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Planetary Mill with Friction Wheels Transmission Aided by an Additional Degree of Freedom

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Abstract: Processing in planetary ball mills is well suited to a large number of applications because they are easy to operate and versatile, grinding faster than other mills. Research related to planetary mills are mainly about the process evaluation, and there are few studies on the mechanical design of such equipment. This paper describes the decision process in the design of an innovative planetary mill in which design for manufacture and assembly (DFMA) principles were used to provide compact equipment made of simple and standardized parts. We developed a friction wheel mechanism with an additional degree of freedom that improves transmission and facilitates assembly, reducing the need for adjustment. It can be applied to different equipment that relies on planetary motion or rotating devices. A prototype was built, and its grinding performance surpasses that of other types of traditional mill. The mean particle size of alumina powder was reduced from 4.2 µm to 0.9 µm in 60 minutes.

Keywords: design; DFMA; friction wheels; planetary ball mill

1. Introduction

Laboratories and modern industry require fast and effective grinding in small volumes. Planetary ball mills are well-suited to these applications because they are easy to operate and versatile, capable of performing dry and wet grinding. A planetary mill is a centrifuge machine in which pots containing feed material and grinding media rotate around its own axis (rotation) and around the main axis of the base (revolution) [1], as shown in Figure 1.

Research related to planetary mills has mainly focused on process evaluation. Computer simulations based on the discrete element method (DEM) are widely used to optimize the grinding parameters [1–4] and experimental analysis of the commercial equipment is used to validate the models [5,6], or to test performance [7–9]. However, there are few studies on the mechanical design of these mills.

This article studies the state of art of planetary machines. Understanding the motion transmission system of existing equipment is invaluable to support the creation of a new and innovative mechanical design. Different patents have been claimed for planetary mills with belt transmission [10], friction transmission between the outer surface of the mill pot and a fixed external ring [11,12] or even two independent electric motors [13] to drive rotation and revolution. Considering other equipment that relies on planetary motion, such as the dual asymmetric centrifugal mixer, gears [14,15], belts [16], independent motors [17] and friction wheels [18] have been used to drive the rotational motion. A detailed review of the subject has been discussed in a Masters dissertation [19].

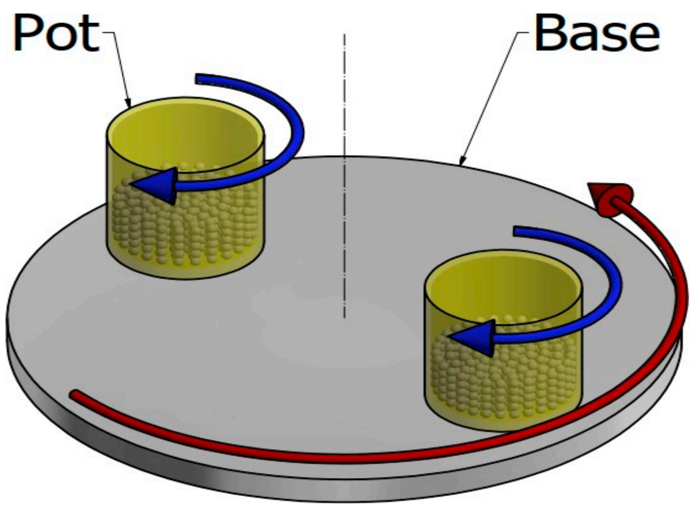


Figure 1. Schematic diagram of the planetary ball mill.

To design an innovative product as a low-cost planetary mill that is viable for a vast number of applications, a large number of decisions need to be made. The decision process in engineering design is influenced by the input, business, and environmental context. The input context is related to the knowledge base, requirements, constraints, and options. The business context represents the aspects related to the institution that develop the project, such as the technology level and culture. However, the environmental context must be considered as a variable, because it is not controlled by the institution; for instance, the state of the economy, customer needs, competition and government regulations [20].

