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The Study on Behavior of Attrition Surface Grinding

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Abstract- The purpose of this study was to develop a model to analyze and evaluate the behavior of attrition surface grinding in separating the coat-layer from the substrate. In this paper, two types of kinetic grinding models were developed to describe the attrition grinding behavior of double-decked materials. A new evaluation diagram of the CG-FW relationship was demonstrated. We find that the attrition force was first applied to the sharp edges or corners of the sample, which was mainly composed of an alumina/ceria phase, resulting in the generation of fine particles with a high CG from the sample. The grade was gradually decreased with increasing grinding time and that the CG-FW relationship was mainly determined by the original feed properties, whereas the grinding conditions had no effect on this relationship.

Keywords- *Waste Management, Attrition Surface Grinding, Recycling*

I. INTRODUCTION

Previous studies have shown that the predominant mechanism of attrition is surface abrasion generated by collisions among parent particles during the running process [1]. Nevertheless, there are two different attrition mechanisms: (a) particle impact attrition, which occurs when particles collide with the vessel wall, and (b) particle–particle surface abrasion, which occurs when particles flow against each other. The impact attrition rate is dependent on the total impact surface area of the particles, the number of impacts, the particle velocity, and the material properties of the particles [2]. The rate of particle-particle surface abrasion is dependent on the particle velocity and its material properties. These mechanisms ensure that solid particles undergo attrition, which results in an increased fractional weight of fine particles and a reduced fractional weight of parent particles. These influential parameters of attrition rate change over time. A number of reports in the literature have studied attrition grinding and are summarized in the following sections.

A. Gwyn attrition grinding rate

Gwyn (1969) obtained an empirical equation based on a large number of attrition experiments for silica-alumina catalysts [3]:

$$FW = k \times t \times m \qquad (1)$$

where FW is the weight fraction of fine particles attrited (i.e., ground into fine particles) from the feed particles; t is the grinding time; m is an exponent that is approximately constant for a given feed particle size; and k is a constant that is a function of the initial particle size. The attrition rate of particles of the same size can be expressed by a simple function of the initial diameter and grinding time, shown in (1). The Gwyn model has been applied to a number of other attrition experiments [4]. This model indicates that attrition grinding mainly proceeds by surface abrasion, which is caused by the action of particles sliding over each other, rather than fragmentation, which is caused by collisions between particles.

B. Impact attrition

Zhang (1994) investigated the mechanism of impact attrition based on the fracture mechanics of subsurface lateral cracks [5]. In that study, a 1 mm cubic NaCl crystal was impacted against a glass target at a velocity of 10 m s−1, and the impact attrition grinding process was observed by high-speed photography, as shown in Fig. 1. The result of the impact grinding is shown in Fig. 2.

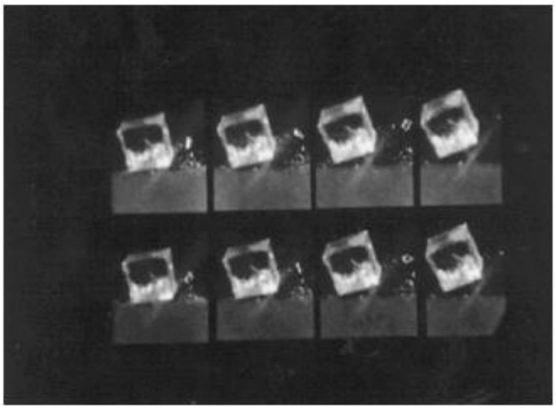

Figure 1. High-speed photographs of the impact of a cubic 1 mm NaCl crystal on a glass target at an impact velocity of 10 m s^{-1} (Zhang, 1994)

