

Wear of disc mill hammer in wet grinding processes on groundnut cake for fish feed production

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Abstract

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There is need to determine the wear rates of disc mill hammer used for grinding groundnut cake, a major plant protein in fish feed. This surface wear damage characterised by scoring, cutting, deep grooving and gouging on a metal surface leads to high costs of production. The hammer wear rate was carried out using disc mill for different combinations of processing conditions: disc speed of 2,175, 3,900 and 4,350 rpm; screen size of 1.0, 2.0 and 3.0 mm; moisture contents of 12, 14 and 16% w.b. at 300 operating hours. Response Surface Method was used to optimize the operating variables. The wear rate was found to increase as the moisture content of the groundnut cake decreased. Quadratic models developed for the four responses (tip length loss, width loss, thickness loss and absolute mass) studied indicated the optimum conditions at disc speed 3,262.50 rpm, screen size 2.0 mm and moisture content 14% w.b. The study established that experimental data and model predictions agreed well.

Keywords: plant protein; processing conditions; metal surface; optimize; responses

A conventional disc mill is a device consisting of a rotating disc with fixed hammers, which reduce grains or similarly hard objects to a predetermined size through a perforated screen (Science-Technology Dictionary 2003). Disc mills are widely used in the agricultural, wood, mining and chemical industries. Conventional disc mills that are extensively employed in the processing of solid materials and grains suffer from a number of weaknesses that greatly hamper their productivity, efficiency and effectiveness. (EBUNILO et al. 2010)

Wear due to highly hard materials have surface damage characterized by scoring, cutting, deep grooving and gouging on a metal surface (FERGUSON et al. 1998). Wear of hammer leads to frequent work stoppages for replacement and contributes to high costs of labour, downtime and parts. In Aus-

tralia, Canada, and South Africa, wear of agricultural tools is estimated to be several million dollars annually (YU, BROLE 1990). According to WILLIAMS (1997), replacement costs of worn parts by farmers have led to the abandonment of the technology. The defects and shortcoming of used disc mills may suggest that most operators in Nigeria are running their business at marginal profit levels.

Generally, abrasive wear of processing machine tools is influenced by several factors. These include chemical composition of the steel and its heat treatment, operational factors and characteristics of the tools, physical conditions of the material, and machine design parameters (ZYGMENT 1998). Investigating of wear of agricultural machine parts designed for work in agro-processing line is performed either under laboratory conditions or dur-

ing field tests. Most often, laboratory tests are carried out in order to determine relative resistance against abrasive wear.

According to FERGUSON et al. (1998), no relationship was found between wear resistance of steel and its conventional mechanical properties. Although a linear relationship was found between the hardness of steel and its wear resistance, this can be used only for pure metals or alloys of identical microstructure. Agro-processing equipment imported or developed locally is not subjected to any organized testing prior to their commercial production. Moreover, most of this equipment is not suitable for the local conditions, farmers thus experience frequent equipment breakdown and malfunction and increased production costs (ODUNTAN et al. 2014). Fish feed processing technology is gaining popularity among resource-poor farmers in Nigeria. This resulted in increasing numbers of farmers adopting the technology thus contributing to fish production. Field observation shows that the average size of ingredients milled by Nigeria fish farmers' ranges from 3.0 to 60 mm, with milling often carried out at lower moisture content. These differences lead to high wear rates of disc mill hammers and time-consuming changeovers, reducing the productivity of fish feed manufacturers.

Most research studies to determine wear and durability of farm implements have focused on tractor-drawn implements, mainly in the developed countries. Few studies have been reported on the wear of agro-processing machines. The wear of parts consists in change of their thickness, whereas the wear of cutting parts is more severe in general, and includes not only change of thickness but also of length and width. Therefore, there is the need to determine the wear rates of commercial disc mill hammer used for grinding groundnut cake (GNC), a major plant protein ingredient used for fish feed production in Nigeria. This is due to the differences in moisture content of GNC leading to quick wearing of the disc mill hammer. The objective of this study is therefore to determine wear and durability of disc mill hammer use in grinding GNC at different moisture contents

for fish feed production in order to increase the productivity of fish feed producer.

