STATISTICAL ANALYSIS OF FATIGUE DAMAGE LIFE OF CORN KERNELS
/
玉米籽粒疲劳损伤寿命统计分析

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ABSTRACT

It is urgent to study the damage mechanism of corn kernels and find ways of reducing the rate of kernel breakage in mechanical threshing. This paper, by studying the mechanical curves and deformation characteristics of corn kernels with different moisture contents, points out the brittle mechanical characteristics of corn kernel damage fracture with low moisture content, and clarifies the variation law of mechanical properties of kernels with moisture contents. The experimental data of fatigue load - fatigue life curves of corn kernels with different moisture contents were described by the power function equation. At the same time, the fatigue life and damage characteristics of kernel with different moisture content were analyzed, and the accuracy of the fitting equation was verified. Through mathematical statistical analysis, the normal distribution curve of fatigue life was fitted, and the variation law of normal distribution curve with moisture content and fatigue load was determined.

摘 要

研究玉米籽粒损伤机理，降低籽粒破碎率是当前机械脱粒的热门问题。通过研究不同含水率玉米籽粒的力学曲线与变形特点，确定了低含水率玉米籽粒损伤断裂的脆性力学特点，明确了籽粒力学特性随含水率变化规律。采用幂函数方程描述了不同含水率玉米籽粒的疲劳载荷 F_j–疲劳寿命 N_j 曲线试验数据，对不同含水率籽粒的疲劳寿命及损伤特点进行了分析，并验证了拟合方程结果的准确性；通过数理统计分析，拟合了疲劳寿命正态分布曲线，确定了正态分布曲线随含水率、疲劳载荷的变化规律。

INTRODUCTION

Corn is the most productive food crop in the world, which has been planted in more than 170 countries and regions. In 2021, about 206.77 million hectares of corn were planted worldwide *(Geng D. et al., 2019; Wang J. et al., 2019; Zhang C.G., 2016)*. Corn is not only one of the world's three major staple crops, but also an important raw material for medicine, chemical industry and light industry, and an indispensable high-quality roughage for animal husbandry. Therefore, corn production plays an important role in world food security, industrial production and animal husbandry development *(Berry N.K. et al., 2014; CHENG M. et al., 2022)*. The comprehensive crushing rate of corn kernel harvest remains high, and there are serious threshing damage and food loss and waste problems *(Chen Z. et al., 2021; Xiangqian D. et al., 2022; Yang Y. et al., 2021; Yin X. et al., 2021)*. Therefore, to explore the low loss threshing technology of corn grain, reduce the loss of corn grain harvest and improve the efficiency of agricultural production, is the current research hotspot and difficulty in the field of agricultural engineering.

The mechanical property of corn kernel is a key index to study corn threshing damage, which provides a data basis for the design of corn threshing device, and many scholars have conducted a lot of research on this *(Chen Z. et al., 2022; Kruszelnicka W. et al., 2021 Yiren Q. et al., 2022)*. Brass, Srivastava and Kustermam et al. conducted impact and shear tests on corn kernels, respectively, and initially determined the modulus of elasticity of corn kernels, and proved that the moisture content has a significant effect on the performance of corn kernels *(Geng D. et al., 2017; Shi Z. et al., 2018; Zhang X. et al., 2015)*.

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Volkova’s, Mohamed et al. conducted a detailed study on the impact resistance of corn kernels, obtained the corresponding loading force-deformation curves, and conducted a preliminary study on the crushing pattern of corn kernels *(Shahbazi F. et al., 2012; Zhang X. et al., 2015; Zhang Y.L. et al., 2007)*.

Gao Lianxing's group at Shenyang Agricultural University conducted experiments on the hydrostatic breaking, impact mechanical properties, and threshing characteristics of corn seed kernels *(Li X. et al., 2007; Liu M. et al., 2013; Zhang Y.L. et al., 2007)*. Li Xinping's group at Henan University of Science and Technology, Zhao Wuyun's group at Gansu Agricultural University have studied the mechanical properties of a corn cob, breaking laws, and threshing performance on seeds *(Li X., 2010; Putri R E.et al., 2015; Wang B. et al., 2018)*.

MATERIAL AND METHODS

Materials and Instruments

The corn kernels used in all experiments in this paper, with the same moisture content, regular shape and no damage in appearance. After strict detection and screening, the corn variety is Zhengdan 958 (semi-horse-toothed type, thousand kernel weight 307 g).

