Mechanical analysis and parameter design of walnut flexible shell-breaking equipment

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ABSTRACT

Walnut is a kind of nut with high nutritional value, but there is still a lack of research on using mechanical method to crack the shell. To complement the process of breaking walnut shells with mechanical approaches, a walnut shell-kernel separation device was designed. Based on the flexible-belt shearing extrusion breakage system, conditions for the walnut entering the extrusion space as well as the extruding-in angle (α₀) and the extrusion angle (α) of the walnut during breakage were assessed theoretically and empirically. Results show that when 0°<α₀≤44°, the walnut can enter the extrusion space. When the upper working belt (that is, the extruding roller) is 23 mm away from the lower working belt, walnut shells crack when α is 20° and break when α is 15°. A mathematical model of extrusion force and shear force on walnut shells by upper and lower working belts was established theoretically. Stiffness at different positions of the walnut shell was analyzed by the theory of elastic mechanics, which contributed the critical force of instability of different positions. Conditions for crack extension after walnut shell breakage were analyzed and calculated by the fracture mechanics theory. The results demonstrated when the mean crack length is 20 mm, the critical external force for crack extension is 19.1 N.

INTRODUCTION

Manual walnut breaking methods present various defects such as low processing efficiency, high costs, the inability to ensure food hygiene and the potential of threatening the health of customers (Zhang and Gong, 2006). For mechanical shell breaking, the process requires acceptable additions to devices and acceptable costs. In addition, improvements on mechanical shell breaking can be made through restructuring the components. Therefore, this is a method worthy of research and application.

Researchers have developed many shell breaking theories for nuts such as the walnut. For example, Wu (1995) and He and Shi (2009) adopted finite element analysis and performed extensive experiments to research shell breaking principles and mechanical properties of walnuts. From these studies, they successfully identified the optimal force application location for shell breaking. Additionally, Li et al. (2012) built upon these observations and established a "cone-basket shell breaking model". With this model, they determined the most effective force application location and direction for walnut shell breaking. They also proposed the influence of various characteristics of the machine, such as the shell breaking clearance, hardness of shell breaking plate and feeding velocity, on the efficiency of walnut
extraction. Dong and Shi (2011) experimented with a multi-roller extrusion walnut shell breaker and indicated that the rotation velocity of the shell breaking roller should be higher than the rotation velocity of the supportive shell breaking roller. Indeed, the differences in velocities of the two rollers can be optimized to improve the shell-breaking rate and the rate of generating unbroken kernels. Liu et al. (2017, 2018) conducted internal force analysis and experimental research on the shell breaking process of walnut. Zhang et al. (2014) invented a flexible shell breaking device. Celik (2016, 2017) performed many kinetic simulations of pecans. Wu (1995) developed a walnut shelling machine using the principle of double-toothed disc-toothed shell peeling. As shown in Figure 1, the tip of the sprocket and the fixed tooth plate continuously shears the surface of the outer casing. Thus walnut shell surface cracking and crack propagation.

Chai (1990) developed a walnut sheller using the principle of friction grinding to break the shell of the walnut with internal and external grinding with cogging, as shown in Figure 2. The main problem of most shell breaking machines is the low shell breaking rate. Many shell breaking machines incompletely break the shell or do not break the shell altogether (Liu et al., 2012). Indeed, the shell breaking rate is generally no more than 80%. Moreover, when walnuts of different varieties,
sizes and shell shapes are introduced, the shell breaking performance of these shell breaking machines becomes even less (Du, 2005). In response to the shortcomings of existing walnut shell breaking machines, this research presents flexible shearing and extrusion shell breaking equipment. This equipment is applied to determine the influential factors on walnut crushing forces and the effects on walnut shell breaking.