MATERIAL AND METHODS

Material. Groundnut cake (GNC) of Chad variety was supplied from Kano, Nigeria. The moisture content was determined using standard methods. The hammers used for the test were commercial hammer with dimension 100 mm thick and 250 mm wide (Fig. 1). This size and type of hammer was G65 grade which is the grade currently chosen for hammer in Nigeria (Table 1). The hammers were conventionally quenched and tempered.

Grinding machines. The disc mill (Fexod IF 1004; Fexod Fedek Venture, Ibadan, Nigeria) used for testing (Fig. 2). The machine features a direct drive, flexible coupling which greatly improves torque transmission from the motor to the shaft. Rotor bearings are mounted outside the grinder housing, eliminating damage and deterioration

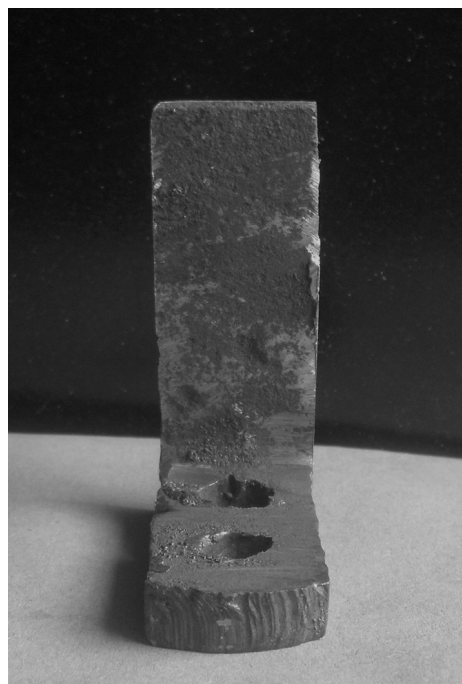


Fig. 1. Hammer (250 mm wide) in new condition

Table 1. Chemical composition and hardness of the steel (hammer)

Steel grade	Chemical composition (%)					Brinell hardness (HBW)
	C	Mn	Si	S	P	
G65	6.0–7.0	9.0–12.0	1.7–3.7	0.4	0.4	2,800

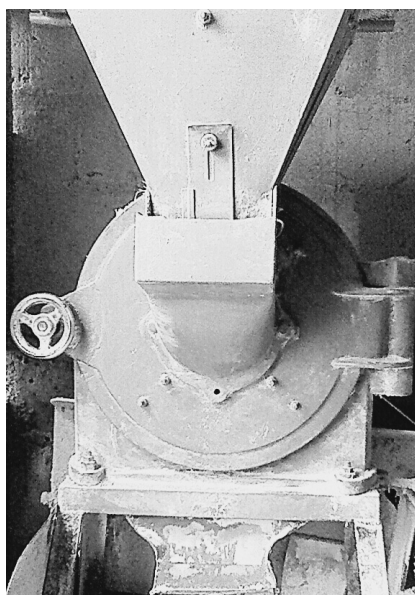


Fig. 2. FEXOD 1004 disc mill used for testing

from exposure to the harsh environment inside the grinder during operation. Five hammers were fixed to the disc plate and feature a 15 hp motor; and with step pulley to vary the rotating speed and in addition, with removable ring screen.

Grinding techniques. *Wet grinding.* The moisture content of the groundnut cake at the time of the experiment was determined using the oven method (ASABE Standard S269.4:2003 on cubes, pellets and crumbles-definitions and methods for determining density, durability, and moisture content). The mixture was conditioned by adding water to the sample to raise the moisture from the initial value to the required level of 12, 14 and 16% w.b. for 10 min in a batch mixer (Fexod AS 170; Fexod Fed-ek Venture, Ibadan, Nigeria). The amount of water that was added was determined by the formula:

$$MC_{db} = (MC_{wb} / (100 - MC_{wb})) \quad (\%) \quad (1)$$

$$M_w = (MC_{db} \times m_d) / 100 \quad (2)$$

where:

MC_{db} – moisture content (dry basis) (%)

MC_{wb} – moisture content (wet basis) (%)

m_d – mass of dry matter (kg)

m_w – mass of water to be added (kg)

Then, the wet samples were ground using the Fexod IF 1004 disc mill. The hammer wear rate was carried out using disc mill for different combinations of processing conditions: disc rotating speed of 2,175, 3,900 and 4,350 rpm; screen size of 1.0,

2.0 and 3.0 mm; moisture contents of 12, 14 and 16% w.b. at 300 operating hours for each treatment after which the hammers were washed, weighed and measured.