The main experimental instruments are Olympus SZX16 microscope, microcomputer controlled electronic testing machine WDW-100M, Instron 8872 fatigue testing machine, etc.

Research Methodology

The research route used in this paper is shown in Figure 1.

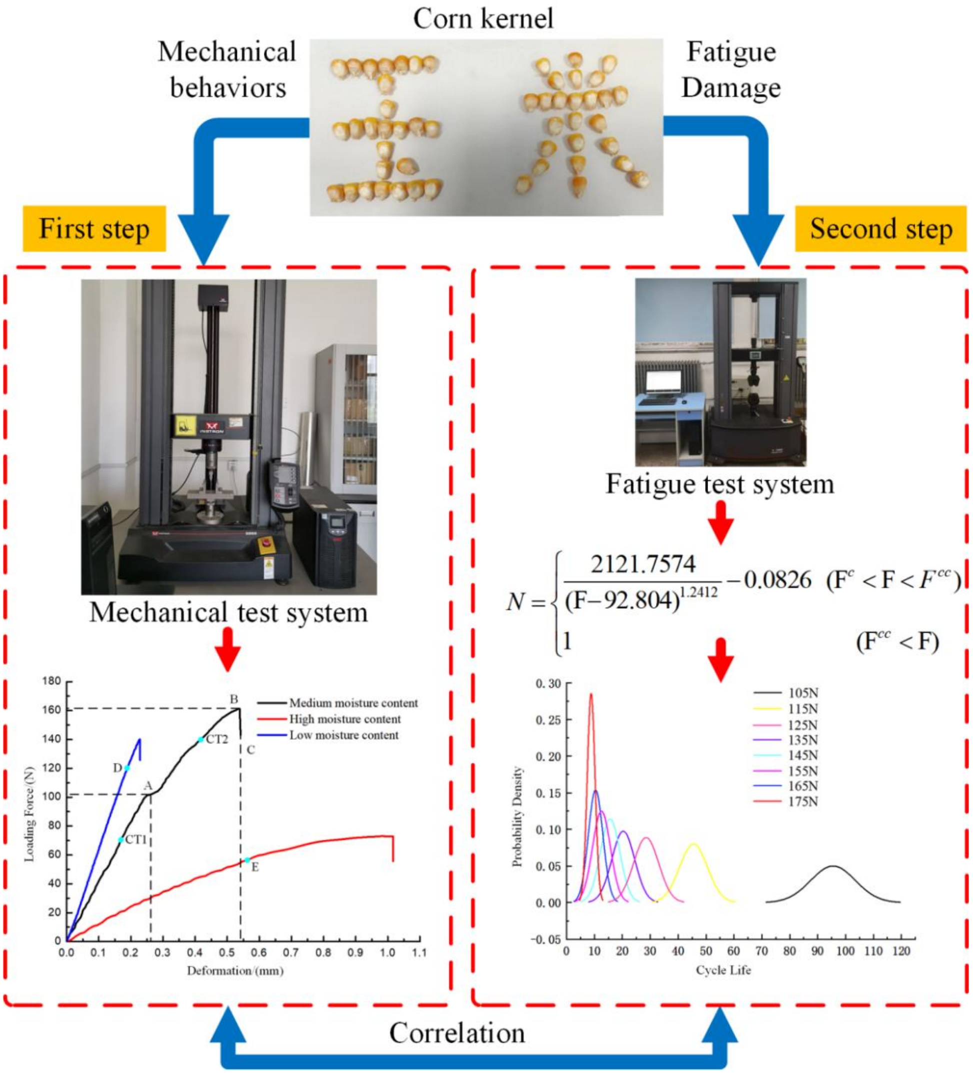

Fig. 1 - Research roadmap of corn kernel

By studying the macro-mechanical properties and fatigue damage of corn kernels with different moisture contents, the variation law of the mechanical properties and deformation characteristics of corn kernels with moisture content are obtained, and the fatigue life-fatigue load of corn kernels is clarified, which provides theoretical guidance for the structural improvement of corn kernel harvesters and harvesting methods.

RESULTS AND DISCUSSION

Mechanical properties of corn kernels

The mechanical curves of corn kernels with different moisture contents were measured by the Mechanical test system. Figure 2 shows the mechanical curves of three kinds of corn kernels with high, medium and low moisture contents, of which the three moisture contents were 30%, 21%, and 14%, respectively. It can be seen from the figure that the mechanical curves of corn kernels with different moisture contents vary greatly, which shows that the moisture content has a great influence on the deformation characteristics of corn kernels.

