Measuring the impact velocities of balls in high energy mills

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Abstract

A simple methodology for the experimental determination of impact velocities in ball mills used for the synthesis of nanophase materials is proposed. The impact velocity of the balls relative to the vial walls is determined from the indent size. A model correlating velocities with indent radius is described. Velocities were determined for the Spex mill (1.8–3.3 m s^{-1}) and for a new high capacity mill (2.6–3.8 m s^{-1}) and were found to be strongly dependent on ball size.

1. Introduction

High energy milling was first employed in materials science (as "mechanical alloying") for the production of composite metallic powders with a fine controlled microstructure [1]. More recently, the method has been used to obtain amorphous alloys [2, 3] and, in general, to drive a wide range of solid state reactions leading to the synthesis of compounds (carbides [4] and intermetallics [5]), or to reduction and exchange reactions (synthesis of composites [6]). The products obtained are nanocrystalline (crystallite sizes typically in the range 10–20 nm) with a high potential for technological applications [7].

The process of high energy milling, performed in ball mills, is characterized by the repeated impact of the grinding medium (balls) on the charge material. Among the key parameters [8] characterizing the process, the impact speed of the balls is one of the most important (together with the impact frequency) in determining the rate of mechanical energy transfer to the charge and therefore the overall kinetic behavior.

The few existing estimations of ball speeds in high energy mills are based on kinematic considerations [8, 9]. The purpose of the present work was to propose a simple experimental method to determine the impact velocities of the balls with the vial walls in ball mills. This method is based on the correlation which can be established between ball indentation size (on a soft-target material) and its velocity.

2. Impact of a hard ball on to a target material

The type of deformation induced by the impact of a body on a target material is largely determined by a dimensionless number [10] (best number, BN) $BN = \rho V^2/Y_d$ (where ρ and Y_d are the density and dynamic yield strength of the target material, and V is the impact velocity of the body). Values of BN below 10^{-5} correspond to deformations in the elastic range, whereas for BN greater than 10^{-4} plastic deformation prevails [11].

In the plastic deformation range a correlation can be established [11] between the relative impact velocity V of a sphere with a target material and the indentation of radius a, assuming normal impact and that the hardness of the sphere material is greater than that of the target:

$$V^2 = \pi m P_d a^4/2R \qquad (1)$$

where m is the ball mass, P_d is the dynamic pressure and R is the ball radius.

Equation (1) can be used to evaluate the speed of the impacting ball, by measuring the indentation radius a, having determined the value of P_d. The ratio P_d/P_m (where P_m is the mean contact pressure) is largely constant [11, 12] for a given target material (typical values are [11, 12] steel 1.28, brass 1.32, copper 1.35, lead 1.58).

In the fully plastic deformation range the ratio P_m/Y (Y is the yield strength of the target material) was determined to be constant with a value equal to 3 [11]. The value of P_d can therefore be easily obtained (from the yield strength of the target material), and eqn. (1) can be used to calculate the velocity of impact from the measured indentation radius.

A fully plastic deformation is assumed [11] when the value of the non-dimensional strain is

$$E^*a^*/YR \gtrsim 30 \qquad (2)$$

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where a^* is the indentation radius assuming plastic deformation (under this assumption $a^*=a$) and E^* is defined as

$$E^* = \left[\frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2}\right]^{-1}$$

in which ν and E are the Poisson ratio and Young's modulus respectively.

To make use of eqn. (1), under the constraint set out in eqn. (2), for the estimation of ball impact velocities in high energy mills, it is therefore necessary to choose a target material which (i) gives rise to a BN greater than 10^{-4} (plastic deformation range) therefore allowing $a^*=a$ to be assumed in eqn. (2) (given that the typical ball velocity range in high energy mills is 2–5 m s^{-1} [8, 13]), (ii) satisfies eqn. (2), (iii) for which the ratio P_d/P_m is already known, and (iv) gives rise to easily measurable indentations.

The above conditions are all satisfied by the choice of copper. The following conditions are assumed: (i) velocity range 1.5–5 m s^{-1}, (ii) ball radius range 3–15 mm, (iii) steel balls, (iv) copper yield strength 150 MPa (from tensile test), (v) range of indentation radii 0.3–3 mm, and (vi) $P_d/P_m=1.35$ [11, 12]. Under these assumptions, the best numbers are always greater than 10^{-4}, whereas the non-dimensional strains (eqn. (2)) are greater than 39. The choice of copper as target material therefore allows eqn. (1) to be used by calculating P_d as $3\,Y1.35=607.5$ MPa.

3. Experimental details

The impact velocities of balls were measured on two types of mills: (i) a commercial ball mill Spex® 8000 mixer/mill, widely used as a high energy mill for mechanical alloying and for the synthesis of nanophase materials; (ii) a high-capacity high-energy mill whose development and design have been described previously [14].

