Optimization of Commination Process Parameters in Particulate Fiber Development

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Abstract- The study is based on optimization of comminution process parameters in particulate fiber development. The influence of comminution process parameters were considered in determining optimum performance of an improved hammer mill. The comminution process control parameters ranged from speed (1450-2000 rpm), hammer weight (40-70g), fiber input (250-363g) and operating time (5-25min). The experiment was conducted following 29 run for different fiber milling conditions. The optimum conditions for the process were predicted using central composite design (CCD) of quadratic regression models. Analysis of variance (ANOVA) confirmed the adequacy of the developed model considering significant terms in order to predict the machine efficiency and throughput. The set of conditions that simultaneously optimized both grinding efficiency and throughput value comprises 1946 rpm of speed, 66g of hammer weight, 351g fiber input and 23min of operating time.

Indexed Terms: Optimization; Comminution Process; Particulate Fiber; Solidworks

I. INTRODUCTION

Comminution is the technical term for the process of reducing a material to very small particles. Mechanical comminution of plant fiber offers promise as a method of manufacture of nano particles enabling a high proportion of this waste to be efficiently utilized in composite development. Different kinds of natural fibres such as hemp, jute, flax, kenaf and coconut have been used as reinforcement for polymers matrices (Sumaila et al., 2013), studies has shown that these applications are in consideration of their low cost, availability, renewability, biodegradability, low densities which makes them attractive for the automotive and packaging industries (Ihueze et al., 2017; Sumaila et al., 2013). Okafor, Ihueze and Nwigbo (2013) indicate that fibre aspect ratio, volume fraction and fibre orientation are significant factors in optimization of strengths response of plantain fibres reinforced polyester matrix composites. The use of natural fibers therefore reduces weight by 10% and lowers the energy needed for production by 80%, while the cost of the component is 5% lower than the comparable fiber glass-reinforced component (Sakthivei & Ramesh, 2013).

Banana and coir fibres at present are a waste product of banana coconut cultivation respectively. The particulate fiber may be compounded into thermoplastics through injection molding process (Ihueze, Oluleye, Okafor, Obele, Abdulrahman, Obuka and Ajemba, 2017). Well treated fibers are compatible with thermoplastic materials (Owens Corning Composites Materials, 2011). Milled Fibers are also compatible with most asphalt, putties, patching cements and other coatings. Communition of natural fibres entails size reduction to accomplish their operation and hammer mills are typical size reduction machines applicable.

Nwakaire, Ugwuishiwu & Ohagwu (2011) designed and analyzed maize thresher for rural dwellers, their results respectively showed human mechanical efficiency, through-put capacity and grain handing capacity of 45%, 26.67kg/hr and 21.1kg/hr at a biomaterial test weight of 20kg at a shelling time 45 minutes. Jibrin, Amonye, Akonyi & Oyeleran, (2013) developed a crop residue crushing machine. Ebunilo, Obanor & Ariavie (2010) conducted a preliminary testing of a hammer mill with end-suction lift capability and obtained efficiency of a conventional hammer mill. Okasha (2016) modified a local thresher machine to suit chopping and grinding different crop residual, this machine was evaluated in terms of production capacity and operating efficiency rotation of the machine on the three operating speeds (1200 - 1600 – 2000 rpm), they reported maximum machine production for corn stalk as 0.72 ton/h at 2000 rpm cutting drum speed at 8% moisture content.

Examination of the various design and developments in particle size reduction is extremely convoluted in light of the fact that machine efficiency and throughputs are influenced by many factors including speed, hammer weight, fiber input, operating time and moisture content (Sakthivei & Ramesh, 2013). Various studies have been carried out using different comminution technology for corn and cassava (Nwaigwe, Nzediegwu & Ugwuoke, 2012; Liberty, Ademola, Abubakar, Olaoye, Abaje, Olasehinde, & Halidu, 2015), maize and millet (Nwadinobi, 2017; Kawuyo, Lawal, Abdulkadir & Dauda, 2017), palm kernel shells (Yahaya, Apeh and Achema, 2017). Polymer matrix reinforcement materials often occur in sizes that are too large to be used and therefore, they have to be reduced in size. Okorafor, Umeasiegbu, Nwosu, Akpojaro, Nwuzor and Okechukwu (2017) made significant efforts in design of particulate fiber mill but failed to optimize various parameters that contribute to the characteristics of the particles. There is need to optimize the grinding control factors for an enhanced natural fiber processing. With most designs of comminuting devices, the level of forces generated can be raised by increasing the speed of load application to the particles of the material being comminuted, but the design and operating characteristics of each device impose certain restrictions on the rate of motion of its working parts and hence on the level of disintegrating forces.

