EFFECT OF LOW-TEMPERATURE ON THE VIBRATION IMPACT COMMINUTION PERFORMANCE OF WHEAT BRAN
/
低温对小麦麸皮振动冲击粉碎性能的影响

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ABSTRACT
With the aim of revealing the effects of low temperature on the vibration impact comminution performance of wheat bran, the impact dynamic performance of wheat bran at different temperatures was simulated by using LS-DYNA. According to the impact collision relationship between grinding medium and wheat bran, a three-component numerical calculation model was established. The impact collision dynamic essence of the model was analyzed, and a solution method based on LS-DYNA was proposed. On this basis, the finite element model of the numerical calculation model was obtained. By adjusting the mechanical parameters of wheat bran in the finite element model, the vibration impact comminution performance of wheat bran at different temperatures were analyzed. It is found that the contact force, contact deformation and comminution energy of wheat bran increase with the decrease of temperature, which indicates that low-temperature comminution of wheat bran is more advantageous than room temperature comminution. However, when the temperature drops from - 40 ℃ to - 80 ℃, the above index parameters almost remain, which indicates that it is more economical to apply low-temperature comminution at the temperature range from - 40 ℃ ~ 0ºC. This research provided a foundation for the analysis, prediction and optimization of vibration impact comminution performance of wheat bran.

摘要
为揭示低温对小麦麸皮振动冲击粉碎性能的影响，利用LS-DYNA模拟分析了不同温度下小麦麸皮的冲击动力性能。根据振动球磨机的振动冲击粉碎机理，建立了三构件粉碎机理的数值计算模型，分析了模型的冲击碰撞动力学本质，提出了基于LS-DYNA的求解方法。在此基础上建立了粉碎机理数值计算模型的有限元模型。通过调整有限元模型中小麦麸皮的力学参数，比较分析了小麦麸皮在不同温度下的振动冲击粉碎性能。结果发现：随着温度的降低，小麦麸皮的接触力、接触变形和粉碎能量均得到了提高，表明小麦麸皮低温粉碎比室温粉碎更具优势。但当温度从-40℃下降到-80℃时，以上指标参数的变化较小，表明采用-40℃~0℃作为小麦麸皮低温粉碎的温度调节范围更为经济。上述研究为小麦麸皮低温振动粉碎性能的分析、预测和优化奠定了基础。

INTRODUCTION
Wheat bran is a kind of by-product of flour processing, and it is rich in protein, dietary fiber, vitamins, amylase, minerals and other nutrients. Thus, it has various potential applications in food processing industry (*Onipe et al., 2016*), medical care industry (*Elmone, 2021*), biochemistry industry (*Martín-Diana et al., 2021*), etc. The superfine comminution of wheat bran has become an important way for its in-depth development and comprehensive utilization (*Craeyveld et al., 2009; Zhu et al., 2010; Rosa et al., 2013*). At present, the low-temperature vibration comminution technology, which combines the advantages of vibration impact comminution and the advantages of low-temperature comminution, has been preliminarily applied in the superfine comminution of wheat bran. As a result, low-temperature vibration comminution technology has shown excellent comminution performance (*Hemery et al., 2011; Huang et al., 2009*).

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In order to further improve its superfine comminution efficiency, it is necessary to study the effects of low-temperature on the vibration comminution performance of wheat bran.

The factors restricting the low-temperature vibration comminution performance of wheat bran mainly include the motion characteristics of grinding medium and the low-temperature mechanical properties of wheat bran. In order to study the comminution effects of grinding medium movement, researchers simplified the grinding medium in grinding cylinder into single rigid body (*Huang et al., 1997*), grinding medium layer (*Sidor, 2010*), discrete grinding medium group (*Lee et al., 2010; Mishra et al., 2015*) and grinding medium flow (*Yang et al., 2018*) respectively. Researchers also established the rigid dynamics model, hierarchical dynamics model and discrete element model (DEM) of grinding medium. However, these models do not contain crushed objects. Therefore, they cannot be used to comprehensively describe the comminution effects of the grinding medium movement on wheat bran. Moreover, these models cannot be used to simulate and analyze the influences of physical properties of the grinding medium on the superfine comminution performance of wheat bran. This is the main reason why the experimental method is generally used to study the low-temperature vibration comminution performance of wheat bran. Although Hemery (*Hemery et al., 2010*) discovered the influences of low temperature on the mechanical properties and strain energy density of wheat bran and its structural layers by using the tensile test, the relationship between temperature and comminution mechanical properties of wheat bran is still not clear. It is because that the temperature field and the comminution force field belong to different physical fields. Therefore, it is impossible to study the low-temperature vibration comminution of wheat bran by using the existing models of grinding medium.

