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Optimization of the high energy ball-milling: Modeling and parametric study

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ABSTRACT

In the present study, the effect of not so much discussed milling parameters such as vial to plate spinning rate, ball size distribution and type of balls on the performance (energy) of the high energy ball milling has been investigated for the first time. Furthermore, different scenarios that lead to an increase in the BPR such as the powder weight loss, the increase of diameter and the number of balls are analyzed and their effects on the efficiency of the milling are discussed. The important point is that contrary to the previous studies in which the milling parameters were independently investigated, in this research the effects of the milling parameters on the performance of the mill are simultaneously investigated. The results showed that the powder weight loss can greatly enhance the performance of milling, while the increase of the number of balls at high BPR ratio, has a quite negative effect on the milling performance. Besides, excessive rise in the ball size distribution is associated with adverse outcomes in the milling efficiency, especially when the number of balls increases. Furthermore, the balls made of tungsten carbide compared to those of silicon nitride and steel have a more positive effect on the milling efficiency especially when the weight of powder is reduced. A mathematical model is also introduced to analyze the effect of milling parameters on the milling energy and the obtained results are compared with the experimental ones. According to the results obtained, if the vial to plate spinning rate is 1.2, the mill has a better performance however, by increasing the diameter of the balls, this ratio is changed to 1.4.

1. Introduction

High energy ball milling (HEBM) is known as an economic, simple and yet powerful method for the production of nanostructured and amorphous materials [1]. The prolonged milling of powder mixtures, results in the formation of supersaturated solid solution, non-equilibrium intermetallic compounds as well as the formation of silicides, nitrides, stable or unstable carbides [2]. The kind of the products made during HEBM depends on the composition of the powders and milling conditions and for different systems are summarized in milling maps [3]. It was also reported that the enhancing energy during milling, resulted by the increase of ball to powder weight ratio (BPR) and vial speed not only can accelerate the formation of the products but also changes the resultant phases [4]. As is clear from the name of HEBM, the balls play an important role in its efficiency so that a small change in type, shape, weight and size distribution of the balls can dramatically affect the milling process [5]. So far, a lot of modeling processes have been performed regarding the impact of the change of milling parameters specially BPR on the performance of HEBM [6–11]. All of these modeling efforts share a drawback, namely they have not investigated the effect of the milling parameters on the performance of HEBM in the presence of BPR changing, simultaneously. However, the HEBM process has a dynamic environment to the effect that all the involved parameters simultaneously play a key role in its performance, [3]. This requires that the effect of parameters during HEBM process be simultaneously checked in order to provide favorable conditions for an optimal milling process.

In the present study, it has been investigated for the first time, the effect of not so discussed milling parameters such as vial to plate spinning rate, ball size distribution and type of balls on the efficiency (energy) of HEBM. In addition to the experiments carried out in this respect, a theoretical model has been developed based on Burgio's model [12] and its accuracy has been evaluated.

2. Materials and methods

The milling system used in the present research was a planetary ball mill (Fritzsch Pulverisette P6) with a steel vial of 250 ml volume and

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Table 1
Summary of the milling parameters that lead to BPR changing.

BPR	Weight of powder (g)	Number of balls	Ball diameter (mm)	Weight of ball (g)	Total weight of balls (g)	Type of BPR
5	13.56	5	15	13.56	67.8	BPR_p
8	8.47	5	15	13.56	67.8	BPR_p
12	5.65	5	15	13.56	67.8	BPR_p
17	3.99	5	15	13.56	67. 8	BPR_p
23	2.95	5	15	13.56	67.8	BPR_p
5	13.56	5	15	13.56	67.8	BPR_d
8	13.56	5	17.5	21.52	107.61	BPR_d
12	13.56	5	20	32.12	160.63	BPR_d
17	13.56	5	22.5	45.74	228.7	BPR_d
23	13.56	5	25	62.74	313.73	BPR_d
5	13.56	5	15	13.56	67.8	BPR_n
8	13.56	8	15	13.56	108.48	BPR_n
12	13.56	12	15	13.56	162.72	BPR_n
17	13.56	17	15	13.56	230.52	BPR_n
23	13.56	23	15	13.56	311.88	BPR_n