THE STRUCTURAL DESIGN OF FLEXIBLE SHELL BREAKING EQUIPMENT

The flexible shearing and extrusion cracking system is on the upper part of the machine. It mainly consists of a lower drive roller (2), an upper drive roller (3), a lower extrusion roller (5), an upper working belt (6), an upper extrusion roller (7), a lower working belt (8), an upper drive roller (9), a lower drive roller (10), a working belt tightness regulator (11) and a supporting plate (12). First, the walnut is broken to a certain extent by extrusion and shearing between the upper extrusion roller and the supporting plate. Then, rubbing, extrusion and shearing of the walnuts with two working belts - the upper working belt at a higher speed and lower working belt at a lower speed - simultaneously ensures effective breakage and protects the walnut meat (Figure 3). The height of the upper and lower extrusion rollers is adjustable. In this way, the space between the two working belts in the rubbing area and the wedge-shaped angle can be adjusted effectively to fit all sizes of walnuts.

The flexible shell breaking equipment can realize the functions of walnut shell breaking and shelling, shell kernel separation and ensuring walnut kernel integrity. In order to achieve the above functions, the overall structure of the device is mainly designed in four parts: flexible belt shear extrusion shelling and shelling system (I), flexible blade hammer hitting system (II), two-way separation system of walnut shell kernel under the coupling effect of pneumatic force and flexible spiral blade (III) and transmission mechanism, as shown in Figure 4.

The flexible belt shear extrusion shelling and shelling system is mainly divided into the shell area (the left side of the dotted line) and the shelling area (the right side of the dotted line), as shown in Figure 5. The upper and lower working belts are made of PVC, the rolls are made of steel, and the walnut used in the experiment is Yunnan Yangbi walnut (Liu, 2012).

The force measuring device uses the YDM-III99 three-way force measuring instrument developed by Dalian.
University of Technology to measure and record the walnut shell breaking force, as shown in Figure 6a and b.

**DISCUSSION**

**Crack initiation position under different loading directions**

In view of the geometric dimensions and the physical parameters of the walnut, He and Shi (2009) carried out mechanical property analyses to test the crack initiation position and extension mode under different loading directions. As such, they used the element stress analysis method. The results showed that when loading along different directions on a walnut, the stress occurred at different positions on the walnut shell and the cracks extended along different directions.

It was concluded that crack extension was limited within a small range only when loading in one direction (Liu et al., 2016b). According to fracture theory, alternating stresses could facilitate production and
extension of cracks (Lui et al., 2016a). To turn a mechanical force into an alternating force, we can make the walnut roll. When the walnut rolls, stress at any one point will be converted from a compression force into a gradual drawing force or from a drawing force into a compression force. Thus, the walnut actually suffers alternating forces (Lui et al., 2016c). Wu (1995) provided experimental evidence that the walnut shell suffers small deformations under rolling extrusion. Thus, rolling extrusion only needs to provide a small amount of compression to crack the walnut shell. Meanwhile, rolling extrusion causes more cracks and fragments, indicating that rolling extrusion is beneficial for crack extension.

Conditions for walnut entering into the extrusion space

In the automated walnut processing machine, the walnut is broken by extrusion between the upper extrusion roller and the lower working belt. Whether it can enter into this space successfully is determined by the size of the space between the upper extrusion roller and the lower working belt as well as the contact between the upper extrusion roller and the walnut. The walnut enters the extrusion space when its long diameter forms a certain angle with the horizontal axis of extrusion roller. Stresses on walnut are shown in Figure 7.

Theoretically, the walnut will be affected by five forces at the contact-gravity (mg), the normal extrusion force of the roller (T), the normal extrusion pressure of the lower working belt (F), as well as frictional forces of the upper and lower working belts (μT and μF, μ is the friction coefficient between the walnut and the working belt). For the walnut to enter the extrusion space smoothly, its horizontal direction must meet a certain criterion:

\[
\mu F + \mu T \cos \alpha > T \sin \alpha
\]  

(1)

Additionally, its vertical direction must meet the following criteria:

\[
F = T \cos \alpha + \mu T \sin \alpha + mg
\]

(2)

Because the walnut weight is far smaller than the suffered forces, it can be neglected:


\[ F = T \cos \alpha + \mu T \sin \alpha \]  

(3)