Due to the rapid progress of computer technology, it is possible to evaluate the low-temperature vibration comminution performance of wheat bran by using nonlinear finite element method. The commercial software LS-DYNA is currently recognized as one of the most outstanding nonlinear finite element simulation software with the functions of explicit analysis and implicit analysis. It has been applied in numerical simulations of material comminution performance in many fields, such as textile (*Barauskas et al., 2007*), wheat stem (*Yuan et al., 2013*), concrete (*Ma et al., 2020*), etc. At present, when LS-DYNA is used to simulate the impact comminution performance of materials, two-dimensional or three-dimensional unilateral impact calculation models of two components are generally adopted (*Barauskas et al., 2007; Yuan et al., 2013; Ma et al., 2020*). In the model, one component is set as a target, and the other component is set as a projectile. However, this model cannot simulate the bilateral comminution effects of grinding medium on wheat bran, such as shear, extrusion and grinding. The other disadvantage of the past work is that this model cannot directly take into account the low-temperature embrittlement effects.

In the current research, a three-component comminution mechanism calculation model which is based on the similarity principle of grinding medium motion was proposed. In the rest of this paper, the model is named as grinding medium-wheat bran-grinding medium model. In order to verify the efficiency of the model, the impact extrusion comminution effects of wheat bran at room temperatures and at low temperatures were simulated and analyzed by adjusting the mechanical parameters of wheat bran. The results showed that the low temperatures have a significant effect on the comminution performance parameters of wheat bran, such as contact force, contact deformation and internal energy, which verifies the reliability of the model.

MATERIALS AND METHODS

Impact dynamics modelling of vibrating ball mill

The results of high-speed camera observation show that the grinding medium of the vibrating ball mill has three motion forms, namely, impact motion, overall rotation and self-rotation (*Gock et al., 1999; Lee et al., 2010*), and the comminution effects such as impact, shear, extrusion and grinding are formed between the adjacent two grinding mediums. Based on the high-speed camera observation results of the grinding medium motion of a vibrating ball mill, the motion diagram of the grinding medium in the grinding cylinder can be obtained, as shown in Fig. 1. It is easy to find that the impact collision contact relationship between the grinding medium group and the grinding cylinder wall is the dynamic essence of the three motions of the grinding medium group. In the superfine comminution process of wheat bran in a vibrating ball mill, the high-speed rotation of a single grinding medium has grinding effects on wheat bran. Meanwhile, the slow revolution of a single grinding medium has grinding and homogenizing effects on wheat bran. Moreover, the impact movement of a single grinding medium forms the impact collision contact relationship between adjacent grinding medium or between grinding medium and grinding cylinder, which has impacting, squeezing or shearing effects on wheat bran.