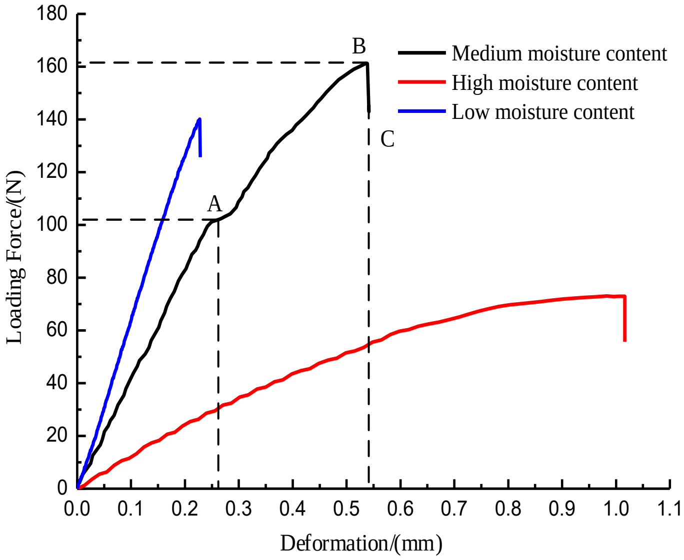

Fig. 2 - Loading force-deformation curve of corn kernels

According to Fig.2, compared with the other two moisture contents, the mechanical curve of corn kernel with 21% moisture content has obvious stages, which can be divided into three stages: 0A, AB and BC.

(1) Linear elasticity stage (0A segment):

When the loading force F on the corn kernel is less than the critical load F^{c} (not reaching point A), defects such as micro-cracks and voids in the corn kernel cannot break through the bond between starch granules and the protein between the granules after being stressed, and continue to develop to form macroscopic defects. Therefore, in this stage, the internal defects of corn kernels basically do not absorb energy, and damage evolution basically does not occur. During this stage, the macro mechanics of corn kernels is linear elasticity.

(2) Nonlinear strain-hardening stage (AB segment):

When the loading force F on the corn kernel exceeds the critical loading force F^{c} (above point A), but is lower than the maximum loading force F^{cc} of the corn kernel, the internal defects of the kernel absorb energy, and the micro-cracks break through the bonding of starch particles and proteins. Hence, more and more micro-cracks will grow steadily, and the crack radius will gradually increase. However, the majority of cracks will stop growing as they hit a stronger interface, and one or even a few cracks will continue to grow and expand through the section, and continuous damage will occur inside the corn kernel. Therefore, the loading force -deformation exhibited a nonlinear relationship and the corn kernels produced some plastic deformation.

(3) Loading force drop stage (BC section):

When the external loading force F exceeds the maximum loading force F^{cc}, the internal defects formed in the AB segment will rapidly develop into macroscopic cracks and cause the corn kernel to change from continuous damage to local damage. On the macroscopic level, the bearing capacity of corn kernels decreases rapidly, and one or more macroscopic cracks are formed due to the development and evolution of micro-cracks, and the kernels will be completely broken.

It can be seen from the above that the mechanical and deformation characteristics of corn kernels with medium moisture content conform neither to the mechanical properties of brittle materials, nor to the mechanical properties of ductile materials. They conform to the mechanical properties of quasi-brittle materials. The mechanical curves of corn kernels with high moisture content and low moisture content are shown in Fig.2.

It can be seen that from the beginning of loading to the breaking of the kernels, corn kernels with low moisture content basically manifested a linear change, while those with high moisture content exhibited a nonlinear relationship. High moisture content corn kernel micro-defects are gradually growing and internal damage is gradually developing and evolving into macro-cracks, which eventually lead to kernel breakage.

Fatigue damage of corn kernels

In this part, the fatigue life and damage evolution of corn kernels under continuous external loading force F will be discussed.

Fatigue damage life of corn kernels

To study the damage of corn kernels under continuous external loading forces, it is necessary to first define a dimensionless damage function D, which is a function of the number of cycles n and the damage life $N(F)$. The function satisfies the boundary conditions,

$$\begin{gathered} D(0,N)=0 \\ D(N,N)=1 \end{gathered} \tag{1}$$

Under one action of external loading force F, the damage is $D(1,N)$, where N is the fatigue life. Theoretically, at the critical load F^c, N should be infinite. But the actual damage performance still needs to be verified by a large number of experiments.