In Equation 3, \( T \) is the roller’s positive pressure on the walnut, \( N \); \( F \) is the lower working belt’s positive pressure on walnut, \( N \); \( \alpha_0 \) is the extruding-in angle (Zhu et al., 2008); and \( mg \) is walnut weight, \( N \). Substitute Equation 3 into Equation 1:

\[ \tan \alpha \leq \frac{2\mu}{1-\mu^2} \]  

(4)

According to a previous study, the friction factor \( (\mu) \) between the plastic cement and the timber is 0.4 (Xu et al., 2013), and \( \alpha_0 \) can be calculated:

\( \alpha_0 \leq 44^\circ \)

It can be seen from Figure 7 that \( \alpha_0 \) widens as the upper extrusion roller moves downward. When \( \alpha_0,44^\circ \), walnut cannot normally enter gaps or crushed.

**Extrusion angle of walnut**

The walnut is extruded by upper and lower working belts when it rolls into the cracking area, thus deforming the walnut shell. With the increase of the extrusion force, the displacement increases and cracks appear gradually until the shell cracks. The relationship between walnut shell displacement and the extrusion angle is shown in Figure 8.

In Figure 8, the extrusion angle \( (\alpha) \) refers to the angle between the extrusion force of the upper extrusion roller at any point in the walnut-upper working belt contact arc and the perpendicular line. When the walnut becomes in contact with the upper working belt for the first time, \( \alpha \) is equal to the extruding-in angle \( (\alpha_0) \). As the walnut moves forward, \( \alpha \) decreases. In extrusion cracking with a round roller and a straight plate, the relationship between the rotation angle of the roller and walnut deformation is (Zhang and Gong, 2007):

\[
\begin{cases}
\delta = r \sqrt{2(1 + \cos \alpha)} - e \\
\delta = d_0 - d_1
\end{cases}
\]  

(5)

In Equation 5, \( r \), is the walnut radius\((mm)\); \( e \), is the spacing between working belt of upper extruding roller and lower working belt \((mm)\); \( \delta \), is the walnut displacement \((mm)\); \( d_0 \), is the walnut diameter without compression \((mm)\); \( d_1 \), is extruding diameter\((mm)\).

Equation 5 reveals that for a given \( r \) and \( e \), a smaller \( \alpha \) will cause greater walnut deformation, so that the walnut is broken easier. The mean radius of testing walnut samples was measured to be 12.3 mm. Upper-lower belt spaces were determined at 22, 23, 24 and 25 mm.
Walnut displacement under different spaces and extortion angles (α) are listed in Table 1.

According to Table 1, α decreases when the space widens and the walnut deformation intensifies accordingly. Based on an experimental measurement, Wu (1995) stated that during extrusion rolling, the mean walnut shell displacement at crack initiation is 1.063 mm, which increases to 1.401 mm at cracking. Under a 22 mm space, the walnut suffers excessive displacement during the whole process, thus the walnut meat is also prone to breakage. Under a 23 mm space, the walnut shell begins to crack when α = 20° and breaks when α = 15°. The mean space between a test walnut shell and the meat was measured to be 1.5 mm. Therefore, when the space between upper and lower working belts was 23 mm, the walnut can be broken effectively while maintaining the integrity of the walnut meat. At 24 and 25 mm spaces, the walnut experiences inadequate deformation to break the shell effectively. However, in actuality, the walnut is ellipsoid instead of an ideal sphere. Therefore, the walnut could probably be shelled effectively at 24 or 25 mm when positioned properly.

**Walnut force analysis**

For any point (a) within the contact arc between the walnut and the upper working belt surface, the walnut is affected by a normal acting force (Fn) and a tangential acting force (Ft). Their joint force is F. The component forces on the X-axis and Y-axis are Fx and Fy, respectively. At point b of the lower working belt (Figure 9), the walnut is affected by a normal acting force (Fn1) and a tangential acting force (Ft1). Fn1 and Ft1 extrude the walnut, and thus are extrusion forces. Ft1 and Ft2 shear the walnut, and thus are shearing forces. Extrusion forces deform and finally break the walnut shell; shearing forces further extend cracks at breakage, causing relative diastrophism and slippage between the broken shells.

