

6.2 Simulation of cell wall fracture process

The simulation results in Fig. 10 indicated that the cell wall was fractured at \( t = 1.0 \times 10^{-5} \text{s} \).

Also, the stress-time plot shown in Fig. 11 revealed that the stresses in the X and Y directions of the cell wall were much lower than the strength limit (12.2 MPa). However, the deflection curve in Fig. 12 showed that the deformation in the cell wall was 21.8 µm, larger than the possible maximum critical elastic deformation \( \lambda_0 \) (20.5 µm). The simulation results were consistent with the theoretical analysis done in Sect. 4.2. Conclusively, we could say that the cell wall fracture was due to the deflection deformation caused by the transverse cutting force. When the strength limit was used to control the fracture, the panel experienced a deformation much larger than 21.8 µm. This indicated that the ultrasonic vibration had a stiffening effect on the material, thereby, causing a brittle fracture in the cell wall.

Small deflection fluctuations were observed in the interval indicated by the circled part in Fig. 11. This was attributed to the inertial vibration in the thin plate once the cutter exited the cell wall.

Fig. 10 Simulation results for the cell wall fracture

Fig. 11 The in-plane stress-time plot of the cell wall (a. stress in X-direction, b. stress in Y-direction)
7 Conclusions

The observations and the results of the study are summarized below:

1. During one vibration cycle of the ultrasonic cutting, the cell wall experienced three different loading effects, including transverse cutting force, longitudinal cutting force, and no loading.

2. The fracture of the cell wall is caused by transverse cutting force rather than longitudinal cutting force. The longitudinal cutting force was smaller than the critical longitudinal load on the cell wall in a buckling state, such that the cell wall could not be fractured. The contributing factor of fracture is the deflection caused by the transverse cutting force exceeds the maximum critical elastic deformation in intermittent cutting.

3. The ultrasonic vibration exerted a stiffening effect on the material due to which the cell wall underwent a fracture even on the application of a small transverse cutting force. The fracture was brittle rather than a tensile fracture. This is more favorable to explain the presence of fewer defects of fiber pull-out on the fractured surface during ultrasonic cutting.

Author contribution Baohua Yu comprehensively analyzed the simulation and data results, drew conclusions and wrote part of the paper. Sufang Yao deduced the theoretical equation, did experiments, and wrote part of the paper. Xin Wu did simulation experiments. Xiaoping Hu designed and studied the technical route.

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

Declarations

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

Consent for publication The authors provide their consent to publish this article.

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References

1. Cheng W, Yuan C, Qiu Q, Wang Q, Chen J (2015) Honeycomb sandwich structure and manufacturing process in aviation industry. Aeronautical Manufacturing Technology 7:94–98
2. Gibson LJ, Ashby MF (1988) Cellular solids: structures & properties. Pergamon Press, Oxford
3. Hu XP, Yu BH, Li XY, Chen NC (2017) Research on cutting force model of triangular blade for ultrasonic assisted cutting honeycomb composites. In: Procedia CIRP, https://doi.org/10.1016/j.procir.2017.03.283
4. Wang Y, Wang X, Kang R, Sun J, Jia Z, Dong Z (2017) Analysis of influence on ultrasonic-assisted cutting force of nomex honeycomb core material with straight knife. J Mech Eng 53:73–82
5. Xiang D, Wu B, Yao Y, Zhao B, Tang J (2019) Ultrasonic vibration assisted cutting of nomex honeycomb core materials. Int J Precis Eng Manuf 20:27–36
6. Zhang Z (2011) Dimensionless unity and integration of engineer program L evaluation indicators. Power Syst Technol 35:352–354
7. Kang D, Zou P, Wu H, Duan J, Wang W (2019) Study on ultrasonic vibration–assisted cutting of Nomex honeycomb cores. Int J Adv Manuf Technol 104:979–992. https://doi.org/10.1007/s00170-019-03883-z
8. Xiu-xiu HU, Xiao-ping HU, Bao-hua YU (2015) Ultrasonic cutting force model of honeycomb composites and selection of the processing parameters. J Mech Electr Eng 2015(1):32–36, 95
9. Huang X, Hu X, Yu B, Wu S (2015) Research on ultrasonic cutting mechanism of Nomex honeycomb composites based on fracture mechanics. J Mech Eng 51:205–212. https://doi.org/10.3901/JME.2015.23.205
10. Li X, Hu X, Wu X, Yu B (2019) Research on ultrasonic machining simulation of finite element model for A ramid honeycomb material. J Hangzhou Dianzi University(Natural Sciences) 39(5):6–61
11. Roy R, Park S-J, Kweon J-H, Choi J-H (2014) Characterization of Nomex honeycomb core constituent material mechanical properties. Compos Struct 117:255–266
12. Timoshenko S-P (2009) Theory of elastic stability. Dover Publications Inc, New York
13. Lin J, Jin S, Zheng C, Yang F, Ding S (2017) Variation analysis of accumulative stresses in multistep assembly processes using output transformation matrices. Int Mech Eng Cong Expo 2:1–13
14. Xie S, Jing K, Zhou H, Liu X (2020) Mechanical properties of Nomex honeycomb sandwich panels under dynamic impact. Compos Struct 235:111814
15. Seemann R, Krause D (2017) Numerical modelling of Nomex honeycomb sandwich cores at meso-scale level. Compos Struct 159:702–718
16. Thoe TB, Aspinwall DK, Wise MLH (1998) Review on ultrasonic machining. Int J Mach Tools Manufact 38(4):239–255

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