Measurements. The mass loss from the hammer throughout each test was recorded at the end of each stage, as were the changes in the hammer dimensions illustrated in Fig. 3. The dimensions measured were the tip length loss, width loss, thickness length loss and the absolute mass. The testing was continued until the hammers were recorded for all treatment.

Experimental design and data analysis. The Design Expert Software (version 7.0) was used for the statistical design of experiments and data analysis. In this study, the response surface methodology (RSM) was applied to optimise the three most important operating variables: disc speed, screen size and moisture content. Experiments were initiated as a preliminary study for determining a narrower range of disc speed, screen size and moisture content to design the experimental runs. Accordingly, disc speeds from 1,450 rpm were tried and the increments continued until appreciable speeds were observed in the process responses (tip length loss, width loss, thickness loss and absolute mass). Likewise, a screen size range of 0.5–6 mm was examined to search for a narrower and more effective range. Also for the moisture content, a range of 12–16% was examined. As a result the study ranges were chosen as disc speed 2,175–4,350 rpm, screen size 1–3 mm and moisture content 12–16 %. Table 2 shows the responses of surface design type IV – optimal point exchange in the form of a 27 full factorial design with quadratic model experimental trials (run No. – 20) and obtained experimental results at each assay. In this table the levels of independent variables are presented in terms of the original unit of measurement. Experimental results are shown as loss of the hammer in terms of length of tip, width, thickness and absolute mass.

In order to obtain the optimum wear operation conditions, the dependent parameters were analysed as responses. Significant model terms are de-

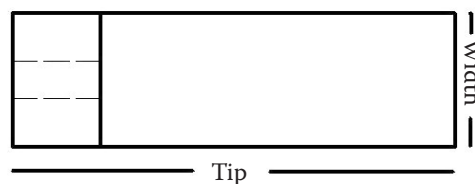


Fig. 3. Dimensions measured description on the hammer

Table 2. Experimental designs used in RSM studies by using three independent variables with six centre points showing observed values of disc hammer wear

Run No.	Factors			Responses			
	disc speed (rpm)	screen size (mm)	moisture content (%)	tip length loss (mm)	width loss (mm)	thickness loss (mm)	absolute mass (g)
1	2,175	2	16	17.0	8.6	4.6	68.0
2	3,900	3	16	9.6	7.2	4.2	62.2
3	2,175	2	14	19.0	8.0	4.7	70.1
4	2,175	3	14	16.8	8.5	4.9	72.0
5	3,900	1	14	21.5	8.1	4.9	75.8
6	3,900	2	14	18.7	8.4	4.5	66.4
7	2,175	3	12	18.0	9.3	4.6	70.0
8	3,900	3	16	9.6	7.2	4.2	62.2
9	2,175	1	12	26.5	9.1	5.4	70.4
10	4,350	3	14	7.2	4.3	3.4	55.0
11	4,350	1	12	17.0	8.1	4.1	74.6
12	3,900	1	16	20.0	8.0	4.6	72.5
13	4,350	2	16	8.5	6.5	4.1	65.0
14	2,175	2	12	21.6	9.2	4.6	70.1
15	3,900	2	14	18.7	8.4	4.5	66.4
16	4,350	2	16	8.5	6.5	4.1	65.0
17	3,900	2	12	21.4	9.4	4	68.2
18	2,175	1	16	22.9	9.7	4.4	80.4
19	3,900	2	12	21.4	9.4	4	68.2
20	3,900	2	14	18.7	8.4	4.5	66.4