steel balls. To investigate the effect of BPR, three different tests were conducted. In the first experiment the number and diameter of the balls remained constant (according to Table 1) and the weight of powder began to decrease during which the obtained BPR was named BPR_p. In the second experiment, the number of balls and the weight of powder were fixed and the increase of the ball diameter led to the increase of BPR which was named BPR_d. In the third experiment the diameter of the balls was increased and the other two parameters remained constant as is shown in Table 1. Here, BPR_n is used. As is clear from Table 1, in each case, we tried that the BPR (BPR_P, BPR_d, BPR_n) rises from 5 to 23. In each of the above mentioned tests, the effects of the ball type, ball size distribution and vial to plate spinning rate (ω_v/ω_p) on the HEBM efficiency were analyzed, in a simultaneous manner. To study the effect of ball type, steel, silicon nitride (Si_3N_4) and tungsten carbide (WC) balls were used. Besides, the effect of the distribution of the balls with the same diameter ($S = 1$), with two different diameters ($S = 2$), to five different diameters ($S = 5$) was also analyzed. For investigation of the effect of ω_v/ω_p on the HEBM efficiency, different ratios of 1, 1.1, 1.2, 1.3 and 1.4 were used for milling and the obtained results were compared with each other. Raw materials used in this study were titanium dioxide (TiO_2), aluminum (Al) and boron oxide (B_2O_3), which all were manufactured by Merck of Germany. X-ray powder diffraction diagram was obtained with a Panalytical X'Pert Pro instrument (Eindhoven, The Netherlands) equipped with a θ/θ goniometer, Cu Kα radiation source (40 kV, 40 mA), secondary Kβ filter, and an X'Celerator detector. The diffraction diagram was scanned from 20° to 60° (2θ) in step-scan mode with a step size of 0.05° and a counting time of 80 s/step. To search for ignition time in the combustion system, a digital thermometer was used that reported the outside temperature of the milling vial from beginning to end of milling process.

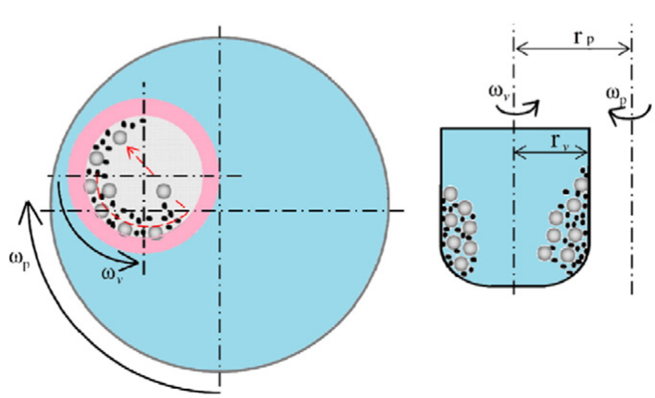

Fig. 1. A schematic diagram of the planetary ball mill and the vial.

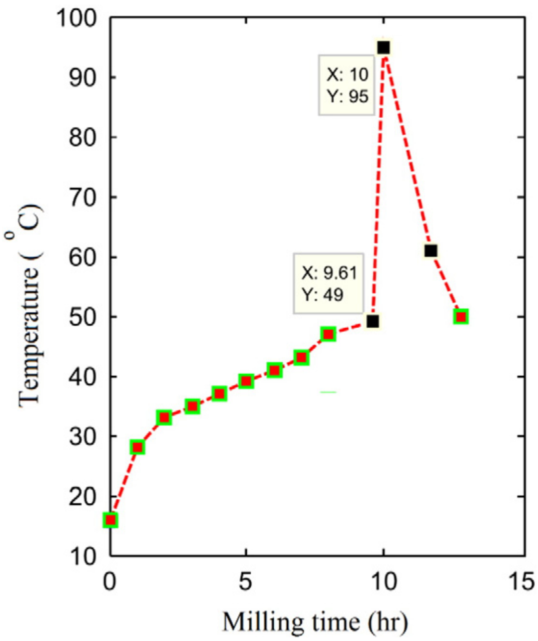

Fig. 2. Sudden increase in the vial temperature after ignition in TiO_2, Al, B_2O_3 system.

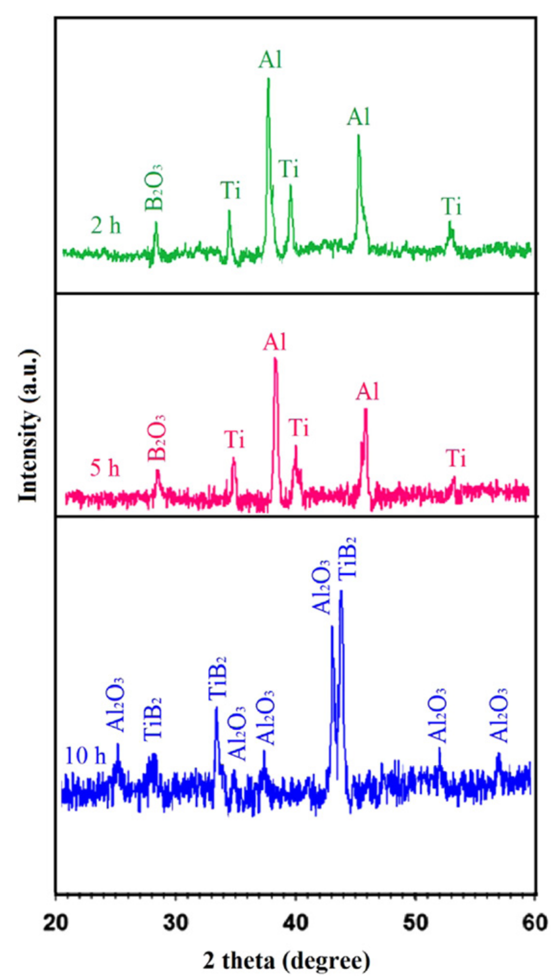

Fig. 3. XRD patterns of TiO_2, Al, B_2O_3 milled powders before and after ignition.