II. METHODOLOGY

The characteristics and structure of the machine parts as follows in Fig. 1, the selection of materials and methods of construction are based on the preliminary investigation, design and the drawing of the machine components.

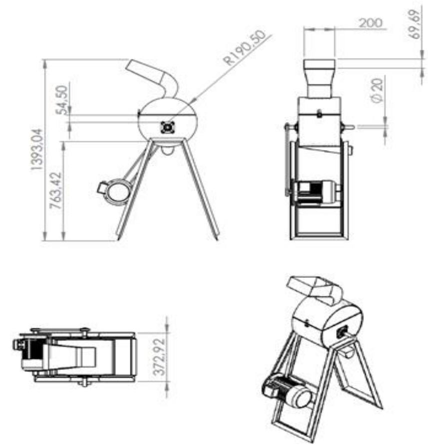


Figure 1: Orthographic Projection of the comminution equipment

A. Design of machine components

The Hammers: The centrifugal force of the hammers, F_h was determined according to Ebunilo, Obanor, & Ariavie, (2014) as

$$F_h = n_h m_h r_h \omega_h^2 \quad (1)$$

Where, F_h is the centrifugal force in N, n_h is the number of hammers, m_h is the mass of each hammer, r_h is the radius of hammer, and ω_h is the angular velocity of hammers which can be computed by $\omega_h = 2\pi * N_h$. Assuming inelastic impact between the blades and material, the velocity of material, V_m was proposed by Khurmi & Gupta, (2005) as,

$$V_m = \sqrt{\frac{2F_h r_h}{m_m n_m}} \quad (2)$$

Where, V_m is the velocity of material being milled, m_m is the mass of material being milled, and n_m is the number of material imparted. The tip velocity, V_t of the hammer is given by,

$$V_t = \pi D_h N_h (\text{m/min}) \quad (3)$$

where, D_h is the hammer diameter and N_h is the speed of the hammer's shaft.

The Hammer Shaft: The hammer shaft is subjected to combined bending and torsional stresses. The equivalent twisting moment, T_e and equivalent bending moment, M_e are given by Khurmi & Gupta, (2005) as,

$$T_e = \sqrt{(k_m M)^2 + (k_t T)^2} \quad (4)$$

$$M_e = \frac{1}{2}\left[k_m M + \sqrt{(k_m M)^2 + (k_t T)^2}\right] \quad (5)$$

Where, T_e is the equivalent twisting moment, M_e is the equivalent bending moment, M is the maximum bending moment of the shaft, T is the torque transmitted by the shaft, k_m is the combined shock and fatigue factor for bending, and k_t is the combined shock and fatigue factor for torsion. Then the shaft diameter can be related to the equivalent values through the following equations from Khurmi & Gupta, (2005).

$$T_e = \frac{\pi}{16}\tau d^3 \quad (6)$$

$$M_e = \frac{\pi}{32}\sigma_b d^3 \quad (7)$$

Where, τ is the permissible shear stress in N/m^2, $\sigma_b$is the maximum tensile or compressive stress, and d is the diameter of the shaft.

The Transmission Drive: The drive selected for the machine is a v-belt drive.

The velocity ratio of the drive according to Khurmi & Gupta, (2005) is given as

$$\frac{N_2}{N_1} = \frac{d_1}{d_2} \quad (8)$$

This ratio does not consider slip and creep, when creep and slip are considered the velocity ratio now becomes,

Considering slip, $\frac{N_2}{N_1} = \frac{d_1}{d_2}\left(1 - \frac{S}{100}\right)$ (9)

Considering creep, $\frac{N_2}{N_1} = \frac{d_1}{d_2} * \frac{E+\sqrt{\sigma_2}}{E+\sqrt{\sigma_1}}$ (10)

Where, N_2 is the speed of the hammer shaft in rpm, N_1 is the speed of the electric motor in rpm, d_1 is the diameter of the motor pulley in mm, d_2 is the diameter of the blade shaft pulley in mm, S is the total percentage of slip, E is the Young's modulus for the material of the belt, σ_2 is the stress on the slack side of the belt, and σ_1 is the stress on the tight side of the belt. The length of an open belt drive is given by Khurmi & Gupta, (2005) as,

$$L = \frac{\pi}{2}(d_1 + d_2) + 2x + \frac{(d_1 - d_2)^2}{4x} \quad (11)$$

Where, x is the center distance between the two pulleys.

