

TEST RESEARCH ON THE IMPACT PEAK FORCE AND DAMAGE DEPTH OF POTATO

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马铃薯碰撞峰值力与损伤深度试验研究

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DOI: <https://doi.org/10.35633/inmateh-61-12>

Keywords: impact peak force, damage depth, potato mass, drop height, impact material, impact times

ABSTRACT

To analyse the influence factors of impact peak force (IPF) and damage depth (DD) on potatoes, the orthogonal test and single factor test were carried out on two potato varieties. The results showed that the IPF of Xiabodi was smaller and DD was greater than those of Gaoyuanhong. Potato mass had the greatest effect on IPF, and that of drop height on DD. The equations between IPF, DD and potato mass, drop height were obtained. Both IPF and DD impacting with steel were the largest, and the smallest with steel- rubber. With the increase of impact times, IPF decreased first and then increased, and DD increased gradually.

摘要

为了分析各因素对马铃薯碰撞峰值力和损伤深度的影响，分别对两个品种马铃薯进行了正交试验和单因素试验。结果表明：夏波蒂的碰撞峰值力小于高原红，损伤深度大于高原红。马铃薯质量对碰撞峰值力影响最大，下落高度对损伤深度影响最大。试验得出了碰撞峰值力和损伤深度与马铃薯质量和下落高度之间的方程式关系。马铃薯与不锈钢碰撞的峰值力和损伤深度最大，与不锈钢-橡胶最小。随着碰撞次数的增加，碰撞峰值力先减小后增大，损伤深度逐渐变大。

INTRODUCTION

Impact damage to potatoes is a common phenomenon during harvesting and post-harvesting operations (Nikara et al, 2018; Yingwang Gao et al, 2018), and it seriously affects the potato yield and causes a dual decline of potato appearance and quality that affect the development of the entire potato industry (Romano et al, 2018; Strehmel et al, 2010). Lots of studies have been performed to analyze the potato impact damage factors. Upon the research, many scholars have adopted testing as the main research method, and some scholars have used the finite element analysis method (Caglayan et al, 2018; Celik et al, 2019; Yingwang Gao et al, 2018). In the field of test research, Some researchers have used a pendulum impact device to study the potato impact response with different tuber temperature, tuber mass, initial height, and impact material, and described the equation of the damage depth and volume of the bruise spots (Mathew and Hyde, 1997; Shengshi Xie et al, 2018). Other researchers have used the free fall device to study the speed, force, respiration and bruise volume of potatoes after impacting with different objects under different conditions (Geyer et al, 2009; Qi Lu, 2016; Rady and Soliman, 2015; Zhizhen Liu, 2016). Some researchers have used an instrumented potato to record the extent of impact and predicted the tissue discoloration in order to find the relationship between potato damage and harvest parameters (Bentini et al, 2006; Canneyt et al, 2004).

Based on these papers, the main research contents are the influence factors of potato impact damage and the evaluation indexes after potato injury, such as drop height, potato mass, potato temperature, impact material, potato variety, cultivation conditions, collision pressure, impact acceleration, potato damage volume, damage area, damage depth, and respiratory rate (Shengshi Xie et al, 2018). In the research of potato collision tests, the impact force was usually obtained by force sensor (Qi Lu, 2016; Zhizhen Liu, 2016), or by the signal measured by acceleration sensors (Bentini et al, 2006; Geyer et al,

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2009; Rady and Soliman, 2015). There has been no research on direct force measurements of potato impacts by hammers' force.

The study both researching on IPF and DD is rare and the relationship between IPF and DD has not been reported. No relevant information is available on the evaluating of significant factor to IPF. Therefore, this article aims to directly test the impact force by a force hammer, find the relationships between IPF and DD, and analyze the primary and secondary sequences of factors that affect both IPF and DD.

MATERIALS AND METHODS

● Potato impact test system

The potato impact test system is shown in Figure 1. The testing device included a bracket, height ruler, light rod and fixture. The testing system consists of a data acquisition device (AVANT - MI7016, Hangzhou Yiheng Technology Co., Hangzhou, China), an impact hammer (5800B5, 1.12 mv/N, DYTRAN Instruments Co., Ltd., USA) and a computer with a data acquisition software (Dynamic Signal Analysis, Hangzhou Yiheng Technology Co., Hangzhou, China). During the test, the potato was lifted to a certain height and released to collide with the hammer tip. The test system could detect the change of force during the collision process.