The methodology of the design for manufacture and assembly (DFMA) reduces costs by using fewer parts, which should be simple and standardized to eliminate adjustments [21–23]. Recent papers have studied the application of DFMA in the design of a wide range of products, such as shopping carts [24], food processors [25] and aircrafts [26].

In this article, the outputs of the decision process are discussed in detail. We designed a compact planetary mill made of simple and standardized parts, using DFMA principles, and compared the prototype's grinding performance to the performance of other types of mill.

2. Materials and Methods

2.1. Design Specifications

To obtain an innovative planetary mill that is viable for a large number of applications, the decision process considered inputs, business, and environmental context. Figure 2 shows the decision process applied to the project under consideration.

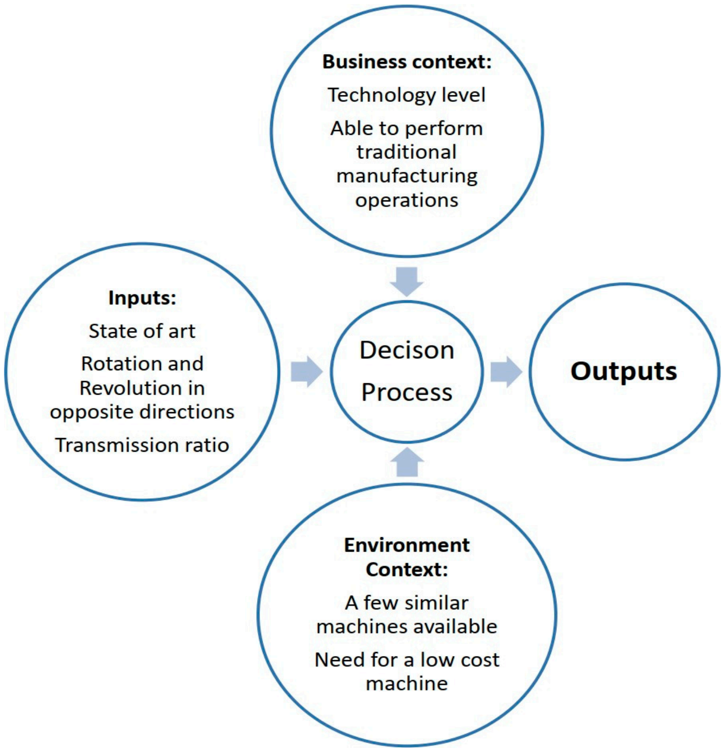


Figure 2. Flow chart for the decision process applied to the project of a planetary ball mill developed by a medium-sized company.

Our implementation is based on a small volume planetary mill in which each pot has a volume of approximately 60 mL (with an inner diameter of 40 mm) and a revolution radius equal to 100 mm, continuing the work that was started and presented in article [27]. Since smaller media lead to smaller particle sizes [7], a media ball diameter of 3 mm was chosen for the tests performed in this article.

The rotation of the pot in the opposite direction to the revolution is more effective in fine grinding materials, mechanochemical activation, and mechanical alloying, due to the larger impact energy of the balls during milling. An optimal rotation-to-revolution speed ratio, *Sr*, can be calculated by Equation (1) [2]:

$$Sr = \sqrt{\frac{2R}{Dp - Db} - 1} \quad (1)$$

where R denotes the revolution radius, Dp is the inner diameter of the pot, and Db denotes the media ball diameter.

The optimal rotation-to-revolution speed ratio applied to the project parameters was calculated from Equation (1) (Sr = 2.09). Therefore, aiming for an effective grinding, we selected the transmission ratio of 2 with rotation and revolution in opposite directions.

Among the motion transmission of the existing equipment presented in the previous section friction wheels can provide the most economical and compact system due to their simple components. They can be produced by traditional manufacturing processes, such as turning and milling, and consequently, they fit the technology level of midsize companies and their need for inexpensive machines. However, the machines in the state of art that uses friction wheels present rotation and revolution in the same direction. Designing a piece of equipment using friction wheels that provides effective grinding, with rotation and revolution in opposite directions, is a major challenge.

