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EVALUATION OF THE EFFECT OF THE NUMBER OF HAMMERS, CLEARANCE, SIEVE OPENING AND THEIR INTERACTIONS ON SOME PERFORMANCE INDICATORS OF THE CORN HAMMER MILL

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Abstract

Due to the difficulty of standardizing hammer mill machine settings due to the many design factors affecting their performance and the varying operating conditions, a factorial experiment was conducted using three factors: number of hammers (8 and 10), clearance (2.5 mm, 5 mm, and 7.5 mm), and screen opening (2.5 mm, 4 mm, and 8 mm). The aim was to evaluate the impact of the main factors and their interactions on some machine performance indicators (productivity, specific energy consumption rate, and the average geometric diameter of processed yellow maize grains), determine the percentage of importance of the factors, and determine the best combination of machine numbers before starting milling. The results showed that the number of hammers and clearance, along with their interaction with the sieve opening, had a slight effect on productivity, specific energy consumption, and geometric mean diameter compared to the sieve opening effect. The sieve opening effect was 100%, compared to 7% and 4% for clearance and number of hammers, respectively. A combination of 2.5 mm sieve opening with any of the two factors can be used for fine grinding, and 8 mm sieve opening with any of the two factors can be used for coarse grinding within the experimental limits. **Keywords**: *hammer mill, sieve opening, clearance, number of hammers*

I. INTRODUCTION

Hammer mills are widely used for grinding feed ingredients due to their low maintenance costs and ease of operation (Patterson and Kitto, 2018; Braun *et al*., 2019). This is a grinding technology that relies primarily on impact force. Compared to other grinding machines, they are capable of grinding a material to a wide variety of grinding degrees, depending on the user's requirements. Like other machines, the machine requires different settings when grinding materials with different natures and physical and mechanical properties. Therefore, making accurate decisions about machine settings before starting work is not easy. Numerous studies have been conducted to understand the factors affecting machine performance, both quantitatively and qualitatively, and economically. These studies have shown that some factors relate to material properties and others to the design characteristics of the machine itself. The speed of the hammers and the size of the sieve opening are factors related to the machine design and the most important ones discussed in scientific research due to their high impact on the size distribution indicators of the ground particles such as the average geometric diameter and the size reduction ratio, as well as on the energy indicators consumed in operating the machine (Mani *et al*., 2004), (Abas, 2013), and Drocas *et al.*, 2014). A study using a mathematical model showed that there is a strong correlation of more than 0.93 between the sieve opening diameter and the average particle diameter Paraschiv *et al*., (2021).

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The clearance (distance) between the tip of the hammers and the inner wall of the screen and other factors such as the number of hammers are factors that have not received sufficient study compared to the speed of the hammers and the screen opening as factors related to mill design. However, (Becca Lu., 2018) strongly recommended that the user determine the appropriate clearance based on the screen opening before starting grinding. He indicated that the recommended clearance for grains is 4-8 mm; and for straw, 10-14 mm, according to test results. Increasing the clearance reduces the problem of screen opening blockage caused by fine grinding (Mark, 2014). Mahmoud K. *et al*., (2006) conducted an experiment in which the clearance was increased from 4.5 to 14.5 mm, while keeping the screen opening and grain type constant. The results showed an increase in the geometric mean diameter and a decrease in productivity.

It was observed that increasing the number of hammers within the same length of the grinding chamber, by reducing the distance between each hammer, increases the number of impacts and thus increases the degree of particle fineness (Becca Lu., 2018). The impact of this factor comes in third place after the speed of the hammers and the grain moisture in the productivity of the crusher and the specific electrical energy consumption (Di wang *at el*; 2020), but its interaction with the sieve opening may differ. In previous studies, we have not yet found a scientific study that addressed the effect of the overlap of the sieve opening with the number of hammers. The distance between one hammer and another is limited, and therefore it is not easy to increase the number of hammers within the same space of the grinding chamber except by changing the thickness of the hammers. Khudher *et al*.; (2021) increased the productivity of the hammer mill and reduced the specific energy consumption by replacing four hammers with two hammers and recommended choosing a smaller thickness for the hammers to give the same results compared to the four hammers with a larger thickness.

