A Preliminary Model for Mechanofusion Powder Processing

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Abstract

Mechanofusion (MF) is a unique high energy powder processing technique, in which powder characteristics can be significantly modified. The effects of MF on powdered materials depend on MF operating conditions and the starting powders. This paper proposes a preliminary MF modeling concept to develop quantitative relationships among MF variables and their effects. In the modeling, an inner piece "action zone" is defined. It is believed that most MF effects are generated when the particles pass through the action zone. From the model, the pressure imposed on the powders by MF can be described via the geometry of the device, operation speed and material properties. In addition, some basic particle kinematics variables can be estimated. The results derived from the modeling are compared to reported experimental results.

1. Introduction

Mechanofusion (MF) is an advanced technology for processing powdered materials, allowing raw materials to be mechanically intermingled with sufficient energy to create a powder with new characteristics. Mechanofusion is similar to mechanical alloying, in that both utilize mechanical forces to process powdered materials. A fundamental difference is that the MF process in essence does not need ball medium, while which is an indispensable working component for mechanical alloying. However, when the medium is added, MF may be considered as a modification of mechanical alloying. In MF processing, the powders are intensively mixed and subjected to compression, attrition, frictional shearing and rolling. Therefore, mechanical-thermal energies are generated, resulting in a variety of distinct effects on powdered materials.

Many phenomenological observations of MF effects on powders have been published (1-16). However, the theoretical modeling of MF has lagged behind the experimental studies, although some schematic models for the MF effects on powders have been reported (4, 5, 11, 16). This paper attempts to establish a basic model so that the mechanism of MF can be better understood. In the following model, mathematical relationships among the device design, the operational variables and the MF effects will be proposed. The equations derived from the model will then be applied to explain some experimental results.

Most of the modeling here is a first attempt in MF research. The attempts are both simple and fundamental. More detailed investigations of the modeling will be necessary in the future.

2. Description of the Model

The modeling of particle movement is gradually developed from pure hypothetical conditions to more realistic operating situations, based on principles of mechanics, fluid mechanics and thermodynamics, as well as the geometry of the machine design. Then, a few mechanical variables are correlated, and their values are estimated. The results obtained here will provide a basis for further development.

2.1 Particles Motion without the Inner Piece

As described in Reference (5), during operation the chamber that contains the powder is spinning, while the inner piece is stationary. The powder therefore is squeezed through the gap between the
inner piece and the chamber wall. However, understanding the particle motion in a chamber without the inner piece can be considered as a starting point. As a first step, we assume that, if the inner piece is not installed or when the particles are moving in the outside region of the inner piece “action zone”, which will be defined later, the powder rotates together with the chamber at the same angular speed. Therefore, at a given chamber rotation speed, the particles are moving in a circle with constant speed, i.e., uniform circular motion. It will be convenient to deal with such motion in cylindrical coordinates \((r, \theta, z)\). Provided that the powder movement is independent of the \(z\) direction, the particle motion can be essentially described by two dimensional polar coordinates. Under the above assumptions, when the chamber rotates at an angular speed \(\omega\), a particle at a distance \(r\) from the axis through the origin \(O\) has a linear speed

\[
\nu = \omega r
\]

and a radial acceleration

\[
a_r = \frac{\nu^2}{r} = \omega^2 r
\]

By choosing the rotational chamber as a reference frame, a particle at a distance \(r\) from the axis is subjected to a centrifugal force

\[
f_c = m \omega^2 r
\]

where \(m\) is the mass of the particle.

If the powder in the chamber is also considered as a fluid, the state of the powder can be derived. Take a small volume element within the powder at a distance \(r\) from the axis with a thickness \(dr\) and an area \(A\), as indicated in Fig. 1. The mass of this element is \(\rho A dr\), where \(\rho\) is the powder density, the powder considered as a continuum. The radial forces exerted on the element are the centrifugal force \(\rho A \omega^2 r dr\), and those resulting from the pressures exerted on the element by the surrounding powder, \(PA\) and \((P+dp)A\).

Hence, for radial equilibrium

\[
PA + \rho A \omega^2 r dr = (P+dp)A
\]

rearrangement and integration of the equation gives

\[
\int_0^r dp = \omega^2 \rho \int_0^r r dr
\]

or

\[
P = P_c + \frac{1}{2} \omega^2 \rho r^2
\]

where \(P_c\) is the pressure at \(r=0\).