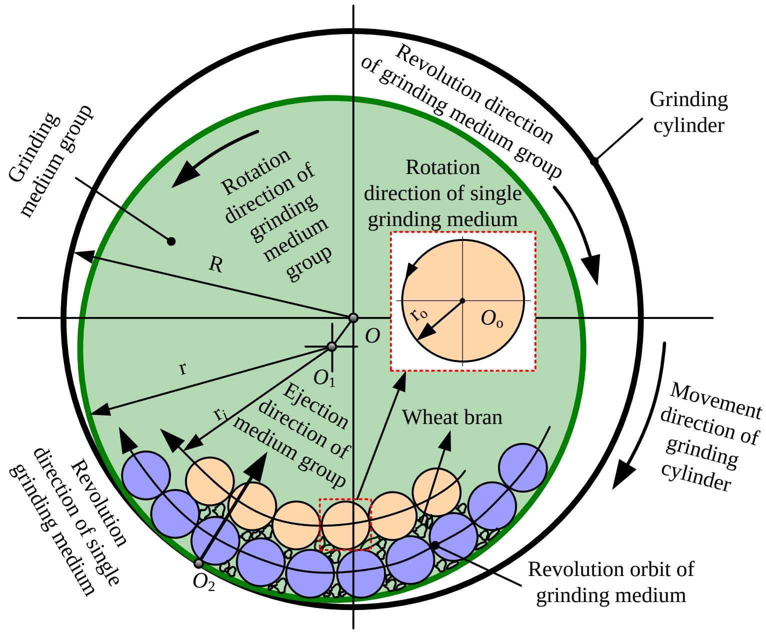

Fig. 1 - Movement of grinding medium in the grinding tube

R —radius of the grinding cylinder of vibrating ball mill; O — the geometric center of the grinding tube; r — radius of the grinding medium group; O_1 — geometric center of the grinding medium group; r_0—radius of the single grinding medium ball; O_O — geometric center of the single grinding medium ball

Ignoring the influences of surrounding grinding medium and wheat bran, and taking any two mutually contacting grinding medium balls and a piece of wheat bran between two adjacent grinding medium layers as shown in Fig. 1, the three-component calculation model named grinding medium - wheat bran - grinding medium can be obtained as shown in Fig. 2. The two grinding balls are labelled as grinding medium 1 and grinding medium 2, respectively. In Fig. 2, s_1 and s_2 represent the distances from the grinding medium 1 and the grinding medium 2 to the contact surface of the wheat bran respectively. O_1 and O_2 are the centroids of the grinding medium 1 and the grinding medium 2 respectively, and the eccentricity is e_{12}. r_1 and r_2 are the radii of the grinding medium 1 and the grinding medium 2 respectively. ω_1 and ω_2 are the rotation velocities of the grinding medium 1 and the grinding medium 2 respectively, and their steering directions are identical. When v_{1r} and v_{2r} represent the impact velocities of the grinding medium 1 and the grinding medium 2 respectively, v_{1c} and v_{2c} can be considered as the revolution velocities of the grinding medium 1 and the grinding medium 2. According to the energy transfer law of the grinding medium in the grinding tube, the directions of v_{1r} and v_{2r} can be considered on the same straight line, but their sizes are different (*Feng et al., 2018*). Due to the different values of v_{1r} and v_{2r}, the impact comminution effect of the grinding mediums on the wheat bran is formed.

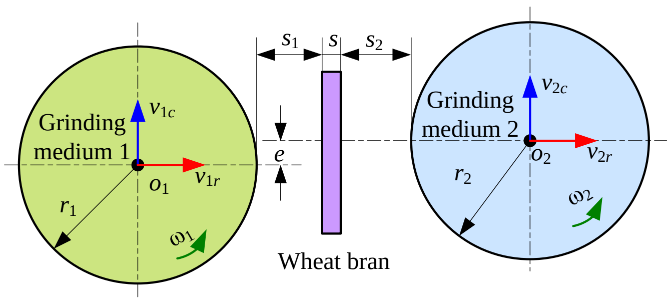

Fig. 2 - Calculation model of vibrating ball mill

According to the relativity principle of motion, the grinding medium 2 can be considered as a fixed state. At this time, only three motions of the grinding medium 1, including impact, revolution and rotation, need to be considered. These three movements produce three kinds of contact forces on the wheat bran. These forces are the high-frequency impact force of the grinding medium impact motion on the wheat bran, the grinding force of the grinding medium revolution motion on the wheat bran, and the grinding force of the grinding medium rotation motion on the wheat bran, respectively. The previous research shows that the impact force of the grinding medium is the primary factor, and the grinding force generated by the rotation and revolution of the grinding medium is the secondary factor in comminution of wheat brans by vibrating ball mills (*Kostishin et al., 2015*). At this time, the grinding medium 1 can be considered to bear only one impact force in any direction, that is, the grinding medium 1 has only one impact movement in any direction. The rectangular coordinate system xO_1y is established with the geometric center O_1 of the grinding medium 1 as the origin point. The simplified calculation model is shown in Fig. 3. The impact velocity of the grinding medium 1 is v and the impact angle in X direction is α.