Due to the difficulty of determining uniform settings for poultry feed mills due to the multiplicity of factors affecting hammer mill performance and the variation in operating conditions and material properties, there is a need for focused studies on each type of factor related to the material to be ground and on the impact of design factors and their interactions of varying importance on machine performance. This will facilitate the user's task of accurately and optimally setting up the machine before commencing grinding. The current research aims to study the effect of sieve opening, clearance, number of hammers and their interactions, determine the percentage importance of the effect of these factors, and find a combination that achieves the targeted size distribution without excessive energy consumption and deterioration of machine productivity.

II. MATERIALS AND METHODS

Crushing Machine: A hammer mill (made in China) available in local Iraqi markets (Table 1) was used to conduct a three-factor laboratory experiment to grind yellow corn (the average initial grain diameter was 10, which is the sieve opening diameter through which more than 90% of the grain passed).

Table(1) Hammer mill description
Mill length (cm) = 10
Mill diameter (cm) = 25
Motor is 6 hp ; Rotor (rpm)=3000 ; Hammer tip speed (m/s)= 66.8
The number of hammers varies according to the experimental design: 10 hammers, each 6 cm long, where 4 of them are distributed in two rows and 2, each 10 cm long, are fixed directly on the rotation axis on the far side, Hammer length, width and thickness(mm)= 60 , 50 and 2 ;Hammer edge shape lengthwise = toothed
The clearance varies according to the experimental design(mm): 2.5 , 5 and 7.5
sieve opening varies according to the experimental design(mm): 2.5 , 4 and 8
Feed opening area(cm)= 17 ; diameter =4.7
Underscreen aperture (cm^2)= 25×10= 250
Underscreen orientation = Lateral

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Experimental Design and Analysis: A factorial experiment was conducted with three factors, 54 treatments with replication (2 hammers × 3 screen openings × 3 clearance × 3 replicates). The studied characteristics were determined in the experiment for some performance indicators (geometric mean diameter, specific energy consumption, and machine productivity). The results were analyzed using GenStat 25 program according to CRD design. SPSS 25 program was also used to analyze the importance gradient of factors in influencing the performance indicators.

Measurement and Calculations: Mill productivity: This reflects the quality of the machine's performance on a quantitative basis, as it is extracted as a time-weighted average of the milled product. Mill productivity was calculated from Equation 1 (KHudher *et al.*, 2021).

$$PC = \frac{W}{T} \qquad \ldots\ldots (1)$$

Where, PC is the machine's productivity (tons.h-[1]), W is the weight of the grains after grinding (tons), and t is the operating time (hours).

Geometric mean diameter (DGW): It is one of the quality standards of mill performance on a qualitative basis. Before starting grinding, the machine user targets a final product size. Therefore, the more the output size matches the target size, the higher the grinding quality. The geometric mean diameter constitutes 64% of the weight of the examined sample after the grinding process is completed using one of the flour size distribution analysis tools. In the current research, the sieve analysis method (ASAE, 1969) was used, where a 100-gram sample of grains was taken after grinding for each experimental treatment to extract the size distribution of the grinding product. The geometric mean diameter (microns) was then calculated from Equation 1 (ASABE, 2017).

DGW = Log-1 [_(wiLog D i) / _wi]

Where, Wi: particles weight in the sieve (i) gm. ; D i: Geometric mean diameter of the particles in the sieve (i) micron. ; D i = (Di *(Di+1)0.5 ; i : the sieve number ; Di : the diameter of the sieve perforations micron ; Di+1 : the perforations diameter of the next sieve bigger than the sieve (i) that is on the top in sequence /order.

Target Final Diameter: There are several methods for determining the fine, medium, and coarse grind ratios, but first, a range of milled particle diameters for each grinding degree must be determined. These target ranges vary depending on the grinding application. The desired average diameter for compressed feed production differs from the target diameter for direct feeding to poultry or ruminants. The requirements of each grain-based industry also vary. These different target diameter ranges are not internationally standardized, as each country has its own local standards. In the current study, we will use the following ranges for fine, coarse, and medium, respectively: (600 to 900 µm), (901 to 1300 µm), and (> 1300 µm). These ranges were selected based on the references of a group of researchers who used standards for countries such as the United States, Egypt, China, and Russia (Reece *et al*. 1986), (Wondra, 1993), (El Shal *et al.* 2010), and Ramil *et al*. (2018).