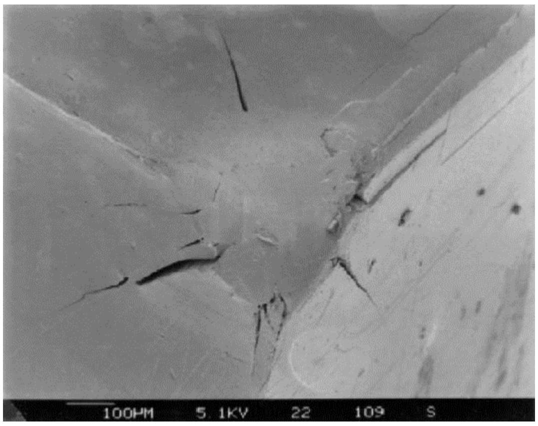

Figure 2. SEM of the impact damage to the corner of a 1 mm NaCl cube at an impact velocity of10 m s^{-1} (Zhang, 1994)

The result observed by high-speed photography indicated that attrition was a chipping process and that material was removed from the corners and edges of the particles. In their analysis, the volume of material bounded by these cracks and the fine particles generated on the surface were considered to be readily detached from the impact site. This volume can be estimated from the depth and length of the lateral cracks, which depend on the material properties and impact velocity.

C. Ouchiyama model

The Ouchiyama model, based on a population balance method, has been used to evaluate the results of attrition surface grinding under various grinding conditions. Many theoretical studies have been devoted to the kinetic analysis of grinding and attrition [6][7], which Ouchiyama modified in his model. Nakajima and Tanaka (1974) proposed the “selection function” and “breakage function” to analyse the grinding equation [8]. According to the kinetic theory of surface grinding, the size distribution of particles in the grinding process can be described by an integral-differential equation, which includes the concepts of the selection and breakage functions [9]. In this model, an integral-differential equation based on population balance was established to describe the process of attrition surface grinding, which is assumed to contain bulk and surface grinding. This equation was solved with a few assumptions: (1) the sample particles were spherical and of pure and uniform compositions, and (2) the particle size distribution produced by bulk grinding followed the Gaudin–Schuhmann distribution. The aforementioned studies focused only on pure single-phase samples. In the present work, the studied sample was a double-decked material, and the sample material itself (i.e., PGM-bearing alumina) was coated on a cordierite substrate. The purpose of this study was to develop a model to analyse and evaluate the behaviour of attrition surface grinding in separating the coat-layer from the substrate.

II. Models of Surface Grinding Behaviors of Double-Decked Material

A. Conventional model (Model A)

The conventional concept of attrition surface grinding holds that the coat-layer composition material is first attrited and separated from the parent particle. Then, the attrition impact affects the previously covered (and newly exposed) material surface, as shown in Fig. 3. In this study, a sample particle was composed of coat-layer (i.e., the red-colored part), which covered the substrate (i.e., the blue-colored part). In this 2D model of attrition grinding, TW_c(t) and TW_s(t) are the total weights of the coat-layer and substrate in the parent particle, respectively. The initial weight ratios of the coat-layer and substrate in the feed are $TW_c(0)$ and $TW_s(0)$, respectively. If the total weight of the feed particles (*TW*) is assumed to be the unit basis weight, $TW_c(0)$ can be assumed to be the coat-layer grade of the feed. *FW*(t) is the weight ratio of fine particles ground from the parent feed particles. If the attrition occurred following Model A, the Coat-layer Grade in the fine product, *CG*(t), can be calculated by the (2), and Fig. 4 can be obtained:

$$CG(t)=\begin{cases}100, TF(t)\le TW_c(0)\\ \dfrac{TW_c(0)}{FW(t)}, TW_c(0)<TF(t)\le 1\end{cases} \tag{2}$$

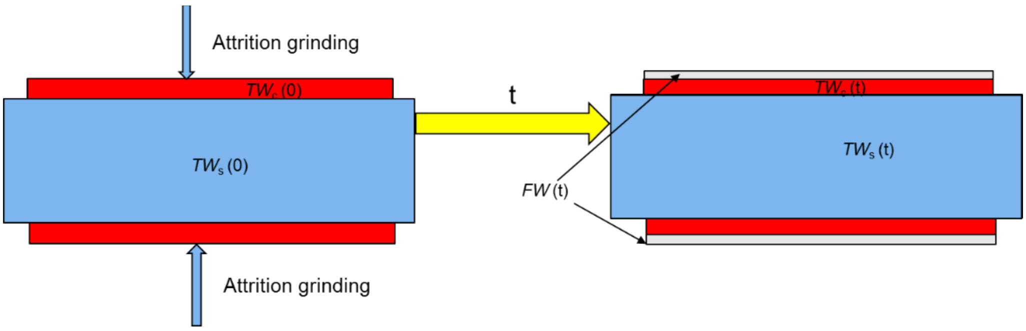

Figure 3. Model A: Conventional attrition grinding model of the double-decked sample