(1) No damage stage:

When the external loading force is lower than F^c, it can be cycled for infinite times, but when the external loading force is higher than F^c, it can be cycled for a limited number of times. In this paper, the validation experiments were conducted in 100 sets using corn kernels with 21% moisture content and 40N external loading force. The results showed that the kernels all produced significant macroscopic damage when the cycles exceeded 500 times. This is because corn kernels are not ideal isotropic homogeneous materials, and there are microscopic defects inside the kernels, which will gradually undergo meso damage after the force is applied. Therefore, even if the degree of damage is small, macroscopic damage can occur when the cycle is large enough.

(2) Fatigue damage stage:

The corn kernels with two different moisture contents (21% and 30%) are used in this part of the experiment and the comparison experiment is conducted between the corn kernels with two moisture contents. 100 groups of fatigue damage experiments on corn kernels were conducted under each fatigue load F_j, and these 100 groups of life were averaged to obtain a set of average life data N_j corresponding to F_j. Table 1 and Table 2 show the data from fatigue damage experiments of corn kernels with 21% and 30% moisture content respectively. The smaller the fatigue life, but the fatigue life of corn kernels with different moisture contents under different loading forces still needs further analysis, and there is no qualitative conclusion on the law of fatigue damage accumulation of corn kernels. Therefore, further research is needed on the data in the tables.

Table 1

Experiment on fatigue damage of corn kernels with 21% moisture content

Fatigue load F_j （N）	Average fatigue life（Time）	Maximum fatigue life（Time）	Minimum fatigue life（Time）
105	95.5	117	80
115	45.3	60	35
125	28.5	42	22
135	20.3	33	15
145	15.6	26	11
155	12.5	22	9
165	10.4	18	6
175	8.8	13	2

Note: *"Time" means the number of times*

Table 2

Experiment on fatigue damage of corn kernels with 30% moisture content

Fatigue load F_j （N）	Average fatigue life（Time）	Maximum fatigue life（Time）	Minimum fatigue life（Time）
20	69.6	83	52
30	20.9	28	14
40	10.4	15	7
50	6.4	10	4
60	4.3	7	2
70	3.2	5	1

Fig.3 and Fig.4 are the fatigue load F_j and fatigue life N_j curves of corn kernels with 21% and 30% moisture contents respectively. Combining the characteristics of the curves shown in the figures and the results of the previous research on corn kernel damage, the curves can be estimated and described by the power function equation:

$$(N + a)(F - F_0)^m = C \tag{2}$$

Where: N is the fatigue life; F is the external loading force; F_0 is the linear elastic/non-linear elastic transition critical load F^c; a, m, F_0, and C are all undetermined constants.

After taking the logarithm of the above equation, the following equation can be obtained:

$$log(N + a) + m\,log(F - F_0) = log\,C \tag{3}$$

In the double logarithmic coordinate system, $log(N+a)$ and $log(F\text{-}F_0)$ have a linear relationship, where F_0 is the linear elastic/non-linear elastic transition critical load F^c, and a, m, F_0, and C are all undetermined constants. The power function formula is employed to fit the test data of the fatigue load F_j curve and the fatigue life N_j curve to maximize the correlation coefficient of the linear fitting.

Through calculation, the constants of corn kernels with 21% and 30% moisture contents can be obtained respectively: "a=0.0826, m=1.2412, F_0=92.8404, C=2121.7574" and "a=0.1343, m=1.6540, F_0=10.6047, C=2836.2839". At this time, the $log(N+a)$ and $log(F\text{-}F_0)$ linear correlation coefficients R of the corn kernels with two different moisture contents exceeded 0.99. Therefore, the fitting equations of the fatigue load F_j and fatigue life N_j curves of corn kernels with two different moisture contents can be obtained.

Among them, the fitting equation for the corn kernels with 21% moisture content is:

$$N = \begin{cases} \frac{2121.7574}{(F-92.804)^{1.2412}} - 0.0826 \ \ (F^c < F < F^{cc}) \\ 1 \qquad\qquad\qquad\qquad\qquad (F^{cc} < F) \end{cases} \tag{4}$$

and the fitting equation for the corn kernels with 30% moisture content is:

$$N = \begin{cases} \frac{2836.2839}{(F-10.6047)^{1.6540}} - 0.1343 \ (F^c < F < F^{cc}) \\ 1 \qquad\qquad\qquad\qquad\qquad (F^{cc} < F) \end{cases} \tag{5}$$