Specific electrical energy consumption rate: The specific electrical energy consumed for each treatment was calculated from the following equation, Payne (1997).

$$S_{pec} = E\,P \div CP \qquad \ldots\ldots.. \qquad (2)$$

Where, Spec is specific energy consumption rate ($kW.h.ton^{-1}$)

EP, electrical power consumed (kW) , calculated from Equation 3 (Evans *et al.*, 2021)

$$EP = \frac{I \times V \times PF \times COS\emptyset}{1000} \qquad \ldots\ldots\ldots\ldots.. \qquad (3)$$

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I = electric current, Amperes ; V= electrical voltage, V ; PF = Mechanical efficiency assumed to be 0.95 ; COSØ 1.73.

III. RESULTS AND DISCUSSION

The results of the analysis of variance (Table 2) illustrate the effect of the main factors A, B and C: number of hammers, sieve opening diameter and clearance, respectively, and the effect of the binary interactions AB, AC and BC, and the triple interaction ABC, between the main factors, on productivity (PC), geometric mean diameter (GDW), and specific electrical energy consumption (Spec). The analysis results showed that the main independent factors A and B, and their interaction AB, had a highly significant effect ($p \leq 0.001$) on productivity, while clearance (C), binary interactions, and triple interactions had no significant effect on productivity. As for the effect on geometric mean diameter, the analysis of variance showed that there was a highly significant effect ($p<0.001$) for all the studied main factors and their interactions, except for the interaction AC, which had no significant effect. Regarding the effect of factors and their interactions on the specific energy consumption rate, the same table shows that there is a highly significant effect of all factors and their interactions except for the number of hammers A which did not have a significant effect on the specific energy consumption rate. This may be due to the slight difference between the number of 10 and 8 hammers relative to the energy supplied to the machine to move the hammers, in addition to the fact that the hammers are small in size. Also, the triple interaction ABC did not have a significant effect on the specific energy consumption rate.

Table 2 ANOVA table of productivity mill(pc), geometric diameter (GDW) and specific energy consumption(Spec)

Source of	d.f.	F pr.		
		PC	GDW	Spec
variation	1			
A	2	<.001*	<.001*	0.096 NS
B	2	<.001*	<.001*	<.001*
C	2	0.549 NS	<.001*	<.001*
A.B	2	<.001*	<.001*	<.001*
A.C	4	0.503 NS	0.999 NS	<.001*
B.C	4	0.415 NS	<.001*	<.001*
A.B.C	36	0.560 NS	<.001*	0.148 NS
Residual	53			

* There is a difference below the significance level of less than 0.01 ;
NS. There is no difference below a significance level of less than 0.01.
A , Number of hammer ; B, Sieve hole diameter ;C, Clearance;
AB, AC ,BC, ABC Overlap between the factors.

1-Machine productivity: The shaded data in Table 3 are the results of the interaction effect between the number of hammers and the diameter of the screen opening on the machine productivity trait, while the data on the right of the table for the reader represent the results of the main effect of the number of hammers on productivity, and the data on the left of the table from the bottom represent the results of the main effect of the screen opening on productivity.

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1-1 The effect of the number of hammers on productivity: The data in Table 3 shows that the number of hammers (10 hammers) is superior to the number of hammers (8 hammers) in machine productivity, as they recorded 0.25 and 0.24 tons per hour-1. This occurs due to the increase in the number of blows on the grains in the crushing chamber. Previous studies have shown such a result, including the study by Khudher *et al.*, (2021).

1-2 The effect of the sieve opening on productivity: The results of 0.19, 0.22 and 0.32 respectively are for the opening diameter of 2.5 mm, 4 mm and 8 mm, showing that there is a direct positive relationship for the effect of the sieve opening on productivity, where the larger the opening diameter, the higher the mill productivity. This result is expected and has been proven before for a number of studies (Carla, 1962) and (Mahmoud K. *et al*., (2006) and (Abas, 2013) ; (Drocas *et al*., 2014) and (Dabbour *et al*., 2015).