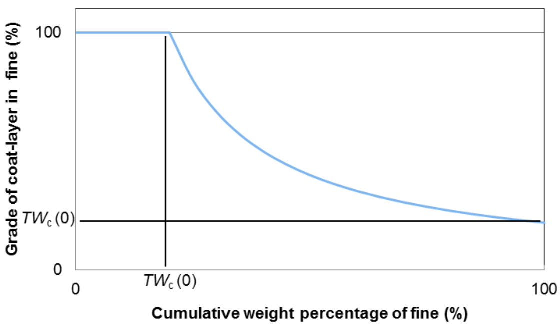

Figure 4. Calculation results of Model A showing the grade of the surface component in fine particles as a function of the cumulative weight of fine particles

Based on Model A, the fine particles were produced from the coat-layer. Thus, the grade was 100% at the onset of attrition grinding. The particle thickness was reduced as a function of the grinding time. The grade of the coat-layer in the fines approached $TW_c(0)$ (i.e., the initial grade of the feed sample) at the end of the grinding (i.e., all particles were ground into fine particles).

B. Introduction of the new model (Model B)

Fig. 5 shows the typical shape of a double-decked particle before and after attrition grinding (feed size of 0.6-1.18 mm, sample volume ratio of 0.5, and grinding time of 2 min) as observed by microscope. The images indicate that both phases, the coat-layer and substrate, were abraded to certain degrees. Fig. 5 (a) shows the image of the feed (before grinding). The alumina/ceria phase covers most of the cordierite surface, and the boundary line approaches the edge of feed particle. After 2 min of attrition grinding, the boundary of the coat-layer (i.e., the alumina/ceria phase) and the substrate (i.e., the cordierite) moved to the right toward the particle, indicating that the area of the coat-layer was rapidly reduced and the substrate was more widely exposed on the particle surface. This observation also indicates that the coat-layer has a higher attrition grinding rate than the substrate. We also measured the particle thickness at the middle section and found that the local thickness did not change significantly during attrition grinding. In an earlier study (Zhang, 1994), attrition grinding was first carried out on the corners and edges of a sample. Then, continuous surface grinding was carried out on the covered material, with newly exposed corners and edges.

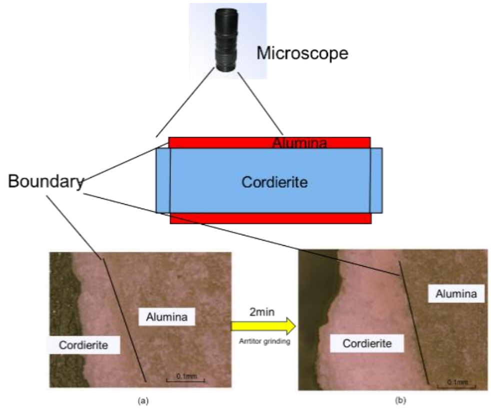

Figure 5. Change in the phase boundary between the coat-layer and substrate (a) before and (b) after 2 min of attrition grinding

