Experimental Determination of Grinding Parameters using a Ball Mill with Innovative Lifters

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Abstract: - In the developed work, experiments were made with a laboratory ball mill with a liner with symmetrical displaced eight innovative lifters with a spheroidal tetrahedron type. Based on experiments done in a previous study, the number of lifters with innovative shapes, as well as their sizes, were determined. The additive material used for grinding media is PLA material and for grinding bodies PLA, SteelFill (based on PLA), and CarbonFil^{TM} (based on PETG) are used which are printed on a 3D printer. The mill's critical speed (CS), the angle of separation (shoulder angle), and the toe angle in the cataract mode of operation were determined experimentally. Experiments were carried out with different mill filling percentages - 20% and 30%. The required speed of the ball mill with grinding media with innovative lifters at cataract mode of operation for the three types of materials is almost the same - with an average value of 45% of CS. The best energy efficiency and grinding efficiency material at 20% filling of the mill is obtained with a SteelFill filament, and at 30% - with a PLA filament.

Key-Words: - ball mill, innovative lifter, additive material, critical speed, angle

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1 Introduction

The essential factors for competition in the industry are low cost, high quality, and fast production. For this reason, to investigate the milling processes, it is necessary to work in laboratory conditions. The use of a laboratory mill, whose grinding media and bodies are made of 3D materials, allows for analyzing the excavation and grinding processes. Investigating the following key factors is performed: the mill shoulder and toe angles, the influence of the coefficients of friction, rolling friction, and restitution, conducting experiments with different sizes, shapes of grinding bodies, and grinding environments, including testing of the yield point of different materials with acoustic emission methods. In, [1], [2], [3], is ascertained that the different sizes, shapes of grinding bodies, and grinding environment influence the mill shoulder and toe angles as well as the coefficients of sliding friction, rolling friction, and restitution. When the fill percentage of the ball mill is changed, including the shape, size, and composition of the grinding bodies, the required power is also changed through their effect on the shear strength of the charge, [4]. The shape and profiles of the liners are used for shield plates and milling, and the lifters have a significant influence on the productivity and effective grinding of the output product, [5]. In, [6], a type of lifter for the experiments is presented and shows a cataract mode of operation in a laboratory ball mill with clockwise rotation at which regime the grinding results are better. The mill shell inside the mill which has 8 innovative lifters with a spheroidal tetrahedron form and displaced symmetrically, protects the grinding bodies and the drum from rapid wear, [7], [8].

Another possible solution to determine and optimize processes in the ball mills is the DEM simulations, [9]. The simulations can reduce time for investigations, as well as ball consumables and environment such as grinding bodies, lifters, drums, etc.

The investigation aims to determine the parameters of grinding a laboratory ball – the critical speed, the separation angle, and the toe angle at the cataract regime of operation. The liner with lifters is produced from PLA material and the charge of a ball mill is at 20% and 30% made from 3 types of material – PLA, SteelFill, and CarbonFil^{TM}, by using a 3D printer. The experiments are performed without the presence of grinding material.

2 Apparatus and Materials

The laboratory ball mill used throughout this study has an outer diameter of the chamber of 0,269 m, an inner diameter of 0,228 m, and a length of the mill of 0,013 m. The length of the mill is constructed to work with one row of balls. There are 2 transparent plexiglass covers allowing us to investigate the interaction of the grinding ball. The motor has 1.1 kW power, controllable speed, and intelligent control. The PLA filament is used for 3D printing of the drum and mill shell with lifters due to its good mechanical properties and the high aesthetic quality of the surface. By unscrewing the bolts holding the two covers, the grinding media (lifters) can be easily replaced with ones of different materials, shapes, and lengths. The parameter of the innovative lifters can be seen in, [6]. The direction of rotation of the ball mill is clockwise. The speed of the ball mill is determined with an electronic tachometer. According to the volume of the innovative lifters, the volume of the free inner space of a ball mill is V- $5{,}195.10^{-4}$ m^3.

The grinding bodies in the shape of spheres are 3D printed with three types of filament: PLA, SteelFill, and CarbonFil™ according to the producer's recommendations and according to performed experiments, [10], with 100% infill after which their weight was measured, [3], [11].

Each mill charge is determined experimentally, specifying the number and mass of spheres required. For 20% filling of a ball mill, the required number of spheres is 142, and for 30% filling- 210 pieces.

The coefficients of sliding friction, rolling, and restitution for the pair PLA-PLA, PLA-SteelFil, and PLA-Carbon can be seen in, [12], [13], [14], [15].