Therefore, the pressure imposed on the powder is proportional to the square of angular speed of the chamber.

Also, from fundamental physics and Fig. 2, we can have the slope of the powder surface, \(\tan \theta\), at a distance \(r\),

\[
\tan \theta = \frac{\omega^2}{r}
\]

and the shape of the powder surface,

\[
Z = \frac{\omega^2}{2g} r^2
\]

i.e., the surface of the powder is a paraboloid of revolution.

The equations derived above are for some basic conditions of the powder in a chamber without the inner piece or in the outside region of the inner piece “action zone” during rotation. They can be applied to understanding some experimental phenomena, which will be presented later.

2.2 Inner Piece Action Zone

Now take into account the effects of the inner
The inner piece action zone mentioned above is defined as the first half region between the inner piece and the chamber wall, whose cross-section is marked by ABCD* in Fig. 3, as we look downward on it from above, along the z-axis. It is believed that most MF effects are generated while the particles pass through this region.

For the powder within the inner piece action zone, ABCD, three major interactions may occur: inner piece-particles, particles-particles, particles-chamber wall. Here, only the small volume of the powders, the area labeled by AA'B'B in Fig. 3, is selected for analysis, and the particles contained inside the small volume are treated as an assembly. The system interactions with the inner piece and the chamber wall will be investigated. The relationships among the particles within the assembly are more complex and need to be further examined.

When the assembly enters the action zone, those particles immediately touching the inner piece or the powder within the small volume as a whole are subjected to the inner piece tangential force \( f_i \). The average tangential force is related to the velocity of the particles by

\[
 f_i = \frac{\Delta M \nu}{t} + f_w
\]

where \( M \) is the mass of the assembly, \( \nu \) represents the particles velocity, \( t \) is the time required for the particles to pass through the zone (or move from line AB to CD in Fig. 3), \( \Delta M \nu \) is the change momentum of the particles during the time \( t \) and \( f_w \) is the tangential force of the chamber wall acting on the particles.

If the powder is assumed to be a compressible fluid, and the particles are considered to have the same angular speed during their motion through the action zone (i.e., all powder in AA'B'B will move to CC'D'D after time \( t \)), we can introduce a compression ratio \( R \), which is defined as:

\[
 R = \frac{V_{AA'B'B}}{V_{CC'D'D}}
\]

or

\[
 R = \frac{AB}{CD} \frac{AB}{D_g}
\]

where \( V_{AA'B'B} \) is the volume of the powder in AA'B'B, and \( V_{CC'D'D} \) is the volume of the same powder in CC'D'D. \( R \) is then determined by the geometry of the inner piece and the gap distance \( D_g \), which is adjustable.

The above hypotheses may apply only to some powders under certain conditions. In reality, the particles in AA'B'B may not move into CC'D'D concurrently. For a given powder, the higher chamber rotation speed, the actual compression ratio will be closer to that expressed in Eq. (8), since the powder with the higher speed has more momentum to push through the gap.

The volume change of the powder during moving through the action zone is due to a pressure imposed on the system. From thermodynamics, the relationship between the pressure (thus, forces) and the volume can be established through the compressibility of a system, which is defined as

\[
 \beta = -\frac{1}{V} \left( \frac{dV}{dP} \right)_T
\]

\( \beta \) is the compressibility factor, or the fractional decrease in the volume of the system for unit increase of pressure acting on the system at constant temperature. The \( \beta \) depends on the material. \( V \) is the volume of the system, and \( P \) is the applied pressure. The negative sign is used in order to make \( \beta \) a positive number.

Thus, for an isothermal process (the temperature effect can be ignored here),

\[
dP = -\frac{1}{\beta} \left( \frac{dV}{P} \right)
\]

and integrating Eq. (10) with assuming that \( \beta \) is constant** gives

\[
P = P_0 + \frac{1}{\beta} \ln \frac{V}{V_0}
\]

or

\[
P = P_0 + \frac{1}{\beta} \ln \frac{AB}{D_g} = P_0 + \frac{1}{\beta} \ln R
\]

Where \( P_0 \) is the initial pressure, and \( V_0 \) is the initial volume.