RSM – Respond Surface Method

sired to obtain a good fit in a particular model. The RSM studies shown in Table 2 allowed the development of mathematical equations where predicted results (Y) were assessed as a function of disc speed (A), screen size (B) and moisture content (C) and calculated as the sum of a constant, three first-order effects (terms in A , B and C), three interaction effects (AB , BC and AC) and three second-order effects (A^2 , B^2 and C^2). The results obtained were then analysed by analysis of variance (ANOVA) to assess the “goodness of fit”. Equations from the first ANOVA analysis were modified by eliminating the terms found statistically insignificant. ANOVA was used for graphical analyses of the data to obtain the interaction between the process variables and responses. The quality of the fit polynomial model was expressed by the coefficient of determination R^2 , and its statistical significance was checked by

the Fisher’s F -test in the same programme. Model terms were evaluated by the P -value (probability) with 95% confidence level. Three-dimensional plots and their respective contour plots were obtained for the wear based on effects of the three factors.

RESULTS AND DISCUSSION

Dimension and mass losses

The dimensional losses and absolute mass of the disc hammer were worn under different conditions. This represents the wear throughout the life of the hammer as shown in Fig 4. Under these conditions, the hammers were observed to wear from the bottom up to the tip on the right side due to rotation of the disc mill at clockwise direction causing rapid

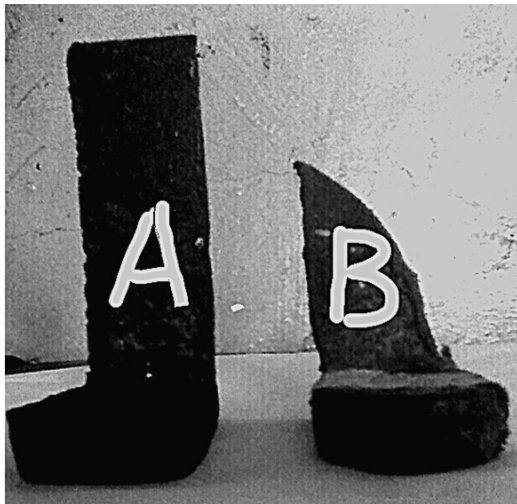


Fig. 4. Hammer (A) in new condition and (B) in worn condition after hours of operation with wet grinding groundnut cake

loss of material and hence, the observed shape. The subsequent reduction in wear rate was complemented by an increase in the rate of dimensional loss of both edge length and width in the later stages of life. It was observed that approximately half of the total loss of tip and width length occurred in the second third of the total hours of operation.

Relationship between the variables

Table 3 illustrates the reduced quadratic models in terms of coded factors and also shows other statistical parameters. Data given in this table demonstrates that all the models were significant at the 5% confidence level since P values were less than 0.05.

The lack of fit (LOF) F -test describes the variation of the data around the fitted model. If the model does not fit the data well, this will be significant.

The large P values for lack of fit (PLOF) (> 0.05) presented in Table 3 show that the F -statistics was insignificant, implying a significant model correlation between the variables and process responses. The R^2 coefficient gives the proportion of the total variation in the response predicted by the model, indicating the ratio of sum of squares due to regression (SSR) to total sum of squares (SST). A high R^2 value, close to 1, is desirable and a reasonable agreement with adjusted R^2 is necessary (NORDIN et al. 2004). A high R^2 coefficient ensures a satisfactory adjustment of the quadratic model to the experimental data. Adequate precision (AP) compares the range of the predicted values at the design points to the average prediction error. Ratios greater than 4 indicate adequate model discrimination (BEG et al. 2003; MASON et al. 2003). Diagnostic plots such as the predicted versus actual values help us judge the model satisfactoriness. The predicted versus actual values plots of parameters wear are presented in Fig. 5. The plots indicate an adequate agreement between real data and those obtained from the models. Besides, AP values higher than four (Table 3) for all the responses confirm that all predicted models can be used to navigate the experimental design. The coefficient of variance (CV) as the ratio of the standard error of estimate to the mean value of the observed response defines the reproducibility of the model. A model can be normally considered reproducible if its CV is not greater than 10% (BEG et al. 2003). According to Table 3, all models fall within the range of reproducibility.

