Development of Two Axis Rotational Small Ball Miller for Powder Metallurgy Applications

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DOI: https://doi.org/10.30880/paat.2024.04.02.001

Abstract

In powder metallurgy, milling involves reducing solid metal into fine particles through grinding or crushing, which enhances its properties and applications. This study aims to fabricate a two-axis small milling machine for powder milling and to investigate the relationship between rotational speed and milling time effectiveness. The research begins with analyzing the requirements for powder metallurgy processes, focusing on factors like particle size distribution and homogeneity. SolidWorks software designs the milling machine, emphasizing optimal functionality for powder milling. The machine tests use aluminum chips, and an optical microscope assesses the post-milling particle sizes at various time intervals. The study employs two motors: a 12V DC motor and a 24V DC motor, each capable of reaching up to 1500 rpm. A potentiometer is used for user control and automation. After adding a fixed bar, particle sizes are measured at 1.02 mm for 500 rpm and 1.08 mm for 1500 rpm after two hours of milling. After an additional two hours, sizes decrease to 0.50 mm for 500 rpm and 0.56 mm for 1500 rpm, indicating effective particle size reduction with extended milling time. Results demonstrate that integrating a fixed bar into the two-axis small milling machine enhances particle size distribution and milling efficiency. Additionally, critical speed analysis underscores the importance of maximizing mill rotation for efficient milling operations. In conclusion, the two-axis small milling machine is successfully fabricated, demonstrating high quality and efficiency in powder metallurgy milling processes.

1. Introduction

The ball mill operates as a grinder intended to finely grind and mix various materials into powder [1]. It is critical in producing nanocrystalline materials, achieving grain sizes between 5 and 22 nm for FCC, BCC, and HCP structures [2, 3]. In the aerospace industry, nanocrystalline materials are vital for manufacturing high-performance components with enhanced mechanical properties, such as lightweight alloys for airframes and turbine blades. These materials exhibit superior strength-to-weight ratios, thermal stability, and wear resistance, making them ideal for demanding environments. Along with studying these materials' thermal stability and grain growth behavior, it is very important to find a balance between strong interparticle bonding, low porosity, and controlled grain growth. Key characteristics of milling bodies include their mass, dimensions, wear rate, and

impact on particle breakage and grinding efficiency. Grinding can be conducted dry or wet; planetary ball mills, a smaller type widely used in labs to grind ceramic samples and other materials into fine powders [4], typically operate in closed systems with at least one grinding jar. Achieving effective grinding necessitates precise control of operating speeds. Adjusting the speed causes the particles near the cylinder wall to break sequentially, followed by those in the upper regions, creating a cascading effect where layers of balls are separated by varying material thicknesses [5]. This milling action involves balls or pebbles rotating and undergoing secondary movements like rubbing or rolling inside the cylinder. The high energy input of this mill type is notable, as it causes the milling stock and balls to dislodge from the wall and experience centrifugal forces up to twenty times the gravitational acceleration. When milling, the specific impact energy of balls peaks around the critical speed ratio. This is where the ratio of rotation to revolution speeds increases the impact of energy at first before becoming stable [6]. However, breakage rates decrease as fines accumulate in the milling bed, affecting particles of all sizes [7]. Achieving uniform particle size distribution in aerospace materials is critical for producing advanced composites with consistent properties. Increasing powder volume fills collision spaces between balls, thereby boosting breakage rates.

Moreover, under dry conditions, larger grinding balls narrow the particle size distribution, which impacts the optimal milling times depending on the type of mill, the size of the grinding medium, the milling temperature, and the ball-to-powder ratio [8]. Specific energy consumption determines breakage rates, assessed with monosized feeds. Scaling ball mills and their circuits from lab tests typically involve using empirical equations or factors based on practical experience, with variations among manufacturers to ensure sizing accuracy [9]. In this study, the two-axis rotation small ball miller is fabricated and can be used in powder metallurgy techniques. The relationship between milling speed and milling time affecting particle sizes is determined.