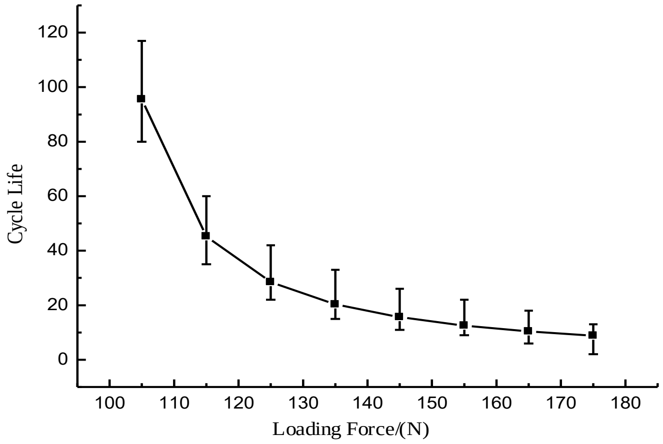

Fig. 3 - Fatigue load-fatigue life curve of corn kernels with 21% moisture content

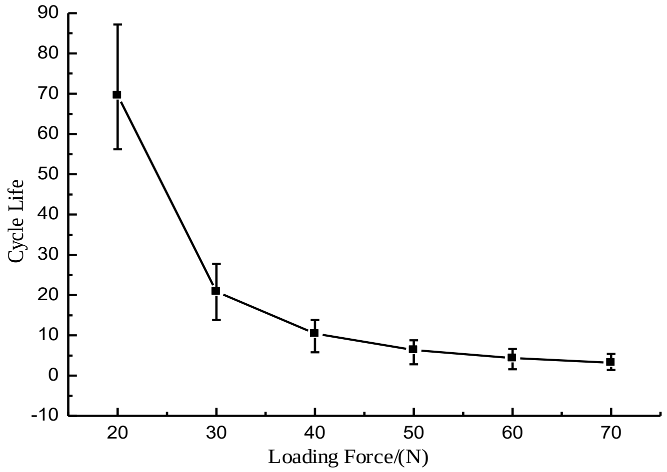

Fig. 4 - Fatigue load-fatigue life curve of corn kernels with 30% moisture content

From the fitting formula, Fig.6 and Fig.7, it can be obtained that in theory, the critical load F^c of linear elastic/non-linear elastic transition caused by damage to corn kernels with 21% moisture content is about 93N and the maximum loading force F^{cc} fluctuates in the ranges from about 170N to 190N; the critical load F^c of linear elastic/non-linear elastic transition caused by corn kernel damage with 30% moisture content is about 11N and the maximum loading force F^{cc} ranges from about 65N to 80N.

Distribution pattern of fatigue damage life

Corn kernels with 21% moisture content were used as experimental samples in this study. The number of cycles was recorded when the kernel was destroyed under a 175N fatigue load, and the number of cycles was statistically analyzed.

The histograms are shown in Fig.5. The arithmetic mean $\overline{x}$ and standard deviation S of the kernel cycle life samples were determined from the following equations.

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{6}$$

$$S = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2} \tag{7}$$

Where, x_i is the fatigue life of each kernel, and n is the sample size.

Bringing the groups of data in the histogram into the above formula, the arithmetic mean $\overline{x} = 8.73$ and standard deviation S = 1.64 are obtained, respectively. According to the probability theory, a large number of random variables are independent of each other, and the results are normally distributed. Meanwhile, the individual corn kernels in this part of the study are independent of each other. Therefore, the fatigue life of corn kernel is in accordance with normal distribution, and satisfies $\mu=\overline{x}$, σ=S. The corresponding normal distribution curve is shown in Fig.5, and the expression of the probability density function for the fatigue life can be expressed as:

$$y = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}(\frac{x-u}{\sigma})^2} \tag{8}$$

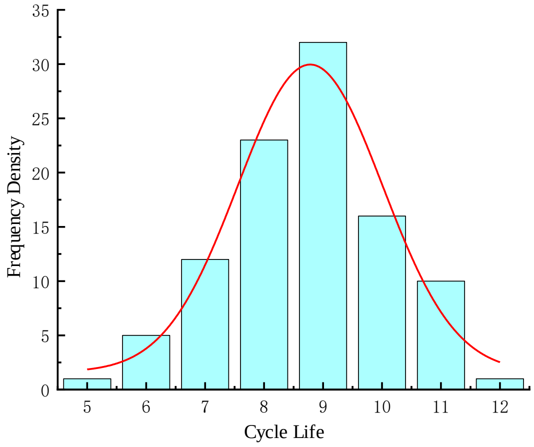

Fig. 5 - Frequency density of corn kernels with 21% moisture content under 175N fatigue load