Fn1 can be measured by a measuring cell and Ft1 can
be calculated from Equation 6:

\[ F_{n1} = \mu \cdot F_{t1} \quad (6) \]

In Equation 6, \( \mu \) is the friction factor between the walnut and the working belt.

The space between the upper and lower working belts is smaller than the walnut diameter. This is why the walnut cannot move along the \( Y \)-axis in the extrusion area and the joint force on the \( Y \)-axis is 0 (Shen, 2002):

\[ F_y = F_{n1} \quad (7) \]

By the geometric relationship, \( F \) can be calculated with Equation 8:

\[ F = \frac{F_y}{\cos(\varphi - \alpha)} \quad (8) \]

In Equation 8, \( \alpha \) is the extrusion angle \(^\circ\), \( \varphi \) is the friction angle \(^\circ\), and \( \mu \) is the friction factor between the walnut and the working belt. If the friction factor \( \mu \) between the plastic cement and the timber is 0.4, then the friction angle \( \varphi \) can be calculated with Equation 9:

\[ \mu = \tan \varphi \quad (9) \]

The friction angle \( \varphi \) between the walnut and upper working belt was then calculated to be 21.8°. Subsequently, \( F_{n2} \) and \( F_{t2} \) at point \( a \) could be calculated from Equation 10 according to the following geometrical relationship:

\[ \begin{cases} F_{n2} = F \cdot \cos \varphi \\ F_{t2} = F \cdot \sin \varphi \end{cases} \quad (10) \]

**Mechanical properties of the shell**

According to previous studies, different positions of the walnut shell have different compression stiffness, that is, different mechanical properties. The positional dependence of the properties is caused by the uneven thickness of walnut shell. When the external load increases to a certain value, the walnut shell is deformed, producing instability cracks. The critical compressive stress of walnut shell instability is (Xu, 1990):

\[ P_{cr} = \frac{2E}{\sqrt{3(1-\mu^2)}} \left( \frac{h}{r} \right)^2 \quad (11) \]

In Equation 11, \( P_{cr} \) is critical compressive stress (Pa), \( E \) is the modulus of elasticity (GPa), \( \mu \) is Poisson’s ratio, \( h \) is the walnut shell thickness (mm), and \( r \) is the walnut radius (mm).

Due to the small \( h/r \) (\( h \) is walnut shell thickness and \( r \) is...
walnut radius), the elastic stability is rather low (Xu, 1990). In other words, when the external load reaches a critical value, the shell will suffer flexure that intensifies quickly, flattening or causing ripples along the circumferential direction of the shell. It can be seen from Equation 11 that, for some types of walnuts with a fixed $E$, $\mu$ and $r$, the thickness of the shell depends on its position, and thus the corresponding critical compressive stress of instability is also dependent on its position. The thicker the shell, the higher the critical compressive stress is.

Based on survey and measurement, the walnut for experiment has $E = 0.18$ GPa, $\mu = 0.3$ and mean $r = 12.5$ mm. We used a vernier caliper to measure the shell thickness at 4 positions, as shown in Figure 10. The thickness at four different positions is listed in Table 2. Suture line in appearance is flat or convex. When Suture line is flat, shell is thin; when suture line is convex, shell is thick. For experimental walnuts, the shell is convex and thicker at upper and middle suture line. Shell is thickest on the top of the walnut and thinner on the bottom of walnut. Shell is thicker near the suture line than that far away from the suture line.

Taking $E$, $\mu$ and $r$ into Equation 11, the critical compressive stress at four positions were calculated to be $P_{c1} = 6.62$, $P_{c2} = 4.62$, $P_{c3} = 1.54$ and $P_{c4} = 2.89$ MPa. When the walnut is being extruded by the upper and lower working belt, the contact positions of the walnut can be assumed to be round faces. The area of the round faces was calculated to be $S = 7.1 \, mm^2$. Then, the critical extrusion forces at the four positions can be calculated with Equation 12:

$$F_{cr} = P_{cr} \cdot S \quad (12)$$

The critical extrusion forces at four positions were calculated to be $F_{c1} = 46.8 \, N$, $F_{c2} = 32.8$, $F_{c3} = 10.9$ and $F_{c4} = 20.5 \, N$.