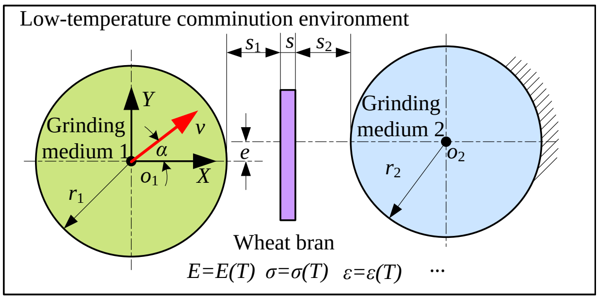

Fig. 3 - Low-temperature calculation model of vibrating ball mill

In actual comminution processes, low-temperature will affect wheat brans and grinding mediums, such as the emergence and propagation of surface cracks, the changes of geometric dimensions and mechanical properties, etc. In fact, in the tensile test of mechanical properties of wheat brans at low-temperature, the effects of changes on surface cracks, geometric dimensions and morphological structure caused by low temperature on wheat bran will be converted into mechanical properties. Therefore, based on the calculation model of the vibrating ball mill, a low-temperature comminution model describing the low-temperature vibration superfine comminution of wheat brans can be obtained, as shown in Fig. 3. In Fig. 3 s represents the thickness of the wheat bran, and E=E(T), σ=σ(T), ε=ε(T) represent the physical relationships between the mechanical parameters of the wheat bran and the comminution temperature. According to Fig.3, the influence of the comminution temperature on the comminution performance of the wheat bran can be analyzed by changing the elastic modulus E, ultimate stress σ and ultimate strain ε of the wheat bran in the comminution model. Thus, it provides an economical and convenient method to study the effects of low-temperature on the vibration comminution performance of wheat bran.

According to the comminution mechanism model shown in Fig.3, the low-temperature vibration comminution of wheat brans is a typical contact collision elastoplastic large deformation problem. Therefore, using nonlinear finite element numerical method to solve this problem has significant advantages. From a mechanics point of view, the most notable technical characteristic of LS-DYNA is that it can solve highly nonlinear problems such as dynamic contact of objects, large deformations, material nonlinearities, and high-speed transient problems such as explosions, impacts, pouring, and material forming (*Menezes et al, 2014*). Therefore, the vibration superfine comminution mechanism of wheat bran under low temperature fully meets the application requirements of LS-DYNA. In this research, the Lagrangian method of LS-DYNA with updated format algorithm is selected to solve the simplified low-temperature vibration comminution mechanism calculation problem of wheat bran.

Finite element modeling and solution setting of low-temperature calculation model

Considering the non-fracture phenomenon and large deformation characteristics of wheat brans in vibration impact experiments, the plate shell unit shell163 is selected for the wheat bran, with the length of 3 mm, the width of 2 mm and the thickness of 80 μm. Fig. 4 shows a set of stress-strain curves of the wheat bran at comminution temperatures of 30 °C, 0 °C, − 40 °C and − 80 °C, respectively (*Cheng et al, 2019*). As shown in Fig. 4, when the stress-strain curve of the wheat bran includes two stages of elastic deformation and plastic deformation, the bilinear BKIN model is selected as the material model; when the stress-strain curve of wheat bran only includes an elastic deformation stage, the Isotropic model is selected as the material model. The input parameters of the bilinear BKIN model of wheat bran include Young's modulus E, density ρ, Poisson's ratio μ, Yield stress σ_s and Tangent modulus E_p. The yield stress σ_s is approximately equal to the elastic stress σ_{ela}, the Poisson's ratio is 0.3, and the tangent modulus E_p=(σ_{max}-σ_{ela})/(ε_{max}-ε_{ela}). Moreover, σ_{max} is the ultimate stress, ε_{max} is the ultimate strain, and ε_{ela} is elastic strain. The input parameters of the isotropic model of the wheat bran only include Young's modulus E, density ρ and Poisson's ratio μ. The mechanical and physical parameters of wheat bran identified based on Fig. 4 are shown in Table 1.