1-3 Effect of interaction between sieve opening and number of hammers: The shaded data in Table 3 illustrates the effect of interaction AB where number of hammers A (10 and 8) and sieve opening B (2.5, 4, 8 mm) on productivity trait, as there are significant differences according to LSD test between the means (less than 0.05). The results prove the strong effect of sieve opening as an independent factor compared to the effect of number of hammers as an independent factor in crusher productivity trait, as when the two factors A and B interacted together, the interaction of sieve opening diameter 8 mm with both levels of number of hammers 10 and 8 recorded the highest value compared to the interaction of sieve opening 4 mm and then 2.5 mm with number of hammers 10 and 8, where it recorded 0.32 tons.h-1 compared to 0.22 and 0.20 tons.h^{-1}.

2- Specific Energy Consumption Rate: Specific energy consumption rate represents the energy consumption per unit weight of the final product during the crushing time. It is a more accurate measure of energy costs and efficiency in machine operation, as it relates to the amount of output per unit time.

Table 3 Effect of Number of hammer , Sieve hole diameter and Overlap Between them on the productivity of the hammer mill.

B / A	2.5 mm	4 mm	8 mm	Average productivity affected by the number of hammers
10	0.20	0.22	0.32	0.25[a]
8	0.18	0.22	0.32	0.24[b]
Average productivity affected by sieve opening	0.19[c]	0.22[b]	0.32[a]	A , Number of hammer ; B, Sieve hole diameter; AB Overlap between hole and number of hammers. l.s.d. , A =0.003 ; B= 0.004 ; AB= 0.006

2-1 Effect of sieve aperture and clearance on specific energy consumption rate: From Table 5 (part 1-1), an inverse relationship is evident between the specific energy consumption rate and the sieve aperture. As the sieve aperture increases, the specific energy consumption rate decreases. The 2.5 mm, 4 mm, and 8 mm apertures recorded rates ranging from 3.9 to 6.6 to 3.9 kWh/ton, respectively. This is due to the ease of passage of the ground particles through the sieve with the large aperture and the reduction of grinding time. As for the results related to the effect of clearance (Table 5-part 1-2), the 2.5 mm clearance recorded the highest specific energy consumption rate of 6.41 kWh/ton, followed by the 7.5 mm clearance which recorded the lowest rate of 6.01 kWh/ton. That is, the direction of the relationship between clearance and specific energy consumption rate is inverse.

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2-2 Effect of the binary interaction between the number of hammers and the screen opening on the specific energy consumption rate: Table 5-part 2-1 shows the effect of the binary interaction AB on the specific energy consumption rate. There were significant differences between all averages of these interactions, as the highest value of the specific energy consumption rate was at interaction A2B1, reaching 8.43 kWh/ton, compared to the lowest value at interaction A2B3, reaching 3.77 kWh/ton. That is, the highest, lowest, and average values of the specific energy consumption rate were obtained when the number of hammers (8) was interacted with the screen openings from smallest to largest. The explanation for this result is due to the greater effect of the screen opening compared to the number of hammers when they are interacted.

2-3 Effect of the combination of hammer number and clearance on the specific energy consumption rate: The highest energy consumption rate was achieved at combination A2C1, reaching 6.46 kWh/ton, while the lowest specific energy consumption rate was achieved at A2C3, reaching 5.9 kWh/ton (Table 5, Part 2-2). This result can also be explained by the greater effect of the screen opening compared to the hammer clearance when they overlap.

2-4 The effect of the two-way interaction between the sieve opening and clearance on the specific energy consumption rate: The B1C1 interaction (Table 5, Part 2-3) recorded the highest value of 8.21 kWh/ton, while the B3C3 treatment recorded the lowest value, at 3.9 kWh/ton. This result demonstrates the combined effect of directing the inverse relationship, whereby the larger the sieve opening and clearance, the lower the energy consumption rate.