2. Methodology

The main component of a ball mill is a jar with a proportionate diameter and length. As the jar rotates via transmission machinery, the material within it is agitated. Due to the impact of steel balls descending from a higher position, the material is crushed into pieces and eventually reduced to powder if left in the jar long enough. Inside the mill cavity, larger balls are propelled to the top by centripetal force and then fall to the bottom, crushing the material. Smaller balls grind the material at the bottom of the cavity. To construct this system, we first selected a suitable material for the jar that has a higher hardness than the raw material to be ground. Stainless steel balls are preferred for their hardness and anti-corrosion properties, as corrosion can occur in the high-metal environment of ball milling. Different motor speeds are used to break the material into various size portions. Comminution in the ball mill occurs through impact, friction, and abrasion. Since the jar is continuously rotating, a sturdy stand is necessary to support the system. Mild steel is chosen to fabricate the shafts and blocks due to its adequate strength and availability. Bearings are installed to facilitate rotational or linear movement for the shafts, reducing friction and handling stress. To rotate this heavy model, a high-power motor is required, running at 21 W, 220-240 V, and 50 Hz. A pulley system transfers torque from the motor to the shaft. A second motor is required to transfer torque from the motor to the jar. This motor gives higher speed and higher torque. Once the grinding is complete, the ground material and stainless-steel balls are poured onto a sieve to separate the finer components. Three methods for sizing ball mills have implicit assumptions and interconnections. The first method, rate-of-production analysis, describes the output of a test mill by the rate of production of material below a certain size per unit of mill volume, scaled to the production mill by a function of mill diameter. The second method, sizing-by-energy, assumes that the specific energy of grinding is the same for both test and production mills, adjusted by a scale factor dependent on mill diameter. The third method, mass-size balance, is a mill simulation method using specific rates of breakage.

2.1 Experimental Setup

In this study, AISI 304 stainless steel, composed of 70.6% Fe, 0.1% carbon, 1% Si, 2% Mn, 0.045% P, 0.15% S, 17% Cr, 8% Ni, 1.0% Cu, and 0.01% N, is used for both the grinding media and the grinding jar. The jar has an inner diameter of 2.6771" and a thickness of 1 mm, with an approximate volume of 750 ml. For the grinding media, stainless steel balls with a diameter of 10 mm have been used. For the shafts, stainless steel has an 8mm diameter and a 1000mm length shaft. The length of the shaft is reduced by cutting it using cutting tools to 50 mm in length. This shaft is welded onto the brackets of the mill jar (Fig. 1).

Fig. 1 *Shaft is welded onto brackets of the mil jar*

The motor is locked onto its bracket (secured to the stand) to ensure the pulley belt is held tightly between the two shafts. The belt is pulled until tight enough to connect the two pulleys, one with 40 teeth and the other with 20 teeth. The belt length is 300 mm with a width of 6 mm (Fig. 2). Fig. 3 shows the isometric view of a two-axis ball mill machine in SolidWorks.

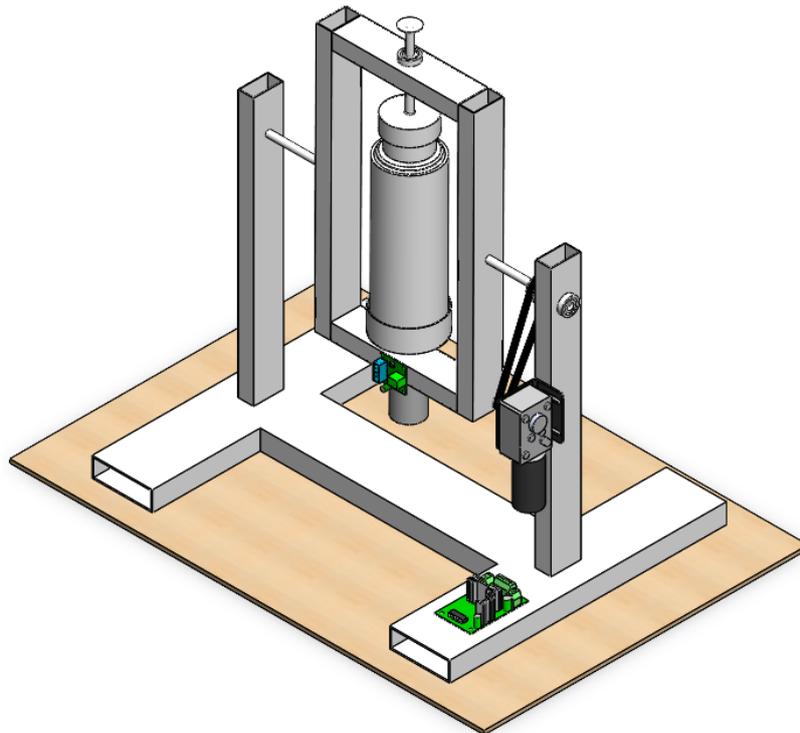**Fig. 2** *Belt being fixed into two pulleys*