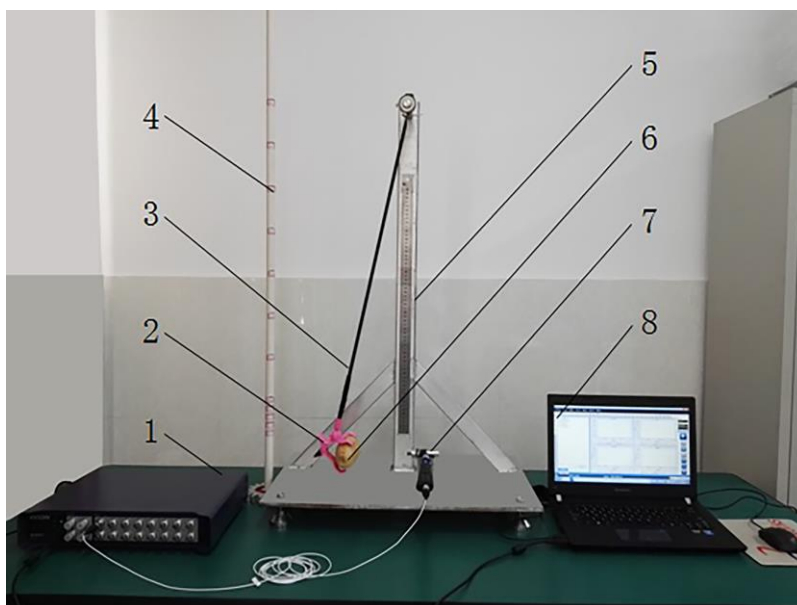


Fig.1 - Test equipment

1. Data acquisition device 2. Fixture 3. Light rod 4. Height ruler
5. Bracket 6. Potato 7. Impact hammer and fixing device 8. Computer

The original tip materials of the 5800B5 impact hammer are aluminum ($m = 2.1$ g), aluminum-hard plastic ($m = 2.7$ g) and aluminum-soft plastic ($m = 2.7$ g). The connection between the tip and the hammer body is threaded. During a mechanized potato harvest, the potato-soil separator is usually made of steel. To simulate field harvest conditions during the impact process, the steel tip of the impact hammer was covered with 3 mm either soft plastic, rubber or leather. The main factor influencing the test results was the mass of the hammer tip. Fine wire was wound on the hammer tip to make the mass close to that of the original. The tip masses of steel, steel-soft plastic, steel-rubber and steel-leather hammers were 2.11 g, 2.72 g, 2.69 g and 2.68 g, respectively.

● Accuracy of hammer tips

In order to check the accuracy of the changed hammer, the light rod and fixture shown in Figure 1 were removed, and a standard weight ($m = 500$ g) was connected to the test bracket with nylon wire and fine iron wire. An acceleration sensor with dimensions of $\Phi 10$ mm \times 22 mm (1A102E, Jiangsu Donghua Testing Technology Co. Jiangsu, China) was attached to the weight. When the weight was lifted to a certain height and released, it collided with the impact hammer. The collision process followed the integral expression of Newton's second law.

$$\int_{t_1}^{t_2} F(t) dt = m \int_{t_1}^{t_2} a(t) dt \quad (1)$$

where:

t_1 is the impact start time; t_2 is the impact end time; $F(t)$ is the impact force; m is the impact mass; $a(t)$ is the impact acceleration.

From the beginning to the end of the collision, the data acquisition system detected the acceleration and force signals simultaneously. According to equation (1), the error between the impact hammer and the acceleration sensor was obtained. The test errors of the steel, steel-soft plastic, steel-rubber and steel-leather hammer tips were 4.25%, 4.7%, 5.17% and 4.77%, respectively.

● Theoretical analysis of the collision process

According to the kinetic energy theorem, the following relation is satisfied before collision.

$$mgh = \frac{1}{2}mv_1^2 \quad (2)$$

where:

m is the potato mass; g is the acceleration of gravity; h is the drop height; v_1 is the initial impact speed.