The solid unit solid164 with the radius of 2 mm is adopted by grinding medium. The Rigid body model is selected as the material model of the grinding medium. The intervals s_1 and s_2 between the grinding medium and the wheat bran surface are set as 0.5 mm. There is no eccentricity between the two grinding mediums. The wheat bran is discretized with quadrilateral mapping grid, and the grinding medium is discretized with hexahedral mapping grid. The finite element model of the low-temperature calculation model of wheat bran is shown in Fig. 5. After discretization, the element number of the wheat bran is 3600 and the element number of the grinding medium is 16384. The input parameters of the rigid body model of grinding medium include density ρ, Young's modulus E and Poisson's ratio μ. Zirconia ball is selected as the grinding medium, and its material characteristic parameters are shown in row 6 of Table 1. As shown in Table 1, the Young's modulus of zirconia is much higher than that of the wheat bran. Therefore, the rigid body model is suitable for the finite element model of the grinding medium.

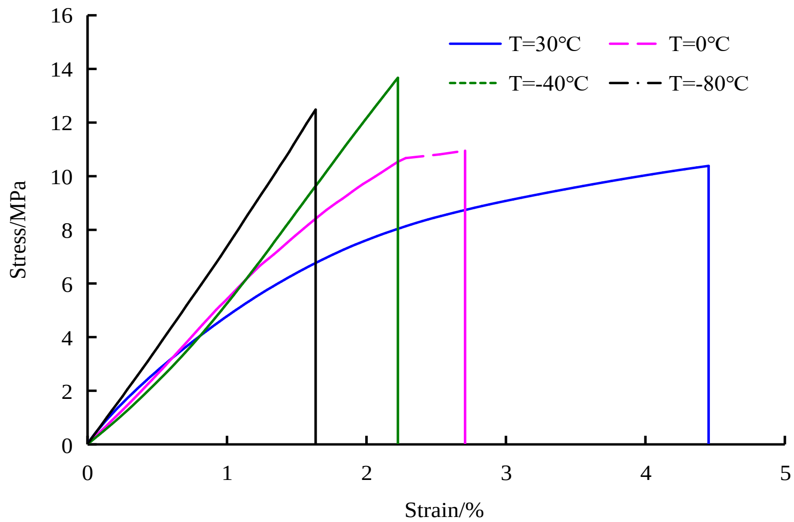

Fig. 4 - Stress-strain curves of wheat bran at different temperatures

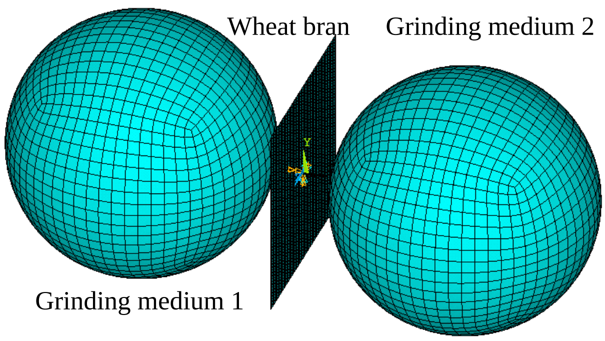

Fig. 5 - Finite element model of Low-temperature calculation model of wheat bran

Table 1

Material characteristic parameters of wheat bran and grinding ball

Name	Temperature	Density ρ	Elastic strain ε_{ela}	Elastic stress σ_{ela}	Young's modulus E	Ultimate strain ε_{max}	Ultimate stress σ_{max}	Tangent modulus E_p	Poisson's ratio μ
	[℃]	[kg/m³]	[%]	x 10^6 [N/m²]	x 10^8 [N/m²]	[%]	x 10^7 [N/m²]	x 10^8 [N/m²]	/
wheat bran	30	1250	1.24	6.40	5.00	4.45	1.04	1.40	0.30
	0		1.29	7.12	5.48	2.71	1.10	3.43	
	-40		—	—	6.35	2.23	1.37	—	
	-80		—	—	7.58	1.64	1.25	—	
Zirconia ball	—	5800	—	—	2200	—	—	—	0.23

Furthermore, the movement and rotation degrees of freedom of grinding medium 2 are restrained. The impact velocity and impact angle of grinding medium 1 can be set by defining the velocity components in X and Y directions. The X-direction impact velocity of grinding medium 1 is set as 3 m/s, and the Y-direction impact velocity is set as 0 m/s. At this time, the impact angle is 0 degree. The eccentricity between the two grinding mediums is 0 mm. At this time, the grinding medium has only impact extrusion grinding effect on the wheat bran. The contact type between wheat