Process analysis

The 3D response surface plots were used to understand the interaction effects of medium com-

Table 3. ANOVA results for response parameters

Response	Final equation in terms of coded factor	P	PLOF	R^2	Adj. R^2	AP	S.D	CV	PRESS
Tip length	$y = 23.54 - 4.25A - 4.25B - 2.81C - 0.95BC - 7.66A^2$	< 0.0001	6.83	0.9890	0.9790	32.134	0.80	4.66	42.12
Width loss	$y = 9.53 - 1.20A - 0.43B - 0.41C - 2.20A^2 + 0.81C^2$	< 0.0001	2.84	0.9098	0.8286	12.006	0.53	6.57	30.77
Thickness loss	$y = 4.88 - 0.48A - 0.32B - 0.2AB + 0.25AC + 0.23BC - 0.46A^2 - 0.23C^2$	< 0.0001	0.19	0.9443	0.8943	18.078	0.14	3.14	1.47
Absolute mass	$y = 68.92 - 2.92A - 4.83B - 3.13AB$	0.0002	91.27	0.2601	0.7664	11.206	2.65	3.87	422.53

P – observed significance levels; PLOF – P values for lack of fit; R^2 – squared multiple correlation coefficient; Adj. R^2 – adjusted squared multiple correlation coefficient; AP – adequate precision, S.D. – standard deviation; CV – coefficient of variance; PRESS – prediction error sum of squares