The impulse theorem is also satisfied during the collision process.

$$\int_{t_1}^{t_2} Fdt = m\Delta v = m(v_1 - v_2) \quad (3)$$

where:

t_1 is the loading start time; t_2 is the impact contact time; F is the impact force; and v_2 is the potato impact speed in t_2 .

When v_2 is zero, the potato compression displacement reaches its maximum, and t_s is the corresponding time. Equation (4) is derived from (2) and (3).

$$\int_{t_1}^{t_s} Fdt = mv_1 = m\sqrt{2gh} \quad (4)$$

A potato can be characterized as a type of nonlinear viscoelastic material. According to the generalized Hertz theory, during a collision contact, the relationship between impact force and displacement can be written as follows (Jankowski, 2006; Wenxi Wang et al, 2017).

$$F = k\delta^n + c\dot{\delta} \quad (5)$$

where: F is the impact force; δ is the compression displacement; $\dot{\delta}$ is the compression speed; k is the stiffness coefficient and c is the damping coefficient.

The value of k and c depends on potato varieties and impact materials. Based on the above equations, both the IPF and DD of potato are related to the potato mass, drop height, potato varieties and impact materials.

● Orthogonal tests

In order to clarify the significance of the various factors on the impact force and damage depth of potato, the orthogonal test was conducted. The IPF and DD were taken as the evaluation index. Meantime, the potato mass (A), drop height (B), impact material (C), and impact times (D) with four levels were selected as factors in the experiments. Considering that the potato mass was mainly distributed in the range of 200-250g during harvest, the level ranges of factor A were determined. The level ranges of factor B were determined by the impact of potato dropping from different heights with the tip of hammer in the pre-test. The test factors and levels were shown in Table 1.

Table 1

Factors and levels

Level	Factor			
	Potato mass A [g]	Drop height B [mm]	Impact material C	Impact times D
1	150	40	steel	1
2	200	60	steel-soft plastic	2
3	250	80	steel-rubber	3
4	300	100	steel-leather	4

16 groups of orthogonal tests were designed with $L_{16}(4^5)$ program, and the test scheme was shown in Table 2. In order to analyze the influence of potato varieties on the test results, two potato varieties, Xiabodi and Gaoyuanhong, were selected for comparative test. The peel of Xiabodi is yellow and it is one of the main varieties planted in Inner Mongolia Autonomous Region. Gaoyuanhong is red, which is one of the main varieties planted in Ningxia Hui Autonomous Region.

According to the scheme in Table 2, three repeated impact tests were carried out. In each impact test, each group was repeated 5 times, and the average value of IPF was taken as the final result. After collision, the potato was left at room temperature for 48 hours, and the average of DD in each group, which was measured by slice method (*Baritelle et al, 2000; Blahovec, 2006*), was taken as the test result. To reduce the influence of curvature difference on the impact force, a flat surface with a small curvature in the middle part of potato was selected as the impact site. The results of repeated orthogonal tests were shown in table 3.

Table 2

Scheme of orthogonal experiments

Test number	Potato mass A	Drop height B	Impact material C	Impact times D	Free
1	1	1	1	1	1
2	1	2	2	2	2
3	1	3	3	3	3
4	1	4	4	4	4
5	2	1	2	3	4
6	2	2	1	4	3
7	2	3	4	1	2
8	2	4	3	2	1
9	3	1	3	4	2
10	3	2	4	3	1
11	3	3	1	2	4
12	3	4	2	1	3
13	4	1	4	2	3
14	4	2	3	1	4
15	4	3	2	4	1
16	4	4	1	3	2