bran and grinding medium is automatic face-to-face contact, and the dynamic and static friction coefficients are defined as 0.3. The wheat bran has no fixed boundary and its central node moves along the *X* direction, which is similar to the actual vibration impact grinding. Due to the large deformation and even mesh distortion of the wheat bran in the process of impact collision, hourglass control (0.1) and adaptive mesh control are adopted. In order to ensure the calculation accuracy and convergence speed, five integral points of the wheat bran model are selected.

RESULTS

The contact force, contact deformation and internal energy between the wheat bran and the grinding mediums were selected as evaluation indexes to analyze the effects of low-temperature on the comminution performance of the wheat bran. Fig.6 shows the contact force curves between the wheat bran and the grinding mediums at 30 ℃, 0 ℃, - 40 ℃ and - 80 ℃, respectively. According to Fig. 6, when the grinding temperatures are at 30 ℃, 0 ℃, - 40 ℃ and - 80 ℃, the maximum contact forces generated by the impact extrusion of the wheat bran by the grinding medium 1 are 11.5733 N, 12.8110 N, 16.0461 N and 16.2857 N, respectively. And the disengagement times between the grinding medium 2 and the wheat bran are 0.52 ms, 0.48 ms, 0.47 ms and 0.47 ms, respectively. Compared with the value obtained at 30 ℃, the maximum contact forces of the wheat bran at 0 ℃, - 40 ℃ and - 80 ℃ are increased by 10.69%, 38.65% and 40.72%, respectively. Obviously, when the comminution temperature is - 80 ℃ and - 40 ℃, the grinding time of wheat bran are exactly the same. It can be seen that with the decrease of the grinding temperature, the contact force produced by the grinding medium gradually increases and the contact time gradually shortens. At the same time, it was found that when the comminution temperature decreased from - 40 ℃ to - 80 ℃, the contact force increased only 0.2396 N and the sensitivity was 0.006 N/℃. However, when the comminution temperature decreased from 0 ℃ to - 40 ℃, the contact force increased by 3.2351 N and the sensitivity was 0.081 N/℃. It shows that the effects of the comminution temperature on the contact force is uneven. With the decrease of comminution temperature, the sensitivity of the contact force and the economy of low-temperature comminution keep decreasing. Therefore, it is economical to set the comminution temperature to - 40 ℃.