2.2. Experimental Validation Procedure

To evaluate performance, calcined alumina powder (considered a hard material reference) was ground in different mills: the prototype built discussed in this work, a vibratory mill [28] and an attritor (Szegvari Attritor System01 STD, Union Process). The material used was a commercially pure (99.7%) Al_2O_3 powder (APC-G, ALCOA) with a median particle size equal to 4.2 microns.

For the planetary and vibratory mills, an aluminum pot with alumina coating with a volume of 62.0 mL, one-third of which was filled with zirconia balls (3 mm in diameter) as media (120 g), and other one-third was filled with: alumina powder 24 g, distilled water 14 g, ammonium polyacrylate as deflocculant 0.24 g. The ball filling ratio was chosen according to [6]. A recent study [29], however, has noted that higher densities of grinding media provide a higher breakage rate. This therefore justifies the choice of zirconia balls, which have higher densities compared to other ceramics such as alumina. For the attritor, which has a larger milling volume, the ball-to-powder (5:1) and deflocculant to powder ratio (0.01) were maintained. Accordingly, 100 g of alumina powder, 50 g of water, 1g of Ammonium Polyacrylate, and 500 g of media balls were used

The particle distributions of the raw material and ground alumina were analyzed using a sedigraph known for using sedimentation and photon absorption to determine particle size.

3. Results and Discussion

3.1. Design

Figure 3 is a sketch of the designed planetary ball mill. This piece of equipment has an external structure made of steel, which isolates the rotating parts from the external environment, protecting the operator from the risk of accidents from detached parts. Figure 4 shows the core elements of this centrifugal machine. The central friction wheel is attached to the electric motor flange and the disk is attached directly to the electric motor shaft, demanding a careful choice of the electric motor that will undergo under mechanical stress. In this way, the project is more compact and requires fewer parts.

Figure 3. Sketch of the planetary mill designed with a protective external structure.

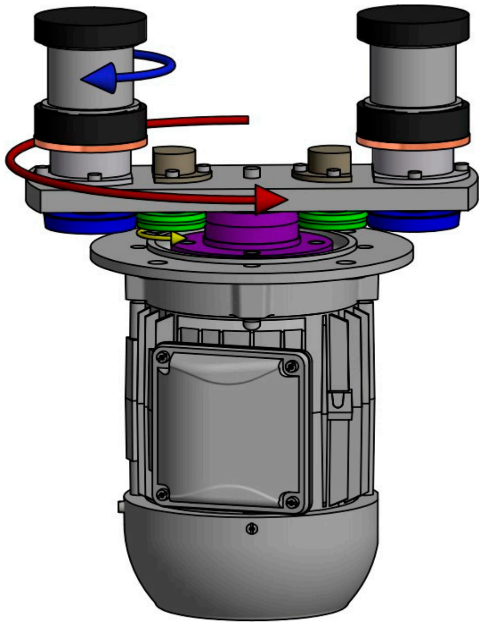


Figure 4. Sketch of the core elements of the designed planetary ball mill.

Figure 5 shows a section view of the moving parts and the central friction wheel. To make the jar rotate in the opposite to the revolution, three friction wheels are required for the motion transmission. The central friction wheel, fixed to the motor flange, stands still. The motor drives the revolution movement. The intermediate friction wheel moves in the same direction as the disk. In contrast, the external friction wheel rotates in the counter direction against the revolution.