*We assume that the particle movement is independent of \( z \) direction, so in the following paragraphs the three dimensional issues are described in the terms of two dimensions.

**Note: \( \beta \) for the assembly may vary during the system passing through the action zone.
Equation (12) indicates that pressure (compression or forces) acting on particles increases with reducing gap distance, \(D_g\), or with increasing compression ratio, \(R\).

The pressure can be converted to radial force, \(f_r\), and for particles sliding over the inner piece, \(f_r\) is connected to tangential force, \(f_t\), by

\[
f_t = \mu f_r	ag{13}\]

where \(\mu\) is the friction coefficient.

The tangential forces are linked to shear and attrition. These forces are most responsible for grinding and friction. Also, a pair of tangential forces, such as \(f_t\) and \(f_{rw}\), can exert a torque on the particles. It is this torque that causes the rolling of the particles and provides the fundamental mechanism for particle shape spheroidization. The radial forces are more related to compression and yield deformation and fragmentation or coalescence of the materials.

### 2.3 Particle Kinematics in the Inner Piece Action Zone

A primary analysis of the kinematics of particles will offer valuable information about particle motion during MF. The maximum relative velocity \(v_{\text{max}}\) of a particle with respect to the inner piece (i.e., slide velocity or impact velocity) can be calculated from the particle linear speed in Eq. (1), i.e.,

\[
v_{\text{max}} = \omega R s\tag{14}\]

where \(\omega\) is the particle angular speed, and \(R_s\) is the radius of the chamber wall. For a rotation speed \(\omega\) of 2500 rpm or 262 rad/s and the MF unit used in this research with radius \(R_s\) of 0.075 m, the maximum relative velocity \(v_{\text{max}}\) can be as high as 20 m/s.

From Eq. (14), the minimum time required for a particle to travel through the action zone (i.e., the duration of each pass) can be estimated by the following formula,

\[
t_{\text{min}} = \frac{BC}{v_{\text{max}}}\tag{15}\]

For a \(v_{\text{max}} \approx 20\) m/s and \(BC \approx 0.025\) m, the \(t_{\text{min}}\) is about \(1.25 \times 10^{-3}\) s.

At the other extreme, if we hypothesize that a particle only rolls through the inner piece action zone without sliding, then the maximum turns of rolling, \(N_{\text{max}}\), for the particle during passing through the action zone, are approximated by

\[
N_{\text{max}} = \frac{AD}{\pi d}\tag{16}\]

where \(AD\) is the length of the arc in Fig. 3, and \(d\) is the particle diameter.

For a particle size of 30 micrometers or \(3 \times 10^{-5}\) m and an arc \(AD\) of 0.025 m, theoretically the particle has to make over 260 turns to pass through the action zone. However, a more realistic condition of particle movement in the action zone should be a combination of rolling as well as sliding with respect to one-another.

We can now apply the above results to explain the phenomena observed in the experiments.

### 3. The Model and Reported Data

The relationships of rotation speed-loading-force were reported by Yokoyama et al. (2) using a chamber diameter of 35 centimeters to process talc powder with an average size of 44 micrometers. Their results are presented graphically in Figs. 4, 5 and 6. Here, efforts are made to interpret these figures based on the fundamental model proposed above.

#### 3.1 Relationship of Loading and Force at a Given Speed

In Fig. 4, when a small charge is processed at a given low speed, the tangential force \(F_t\) exerted on the inner piece is small. As the load increases, the \(F_t\) increases accordingly. This can be explained roughly as follows. When the chamber rotates, there is a centrifugal force imposed on the powder, Eq. (3), in addition to gravity and forces among the particles. As a result, the surface of the powder within the chamber will appear as a parabolic shape, as indicated by Eq. (6), i.e., the powdered material rises near the chamber wall and descends as it approaches the center. At a given speed, the shape of the surface is fixed. For a small quantity of
powder, the inner piece is subjected to only minor action from the particles. Adding the charge increases the entire surface level, as shown in Fig. 7, and more particles will interact with the inner piece, yielding a larger $F_t$. Therefore, the curves shift upward with increasing loading at a given speed. This is more obviously shown in the first part of each curve or at lower charges in Fig. 4.