Table 3

Results of orthogonal tests

Test number	IPF-Xiabodi F [N]			IPF-Gaoyuanhong F [N]			DD-Xiabodi S [mm]			DD-Gaoyuanhong S [mm]		
	F1	F2	F3	F1	F2	F3	s1	s2	s3	s1	s2	s3
1	54.08	50.46	59.61	61.31	66.64	64.46	3.24	3.74	3.12	1.9	1.88	1.78
2	42.80	44.98	47.17	52.82	53.05	45.18	3	4.20	3.14	1.3	1.7	1.66
3	43.17	39.95	35.55	49.66	50.54	50.12	3.35	3.58	3.93	2.86	2.76	2.7
4	66.67	63.53	64.94	72.35	71.86	66.55	5.44	4.88	4.62	4.4	4.22	4.3
5	49.03	47.82	42.75	66.89	57.16	69.13	2.74	2.56	2.68	2.2	2.38	2.06
6	56.04	52.02	76.26	79.29	80.55	73.40	4.12	4.38	4.88	4.22	4.18	4
7	48.90	46.31	55.44	58.01	64.06	62.91	4.42	3.44	3.66	1.8	1.52	1.22
8	63.68	55.85	57.19	60.06	57.96	62.26	5.26	5.12	5.58	3.44	4.16	3.8
9	80.18	74.64	77.79	82.98	88.46	83.8	3.44	3.22	3.38	1.4	1.66	1.26

Table 3
(continuation)

Test number	IPF-Xiabodi F [N]			IPF-Gaoyuanhong F [N]			DD-Xiabodi S [mm]			DD-Gaoyuanhong S [mm]		
	F1	F2	F3	F1	F2	F3	s1	s2	s3	s1	s2	s3
10	79.42	72.74	69.83	82.6	74.51	79.18	4.92	5.00	4.28	3.56	4	3.92
11	74.27	72.00	77.92	80.74	75.27	93.25	5.4	5.46	5.88	4.1	4.16	4.3
12	73.48	68.44	69.89	73.83	77.13	67.34	4.84	4.44	4.32	4.06	4.2	4.08
13	64.66	65.89	67.15	80.30	75.09	76.04	2.36	2.38	2.24	1.28	1.18	1.4
14	85.88	75.91	68.23	85.34	85.34	90.07	3.22	3.16	3.6	1.7	1.26	1.7
15	94.83	98.18	107.05	106.38	114.34	101.82	5.8	5.92	5.58	5.6	5.5	5.9
16	114.94	105.00	103.70	125.27	130.14	133.64	7.76	6.98	6.94	6.02	5.75	6.92

● **Single factor tests**

In order to obtain the mathematical model between potato mass, drop height and IPF, DD, a single factor test was designed. The evaluation index was IPF and DD. Each group of the test was repeated 10 times and the average value was taken as the test result. Considering the planting and distribution characteristics of potato in Inner Mongolia Autonomous Region, Xiabodi was selected as the experimental potato variety. The test schemes and results were shown in Table 4.

Table 4

Test number	Potato mass / g	Drop height / mm	Impact material	Evaluation index	
				IPF [N]	DD [mm]
1	100	60	steel	40.53	1.53
2	150			61.76	2.53
3	200			71.09	3.1
4	250			86	3.83
5	300			108	4.87
6	200	20	steel	44.17	0
7		40		62	1.9
8		60		71.09	3.1
9		80		89.25	3.87
10		100		96.97	4.53

RESULTS

● **Orthogonal test results**

The range analysis results were shown in table 5. The order of influencing factors for IPF of Xiabodi was found to be: potato mass > impact times > drop height > impact material. For Gaoyuanhong, the order was as follows: potato mass > impact material > impact times > drop height. The orders for DD of both Xiabodi and Gaoyuanhong were the same as: drop height > impact material > impact times > potato mass.

It can be seen from the range analysis that the larger the potato mass and drop height of the two potato varieties, the greater the IPF and DD. Equation (4) showed that the impulse of the collision process was determined by the potato mass and drop height. The larger the potato mass and drop height was, the greater the impulse was. Based on the research of some scholars, it can be inferred that under the same impact material, the trend of potato impact force and the contact time were little affected by the changes of potato mass and drop height (*Bajema and Hyde, 1999; Qi Lu, 2016; Zhizhen Liu, 2016*).

Therefore, the larger the impact impulse was, the larger the IPF was. So, with the increase of potato mass and drop height, the IPF will increase correspondingly. Geyer M. O. analysed the influence of potato mass and drop height on the IPF through acceleration sensor (Geyer *et al*, 2009), which was consistent with the results in this paper. Xie Shengshi developed a model to predict the potato impact damage depth, which showed that DD increased with the increase of potato mass and drop height (Shengshi Xie *et al*, 2018). Baritelle found that the larger the potato mass was, the larger the DD was (Baritelle *et al*, 2000). Mathew and Hyde also found that the DD increased with the drop height (Mathew and Hyde, 2013).