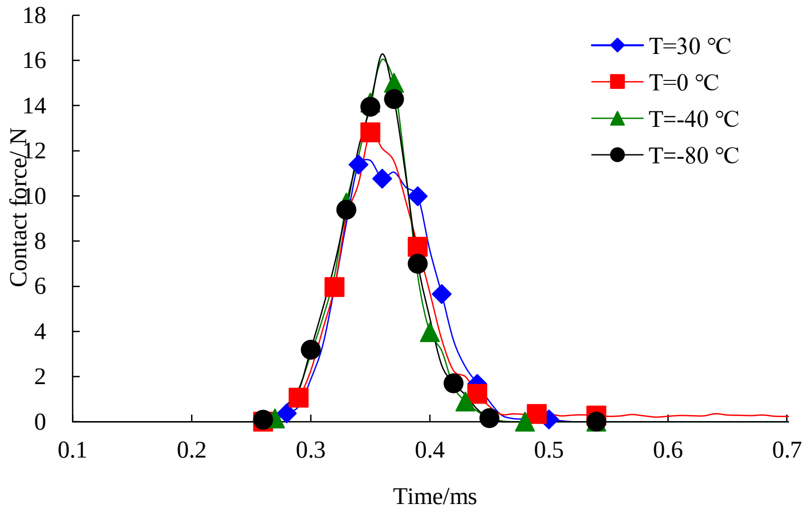

Fig. 6 - Influence of comminution temperature on the contact force of wheat bran

Fig. 7 shows the contact deformation of the wheat bran when the comminution temperatures are at 30 °C, 0 °C, - 40 °C and - 80 °C, respectively. At this time, the wheat bran has completely disengaged from the grinding medium 2, and the impact extrusion comminution process is over. According to Fig. 7, the contact areas of wheat bran at 30 °C and 0 °C are basically the same, and that at - 40°C and - 80 °C are also basically the same, but their contact area are less than those at 30 ℃ and 0 ℃. When the comminution temperature was - 40 °C or - 80 °C, the contact area of the wheat bran was distorted and overlapped. It can be seen from Fig. 4 that the low-temperature embrittlement of the wheat bran has occurred at the comminution temperatures of - 40 ℃ and - 80 °C. Theoretically, this phenomenon of distortion and overlap should not occur. It is because that when using LS-DYNA for numerical simulation calculation, the wheat bran at - 40 ºC and - 80 ºC is considered as isotropic linear elastic material, and its elastic modulus and ultimate stress are greater than those at 30 ºC and 0 ºC. It is equivalent to enhancing the comminution resistance of the wheat bran, resulting in smaller contact area and increased distortion of the wheat bran when impacted and extruded.

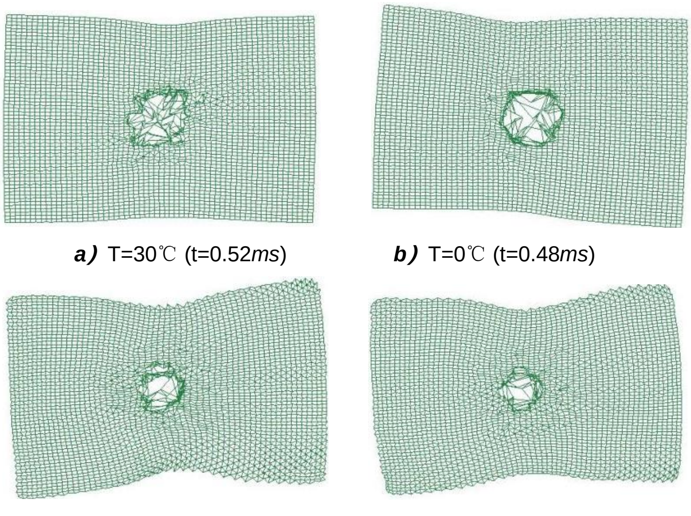

Fig.7 - Influence of comminution temperature on the contact deformation of wheat bran

