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Experimental Supports to the Energy Transfer Collision Model in the Mechanical Alloying Process

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ABSTRACT

Several attempts have been carried out in recent years in order to quantify the energy transfer phenomena occurring during the milling process. Such attempts have been substantially based on the assumption that collision is the main event by which energy is transferred from the milling tools to the powder under processing. No direct evidence, however, has been reported up to now confirming the modelisations appeared in literature. In the present work experimental measurements of the power consumption (electrical and mechanical) during milling are reported. The obtained results strongly support a collision model regardless the level of filling of the milling vessel. Further, the power measurements are in quite good agreement with those predicted by the collision model.

1. INTRODUCTION

Over the last decade several attempts at modelling have been made in order to establish predictive capabilities for the Mechanical Alloying process. Such a capability should allow to infer which energetic parameters (rotation or vibration frequencies, mass and diameter of the balls...) have to be properly considered in order to obtain one or another end product. Fundamental aspects of the process have been faced by Maurice and Courtney who tried to describe parameters like impact times, powder strain, temperature rises etc. assuming that collision is the primary event by which energy is transferred from the milling tools to the powder under processing [1]. For a planetary mill, the first comprehensive attempt has been done under the assumption that collision is the main energy transfer event [2]. We described the kinematic equations of the ball movement and gave an estimation of the energy transferred per hit, of the collision frequency and of the total power transferred. Improvements of the collision model have been reported by McCormick et al [3] and, recently, by Abdellaoui and Gaffet [4] who constructed a "dynamic phase diagram", on the basis of the calculated power injections, able to correlate results from different milling devices.

Modelisations apart, no experimental approach directed towards the quantification of the energies involved in the process has been carried out.up to now Therefore, until now, no systematic experimental investigation has been undertaken to evaluate both the energies involved and the mechanisms underlying the energy transfer.

2. COLLISION MODEL

The kinetic energy involved in each collision event can be expressed by:

$$\Delta E = K_a \frac{1}{2} m_b V_b^2 \qquad (1)$$

being m_b the mass of the ball and V_b the *relative impact velocity*. K_a is a coefficient depending on the elasticity of the collision: for K_a=0 the energy release is null (perfect elastic collision) and is total for K_a=1 (perfect inelastic collision). The elasticity of collision has been dealt with in reference [5]. In a *planetary mill,* the relative impact velocity of a ball is given by an equation of the type [2]:

$$V_b = K_b w_p R_p \tag{2}$$

where w_p and R_p are the rotation speed of the planetary mill disk and its radius, respectively. K_b is a constant that can be evaluated [6] and that primarily depends on the geometry of the planetary mill. The collision frequency of a ball can be expressed by :

$$\nu = K_\nu w_p \tag{3}$$

where K_ν is a constant that, again, mainly depends on the geometry of the mill [2]. Considering a suitable number of balls in a given vial, N_b, for which reciprocal hindering of the balls is negligible (see [2] and below), the total collision frequency is given by:

$$\nu_t = \nu N_b = K_\nu N_b w_p \tag{4}$$

Equations 2 and 3 have been derived in the original paper [2] under the assumption of inelastic collision ($K_a \rightarrow 1$) and are strictly valid for that condition. However, we assume, in a first approximation, that the equations still hold even for a regime different from the perfectly inelastic one, that is, for any K_a value provided that it *can be assumed constant in a given series of milling experiments*. We will see in the following that the assumption is realistic and is justified by the results.

The power involved in a milling process is given by the *intensive factor* of a single event, ΔE, multiplied by the number of events per unit of time (*extensive factor*), i.e.:

$$P_{mod} = \Delta E \nu_t \tag{5}$$

where P_{mod} represents the power consumption during milling predicted on the basis of a collision model. In a real milling experiment on a planetary mill, two or four vials are normally employed and the total number of balls, n_b, is given by $n_b = N_b N_v$ being N_v the number of vials used and N_b the number of balls in each vial. Using the previous equations:

$$P_{mod} = P^* \frac{1}{2} m_b w_p^3 R_p^2 n_b \tag{6}$$

where $P^* = K_a \cdot K_b^2 \cdot K_v$ is an adimensional factor. A given charge of a given experiment can be identified by the filling parameter:

$$n_v = \frac{N_b}{N_{b,tot}} \tag{7}$$

where $N_{b,tot}$ is the total number of balls, of that diameter, necessary to completely fill up the vial so that no ball movement at all is possible. Introducing the filling parameter in equation (6) gives:

$$P_{mod} = P^* \frac{1}{2} m_b N_{b,tot} w_p^3 R_p^2 N_v n_v \quad (8)$$

In a given series of milling experiments it is expected that P*, for a given planetary mill, should only depends on the K_a value and should really be a constant factor as long as the reciprocal hindering of the balls (equation 4) is negligible. It is to be noticed that the product of the mass of one ball, m_b, and of the total number of balls, $N_{b,tot}$, is practically a constant value for the ball diameters considered in the following.