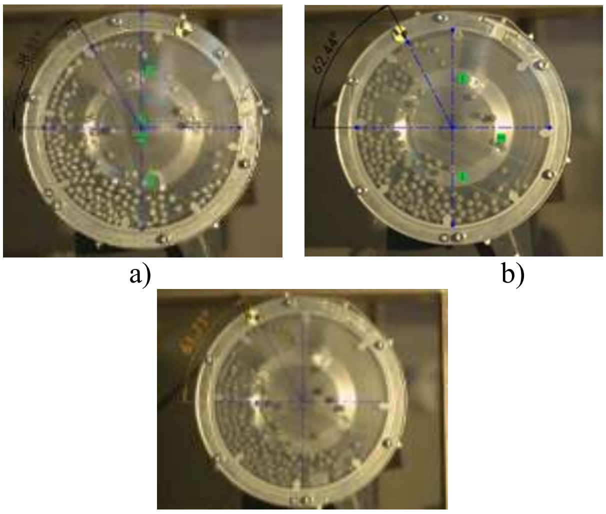
A high-speed camera NAC MEMRECAM HX-6 is used to record the moment of critical speed, separation, and incidence. The camera parameters allow for recording frames with different resolutions per second (fps) where the maximum is up to 360000, [16]. The analyses of the recorded videos are carried out using the Vicasso 2009 software.

3 Experimental Results and Discussion

Firstly, the critical speed of the mill with 20 % filling is determined using spheres made of three types of materials- PLA, SteelFill, and CarbonFil™. The critical speed is reached when all the spheres fit evenly around the circumference. By means of the buttons positioned in the electronic dashboard, the speed is increased until the desired state is reached. The achieved velocity is measured with an electronic tachometer in rpm, positioned stationary on a stand, and a marker is placed in the ball mill. The marker is needed for the tachometer for counting the rpm's. With the help of the high-speed camera, the moment of the critical speed is recorded at 1000 fps. The video is checked for discrepancies and a photo is taken by snapshot application. From the snapshots, the shoulder and toe angles are measured. Figure 1 shows a view from the critical speed at 20% filling of the ball mill.

Fig. 1: Critical speed at 20% filling of the ball mill

The next searched mode of operation is the cataract mode. It is determined by using the data from the video, recorded with the high-speed camera. The determination of the shoulder angle is established in 3 points. The first point is the moment of separation angle (shoulder angle) of the grinding bodies, point two is the mill center and point three is the end point of the mill, placed horizontally from the center. Figure 2 shows the detected speed of the ball mill using different materials.



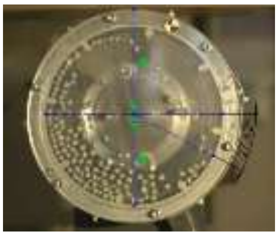
a) b) c)

Fig. 2: Shoulder angle at 20% filling of the ball mill: a) PLA, b) SteelFill, c) CarbonFil™

From the same video, the toe angle is determined. The measurement of the toe angle is performed also in 3 points. The starting point is the moment of incident of the grinding bodies with the chamber, the second point is the center of the mill, and the third point is the end of the mill horizontally from the center, shown in Figure 3.

The same procedure of measurements of the parameters at 30% filling of the ball mill is made. The determined critical speed is measured with a tachometer. The experimental setup is presented in Figure 4.

The determined shoulder angle and toe angle are presented respectively in Figure 5 and Figure 6 for the three materials. The results of all experiments are presented in Table 1.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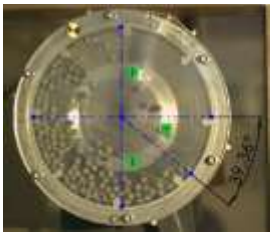
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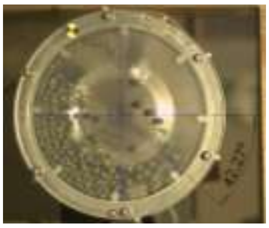
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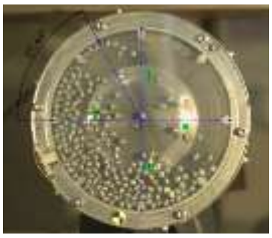
Fig. 3: Toe angle at 20% filling of the ball mill: a) PLA, b) SteelFill, c) CarbonFil™

Fig. 4: Critical speed at 30% filling of the ball mill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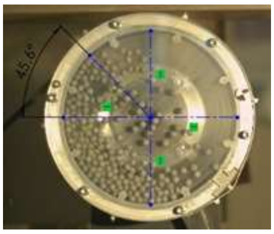
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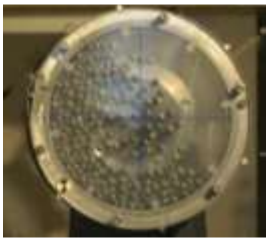
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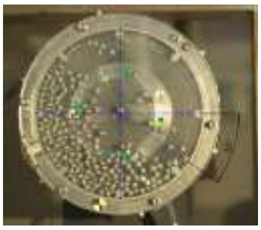
Fig. 5: Shoulder angle at 30% filling: a) PLA, b) SteelFill, c) CarbonFil™