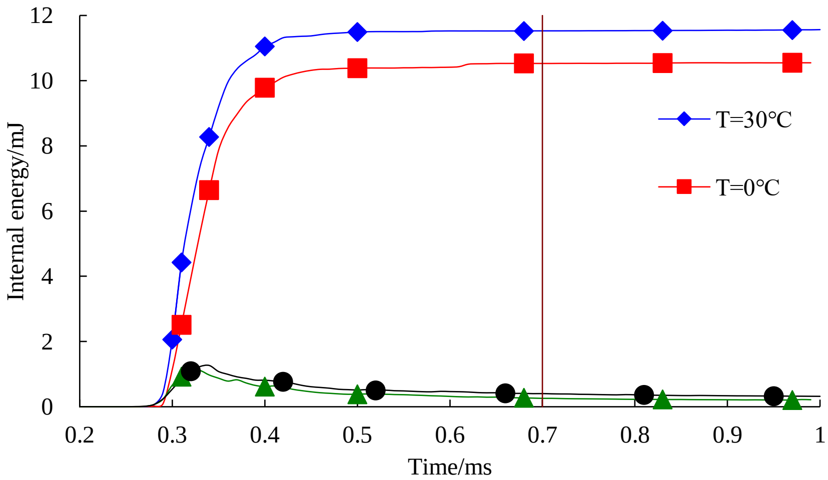

Fig. 8 - Influence of comminution temperature on the internal energy of wheat bran

Fig. 8 shows the internal energy curves of the wheat bran at the comminution temperatures of 30 ºC, 0ºC, -4ºC and -80ºC, respectively. Taking the time of 0.7 ms after the completion of the impact extrusion comminution process as an example, according to Fig. 8, the corresponding internal energy at the comminution temperature of 30ºC, 0ºC, - 40ºC and - 80ºC are 11.5280 mJ, 10.5280 mJ, 0.2576 mJ and 0.4035 mJ, respectively. Compared with the internal energy of wheat bran at 30ºC, the internal energy of wheat bran at 0ºC, - 40ºC and -80ºC decreased by 8.67%, 97.77% and 96.50% respectively. It can be seen that at the same impact velocity, the kinetic energy of the grinding ball is exactly the same, but the energy conversion caused by impact on the wheat bran at different temperatures is different. The internal energy produced at 30 ºC and 0ºC is much greater than that produced at - 40ºC and - 80ºC. The internal energy stored at - 40ºC is the lowest. It is about 2.23% of that at 30ºC. According to the law of energy conservation, the low-temperature comminution consumes most of the kinetic energy of the grinding medium ball as the form of comminution energy of wheat bran. However, the room temperature comminution stores most of the kinetic energy of the grinding medium ball as the form of internal energy, which provides accumulation energy for the next impact comminution. It can be seen that the low-temperature comminution of wheat brans has more advantages than room temperature grinding. At the same time, it was found that the stored internal energy of the wheat bran at - 40ºC was less than that at - 80ºC, which implies that it was more reasonable to take - 40ºC as the low-temperature comminution temperature. However, the tensile breaking strain energy density of the wheat bran at - 80ºC is less than the tensile breaking strain energy density of the wheat bran at - 40ºC. It is probably because that the stress mode of the wheat bran during tensile fracture and vibration comminution is different. Therefore, it is not accurate to directly use the tensile fracture strain energy density to describe the low-temperature vibration comminution performance of wheat bran. It is reasonable to take - 40ºC ~ 0ºC as the temperature regulation range of the low-temperature vibration superfine comminution of wheat bran.

CONCLUSIONS

The three-component numerical calculation model proposed in this paper can completely simulate the vibration impact comminution mechanism of the vibrating ball mill. By adjusting the mechanical parameters of the wheat bran at different temperatures, the effects of low temperature on the vibration impact comminution performance of the wheat bran can be simulated and analyzed.

Low-temperature has a significant effect on the vibration impact comminution performance of wheat bran. Compared with 30ºC, the contact force of the wheat bran at - 80ºC increased by 40.72% and the internal energy decreased by 96.50%. However, compared with - 40ºC, the contact force of wheat bran at - 80ºC only increased by 1.31%, and the internal energy increased by 56.64%. The contact area and deformation degree of the wheat bran at - 40ºC and - 80ºC are basically the same. Therefore, it was more economical to determine - 40ºC ~ 0ºC as the temperature regulating range of low-temperature comminution of wheat bran.

Based on the explicit nonlinear finite element model, the vibration impact comminution performance of the vibration ball mill can be simulated and analyzed, which provides a method for analyzing the low-temperature vibration superfine comminution performance of wheat bran.

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