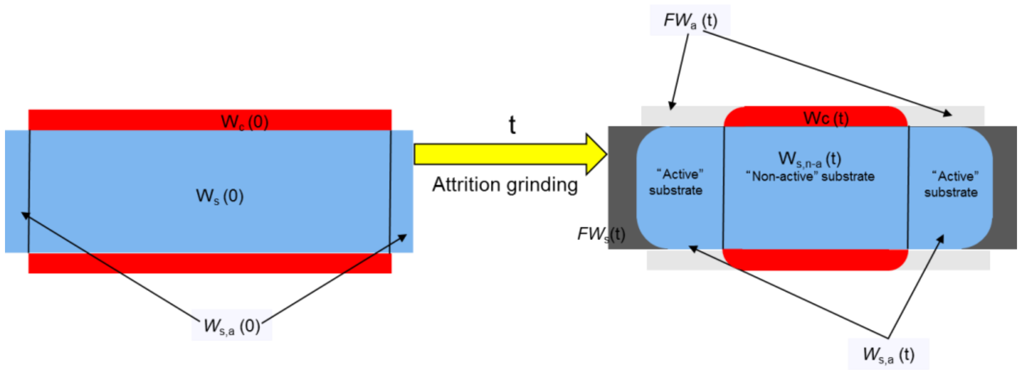

Figure 6. Model B of attrition surface grinding for a double-layered sample

Fig. 6 shows a new 2D model, Model B, for describing the attrition grinding of double-decked particles, in which most of the substrate (i.e., the blue-colored part) is covered by the coat-layer (i.e., the red-colored part). The exposed sections of the substrate are defined as the "active" weight of the substrate (Ws,a). In the process of attrition grinding, the corners of the coat-layer and substrate are first attrited and separated from the parent particle into fine particles; the subsequent attrition grinding occurs on the newly exposed surface. The attrition grinding is carried out from the outside to the inside of each layer of the particle. However, the attrition grinding rates of the coat-layer and substrate are different, as determined by the value of the "active" weight of these two layers and the composition properties. Because the attrition ratio of the coat-

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layer was larger than that of the substrate, the interfacial boundary between the coat-layer and substrate moved inside the particle.

The residual weight of the coat-layer (i.e., the alumina/ceria phase) and the substrate (i.e., the cordierite phase) are defined as $TW_c(t)$ and $TW_s(t)$, respectively, which are functions of the grinding time t. The initial condition is shown in (3):

$$TW_c(0) + TW_s(0) = 1 \tag{3}$$

Because the entire coat-layer is initially exposed on the surface, the total weight of the coat-layer can be assumed to be the "active" weight, which can be defined as the exposed weight on the surface attached by attrition force. Based on (1), the Gwyn attrition rate and the weight of the alumina/ceria phase abraded from a parent particle can be calculated by (4), where m and k_c are the Gwyn grinding rate exponents of the coat-layer, which vary with the initial particle sizes and grinding conditions (e.g., rotation speed and media ball content).

$$FW_c(t) = TW_c(0) \times k_c \times t^m \tag{4}$$

For the cordierite substrate, which is covered by the coat-layer, the "active" weight is less than the total weight of the cordierite phase at any grinding time, as shown in Fig. 6. The "active" weight of the substrate is assumed to be $W_{s,a}(t)$. Equation (5) is the weight balance of the substrate during attrition grinding. Here, $FW_s(t)$ is the weight of fine particles attrited from cordierite. $FW_{s,n-a}(t)$ is the "non-active" weight of the substrate, which is covered by the coat-layer and thus cannot generate fine attrition particles.

$$W_{s,a}(t) + W_{s,u-n}(t) + FW_s(t) = TW_s(0) \tag{5}$$

In this process, the attrition rate of cordierite depends on the grinding time and the "active" weight. Thus, the attrition grinding rate of the substrate can be calculated by (6):

$$\frac{dFW_s}{dt} = W_{s,a}(t) \times \frac{d\left(k_s \times t^m\right)}{dt} = W_{s,a}(t) \times k_s \times m \times t^{m-1} \tag{6}$$

where k_s is the Gwyn grinding rate of the substrate. The cumulative weight of fine particles attrited from the substrate, $FW_s(t)$, is calculated as

$$FW_s(t) = \int_0^t W_{s,a}(t) \times k_s \times m \times t^{m-1} dt \tag{7}$$

The "non-active" weight of substrate, $W_{s,n-a}(t)$, i.e., the substrate covered by the coat-layer, changes with the grinding time such that $W_{s,n-a}(t)$ is proportional to the weight of the coat-layer, as shown in (8):

$$W_{s,n-a} = \frac{TW_c(t)}{TW_c(0)} . TW_s(0) = TW_c(0) . \left(1 - k_c . t^m\right) \tag{8}$$