Power and Torque Transmitted by the Belts: According to Khurmi & Gupta, (2005) the following parameters can be calculated as, Power (P) transmitted by a belt,

$$P = (T_1 - T_2)v \quad (12)$$

On the driving pulley, the torque exerted is given by,

$$\tau_1 = (T_1 - T_2)\frac{d_1}{2} \quad (13)$$

On the driven pulley, the torque exerted is given by,

$$\tau_2 = (T_1 - T_2)\frac{d_2}{2} \quad (14)$$

The ratio of driving tensions for the v-belt is given by,

$$2.3\log\left(\frac{T_1}{T_2}\right) = \mu\theta cosec\beta \quad (15)$$

Where, P is the power transmitted in watt (W), T_1 is the tension in the tight side of the belt in newton (N), T_2 is the tension in the slack side of the belt in newton (N), v is the peripheral velocity of the belt in m/s, T^I is the torque exerted on the driving (Motor) pulley in Nm, T^h is the torque exerted on the driven (Hammer shaft) pulley in Nm, μ is the co-efficient of friction between the belt and the sides of the grooves, θ is the angle of contact, and β is half (½) of the groove angle of the pulleys. Centrifugal tension caused by the running of the belt, T_c is given by Khurmi & Gupta, (2005)

$$T_c = mv^2 \quad (16)$$

Where, v is the peripheral velocity of the belt (m/s) given as $\frac{\pi dN}{60}$, $d$is the pulley diameterand m is the mass per unit length in kg. When centrifugal tension is considered, according to Khurmi & Gupta, (2005)

Total tension in the tight side is given as,

$$T_{t1} = T_1 + T_c \quad (17)$$

And, total tension in the slack side is given as,

$$T_{t2} = T_2 + T_c \quad (18)$$

Maximum tension, T in the belt is given by,

$$T = T_{t1} = \sigma bt \quad (19)$$

Where, σ is the maximum safe stress, b is the width of the belt and t is the thickness of the belt. Initial tension in the belt is given by Khurmi & Gupta, (2005) as,

$T_{t1} = \frac{T_1+T_2}{2}$, neglecting centrifugal forces (20)

$T_{t1} = \frac{T_1+T_2+2T_c}{2}$, considering centrifugal forces (21)

The Power Recommendation: Power recommended for the running of the machine can be computed using equation 23.

$$power = \tau * a * v \quad (22)$$

Where, τ is the toughness of the fibre (banana fibre in this case), which is 816MPa according to Salit, (2014), a, is the area of the fibre to be milled which can be expressed as,

$$a = \frac{\pi d^2}{4} \quad (23)$$

Where, d is the average diameter of a banana fibre,

The Bearing: The rolling contact bearing was chosen for its low starting and running friction. Angular contact ball bearings are typically used when there are combined loads (SKF Group, 2016). The actual operational Shaft load, F is given by NTN Global, (2016) as,

$$F = kF_0 \quad (24)$$

Where, k is the load application factor, which can be gotten from Budynas & Nisbett, (2008) and F_0 is the theoretical shaft load in N. The tangential loads, F_t on sprockets or pulleys when power (load) is transmitted by means of chains or belts is given by NTN Global, (2016) as,

$$F_t = \frac{19.1*10^6 * P}{D_p * N} \quad (25)$$

Where, P is transmitted power in KW, D_p is the diameter of the pulley in mm and $N$is the rotational speed of the shaft. For belt drives, an initial tension is applied to give sufficient constant operating tension on the belt and pulley. Taking this tension into account, the radial loads, F_r acting on the pulley are expressed by NTN Global, (2016) as,

$$F_r = k_b . F_t \quad (26)$$

Where, k_b is the belt factor that can be gotten from NTN Global, (2016). The basic dynamic load rating, $C$is given by Budynas & Nisbett, (2008) as,

$$C = F * \left(\frac{L_d N_d * 60}{L_r N_r * 60}\right)^{1/a} \ (KN) \quad (27)$$