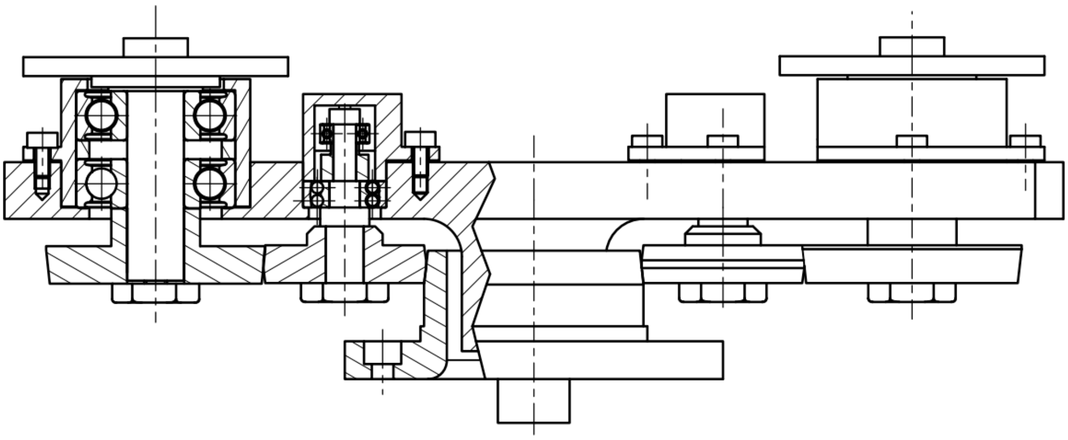


Figure 5. Partial section view of the moving parts and the central friction wheel.

A major breakthrough in this design is the intermediate friction wheel mechanism. A self-aligning ball bearing is used so that the seated shaft can deflect around the bearing center. A standard ball bearing has its inner ring seated in the top part of the shaft and the outer ring in an oblong, as shown in Figures 6 and 7. This not only provides the movement around the axis, but also a displacement occurring in the contact plane of the friction wheels, as shown in Figure 8. This second degree of freedom causes the centrifugal force that acts in the middle friction wheel during operation, which in addition to the interference between the wheels, increases the normal force necessary for the motion transmission. It also facilitates the assembly process, eliminating adjustments, and can be used in other types of rotary mills (such as the recently presented mixer [30]). A patent application for the present innovation has been filed [31]. This transmission demonstrates good performance for loads up to 1 kg and speeds up to 2000 rpm.

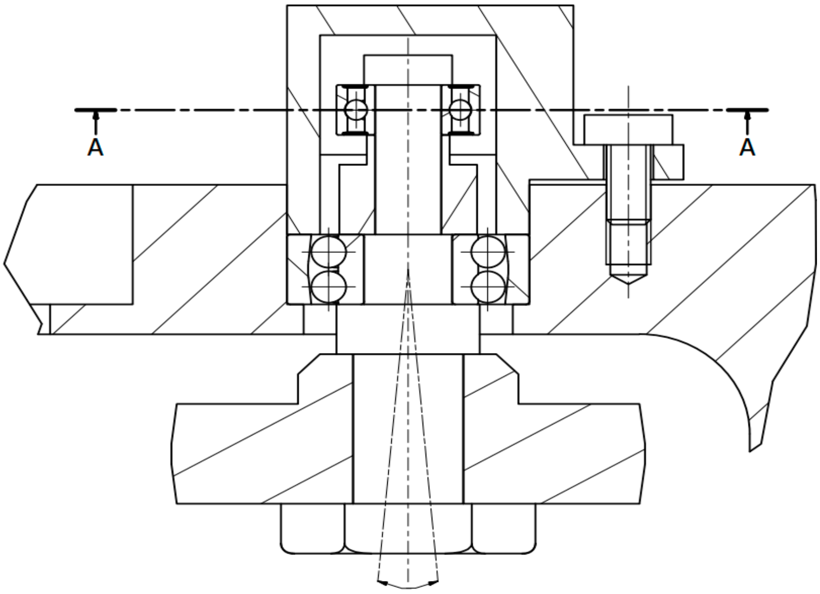


Figure 6. Detailed drawing of the intermediate friction wheel mechanism: the shaft can deflect around the self-aligning ball bearing center. The movement is limited to just one plane due to the ball bearing seated in the top of the shaft with its outer ring seated in an oblong as shown, in Section "A-A" (Figure 7).