3. ELECTRICAL AND MECHANICAL POWER MEASUREMENTS

3.1 - Feasibility of electrical and mechanical power absorption measurements

The energy consumption due to the collisions, predicted by the collision model, should be measured by measuring the electrical power absorption of the motor of the mill. It should be expected, in fact, that there should be some difference in the power absorption when milling with the vials filled with a given charge (process on) and with the same vials empty (no process). Further, as indicated by equation (1) (see reference [5]), the energy spent in each event is little when the collision is elastic (typically bare balls without powder) and much greater in the presence of powder when the collision becomes inelastic ($K_a \rightarrow 1$). Therefore, again, carrying out milling experiments in exactly the same configuration by changing only the elasticity of collisions, differences of power absorbed should be revealed.

In order to verify the previous points, we measured the power consumption during milling by a power meter as indicated in Fig. 1-a.

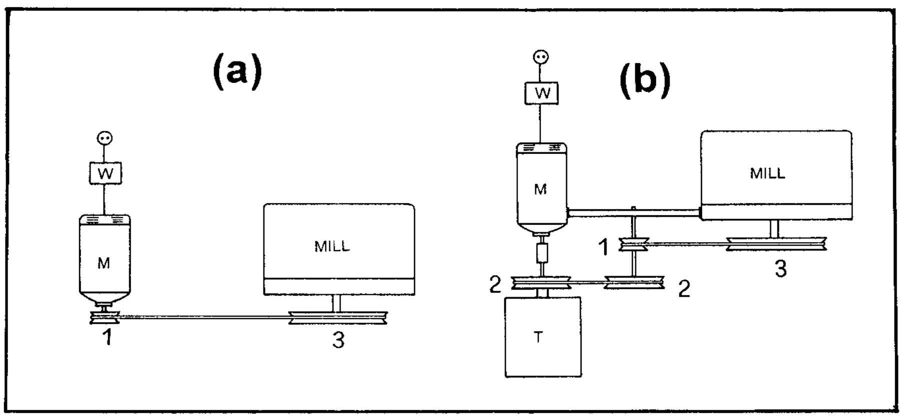

Fig. 1-*(a)* *The power consumption of the mill is measured by the power meter indicated by W in the figure. M is the electric motor.* ***(b)*** *Scheme of the direct measurement of the torque applied on the motor shaft through the torque-meter T. (1), (2) and (3) on both (a) and (b) sketches indicate different dimensions of the various pulleys.*

Figure 2-a shows the sets of data carried out with empty vials or filled with balls of different materials. The experimental data show that: (i) there is an appreciable net electrical power difference, P_e, between empty , P_e°, and filled vials, $P_e^{'}$:

$$P_e = P_e^{'} - P_e^{\circ} \tag{9}$$

and: (ii) the power absorption registered with different materials is in line with the elasticity of their collisions. The second point is better seen in Fig. 2-b where the *net power differences* between filled and empty vials are reported. With tungsten carbide the collision is much more elastic than with stainless steel. Consequently the net power consumption is much lower in the former case.