Where, L is the life in hours, a is *3* for ball bearings and *10/3* for roller bearings Khurmi & Gupta, (2005), F and C are both in KN, d denotes the desired properties and r denotes the rated properties. The equivalent static load carrying capacity, P_0 is given by SKF Group, (2016) as,

$$P_0 = X_0 F_r + Y_0 F_a \quad (28)$$

Where, F_a is the axial load on the bearings, and X_0, Y_0 are the radial and axial load factor for the bearing respectively(Budynas & Nisbett, 2008; Khurmi & Gupta, 2005). The basic static load rating, C_0 is given by SKF Group, (2016) as,

$$C_0 = kP_0 \quad (29)$$

B. Experimental design and parameters in performance evaluation

The equipment performance evaluation was carried out in the laboratory using the manufactured hammer mill, the grinding efficiency with respect to each fibre sample processed was calculated using equation 30 (Hesham, Yasser, Hanafi, & Tarek, 2015), and the throughput of the mill was calculated using equation 31 respectively for both fibre samples.

$$Grinding\ efficiency = \frac{Net\ output\ weight}{Net\ input\ weight} * 100 \quad (30)$$

The throughput of the machine indicates the amount of product it can achieve over a time interval usually an hour.

$$Throughput\ (g/min) = \frac{Output\ weight\ (g)}{Operating\ time\ (min)}$$

(31)

Table 1 was utilized in calculating the values of the codes as shown in table for minimum and maximum values of X (Mahalik et al., 2010).

Table 1 Relation between coded value and level of the variable

Coded Value	Level of Variance
-α	X_{min}
-1	$[(X_{min} + X_{max})/2] - [(X_{max} - X_{min})/2b]$
0	$[(X_{min} + X_{max})/2]$
+1	$[(X_{min} + X_{max})/2] + [(X_{max} - X_{min})/2b]$
+ α	X_{max}

The levels, coding and input factor can be seen in table 2. The response surface functions to be determined are grinding efficiency and throughput of the miller. This can be described in equation (32).

$$V_i = C_o + \sum_{i=1}^{n} C_i A + \sum_{i=0}^{n} A_{ii}\ A_i^2 + \sum_{i=1}^{n}\sum_{i=i+1}^{n} C_{ij} A\, B_j + \varepsilon \quad (32)$$

Where V_i is the predicted response, C_o is the constant coefficient, C_i the linear coefficients, C_{ii} is the quadratic coefficients, Cij is the interactive coefficients, A_i and B_j are the coded values of the variables, n is the number of independent test variables and ε is the random error (Montgomery, 2001).

Table 2 Levels of independent variables for CCD experimental design

S/N	Independent variables	Unit	Coded variable levels				
			- α	-1	0	1	+ α
1	Speed	rpm	1450	1542	1725	1908	2000
2	Hammer weight	g	40	45	55	65	70
3	Fiber input	g	250	258	275	292	300
4	Operating time	min	5	8	15	22	25

III. RESULTS AND DISCUSION

A. Design calculations

The average fiber diameter of 150μm and the UMA Engineering (1990) recommended tip speed of the hammer mill of 70m/s was used in equation 22 to select 2 horsepower single phase electric motor for the operation. Equation 1 gave the centrifugal force of the hammers as $3.3KN$ for incorporated 24 hammers at rotational speed of 1450rpm. The results of other key specification are shown in table 3.

Table 3 Key specifications

Variable	Value	Source equation
Equivalent twisting moment (T_e)	20.34Nm	Equation 4
Equivalent bending moment (M_e)	12.59Nm	Equation 5
The length of the belt, L	1.0 m	Equation 11
Maximum tension in the belt, T	260N	Equation 19
Basic dynamic load rating C	11790N	Equation 28
The equivalent load carrying capacity of the bearing P_o	396N	Equation 29
Basic static load rating C_o	1327.5N	Equation 30

Model development is achieved based on regression analysis with respect to the factors and corresponding responses. It is also dependent on the analysis of variance which is subjected to improvement and examining the model capability. The model terms for the complete and improved ANOVA for grinding efficiency and throughput responses are presented in tables 4 and 5.