3.2 Relationship of Loading and Force at Varying Speeds

In Fig. 4, the starting point of each curve is observed to depend on the rotation speed. This may be due to the following. When the chamber rotation speed is increased, the shape of the powder surface within the chamber will change correspondingly. According to Eq. (5)

$$\tan \theta = \frac{\omega^2 r}{g}$$

the slope or $\tan \theta$ for a point on the surface at a distance $r$ from the axis increases with angular speed, $\omega$. For a limited quantity of charge, the powder will be pushed up and outward to the cham-
ber wall, as shown in Fig. 8, so that its surface can satisfy the Eq. (5) condition.

Furthermore, from Eq. (4)

$$P = P_c + \frac{1}{2} \omega^2 \rho r^2$$

the pressure exerted on the particles also increases, resulting in a higher density of the powder. This means that for a given charge, the higher the rotation speed, the smaller the volume. Those two factors decrease the interaction area between the powder and the inner piece, especially for the relatively small amount of charge, since the inner piece is located at some distance away from the chamber wall, as illustrated schematically in Fig. 8. Consequently, the higher the rotation speed, the smaller is $F_t$. The $F_t$ may even be reduced to zero. Thus, the starting point of the curves is shifted with the rotation speed. The following paragraphs will further clarify this issue.

A phenomenon similar to pinning in ball milling will take place under the following two conditions. If the chamber rotation speed exceeds a critical value, which will be discussed in the next paragraph, the centrifugal force can “pin” the particles against the chamber wall, and if the volume of the charge $V$ is also smaller than a critical volume $V_c$, the powder will form as a thin layer on the surface of the chamber wall with a thickness less than the $D_g$. This layer can pass through the gap without interaction with the inner piece. The critical volume $V_c$ is given below,

$$V_c = 2\pi rhR_sD_g$$

where $R_s$ is the radius of the chamber wall, $h$ is the height of the chamber, $D_g$ is the gap distance.

A particle will be pinned if its weight

$$W = mg$$

is balanced by vertical frictional force $f_v$. Using Eq. (3) gives

$$f_v = \gamma f_r = \gamma m \omega^2 R_s$$

where $m$ is the mass of the particle, $g$ is the acceleration due to the gravity, $\gamma$ is the coefficient of static friction, $\omega$ is the angular speed, can be expressed as $2\pi n$.

The rearrangement of Eq. (19) gives

$$n_c = \frac{1}{2\pi} \sqrt{\frac{g}{\gamma R_s}}$$

This value $n_c$ is the critical speed in revolutions per second for pinning particles. The critical volume determined in Eq. (17) can also be considered as the minimum volume of powder required for the MF process, which is about 60 cm$^3$ for the unit used in this research.

Thus, when processing at 800 rpm, there is no force exerted on the inner piece until 800 g of talc is loaded, Fig. 4. Once the charge exceeds the critical volume expressed in Eq. (17), the powder has to "squeeze" through the gap, so the $F_t$ increases steeply, approaching saturation.

### 3.3 Relationship of the Radial Force $F_c$ and the Rotation Speed

Yokoyama et al. (2) also reported that the radial force $F_c$ acting on the inner piece varies with the rotation speed, Fig. 5. $F_c$ displays a linear increase with the rotation speeds, $n$, in a log-log plot. This indicates that the relationship between $F_c$ and $n$ can be expressed approximately by

$$F_c = \lambda n^q$$

where $\lambda$ and $q$ are experimental constants.

From the model of particle motion proposed in this study, when the powder first enters the action zone, or AA'B'B in Fig. 3, the initial pressure $P_0$ is given by Eq. (4), and is rewritten as

$$P_0 = P_c + \frac{1}{2} (2\pi n)^2 \rho r^2$$

Hence, the pressure exerted on the inner piece in Eq. (11) becomes

$$P = P_0 + \frac{1}{2} \ln \frac{V}{V_0} = P_c + \frac{1}{2} (2\pi n)^2 \rho r^2 + \frac{1}{2} \ln \frac{V}{V_0}$$

Equation (23) implies that the radial force $F_c$ is a function of $n^q$. This result basically agrees with the linear relationship between the force and the rotation speed in the log-log plot shown in Fig. 5, i.e., the derived expression Eq. (23) is consistent with the empirical formula Eq. (21).