The geometic characteristics of the vials used are shown in Table 1. Plates of copper ETP (electrolytic grade, tensile strength 300 MPa) 5 mm thick were placed on one side of the vial closures as illustrated in Figs. 1 and 2 for the two mills. The plates were tightly connected to the vial body.

The balls used for the experiments were made of AISI 5210 (a ball bearing steel) with hardness 62–64 HRc and with the following diameters (in millimetres): 6.35, 9.52, 12.70, 25.40, 28.57.

The indentation radius, of a single sphere travelling in the vial oscillating under steady state conditions during 5 s, was measured as the average of the ten largest indents (therefore transient regime impacts, less than 10% of the total, were excluded) out of the total of approximately 100 generated.

The indent size was meassured as the average of two perpendicular measurements using a microhardness tester.

The impact velocities were then evaluated using two methods: (i) using eqn. (1) and the assumptions of the preceding section; (ii) using an experimental correlation (for the actual target and ball materials and ball diameter) between the indent radius and impact velocity.

Correlations as for point (ii) were established by calibrated falls of a steel (AISI 5210) ball on to a copper (ETP) plate as shown in Fig. 3.

4. Results and discussion

The correlations established between velocity and indentation radius, for five ball sizes, are presented in Fig. 4. Calibrated impact ball velocities were obtained (Fig. 3) from free fall of the ball assuming a constant acceleration of $g=9.81$ m s^{-2}. The continuous line in Fig. 4 corresponds to eqn. (1) with the assumptions described above. It appears that the model represented by eqn. (1) describes quite well the experimental correlation, and the differences in the estimated velocity between the two methods are negligible.

Although we did not follow this procedure, it may be convenient for other materials or ball diameters to "calibrate" eqn. (1). This can be done with a few experimental points (assuming that the necessary conditions for fully plastic deformation occur), and then the cali-

TABLE 1. Main geometric and kinematic characteristics of mills and vial used

Mill	Vial volume (cm^3)	Vial height (mm)	Oscillation frequency (Hz)	Maximum vial velocity (m s^{-1})	Maximum vial acceleration (m s^{-2})
Spex®	50	45	20	≈ 1.5[a]	
High capacity	1100	60	17	1.61	170

[a]Estimated.

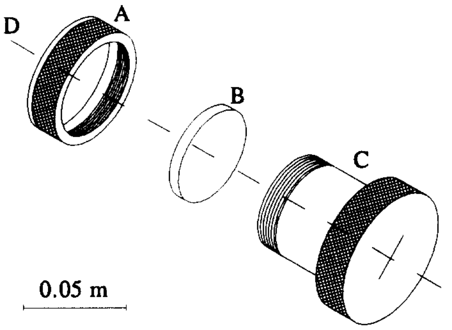

Fig. 1. Exploded view of the vial used in the Spex® mill: A screwed cap, B copper target plate, C vial body with screwed-in cap, D main oscillation axis.

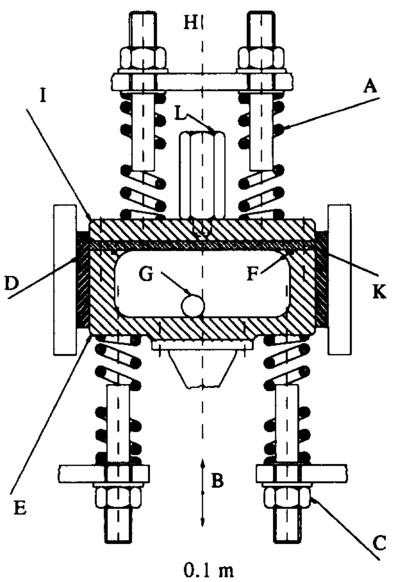

Fig. 2. Section view of the high-energy high-capacity mill: A spring, B driving force (sinusoidal-like), C nut for spring preloading, D Teflon sliding block, E vial, F O-ring, G ball, K copper target plate, I closure plate, L fluids in-out (vacuum, inert or reactive gas), H oscillation axis.

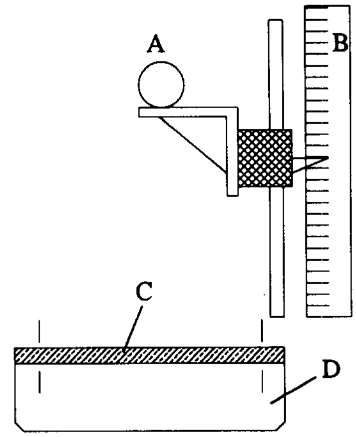

Fig. 3. Experimental set-up for correlation of the indent size with impact speeds by calibrated (B) falls of a ball (A) on to a copper plate (C) supported on a rigid body (D).