Of the base of measured values, a percentage of the critical speed at 20% and 30% filling of the mill at cataract mode of operation is calculated, according to eq. (1). The values are shown in Table 1.

$$\% \text{ Vcr} = \frac{\textbf{\textit{Ball mill speed}}}{\textbf{\textit{Critical speed}}} \text{x } 100, \text{ rpm} \qquad (1)$$

It's seen that the calculated % of critical speeds in which the mill operates in a cataract mode is almost equal at the different filling. The average value is 46 % of the CS and only for the SteelFill material at 20% filling and CarbonFil™ at 30% filling with an average value of 44 %.

At 20% of the mill fill capacity, the SteelFill material has the largest separation angle and the smallest toe angle. This material is measured with the largest weight. The percentage of Vcr in the cataract mode of operation is also the least compared to the other materials. That is why it is the material where the least energy is used. This leads to a reduction in the revolutions of the mill, which will increase energy efficiency.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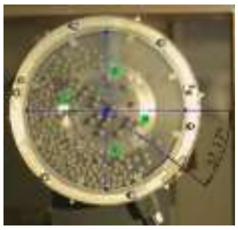
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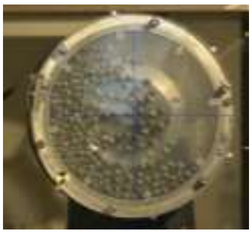
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Fig. 6: Toe angle at 30% filling: a) PLA, b) SteelFill, c) CarbonFil™

At 30% fill of the ball mill, the data differ significantly compared to those at 20% fill of the mill. In this case, the PLA material has the largest separation angle and the smallest toe angle. At this charge, the weight of the material has the greatest influence and the rolling friction coefficient is the smallest – 0,060. The lighter the material and the lower the coefficient of rolling friction, the more energy-efficient the mill's operation.

4 Conclusion

In the present work, the parameters of work of a laboratory ball mill with 8 innovative lifters, produced from PLA material interacting with grinding bodies produced from three different materials- PLA, SteelFill, and CabronFil^{TM} are determined at two different charges- 20% and 30% filling of the ball mill.

Table 1. Experimental Results

% of Filling	***Material***	***Critical speed, [rpm]***	***Shoulder angle,[°]***	***Toe angle,[°]***	***Ball mill speed, [rpm]***	***% of Critical speed, Vcr***
20% filling	PLA	131	58,61	27,62	59,8	45,6
	CarbonFil^{TM}	124	61,71	42,27	57	46
	SteelFill	123,4	62,44	39,36	54	43,8
30% filling	PLA	134,3	61,44	35	61,6	45,9
	CarbonFil^{TM}	128,6	53,1	41,58	56,2	43,7
	SteelFill	125,5	45,6	37,17	57,3	45,66

The critical speeds, shoulder angles, and toe angles are experimentally determined at the two levels of filling. Due to the use of the high-speed camera, the exact moments for determining the parameters were recorded. The data are reported with Vicasso 2009 software. The ball mill rotates in a clockwise direction, the critical speed at which the particles start to centrifuge differs for each material and with the different % filling of the ball mill.

The results show that the required speed of the ball mill with grinding media with innovative lifters, made by PLA material to reach the cataract mode of operation are almost the same for the three types of materials- on average 45% of CS.

From the observed materials, the best energy efficiency and grinding efficiency at 20% filling of the mill is obtained with the SteelFill filament, which is the heaviest of the observed ones. At 30% charge of the mill, the lighter material and with the lower coefficient of rolling friction – the PLA filament has the best grinding parameters, according to investigated materials.

The contribution of this work is the proving of the influence of the characteristics of the grinding media and the grinding bodies. When studying the movement and interaction between grinding bodies, it is extremely important to consider side factors such as the weight of grinding bodies, coefficients of friction, restitution, shape, lifter size, etc. When the milling process with the aforementioned factors is better understood, it will lead to process optimization, reduction of production costs, and improvement of energy efficiency.

5 Future Steps

In future work, it is planned to conduct experiments on the interaction of the same number and material of the liner but through lifters with different shapes and with grinding bodies made of the same additive materials- PLA, CarbonFil^{TM,} and Steelfill. The data will be compared to that of a mill without lifters. Simulations with software working on the discrete element method will be made with the same parameters, used in this publication aiming to compare the real experiment to the simulation modeling experiment.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

- Nikolay Stoimenov carried out for determining a critical speed.
- Miglena Paneva is responsible for determining a cataract mode and calculation of a % of a critical speed.
- Peter Panev carried out a determination of a shoulder angle and toe angle.

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Conflict of Interest

The authors have no conflicts of interest to declare.