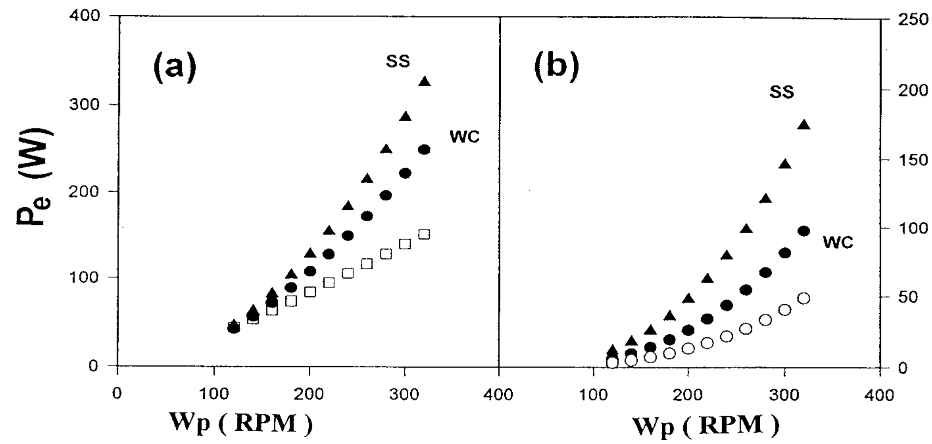

Fig. 2. *Feasibility of electrical power measurements.* ***(a)*** *The gross electrical power absorptions measured with two 250cm^3 empty vials made of stainless steel or having the inner walls coated with tungsten carbide (open squares). The same vials filled with 99 balls of 10x10^{-3} m stainless steel (SS full triangles) and with 99 balls of tungsten carbide of the same diameter (WC full circles). The powers are reported versus the rotation speed of the planetary mill disk plate expressed in RPM (rounds per minute).* ***(b)*** *The net electrical powers for SS and WC balls (full symbols). The open circles gives the electrical power with WC balls recalculated for the same weight of the SS balls.*

According to the collision model the net values shown in Fig. 2-b should obey an equation like (6). However, in doing the difference between filled and empty vials, we make the approximation of considering the yield of the motor constant in the different ranges of power consumptions that actually may vary with empty or filled vials. To directly measure the mechanical power absorptions we mounted a torque-meter on the shaft of the motor (see Fig. 1-b). From measurements of the applied torque the mechanical power absorptions are obtained and the net mechanical powers are given by the difference between filled and empty vials:

$$P_m = P_m^{'} - P_m^{\circ} \tag{10}$$

Electric and mechanical powers were measured simultaneously in a series of experiments so that a calibration curve correlating mechanical and electrical measurements was obtained. Since direct measurements of the applied torque are much longer and delicate than the simple measurements of the electrical power absorption, most of the experiments were carried out by only measuring electric power and converting it to mechanical power using the calibration curve.

3.2 - Milling experiments

The planetary mill used was the model P5 from Fritsch. Two or four stainless steel vials of $250cm^3$ were mounted in each experiment. The walls of the vials were deliberately covered with the thin layer of powder that usually remains attached at the end of a prior milling process. In our case the vials were preliminary treated with Fe-Zr powder. In this way we were able to realise rather inelastic collisions. Bare stainless steel balls of different diameters (6, 15 and mostly $10x10^{-3}$ m) were used. The vials prepared in this way were charged with a given number of balls and then the power absorption recorded as a function of the rotation speed of the planetary mill as shown in Fig. 2-a.

4. RESULTS AND DISCUSSION

The experimental results reported in Table I are in line with the predictions of the collision model. In fact, both electrical and mechanical power data (with a minor difference discussed below) can be fitted by an equation of the type:

$$P_{calc} = Kw_p^{\alpha} \tag{11}$$

with an α exponent for the rotation speed very near to the value of 3 predicted by equations 6 or 8, that is, *predicted on the basis of a collision model.*

Table I. *The α values (see text) from electrical (e) and mechanical (m) powers obtained as a function of the degree of filling of the vials n_v. d_b and m_b diameter and mass of the balls. The total number of balls used in each experiment n_b , is given by N_v (number of vials) multiplied by N_b (number of balls in each vial). (a) indicates WC balls.*

n_v	d_b [mm]	m_b [g]	n_b		α	
			N_v	N_b	e	m
0.086	6.0	0.881	2	125	3.00	3.30
0.17	6.0	0.881	2	250	2.95	3.20
0.90	6.0	0.881	2	1315	3.00	3.20
0.12	10.0	4.074	2	35	2.70	2.90
0.16	10.0	4.074	2	50	2.75	3.00
0.23	10.0	4.074	2	70	2.85	3.15
0.32	10.0	4.074	2	99	2.78	3.05
0.32	10.0	7.760(a)	2	99	2.80	3.05
0.60	10.0	4.074	2	183	3.10	3.30
0.80	10.0	4.074	2	245	3.10	3.30
0.20	10.0	4.074	4	61	2.90	3.13
0.24	10.0	4.074	4	72	3.10	3.28
0.40	10.0	4.074	4	122	3.05	3.25
0.48	10.0	4.074	4	146	3.15	3.45
0.43	15.0	13.745	4	36	2.95	3.28
0.64	15.0	13.745	4	54	3.10	3.30
0.86	15.0	13.745	4	72	3.10	3.33
					2.96(5)	**3.20(5)**