Fig. 3 *Isometric view of two axis ball mill machine in Solidworks*

2.2 Experimental Procedure

In this study, aluminum chips are ground into powder form. To conduct the experiment, it is crucial to ensure that the motor operates at a constant speed, as variations may affect the results. The process begins by filling 25% of the jar volume with stainless steel balls. The motor is then set to operate at different speeds (600 rpm and 1500 rpm) to break the specimen into various sizes. The specimen is also added to fill 25% of the jar volume. After adding the balls and specimen, the feeding part is sealed with the mill jar cap. The machine is stopped at one-hour intervals to observe changes in the specimen's size. The grinding process is repeated until the specimen is reduced to powder. The total time consumed is recorded. Finally, the balls and specimens are poured onto a sieve to separate smaller particles, and the resulting product is observed and documented.

2.3 Formulation of Critical Rotation Speed

It is widely accepted that the critical rotation speed is determined by the radius of the ball and the diameter of the jar. However, research has shown that the critical rotation speed also significantly depends on the ball-containing fraction in the jars. As the ball-containing fraction approaches one, the critical rotation speed approaches a certain value asymptotically [10, 11]. The critical speed needed for a jar is given by Eq. (1):

$$CS = \frac{265.45}{\sqrt{D_i - d}} \tag{1}$$

where CS is the critical speed, D_i is the internal diameter of the jar, and d is the size of the media, all measured in inches, with speed in revolutions per minute (rpm). To determine the desired jar rotational speed, typically 55% to 75% of the critical speed is used. In this experiment, 75% of the critical speed is used to maximize impact energy. Using a $d = 0.3937"$ stainless-steel ball diameter and an internal diameter of the jar $D_i = 2.67717"$, the optimum of the critical speed for the ball mill is determined at 175.66 rpm.

2.4 Selected Components

Table 1 displays the list of equipment and materials used in this experiment to construct the two-axis ball mill machine. All components were subsequently assembled into a single system. The base was designed and fabricated, while the motor, gear pulley system, stainless steel balls, and mill jar were purchased. The setup comprised the following apparatus and materials:

Table 1 *List of apparatus and materials used to build two-axis ball mill machines*

Amount (unit)	Description
1	24V gear motor
1	12V worm gear motor
50	10mm high-density stainless-steel ball
3	8mm ball bearing
1	300mm pulley belt
1	20t pulley
1	40t pulley
1	Tachometer
1	Custom made mill jar
2	8mm diameter stainless steel shaft (50mm)
2	Potentiometer
1	Motor bracket
1	Coupler

3. Results and Discussion

In terms of materials and milling media placement, the balls were positioned within a quarter of the mill jar. Additionally, inserts containing the milling material—in this instance, aluminum chips—occupied half of the mill jar, with the remaining quarter left empty to facilitate the cascading effect. The rotational speed of the mill jar was closely monitored during grinding. Theoretical calculations indicated that the mill jar should operate at 175.66 rpm. However, to induce the cascading effect due to the mixture of differently sized milling balls, the speed of the mill jar needed to be increased to 240 rpm. The higher rotational speed allowed the milling balls to lift and cascade down the side of the mill jar, imparting the necessary impact force on the aluminum chips to promote particle size reduction. The predominant mode of particle size reduction in this system was through impact and friction between the milling media and the material [12].