Table 4: ANOVA for grinding efficiency (%) Response Surface Reduced Quadratic Model

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	141.48	7	20.21	17.4	< 0.0001	significant
A-Speed	10.08	1	10.08	8.68	0.0077	
B-Hammer weight	30.08	1	30.08	25.91	< 0.0001	
C-Fiber input	60.75	1	60.75	52.31	< 0.0001	

D-Operating time	24.08	1	24.08	20.74	0.0002	
CD	4	1	4	3.44	0.0775	
B^2	7.06	1	7.06	6.08	0.0224	
D^2	3.77	1	3.77	3.24	0.0861	
Residual	24.39	21	1.16			
Lack of Fit	19.19	17	1.13	0.87	0.6337	not significant
Pure Error	5.2	4	1.3			
Cor Total	165.86	28				

The Model F-value of 17.40 implies the model is significant. There is only a 0.01% chance that a "Model F-Value" this large could occur due to noise. Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case A, B, C, D, B^2 are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model. The "Lack of Fit F-value" of 0.87 implies the Lack of Fit is not significant relative to the pure error. There is a 63.37% chance that this Lack of Fit F-value could occur due to noise. The "Pred R-Squared" of 0.7124 is in reasonable agreement with the "Adj R-Squared" of 0.8040. "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. The ratio of 14.576 indicates an adequate signal. This model can be used to navigate the design space. Equation 33 and 34 shows the final grinding efficiency model in terms of coded and actual factors respectively.

$$\text{Grinding efficiency } (\%) = +75.82 + 0.92 * A + 1.58 * B + 2.25 * C + 1.42 * D + 1.01 * B^2 \quad (33)$$

$$\text{Grinding efficiency } (\%) = +70.00433 + 3.33333E - 003 * \text{Speed} - 0.38889 * \text{Hammer weight} + 0.013274 * \text{Fiber input} - 0.17922 * \text{Operating time} + 1.76991E^{-003} * \text{Fiber input} * \text{Operating time} + 4.49495E^{-003} * \text{Hammer weight}^2 \quad (34)$$

Table 4: ANOVA for Throughput Response Surface Reduced Quadratic Model

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	93.11	14	6.65	58.8	< 0.0001	significant
A-Speed	21.33	1	21.33	188.63	< 0.0001	
B-Hammer weight	18.75	1	18.75	165.79	< 0.0001	
C-Fiber input	27	1	27	238.74	< 0.0001	
D-Operating time	24.08	1	24.08	212.95	< 0.0001	
AB	1	1	1	8.84	0.0101	

BD	0.25	1	0.25	2.21	0.1592	
CD	1.14E-13	1	1.14E-13	1.01E-12	1	
A^2	0.1	1	0.1	0.9	0.3599	
B^2	0.41	1	0.41	3.58	0.0792	
C^2	0.1	1	0.1	0.9	0.3599	
D^2	1.14E-13	1	1.14E-13	1.01E-12	1	
Residual	1.58	14	0.11			
Lack of Fit	1.58	10	0.16			
Pure Error	0	4	0			
Cor Total	94.69	28				

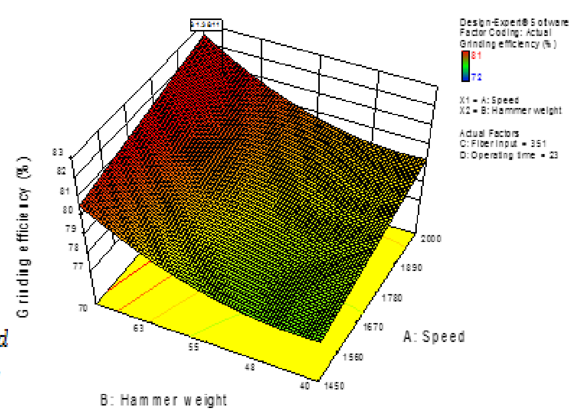
The Model F-value of 58.80 implies the model is significant. There is only a 0.01% chance that a "Model F-Value" this large could occur due to noise. Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case A, B, C, D, AB are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. The "Pred R-Squared" of 0.9037 is in reasonable agreement with the "Adj R-Squared" of 0.9666. "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. The ratio of 26.875 indicates an adequate signal. This model can be used to navigate the design space. Equation 35 and 36 shows the final throughput model in terms of coded and actual factors respectively.

$$Throughput\left(\frac{g}{min}\right) = +40.00 + 1.33 * A + 1.25 * B + 1.50 * C + 1.42 * D + 0.50 * A * B \quad (35)$$

$$Throughput\left(\frac{g}{min}\right) = +34.26683 - 7.52066E - 003 * Speed * Fiber\ input + 0.050000 * Operating * Hammer\ weight \quad (36)$$

B. Optimization of Comminution Process Parameters

In optimization process, the desired goal is either to minimize or maximize the response as a set target within the input process parameter range. Moreover, the best set of optimal value for the processing factors for one response may not be the same for the other. Therefore, the multi-objective optimization (MOO) is adopted to achieve a set of conditions which simultaneously optimizes both responses or at least position the factors within the desirable limits. The optimization interest for this study is to determine a set of the comminution process parameters that gives maximum throughput and grinding efficiency.