The power dependence on the third power of the rotation speed is not substantially affected by the degree of filling as shown by the values reported on the table. This evidence supports the idea that even when the vials filling is high, still collision should be regarded as the main energy transfer event. McCormick showed by video registration [3] that even at low filling the balls, once detached from the wall, rather than *fly* along a given trajectory, follow that trajectory by tumbling over one another with a *cascade* of collision events. Therefore, what in the previous models [2,4] was assumed to be a single collision event spending almost all the accumulated kinetic energy, should be rather regarded as a cascade of collision events through which the same kinetic energy is spent.

The actual results strongly support that collision is the dominant power absorbing process either considering, for each launched ball, a single collision or a cascade of collisions. Concomitant attrition phenomena, likely occurring at high levels of filling, cannot be excluded, in principle, but they can be included anyway in the present approach based on collision as the experimental results indicate.

A remark about the difference on the α values given in Table I. The electrical α value is nearer to three and lower than the one obtained by mechanical data. Admitting that the small difference is significant, we trust more an α value greater than 3 rather than lower. In fact, the final equations 6 or 8 have been derived in the assumption (amongst others) that the elasticity coefficient (K_a) remains constant for a given series of data. However, it has been clearly verified by "free fall" experiments [5] that, at higher energies (i.e. highest rotation speeds), the energy spent in the collision increases slightly faster than expected (i.e. K_a increases a little) so that the powers measured at the highest rotation speeds can be relatively higher than those otherwise registered with a constant K_a value thus justifying an α value slightly greater than 3.

Fig. 3 shows the power consumption as a function of the level of filling. This power consumption represents the answer at macroscopic level to the sum of the microscopic events occurring during the milling process. In the present work the experiments have normally been carried out without powder (one of the exceptions is presented below) but they are very close to the real milling process since the thin powder layer on the vial walls was enough to ensure a high K_a value well above the zero level corresponding to only elastic collisions. Therefore the information coming from the present results are of general interest.

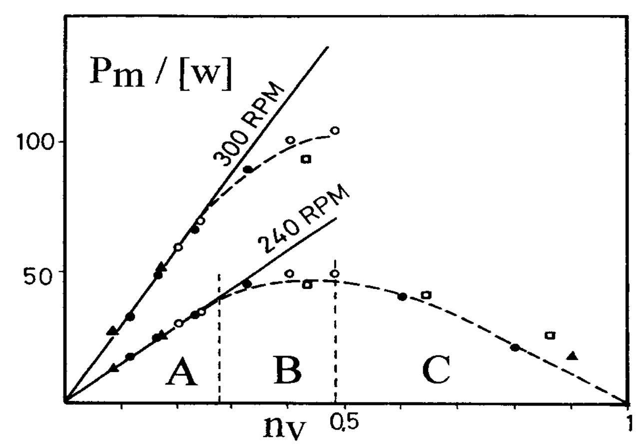

Fig. 3. *Power absorption as a function of the degree of filling n_v for two typical rotation speeds of the planetary mill (240 and 300 RPM). The different ball diameters are indicated by triangles ($6x10^{-3}$ m), circles ($10x10^{-3}$ m) and squares ($15x10^{-3}$ m). The full symbols refer to values obtained with two vials. The open ones refer to the values obtained with four vials normalised to two vials (i.e. divided by two). A, B and C indicate three different efficiency regions (see text).*