Combining (6)-(8), (5) can be written as (9) as a function of $W_{s,a}(t)$:

$$W_{s,a}(t) + \int_0^t W_{s,a}(t) \times k_s \times m \times t^{m-1} dt = TW_s(0) \times k_c \times t^m + W_{s,a}(0) \tag{9}$$

The total weight ratio of the fine particles from the coat-layer and substrate, $FW(t)$, to the feed weight is shown in (10):

$$FW(t) = FW_c(t) + FW_s(t) \tag{10}$$

The fine particle coat-layer grade, CG(t), can be calculated as follows:

$$CG(t) = FW(t) / (FW_c(t) + FW_s(t)) \tag{11}$$

III. Calculation Results and Discussion

A. New evaluation standard of attrition grinding using the relationship between the Coat-layer grade and fine particles weight (CG-FW diagram)

The fine particles weight abraded (*FW*) from the sample surface increased with grinding time, while Coat-layer Grade (*CG*) in the fine particle product decreased with grinding time. The above relationship describes the attrition grinding behaviours: the coat-layer, which was on the surface, first contacted the media balls and were ground into fine particles, especially at the corners and edges. Then, the covered substrate was exposed as the new grinding ("active") surface. The Coat-layer Grade (*CG*) of the fine particles was initially higher and subsequently decreased following attrition grinding. To describe the trend, we used two indices: the Coat-layer Grade (*CG*) of the fine particles and the Fine particles Weight (*FW*) of the feed samples. A *CG-FW* curve was introduced to evaluate the effects of selective surface attrition grinding.

The *CG-FW* curve reflects the trends of *CG* and *FW*. Ideal surface grinding refers to initial surface attrition grinding in Model A; the *CG* value is 100% under these conditions. However, this condition cannot be achieved in practice. High-efficiency surface grinding refers to the preferential breakage of the coat-layer into fine particles. This results in higher-grade fine particles attrited from the coat-layers. As a result, the *CG-FW* curve shifts to the top right, as shown in Fig. 7.

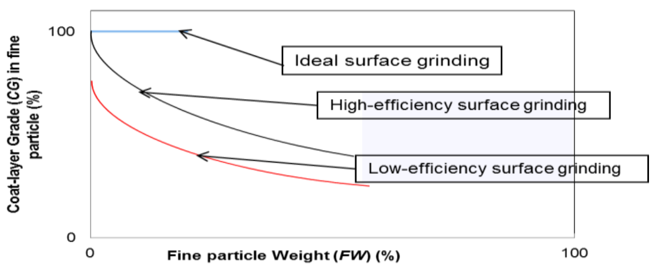

Figure 7. Three typical *CG-FW* curves

B. Calculation procedure

The calculations were designed to be consistent with the experimental results. To this end, fine particles produced by attrition were defined to be within the range of -75 µm. Attrition grinding was performed for 4 min. For numerical calculations, the following parameters were introduced as follows:

$$a=\frac{k_c}{k_s}, b=TW_s(0) \ \textit{and} \quad n=W_{s,n-a}(0) \qquad (12)$$

where a is the ratio of the attrition rate of the coat-layer to the attrition rate of the substrate, b is the initial weight percentage of the substrate, n is the initial "active" weight of the substrate, and $0 \leq n < b < 1$. Equation (9) is reduced to (13), which indicates that the grade was determined by the following five parameters: k_c, m, a, b and n. These five parameters can be divided into two groups: k_c and m represent the rate of *FW* generated from the parent particles, and these values were primarily determined by the grinding conditions, such as the rotation rate and the volume ratio of media ball to sample; a, b, and n represent the ratios of the attrition grinding rates between the coat-layer and the substrate, the initial weight percentage of the substrate, and the initial weight percentage of the active substrate based on the feed sample, respectively. The values of a, b, and n were determined by the property of the samples: a represented the grindability of the two components, b represented the grade of the coat-layer in the feed, and n was determined by the sample shape.

$$W_{s,a}(t)+\int_0^t W_{s,a}(t)\times a\times k_c\times m\times t^{m-1}dt = b\times k_c\times t^m + n \qquad (13)$$