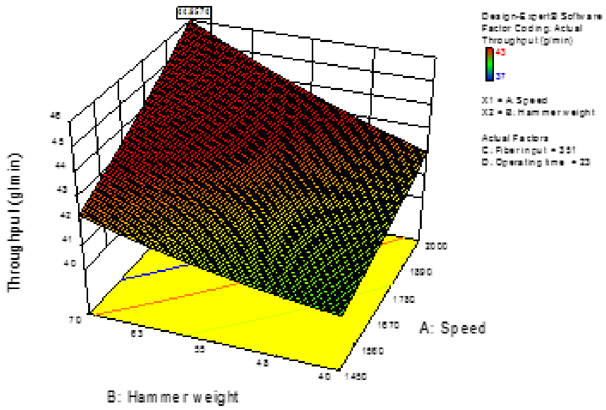


Figure 2. 3-D surface plots for (a) Grinding efficiency and (b) Throughput

Table 5: Optimization criteria for grinding efficiency and throughput

Constraints

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A:Speed	is in range	1450	2000	1	1	3
B:Hammer weight	is in range	40	70	1	1	3
C:Fiber input	is in range	250	363	1	1	3
D:Operating time	is in range	5	25	1	1	3
Grinding efficiency (%)	maximize	72	81	1	1	3
Throughput (g/min)	maximize	37	44	1	1	3

Table 6: Optimal solutions generated for Grinding efficiency (%) and Throughput (g/min)

Solutions

Number	Speed	Hammer weight	Fiber input	Operating time	Grinding efficiency (%)	Throughput (g/min)	Desirability	
1	1946	66	351	23	81.3811	44.9573	1	Selected
2	1605	69	361	24	81.3774	44.8417	1	
3	1981	61	363	23	81.2243	44.6212	1	
4	1794	68	359	20	81.1572	44.8845	1	

Table 7: Confirmation Report for Grinding efficiency (%) and Throughput (g/min)

Factor	Name	Level	Low Level	High Level	Std. Dev.	Coding
A	Speed	1945.524	1450	2000	0	Actual
B	Hammer weight	65.9309	40	70	0	Actual
C	Fiber input	351.4722	250	363	0	Actual
D	Operating time	23.48844	5	25	0	Actual
Response	Prediction	Std Dev	SE (n=1)	95% PI low	95% PI high	
Grinding efficiency (%)	81.38105	1.077616	1.264235	78.75193	84.01017	
Throughput (g/min)	44.95737	0.336296	0.462385	43.96565	45.94909	

The individual response goals are combined into an overall desirability function and a search for optimal solutions is made to provide the best condition that satisfies the criteria. The optimization criterion for this study is presented in table 5. The control parameters are set at their factorial limits, while the grinding efficiency and throughput are set within their performance limits. The optimal solution and confirmation report for grinding efficiency and throughput is shown in table 6 and 7 respectively.

Figure 2. Solidworks model showing hammer arrangements mill chamber using optimal conditions

Fig. 3 Optimized CAD Model and Constructed Fibre Milling Machine

VI. CONCLUSION

The following conclusions were drawn from the study;

1. This machine has been fabricated for comminution of particulate fiber materials and performance test has revealed that the

efficiency and throughput of the machine of 81.38105% and 44.95737 (g/min) respectively.

2. The mathematical model has been successfully developed and can be used to effectively predict the grinding efficiency and throughput value at 95 % confidence level within the range of investigation.

3. From the optimization analysis, the set of conditions that simultaneously optimizes both grinding efficiency and throughput value comprises 1946 rpm of speed, 66g of hammer weight, 351g fiber input and 23min of operating time.

4. It is believed that the commercialization and far reaching use of the new equipment will contribute fundamentally to the development of composite technology in Nigeria.

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