Two typical working rotation speeds (namely 240 and 300 RPM) are represented on figure 3 and several observations can be made. In a first region (A in the figure) the power consumption, at each w_p, *increases linearly* with the number of balls. Doubling the balls doubles the power consumption. The same effect is obtained by mounting 4 equally charged vials ($N_v = 4$) instead of two ($N_v = 2$) as can be seen by the perfect overlap of the open points whose original values were twice those represented in the figure. In this region we have really *no reciprocal hindering* of the balls up to about $n_v \leq 0.28$. Thus the prediction of equation (6) about a linear dependence of the power consumption with the number of balls is perfectly fulfilled. Another point is worth of attention: for each filling, at the same w_p, we *do have* the same power consumption by combining a different number of balls and a different diameter. This fact directly confirms equation (5) that is, using larger balls we will have a greater intensive factor (ΔE governed by eq.1) counterbalanced, however, by a lower extensive factor, (ν_t ,eq. 4) since a lower number of balls is needed to obtain the same filling of the vial. Above the non-hindering region, the power consumption increases less than expected (region B). In other words the efficiency with respect to the charge decreases. This is true up to a plateau value around $n_v = 0.5$. Above the plateau, the power consumption decreases in absolute value and tends towards zero (region C). We would like to point out that with completely filled up vials, the power data closely approach the values of empty vials further confirming that it is not the weight to determine the power consumption but exactly the sum of the occurring microscopic events.

In order to directly prove the validity of the power consumption predicted by equation (5) we have set up some milling experiments at low level of filling (in the non-hindering region) and with powder (to ensure at most a K_a value, to be used in equation (1), very near to one).

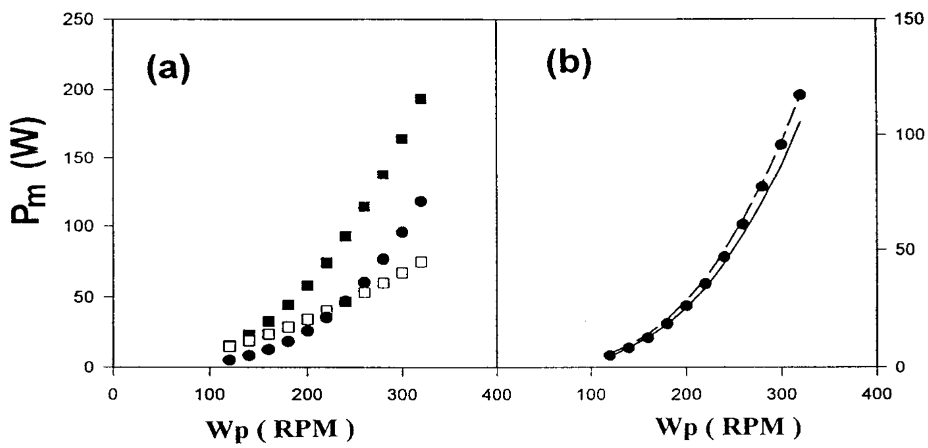

Fig. 4- ***(a)*** *Power absorption, P_m , versus the rotation speed obtained with 99 balls ($10x10^{-3}$ m) and 40 g of Fe-Zr (1:1, at%). Gross, empty and net power differences are represented by full squares, open squares and full circles respectively.* ***(b)*** *Net experimental powers (full circles) compared with theoretical ones using frequency factor from Gaffet [4] (solid line) and our modelisation (dashed line) (see text).*

Fig. 4-a shows the powers recorded in one of this experiment carried out using a Fe-Zr powder. The full symbols of Fig. 4-b shows the experimental net power differences compared with model values

obtained using equations (1) to (5) and suitable values for K_a, K_b and K_v constants. The K_a value (equation (1)) has been set equal to one. The K_b value (equation (2)) is also near to one as can be derived from the planetary mill kinematic equations [2,6]. The collision frequencies (equation (3)) have been evaluated by our model [2] and by Abdellaoui and Gaffet [4] model. The final agreement between experimental and model powers is shown in Fig. 4-b and is more than satisfactory. The agreement definitely proves that the collision model adequately describes the microscopic events occurring during milling and that, at macroscopic level, the final effect can be revealed by suitable power measurements like those described in the present paper.

5. CONCLUSIONS

The main conclusions that can be drawn from the present investigation can be summarised as follows:

1. The power consumptions due to the milling action can be revealed by suitable electric or mechanical power measurements. This has been done on a planetary mill but the principle can be extended to any milling device.

2. The experimental power measurements fit quite well with equations derived from a collision model. In particular it has been verified that the power consumption linearly depends on the number of balls in the "Non-Hindering" region and depends on the third power of the rotation speed at any level of filling.

3. Theoretical and experimental power absorptions agree quite well in experiments with powder where values can reasonably be attributed to the process constants K_a, K_b and K_v.

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