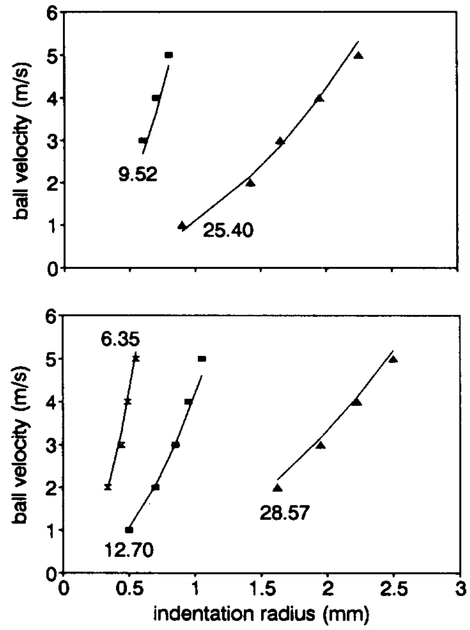

Fig. 4. Correlation of ball (steel AISI 5210) impact velocities with indentation radius (on copper plate) as determined experimentally (points) and with eqn. (1) (continuous lines). Numbers inside the figures are ball diameters (in millimetres).

brated equation can be used to determine the impact velocities, for a range of ball diameters, from the indentation radius.

However, we used the diagrams shown in Fig. 4, with the correlation expressed by eqn. (1), to estimate the impact velocities in the two types of mills. The results obtained are presented in Fig. 5.

In the case of the high capacity mill, the estimated velocities showed decreasing monotonic behaviour with the ball diameter. Impact speeds ranged from 3.85 m s^{-1} to 2.61 m s^{-1} for ball diameters of 6.35 mm to 28.57 mm. The indents were observed as having very close to round shapes, with no "pile-up" at the borders, indicating that almost normal impact occurred. The indent radius showed, for the different ball diameters, small deviations from the average value, indicating that a steady state speed is reached. The behaviour of velocities *vs.* ball diameter can be explained by considering that the travel time τ between the two plates in Fig. 2 is close to 0.5 T (T is the vial oscillation period, 0.0588 s) for ball diameters less than or equal to 12.5 mm. The travel time τ has been evaluated from kinematic considerations and using the experimental impact velocities, taking into account the restitution coefficients for

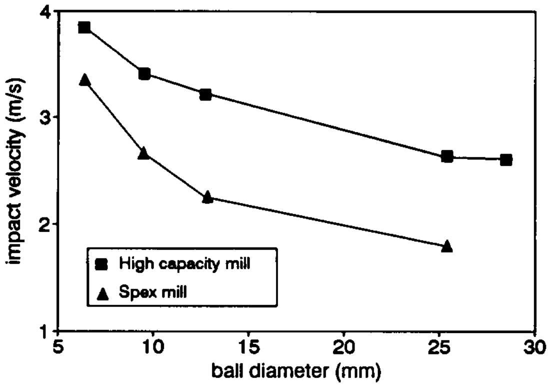

Fig. 5. Impact velocities *vs.* ball diameter for the high capacity mill and and Spex® mill.

the ball impacts [11] and the ball free path (given by the vial height less the ball diameter). The value $\tau \approx 0.5\,T$ corresponds to the resonant condition in which the vial always meets the ball at the maximum value of relative speed. For the largest diameter (28.57 mm) $\tau \approx 0.4\,T$ and therefore displacement from the resonant condition occurs explaining the observed behaviour.

From the point of view of impact velocity the above considerations imply that for given vial and ball materials, vial oscillation frequency and amplitude, and ball diameter, there exists an optimum vial height (or multiples of it) which should be taken into account in the design of the mill.

In the case of the Spex vial a monotonic decrease in impact speeds was also observed (Fig. 5), on increasing the ball diameter from 3.35 m s^{-1} to 1.8 m s^{-1}. As in the previous case, we observed here the same features on the indents (round shape and almost constant radius), implying steady working conditions, although a kinematic analysis was not performed owing to the complexity of the vial motion.

We observe, however, that in both cases a dependence of impact speeds on ball diameter is revealed. A reliable evaluation of such speeds appears to be a basic requirement for modelling [8, 15] the processes involved in high energy milling. The present work shows that impact speeds in the Spex vial are at most 3.35 m s^{-1} (and depend on ball diameter) whereas constant speeds previously assumed were 4 m s^{-1} [15] and 6 m s^{-1} [16]. These velocities would appear to be upper bounds to that achievable under practical conditions using multiple balls. The proposed experimental method may be used to estimate the distribution of ball impact velocities in the case of multiple balls, for example by image analysis of the indent radius spectrum.

5. Conclusions

The direct experimental determination of impact velocities of single balls with the vial walls in high energy mills is feasible through measurement of the indentation size.

The method requires a suitable choice of a target material where indents can be measured. Although an empirical correlation can be established between indent size and impact speeds, a reliable model is proposed according to which few "calibration" points may be needed.

The impact speeds obtained (using a copper target and steel balls) for the popular high energy mill Spex® 8000 mixer/mill are in the range 1.8–3.3 m s^{-1}. Impact speeds obtained in a high capacity high energy mill developed for the synthesis of nanophase materials [14] are in the range 2.6–3.8 m s^{-1}. The impact velocities are found to be strongly dependent on the ball size.

Acknowledgments

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