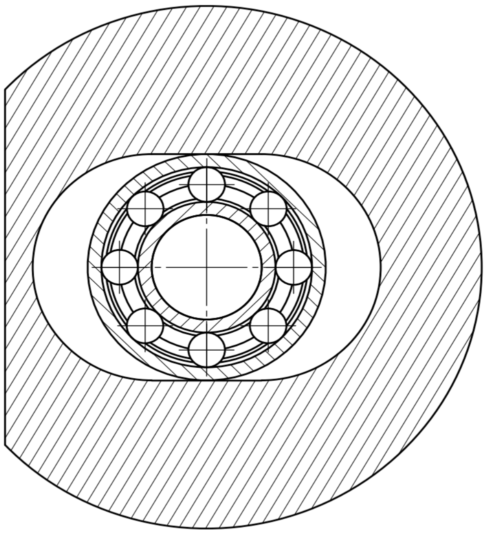


Figure 7. Section "A-A" indicated in Figure 6: the ball bearing outer ring seated in an oblong limits the movement of the mechanism to just one plane.

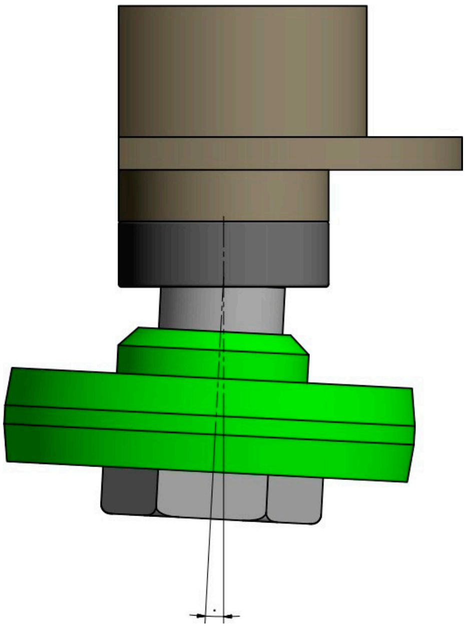
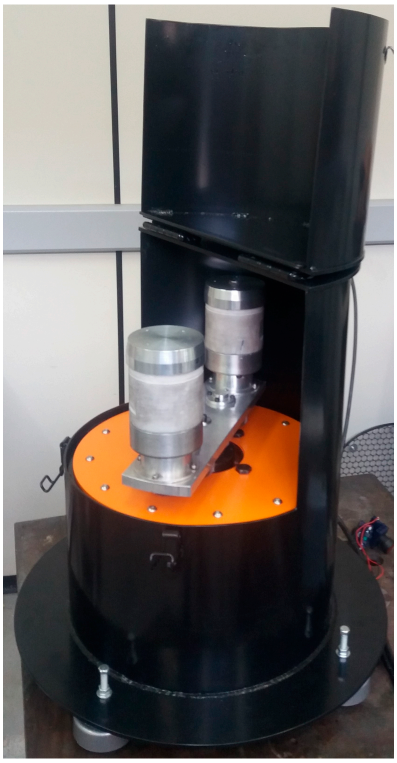


Figure 8. Schematic drawing of the displacement (around the self-aligning ball bearing center) provided by the friction wheel mechanism.

A prototype of the equipment designed was built. Figure 9a shows the external structure and Figure 9b shows the prototype with the door open.

(**a**)



(**b**)

Figure 9. Built prototype: (**a**) external structure; (**b**) device with opened door.

The mill was also equipped with two locks (toggle latch type) and a safety interlock switch to prevent access to the rotating parts of the machine during operation, as well as an accelerometer to detect excessive vibration or impact due to detaching parts.