Table 5 Effect of The impact of independent factors (Clearance and Sieve hole diameter) and their interactions on Specific energy consumption (kw.h/ton)

Part 1-1				Part 1-2			
B	B1	B2	B3	C	C1	C2	C3
	8.226a	6.623b	3.906c		6.411a	6.317b	6.027c
LSD_B	0.0840			LSD_C	0.0840		
Part 2-1				part 2-2			
AB	B1	B2	B3	AC	C1	C2	C3
A1 A 2	8.013b 8.438a	6.796c 6.451d	4.032e 3.779f	A1 A2	6.167c 6.467a	6.560a 6.261b	6.114d 5.940e
LSD_{AB}	0.1188			LSD_{AC}	0.1188		
Part 2-3							
BC	C1	C2	C3				
B1 B2 B3	8.218a 6.947c 3.785	8.363a 6.883d 3.985f	8.095b 6.040e 3.947f				
LSD_{BC}	0.1455						

B, Sieve hole diameter B1=2.5mm , B2=4mm and B3=8mm ;C, Clearance C1=2.5mm , C2=5mm and C3=7.5mm ; A, Number of hammer A1=10 and A2=8 and LSD (<0.05)

3- Mean Geometric Diameter

Effect of the number of hammers on the mean geometric diameter: The results of Table 4, Part 1-1, show that the number of hammers, with 10 hammers, outperformed the number of hammers with 8 in terms of grinding capacity, recording 997.5 µm compared to 1023.3 microns, respectively. The difference exceeded the LSD value of 5.71. This is due to the increased number of hammer strikes on the grains.

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3-1 **Effect of sieve opening on the average geometric diameter**: Table (4, Part 1-2) shows that with increasing the sieve opening, the grinding efficiency decreases as the product coarseness increases (increase in the average geometric diameter), i.e. there is a direct relationship between the sieve opening diameter and the average geometric diameter, as the GDW increased from 676.0 µm to 932.0 to 1423.2 µm for the 2.5 mm, 4 mm and 8 mm openings, respectively. This occurs as a result of reducing the time the particles remain inside the grinding chamber, as the larger opening allows the particles to descend when they are broken to the extent that the sieve opening with the new dimensions allows the particle to pass through. This result is consistent with the results of (Reece et al., 1986), (Mahmoud K. *et al*., 2006), (Mohammed M., 2012), (Abbas B., 2012), and (Abbas B., 2013).

3-2 Effect of clearance on geometric mean diameter: Table (4 (PART 1-3) shows a direct relationship between clearance and geometric mean diameter, where the average diameter increases from 979.1 to 1002.1 to 1050.0 µm with increasing clearance from 2.5 to 5 to 7.5 mm. In other words, the roughness of the product increases with increasing clearance. This may occur due to the decrease in particle density and proximity to each other, thus reducing the possibility of being struck by hammers. This result is consistent with the findings of (Mahmoud K. *et al*., 2006) and the researcher (El Shal *el at*, 2010) who recommended using a larger clearance to obtain a greater percentage of coarse grinding.

3-3 Effect of interaction between number of hammers and sieve aperture on geometric mean diameter: Part 2 of Table 4 illustrates the effect of bilateral interactions on geometric mean diameter. Part 2-1 Table 4 illustrates the effect of AB, where treatment A1B3 (10 hammers with 8 mm aperture) significantly outperformed the other treatments, while treatment A1B1 (10 hammers with 2.5 mm aperture) recorded the lowest average particle diameter after grinding. The interpretation of this result is that the interaction of sieve aperture with the number of hammers was able to direct the results towards an increase with increasing aperture, but the number of hammers during its interaction with the aperture did not show a clear trend, as the number of hammers increases with the increase in sieve aperture diameter, and its role in fineness decreases.

3-4 The Effect of Overlap between Clearance and Screen Aperture on the Geometric Average Diameter: Part 2-2 This section demonstrates that treatment B3C3 recorded the highest value for the geometric average diameter, reaching 1455.4, compared to the other treatments that achieved better grinding efficiency. Treatment A1B1 achieved the lowest grinding degree, recording an average geometric diameter of 650 µm. This result is achieved due to the clear and intrinsic effect of both factors: increasing the screen aperture and clearance increases the product roughness.

3-5 Effect of triple interaction of number of hammers, clearance, and sieve opening on geometric mean diameter: From Part 3 in Table 4, it is clear that there are significant differences between all averages as they are not similar to each other. The result is logical as treatment A2B3C3 achieved the highest geometric mean diameter of 1444.7 µm as roughness increases with increasing sieve opening, clearance, and decreasing number of hammers. While treatment A1B1C1 achieved the lowest geometric mean diameter of 620 µm.