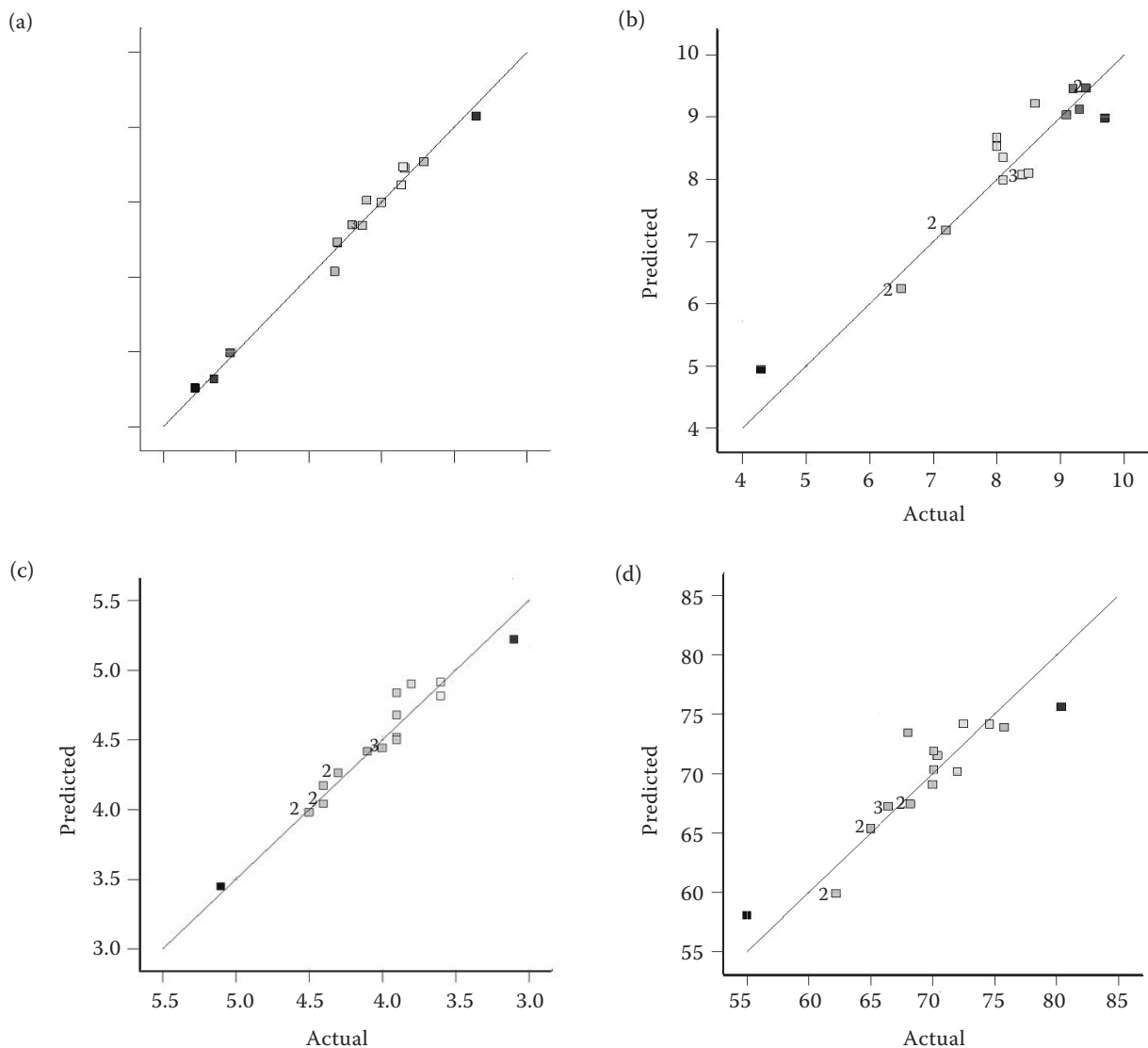


Fig. 5. Design-expert plot: predicted vs. actual value (a) for tip length loss, (b) width loss, (c) thickness loss and (d) absolute mass

ponents and optimum wear of each component required for max. disc wear. Response surface curves for variation in tip length loss, width loss, thickness loss and absolute mass were constructed, and are depicted in Fig. 6. In each set, two variables varied within their experimental range, while the other variables remained constant.

Fig. 6a depicts the tip length loss with respect to screen sizes versus disc speed. From the interaction response of screen sizes with die speed, tip length loss increased with decreasing screen sizes and die speed up to 1.0 mm and 4,350 rpm, respectively. However, the response curve did not show curvature, rather it was flattened. This suggested a demand for higher value of speed. Fig. 6b

represents the interaction effect of screen size and disc speed on width loss of disc hammers. With a decrease in (1.0–3.0 mm) and disc speed (2,175–4,350 rpm), the width loss increased. Thereafter, an increase in screen size up to 3 mm resulted in decreased width loss. Fig. 6c reveals that max. thickness length loss of 5 mm was produced at screen size (2 mm) and slightly lower speed (3,262.50 rpm) in the design range. This accorded a run number of 20, which is considered as the optimal condition of test variables. Fig. 6d represents the interaction effect of screen size and disc speed on absolute mass of disc hammers. Absolute mass decreases with an increase in screen size and disc speed.