The potato mass was the most significant factor to IPF and drop height was the most significant to DD. When potato mass and drop height increased, both IPF and DD increased. Therefore, during the cultivation of potato varieties, the moderate potato mass will be helpful to reduce the impact force during the harvest. In the process of potato harvesting, reasonable working parameters of the harvesting machine can reduce the drop height of potato on the separating device and effectively reduce the DD.

According to the range analysis in Table 5, the IPF of two potato varieties decreased in turn when they collided with steel, steel-soft plastic, steel-leather and steel-rubber.

Table 5

Range analysis of orthogonal experiment results

Evaluation object	Range source	Potato mass A	Drop height B	Impact material C	Impact times D
IPF-Xiabodi F [N]	K1	612.91	734.04	896.31	756.63
	K2	651.28	771.27	786.40	733.55
	K3	890.59	793.56	758.01	803.87
	K4	1051.40	907.31	765.47	912.13
	R	109.62	43.32	34.58	44.65
	Factor order	A>D>B>C			
IPF-Gaoyuanhong F [N]	K1	704.54	872.26	1063.97	856.44
	K2	791.68	881.33	885.07	812.02
	K3	959.09	907.10	846.59	968.84
	K4	1203.77	998.39	863.46	1021.78
	R	124.81	31.53	54.34	52.44
	Factor order	A>C>D>B			
DD-Xiabodi S [mm]	K1	46.24	35.10	61.90	45.20
	K2	48.84	47.90	49.22	50.02
	K3	54.58	56.42	46.84	54.72
	K4	55.94	66.18	47.64	55.66
	R	2.43	7.77	3.77	2.62
	Factor order	B>C>D>A			
DD-Gaoyuanhong S [mm]	K1	31.46	20.38	49.21	27.10
	K2	34.98	33.20	40.64	32.48
	K3	40.70	42.42	28.70	45.13
	K4	44.21	55.35	32.80	46.64
	R	3.19	8.74	5.13	4.89
	Factor order	B>C>D>A			

The stiffness of the impact material affected the impact contact time. When the impact impulse was the same and the impact force had a certain trend, the greater the stiffness of the impact material, the shorter the impact contact time, and so the larger the IPF. Among the four types of impact materials, the stiffness of steel was the largest and that of rubber was the smallest. Therefore, the IPF was the largest impacted with steel and that of steel-rubber was the smallest.

The results of range analysis showed that impact materials had the same influence rule on IPF and DD. It can be inferred that the impact force and damage of potato during harvest can be reduced by covering the surface of potato-soil separator with leather, rubber and other cushions. Geyer M. O. found that in comparison to bare steel, the maximum force and maximum acceleration due to drops from 25 cm were almost halved by both cushions (Poron 20250 and PVC foam) (Geyer *et al*, 2009) Mathew and Hyde considered that the cushioning materials performed well in reducing impact damage occurring in the potatoes (Mathew and Hyde, 2013).

With the increase of the impact times, the IPF of the two potato varieties decreased first and then increased, and the second time IPF was the minimum. It was because in the second collision, the potato damage caused by the previous impact made the contact time longer and so the IPF reduced. However, with the increase of impact times, the influence of the previous damage on the contact time of the next impact decreased, so the IPF increased again. The results also showed that the DD of two potato varieties increased gradually when the impact times increased. It was caused by the cumulative damage of the same site after multiple collisions. Researchers found that with each successive impact, the potato bruise size increased until it stabilized after more than 4 impacts (Bajema and Hyde, 1999; Baritelle and Hyde, 2003). It can be inferred that when the impact times increase from 1 to 4, the DD will gradually increase, which is consistent with the results of this study.

● The effect of potato varieties on IPF and DD

The average values of the three repeated test results in each group in Table 3 were taken to draw the graphs of IPF and DD, as shown in Figure 2 and 3. The trends of IPF and DD of the two potato varieties were the same. The IPF of Xiabodi was smaller than that of Gaoyuanhong but DD was larger than that of Gaoyuanhong. The results showed that potato varieties had an effect on both IPF and DD. The average dry matter content of Xiabodi was 21% (Haiying Qi and Chun Yang, 2006), and that of Gaoyuanhong was 24.5% (Hongyuan Huang *et al*, 2010). So, the internal tissue of Xiabodi was softer, which could absorb and buffer the impact force. And Gaoyuanhong was relatively denser, so it had a better damage resistance effect.