3.2. Validation: Grinding Performance

Alumina was ground in the planetary mill prototype (1 h), attritor (6 h), and vibratory mill (24 h). Figure 10 shows the particle size distribution.

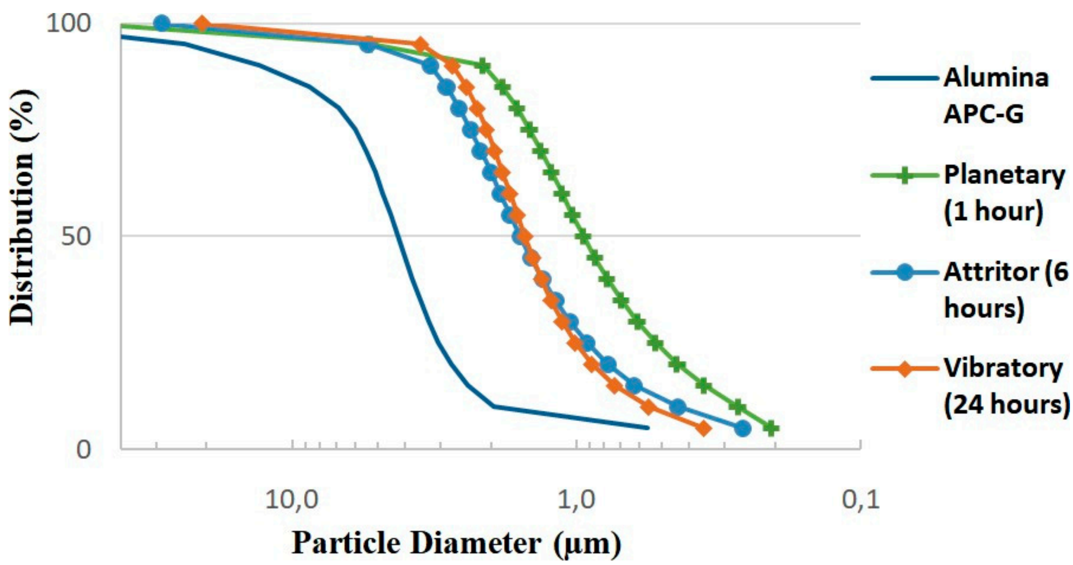


Figure 10. Particle size distribution of alumina powder before grinding, 24 g of alumina after 1 h in the planetary mill, 100 g of alumina after 6 h in the attritor mill and 24 g of alumina after 24 h in the vibratory mill.

The planetary mill provided sub-micrometric alumina powder in just one hour, having a better breakage than the attritor in 6 h and the vibratory mill in 24 h. The alumina ground by the planetary mill had a broad particle size distribution (a span equal to 2.00) while vibratory mill provides the narrowest (a span equal to 1.40). It is important to note that the capacity of the attritor mill used was much higher, under the usual working conditions of the equipment used.

4. Conclusions

In this work, we tackled the engineering design of an innovative planetary mill. A decision process was used to consider the requirements and information from the state of the art technology of midsize companies, and the need for inexpensive machines.

The planetary ball mill designed according to the present study meets the requirements for the effective processing of materials, such as the rotation of the pot in the opposite direction to the revolution and a proper transmission ratio. Its innovative friction wheel mechanism transmission allows for a compact and economic design, composed of few simple parts and with reduced adjustment (DFMA principles).

The built equipment ground calcined alumina powder, and the mean particle size was reduced from 4.2 µm to 0.9 µm in 60 min. This performance surpasses that of other types of traditional mill.

5. Patents

A patent application for the present innovation was filed at INPI (BR 20 2018 067623-2).

Author Contributions: Conceptualization, I.L.d.C. and C.A.F.; validation, I.L.d.C; R.E. and J.F.P.L.; resources, C.A.F.; writing—original draft preparation, I.L.d.C.; writing—review and editing, R.E.; J.F.P.L. and C.A.F.; supervision, C.A.F.

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