In order to compare the fatigue life distribution of corn kernels under different fatigue loads, two sets of fatigue experiments were carried out at 21% and 30% moisture content, respectively. The fatigue load and average fatigue life are shown in Table 1 and Table 2, and the fatigue life distribution results of kernels under each fatigue load are shown in Fig.6 and Fig.7. Fig.6 shows the normal distribution of the fatigue life of corn kernels with 21% moisture content under different fatigue loads. It can be seen that, the larger the fatigue load, the smaller the arithmetic mean μ value and standard deviation σ of fatigue life. Fig.7 shows the distribution of fatigue life of corn kernels with 30% moisture content. Similarly, the larger the fatigue load, the smaller the arithmetic mean μ value and standard deviation σ of fatigue life. But compared with 21% moisture content, the arithmetic mean value of fatigue life decreased, and the standard deviation increased. This indicates that the fatigue life distribution of corn kernels is more concentrated, and the upper boundary of fatigue life is closer to the arithmetic mean under the same fatigue life probability density.

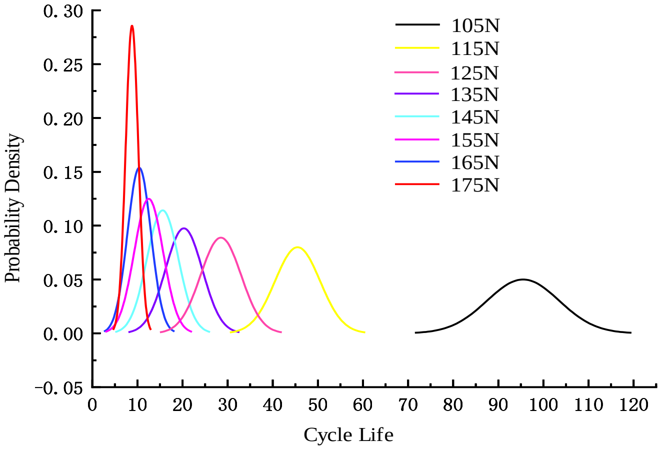

Fig. 6 - Normal distribution curve of fatigue life probability density of corn kernels with 21% moisture content

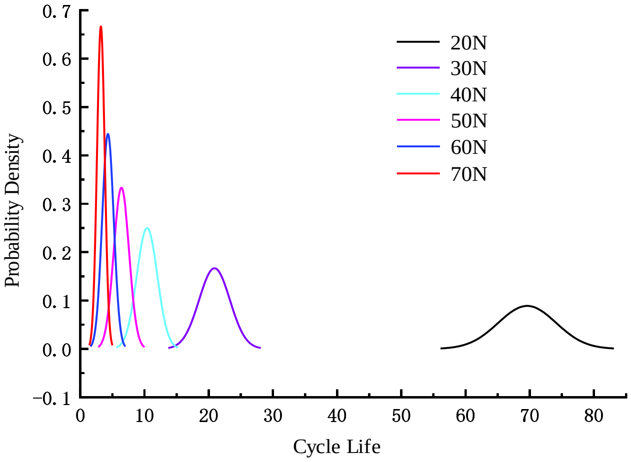

Fig. 7 - Normal distribution curve of fatigue life probability density of corn kernels with 30% moisture content

CONCLUSIONS

(1) By studying the mechanical curves and deformation characteristics of corn kernels, points out the brittle mechanical characteristics of corn kernel damage fracture with low moisture content. With the increase of moisture content, it turns into quasi brittle fracture. And the linear elasticity deformation stage gradually decreased, the maximum loading force that grain can bear increased first and then decreased.

(2) The power function is used to describe the test data of fatigue load F_j and fatigue life N_j curve, and the fitting equation of fatigue load F_j fatigue life N_j curve is obtained, and the accuracy of the fitting equation is verified.

(3) The fatigue life distribution pattern of corn kernels under various loading forces was studied, the normal fatigue life distribution curve was fitted, and the corresponding arithmetic mean and standard deviation were determined. The corresponding arithmetic mean value and standard deviation are determined. The higher the moisture content, the more concentrated the probability density distribution, and the smaller the arithmetic mean and standard deviation.

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