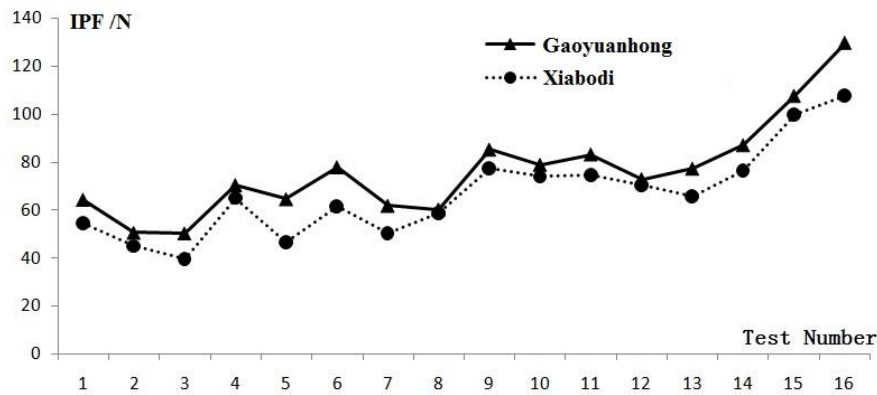


Fig. 2 - The graph of IPF for Xiabodi and Gaoyuanhong

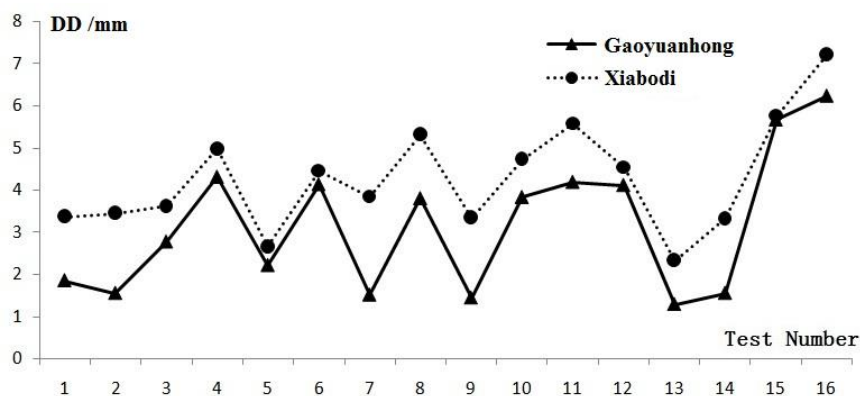


Fig. 3 - The graph of DD for Xiabodi and Gaoyuanhong

● **Single factor test results**

➤ **The effect of potato mass(m) on IPF(F) and DD(s)**

According to the test results in Table 4, the curves of s-m and F-m were drawn, as shown in Figure 4. The results showed that the equation between the potato mass and either IPF or DD was linear. With the increase of potato mass, both IPF and DD increased linearly.

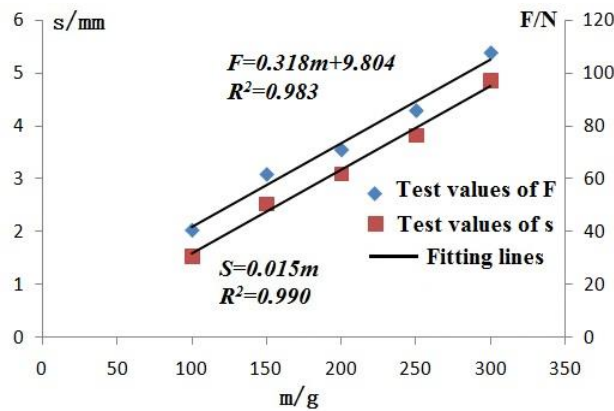


Fig. 4 - The curves of s-m and F-m

➤ **The effect of drop height(h) on IPF(F) and DD(s)**

The curves of s-h and F-h were shown in Figure 5. The results showed that the equation between the IPF and drop height was linear, and it was logarithmic between DD and drop height. With the increase of drop height, both IPF and DD increased gradually.