Table 4 Effect of The impact of independent factors (Number of hammer, Clearance and Sieve hole diameter) and their interactions on Average geometric diameter(µm).

PART 1-1		
A	A1	A 2
	997.5b	**1023.**3a
LSD	5.71	

PART 1-2			
B	B1	B2	B3
	676.0c	932.0b	**1423.**2a
LSD	7.00		

PART 1-3			
C	C1	C2	C3
	979.1c	1002.1b	**1050.**0a
LSD	7.00		

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PART 2-1			
AB	B1	B2	B3
A1	**658.7f**	901.5d	**1432.**3a
A2	693.2e	962.5c	1414.1b
LSD	9.89		

PART 2-2			
BC	C1	C2	C3
B1	**650.**6h	671.6g	705.7f
B2	874.6e	932.5d	988.9c
B3	1412.0b	1402.3b	**1455.4a**
LSD	12.12		

PART 3				
ABC	B	C		
		C1	C2	C3
A1	B1	**626.**0	661.9	688.2
	B2	828.1	919.5	956.8
	B3	1444.3	1386.7	1466.1
A2	B1	675.2	681.2	723.2
	B2	921.1	945.6	1020.9
	B3	1379.7	1418.0	**1444.**7a
LSD	17.14			

A, Number of hammer A1=10 and A2=8 ; B, Sieve hole diameter B1=2.5 mm , B2=4 mm and B3= 8mm ;C, Clearance C1=2.5 mm , C2=5 mm and C3=7.5 mm ; LSD (<0.05).

3-6 Particle size distribution classification: Based on the results of the triple interference ABC, the particle size distribution was classified into fine, medium and coarse according to the ranges specified in the working methods section, namely (600 to 900 microns), (over 900 to 1300 microns) and (over 1300 microns) respectively. From Table 5, Part 3, the values of coefficients A1B1C1, A1B1C2, A1B1C3, A1B2C1, A2B1C1, A2B1C2 and A2B1C3 fall within the fine grinding degree of 600 to 900 µm, i.e. the sieve opening of 2.5 mm when overlapping with all clearance levels and hammer number levels falls within the fine range and within the limits of the specifications mentioned for the crusher and yellow corn in this research. Coefficients A1B2C2, A1B2C3, A2B2C1, A2B2C2, A2B2C3 fall within the medium grinding degree from <900 to 1300 µm. Coefficients A1B3C1, A1B3C2, A1B3C3, A2B3C1, A2B3C2, A2B3C3 fall within the coarse grinding degree <1300 µm, meaning that an 8 mm screen opening, when overlapping with any of the hammer number levels and clearance levels, achieves a coarse grinding degree.

Importance Analysis: Looking at Table 6, which presents the results of the importance ranking of the factors affecting the three studied attributes, it is clear that the importance ranking from least to most important starts with the number of hammers with an importance rate of 4.3%, followed by clearance with 7.3%, and finally the most important factor, which is the sieve opening with 100%. These results were extracted as part of building a neural network using SPSS, which illustrates the impact of the factors in the proposed network model for predicting performance indicators based on the inputs represented by the three factors. These results represent a summary of what the study results showed in Tables 3, 4, and 5.

Table 6 Independent Variable Importance

Variables	Importance	Normalized Importance
Hammer number	.038	4.3%
Clearance	.066	7.3%
Sieve opening	.896	100.0%

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IV. CONCLUSIONS

- The main factors (screen opening, number of hammers, and clearance) and the interaction between the screen opening and the number of hammers affect machine productivity.

- The main factors and their interactions, except for the AC interference, affect the geometric mean diameter.

- The screen opening and clearance affect the specific energy consumption rate, while the number of hammers and triple overlap have no effect.

- The most important factor is the screen opening, followed by clearance, and then the number of arms, within the limits of the experimental parameters and other machine specifications. We recommend changing the screen opening only to obtain fine, medium, and coarse grinding, as the number of hammers and clearance, along with their triple overlap with the screen opening, are insignificant. A combination of 2.5 mm screen opening can be used with any of the A and B factors for fine grinding, and 8 mm screen opening can be used with any of the two factors for coarse grinding.

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