Fig. 4 presents a visual comparison of the material's condition before and after four hours of continuous milling at three different speeds, using a specific size of stainless-steel ball with a diameter of 10 mm. The tests were conducted to observe the effects of different speeds, starting with a minimum speed of 240 rpm, then progressing to a medium speed of 500 rpm, and finally reaching a maximum speed of 1500 rpm. Challenges encountered during the milling process prompted a reassessment to enhance productivity. Employing a single milling speed in the initial attempt resulted in issues such as agglomeration and uneven milling. To address this, a method utilizing different speeds was adopted. This approach effectively mitigated agglomeration and ensured a more uniform milling force distribution, as shown in Fig. 5. The key to the success of this optimized milling process lay in the careful tuning of parameters like rotational speed and jar shape, which collectively enabled the desired particle size reduction and homogenization of the powder [13].

Fig. 4 *Experiment before milling*

Fig. 5 illustrates the notable improvements in particle size distribution and process efficiency after increasing the milling speed. Emphasizing the critical nature of selecting the appropriate media blend to optimize output and elevate the quality of the end product is essential. Furthermore, an additional improvement was introduced to refine the milling process. This entailed the incorporation of a fixed bar to augment the cascading effect within the mill jar during material grinding. Acting as a catalyst, the fixed bar boosted the cascading effect, facilitating a more regulated movement and enhancing impact and shear forces, consequently leading to a more significant reduction in particle size. This aligns with the findings reported in the literature, where the authors observed that the high-speed rotation and revolution of the mill jar and disk, respectively, generate strong ball movements, resulting in fine grinding and mechanochemical phenomena [14] [15].

Fig. 5 *Aluminums chips after 500 rpm milling*

Fig. 6 shows the aluminum chips have turned to powder after 4 hours of milling; it's observed that particle breakage intensifies with the prolonged presence of milling media. Maintaining a constant load on the particle bed is considered energy efficient in milling. These findings illustrate a particle breakage size distribution for product sizes across various milling stages. In essence, discovering the optimal balance between rotational speed and milling duration mirrors the quest for achieving the most favorable milling outcomes. Through trial and experimentation, it becomes apparent that the rotational speed and milling time are the two pivotal parameters for maximizing efficiency in the milling process. Theoretically, maintaining a rotational speed of 175.66 rpm, in proportion to the milling time, ensures efficient and successful milling, resulting in the desired particle size and uniformity. When the ball mill operates at higher rotation speeds, it can facilitate the effective chipping or fragmentation of the processed material. The optimal ball milling speed depends on factors like the initial aluminum powder characteristics, ball-to-powder ratio, milling duration, and the desired final properties of the aluminum powder. Typical ball milling speeds used in aluminum powder metallurgy range from 135-200 rpm. The rotation speed of the ball mill should not surpass 600 rpm to prevent excessive heating and potential thermally induced reactions between the specimens and the milling media (jar and ball) [16].

Fig. 6 *Aluminium chips after 4 hours of milling*

According to the data in Table 2, it is evident that under both medium-speed (500 rpm) and full-speed (1500 rpm) milling settings, the average size of the milled material diminishes as milling time increases. At medium velocity, the average size decreased from 1.02 mm after 2 hours to 0.26 mm after 10 hours. Correspondingly, at maximum velocity, the average size decreased from 1.08 mm to 0.29 mm throughout the same time intervals. During milling, a consistent pattern was observed indicating that extended periods produced finer particle sizes.

Table 2 *Average value for the particle size with different milling time and milling speed*

Time (hours)	Average (mm^2)	
	Medium Speed (500 rpm)	Full Speed (1500 rpm)
2 hours	1.02	1.08
4 hours	0.50	0.56
6 hours	0.35	0.38
8 hours	0.31	0.34
10 hours	0.26	0.29