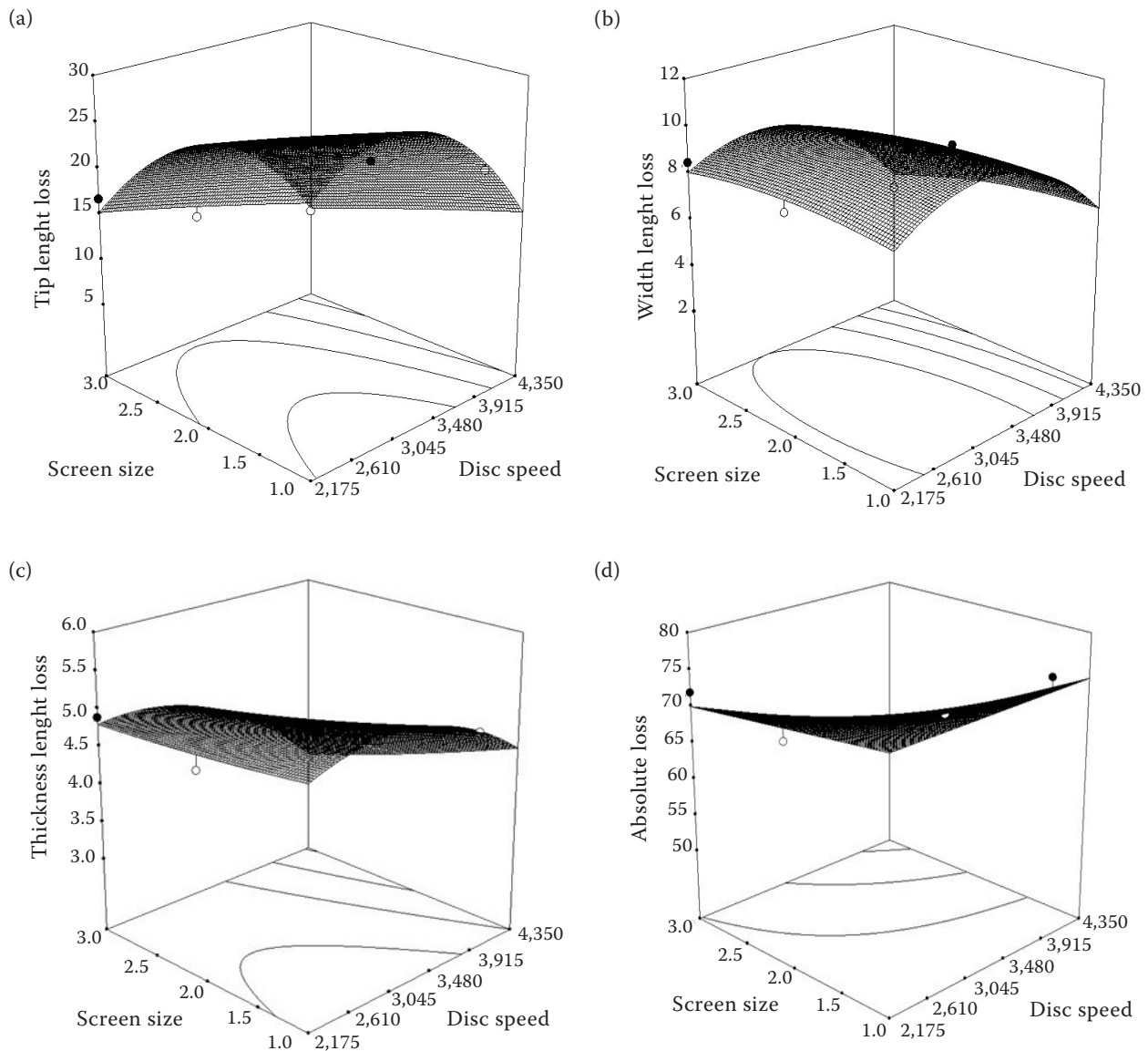


Fig. 6. Design-expert plot: response surface for (a) tip length loss, (b) width loss, (c) thickness loss and (d) absolute mass

In general, the plots are approximately flat in shape. Response surface plots in Fig. 6 indicate low rate of tip wear with an increase in screen size and disc speed, this is similar to all other responses. The optimum points of wear were observed to be at about screen size 2.0 mm and disc speed 3,262.50 rpm and moisture content 14%. At optimum conditions, 25 mm, 9 mm, 5 mm and 70 g of tip length loss, width l loss, thickness loss and absolute mass were achieved, respectively.

The rates of hammer wear are found to reduce when moving away from these optimum points, meaning that either increase or decrease in any of the tested variables results in a decline of the re-

sponses. Furthermore, the hammer worn in lower moisture content conditions wore from the tip to bottom on the right side only and high reduction in width was measured. The hammer worn in higher moisture content conditions, however, were observed to wear from the tip to bottom on the right side and surface, causing less reduction in width. FOLEY et al. (1988) reported similar results but YU and Bhole (1990) showed contrasting results of an increase in wear rate with an increase in water content. In effect, both results are correct. The tests carried out by FERGUSON et al. (1998) showed that the effect of water content on the wear rate of tools is dependent on material the tools operated on.

CONCLUSION

The wear rates of commercial disc mill hammer on groundnut cake at different moisture contents were studied, using disc mill for different combinations of processing conditions. The following conclusions may be drawn:

- The results from the quadratic equations showed no significant difference in the moisture content on wear of the thickness length loss and absolute mass but for disc speed and die size wherein the difference was significant ($P < 0.05$).
- The optimum conditions at which the hammer operated were 25 mm, 9 mm, 5 mm and 70 g of tip length loss, width loss, thickness loss and absolute mass respectively.
- The optimum conditions obtained for the disc mill were observed to be at screen size 2.0 mm, 14% moisture content and disc speed 3,262.50 rpm.

Therefore, this study reveals that the rates of hammer wear are found to reduce when moving away from these optimum points, meaning that either increase or decrease in any of the tested variables results in decline of the responses.

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