### Conditions for crack extension

Ding et al. (2010) studied the effect of loading modes on crack initiation position and the extension ranges of the walnut shell. They found that under a uniform linear load, the stress distribution area on the walnut is approximately oval. The walnut shows linear cracks along the loading direction. There are many local cracking points on the walnut shell, and thus it is easy for the cracks to extend.

Cracks can be divided into three types (I, II and III) according to the mechanics of fracture (Figure 11) (Shen, 1996). Type I is opening cracks; type II is sliding cracks; and type III is tearing cracks. After the walnut shell is broken, the cracks are mainly Type I and Type III. Berry proposed a principle that states that cracks extend...
quickly and cause brittle fractures (Berry, 1960). Influenced by external forces, stresses concentrate surrounding the cracks. Cracks will only extend until the external force reaches a critical value. The relationship between crack length and critical stress is expressed in Equation 13:

\[ \sigma_c = \left( \frac{2E\gamma}{\pi a} \right)^{\frac{1}{2}} \]  

(13)

In Equation 13, \( \sigma_c \) is critical stress (Mpa); \( \gamma \) is the surface energy per unit area (KJ/m\(^2\)), \( a \) is crack length (mm), and \( E \) is the elasticity modulus of the walnut shell (Mpa).

According to a previous report, the surface energy per unit area of timber is 0.12 KJ/m\(^2\) and the elasticity modulus of a walnut shell is 0.18 GPa (Moaveni et al., 2005). The average crack length after walnut breakage was measured to be 20 mm. Taking \( E \) and \( a \) into Equation 13, it could be calculated by Equation 13 that the critical stress (\( \sigma_c \)) for crack extension is 0.83 MPa. The external force needed for crack extension is:

\[ F = \sigma_c \cdot S \]  

(14)

In Equation 14, \( F \) is the external force for crack extension (N), \( \sigma_c \) is the critical stress (Pa), and \( S \) is the crack surface area (m\(^2\)).

The mean thickness of walnut shell was measured to be 1.15 mm. On this basis, the cracking surface area was calculated to be 23 mm\(^2\). External forces needed for crack extension was calculated from Equation 14 to be \( F = 19.1 \) N. This means that after the walnut shell is broken, the extrusion force and shearing force on walnut shell exceeds 19.1 N and cracks can be further extended.

**Conclusion**

As a nutritious nut, the research of walnuts is still far from enough. This study designed and produced a flexible shell breaking device. And the mechanical properties analysis and parameter optimization were carried out. This work can promote the study of the mechanical properties of nuts and fill the gaps in the literature on flexible shell breaking theory. The important points that can be extracted from this study are as follows:

- The flexible belt mechanism is used to break the shell, and the walnut enters the broken shell area and needs appropriate conditions. When \( 0^\circ < \theta_0 < 44^\circ \), the walnut can enter the extrusion space. When the walnut shell rolls in the crushing zone, the relationship between the displacement of the walnut shell and the knocking angle is analyzed. When the space between the upper and lower working belts is 23 mm, the walnut can be effectively broken while maintaining the integrity of the walnut meat.
- The critical compressive stress of instability in different shell thickness \( h \) is different when \( E, \mu \) and \( r \) are fixed. The corresponding critical compressive stress on the top, the suture line, the convex and the bottom are \( P_{cr1} = 6.62 \), \( P_{cr2} = 4.62 \), \( P_{cr3} = 1.54 \) and \( P_{cr4} = 2.89 \) MPa. The corresponding critical extrusion forces are also calculated out, \( F_{cr1} = 46.8 \), \( F_{cr2} = 32.8 \), \( F_{cr3} = 10.9 \) and \( F_{cr4} = 20.5 \) N. The results show that the position of the walnut affects the thickness of the shell at the point of compression and, thus, affects the compression stiffness and mechanical properties.
- When the mean crack length in a broken walnut is 20 mm, the critical external force for crack extension is 19.1 N.
In this study, we have shown several analyses on walnut respectively in different theories. All those theoretical analysis reveal walnut properties and shell broken mechanism.

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