Fig. 7 illustrates the relationship between milling speed and particle size reduction over time. As the milling speed approaches the optimal level of 176 rpm, a significant improvement in particle size reduction is observed. Increasing the speed from the experimental levels of 500 rpm and 1500 rpm to this optimum enhances the efficiency of the milling process, resulting in smaller particle sizes. However, operating beyond this optimum range, such as at 500 rpm and 1500 rpm, does not yield additional improvements in particle size reduction. While higher milling speeds generally promote finer grain sizes due to increased kinetic energy, excessive speeds can lead to negative effects, such as increased agglomeration and the cold welding of powders. This phenomenon highlights the importance of balancing speed to achieve optimal results. The findings suggest that operating near the optimum speed of 176 rpm is advantageous for producing finely milled powders consistently. However, exceeding this threshold may adversely affect particle size distribution and efficiency. To achieve optimal results in powder metallurgy, it is recommended to utilize moderate milling speeds near the optimum range. This ensures consistent production of finely milled powders while minimizing issues like agglomeration and cold welding. These insights emphasize the critical role of milling speed in optimizing the ball milling process for desired outcomes. The results presented in this study demonstrate the effectiveness of the small milling machine designed for powder metallurgy applications. The observed particle size reduction over time suggests that the milling machine's configuration supports efficient energy transfer to the powder particles, a crucial factor in achieving effective comminution. [15][17].
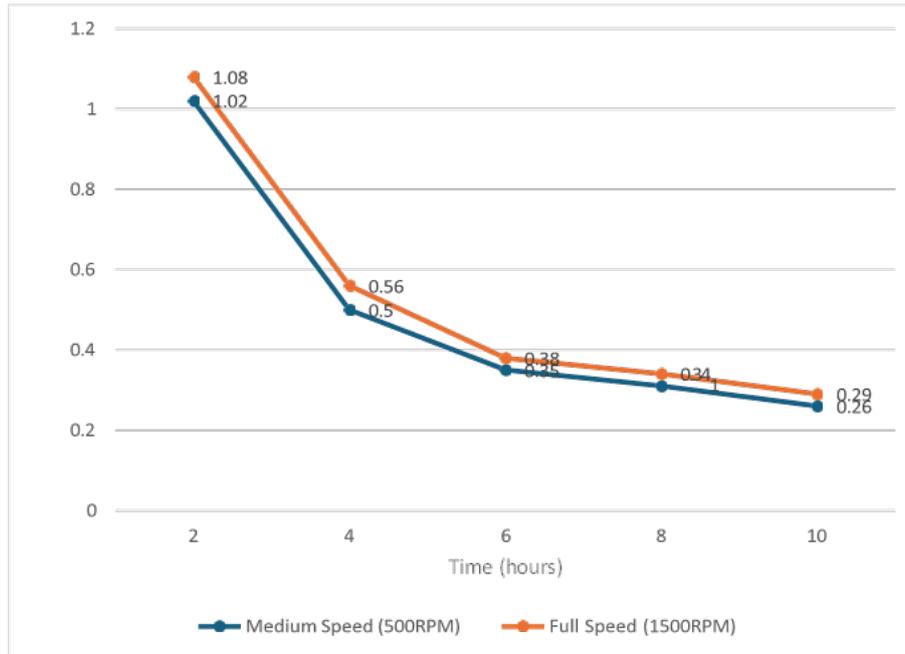
Fig. 7 *Graph average particle size (mm²) compared to time (hours)*

Conclusion

This study successfully achieved the two main objectives of designing and evaluating a two-axis ball mill machine for powder milling. The machine was effectively fabricated and demonstrated its ability to grind aluminum chips into fine powder, with smooth and consistent operation of the electrical system. The relationship between rotational speed and milling time was established, highlighting these parameters' critical role in achieving effective milling. Extended milling times yielded finer particle sizes, as the milling media's kinetic energy significantly influenced particle breakage. Experimental results showed a reduction in chip size from 1.02 mm to 0.50 mm at average speed and from 1.08 mm to 0.56 mm at full speed after four hours of milling. These findings validate the efficiency of the two-axis ball mill machine and its suitability for applications requiring precise powder production. Future work could focus on optimizing milling parameters for different materials and exploring scalability for industrial applications.

Acknowledgement

Conflict of Interest

Authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Ahmad Syakir Fisal, Wan Nur Azrina Wan Muhammad, Md. Nor Anuar Mohamad;* ***data collection:*** *Ahmad Syakir Fisal, Wan Nur Azrina Wan Muhammad, Md. Nor Anuar Mohamad;* ***analysis and interpretation of results:*** *Ahmad Syakir Fisal, Wan Nur Azrina Wan Muhammad, Md. Nor Anuar Mohamad;* ***draft manuscript preparation:*** *Ahmad Syakir Fisal, Wan Nur Azrina Wan Muhammad, Md. Nor Anuar Mohamad. All authors reviewed the results and approved the final version of the manuscript.*

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