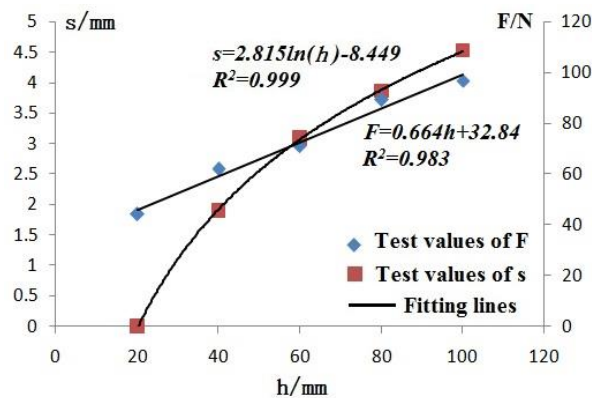


Fig. 5 - The curves of s-h and F-h

➤ **The relationship between DD(s) and IPF(F)**

The curve of s-F was shown in Figure 6 based on the results in Table 4. The curve of s-F₁ corresponds to the results of No.1 to 5 in table 4 and s-F₂ corresponds to that of No.6 to 10.

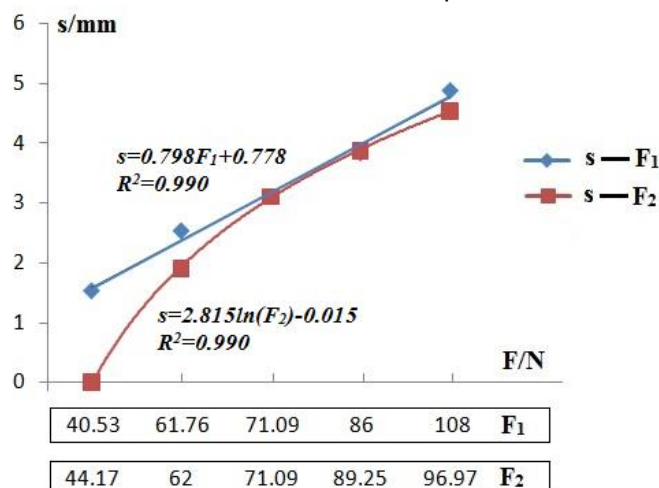


Fig. 6 - The curve of s-F

The figure showed that when potato collided with steel and the drop height was a constant, the equation between DD and IPF was linear, and both of them increased linearly. If the potato mass was a constant, the equation was logarithmic, and the larger the IPF was, the greater the DD was.

CONCLUSIONS

In this paper, the effects of potato mass, drop height, impact material, impact times and potato varieties on the IPF and DD were studied by orthogonal tests and single factor tests. Based on the orthogonal tests, the order of influencing factors for IPF of Xiabodi was found to be: potato mass > impact times > drop height > impact material, and that of potato mass > impact material > impact times > drop height for Gaoyuanhong. The orders of influencing factors for DD of both Xiabodi and Gaoyuanhong were the same as: drop height > impact material > impact times > potato mass. Both IPF and DD of two potato varieties increased with the increase of potato mass and drop height, and decreased in turn when they collided with steel, steel-soft plastic, steel-leather and steel-rubber. With the increase of impact times, IPF decreased first and then increased, and DD increased gradually. Under the same conditions, the IPF of Xiabodi was smaller than that of Gaoyuanhong, but DD was greater than that of Gaoyuanhong. The results of single factor tests showed that the relationship between the IPF and either potato mass or drop height was linear equation. The DD and potato mass equation was linear, and the DD and drop height equation was logarithmic. When potato collided with steel and the drop height was a constant, the relationship between DD and IPF was linear equation. If the potato mass was a constant, the relationship turned to be logarithmic equation.

ACKNOWLEDGEMENT

The research was supported by National Youth Science Foundation of China (31901409), Science and Technology Program of Inner Mongolia Autonomous Region of China (20121310), Natural Science Foundation of Inner Mongolia Autonomous Region of China (2016MS0519, 2019BS05012), Scientific Research Foundation of Higher Education Institutions of Inner Mongolia Autonomous Region of China (NJZY16059).

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