### 3.4 Relationship of Force and Material

It is no surprise that $F_t$ also varies with the processed materials, such as polystyrene and talc investigated by Yokoyama et al. (2) and presented in Fig. 6. Because the compressibility factor $\beta$ in
Eq. (23) depends on the material and powder characteristics, a soft material such as the polystyrene polymer will be expected to have a large \( \beta \) value, i.e., easier to be compressed as compared to talc. Therefore, as can be found in Eq. (23) and Fig. 6, force created in MF processing of the talc will be larger than that in MF processing of the polystyrene.

4. Conclusion

In this paper, through introducing a inner piece action zone, a primary MF model is established. Based on the model, the derived equations indicate that the pressure (force) acting on particles is proportional to the square of angular speed of the chamber, and increases with decrease in gap distance. These results are consistent with the reported data. The model also predicts that the forces imposed on powders vary with the processed materials, as has been observed by other researchers. Some basic particle mechanical variables can also be estimated from the model. For a rotation speed of 2500 rpm and the small MF unit (AM-15F) used in this research, which has a radius of 0.075 m, the maximum particle velocity can be as high as 20 m/s. Correspondingly, the time required for a particle to pass through the action zone is about \( 1.25 \times 10^{-3} \)s. For a particle size of 30 micrometers, the particle may need to make over 260 turns to roll through the action zone. The minimum volume of powder required for processing is about 60 cm\(^3\).

5. References

1) Yokoyama T., Urayama K., and Yokoyama T., KONA No. 1, 53-63 (1983).
2) Yokoyama T., Urayama K., Naito M., Kato M. and Yokoyama T., KONA No. 5, 59-88 (1987).
3) Yokoyama T., Urayama K., Kato M., Herman H. and Chen Z., Proc. of Second World Congress Particle Tech., Kyoto, Japan, 591-598 Sept. (1990).
4) Herman H., Chen Z.J., Huang C.C. and Cohen R., J. of Thermal Spray Technology, Vol. 1, No. 2, 129-135 (1992).
5) Chen Z.J., Herman H., Tiwari R., Huang C.C. and Cohen R., Proc. Inter. Therm. Spraying Conf., Orlando, edited by Berndt C.C., ASM International, Metals Park, OH, 355-361 (1992).
6) Chen Z.J., Herman H., Huang C.C. and Cohen R., "High-Temperature Ordered Intermetallic Alloys V", Materials Research Society Sym. Proc., Vol. 288, edited by Baker L., Darolia R., Whittenberger J.D. and Yoo M.H., Material Research Society, Pittsburgh, PA, 835-840 (1993).
7) Chen J et al., J. of Powder Metall., vol. 29, No. 4, 316 (1993).
8) Chen Z.J., Ph. D. Dissertation, State University of New York at Stony Brook, NY, U.S.A. (1996).
9) Bernard D., Usmani S., Chen Z.J., C.C Berndt, H. Herman, Yokota O., Grimaud A and Fauchais P., "Thermal Spray Industrial Applications", edited by Berndt C.C. and Sampath S., ASM International, Metals Park, OH, 171-178 (1994).
10) Brogan J.A., Gross K.A., Chen Z., Berndt C.C and Herman H., "Thermal Spray Industrial Applications", edited by Berndt C.C. and Sampath S., ASM International, Metals Park, OH, 159-164 (1994).
11) Alonso M., Satoh M. and Miyanami K., Powder Technology, 59, 45-52 (1989).
12) Alonso M., Satoh M. and Miyanami K., KONA, No. 7, 97-105 (1989).
13) Davich K., Powder and Bulk Engineering, 50-54, Feb. (1990).
14) Ito H., Umakoshi M., Nakamura R., Urayama K. and Kato M., Proc. of 4th National Thermal Spray Conference, Pittsburgh, PA, edited by Bernecki T.F., ASM International, Materials Park, Ohio, 405-410 (1992).
15) Naito M. and Yoshikawa M., KONA No. 7, 129-132 (1989).
16) Tanno K., KONA, No. 8, 74-82 (1990).
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