In the calculation process, the "active" mass of the substrate, $W_{s,a}(t)$, was determined by the mass balance of the substrate during surface grinding, as shown in (13). The value of the "active" mass of the substrate as a function of the grinding time, $W_{s,a}(t)$, was determined by the values of the five parameters. The rate of the fine particle weight produced from the substrate, ${dFW_s}/{dt}$, is proportional to the "active" mass of the substrate, $W_{s,a}(t)$, as shown in (7); thus, the fine particle weight produced from the substrate, FW_s, was obtained. The fine particle weight produced from the coat-layer was obtained by (4). To determine each of the above parameters, all other parameters were assigned suitable constant values. Then, the *FW* and *CG* values were obtained as functions of the grinding time.

C. Calculation results

Example calculations of the *CG* of the fine particles as a function of the produced *FW*, i.e., *CG-FW* curves, are illustrated in Figs. 8-11. In each example, the total grinding time was set to 4 min. The *CG-FW* curve of Fig. 8 was obtained by using various Gwyn indices, k_c and m. This result shows the influence of the grinding conditions on attrition grinding. The other three *CG-FW* curves, Figs. 9- 11, used various values of a, b and n. These results illustrate the influence of the type of feed particle used.

The results of the calculations for Model B highlight several important features of attrition grinding for double-decked samples:

1- The plots in Fig. 8 show the results for various Gwyn indices. The rate of attrition grinding is higher at the beginning of the grinding and subsequently decreases, as shown in Fig. 8 (a). The Coat-layer grade in fine product was reduced rapidly, as shown in Fig. 8 (b). The above phenomena can be attributed to the following: attrition grinding began on the sample corners, which were primarily composed of the alumina/ceria phase, resulting in the generation of high-grade fine particles; the exposure ("active" weight) of the cordierite phase increased over time, resulting in a reduced grade of the fine product from the coat-layer. The *FW* and *CG* of the fine particles were both influenced by the value of the Gwyn attrition indices, which were dependent on the grinding conditions.

2- Although three groups of different Gwyn indices led to different *FW* and *CG* values of the fine product, as shown in the *CG-FW* curves in Fig. 8 (c), these results followed similar trends. This observation indicates that the Gwyn indices, k_c and m, had no effect on the efficiency of the *CG-FW* distribution in the process of attrition grinding. This curve reflects the efficiency of a specific attrition grinding, regardless of the grinding conditions of the media ball content or the grinding time.

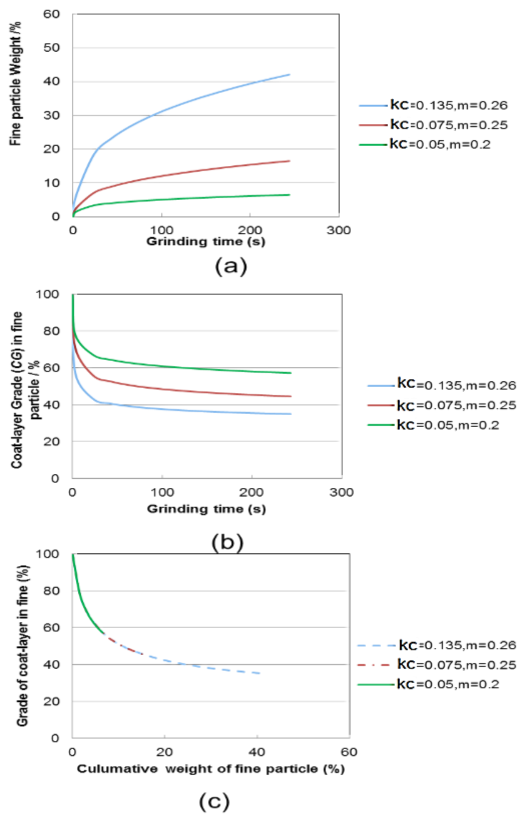

Figure 8. Calculation results showing Coat-layer grade of the fine particles, *CG*(*t*), versus grinding time (a), the fine particle weight, *FW*(*t*), versus grinding time (b), and the *CG*(*t*)-*FW*(*t*) distribution for *a*=4, *b*=0.75 and *n*=0

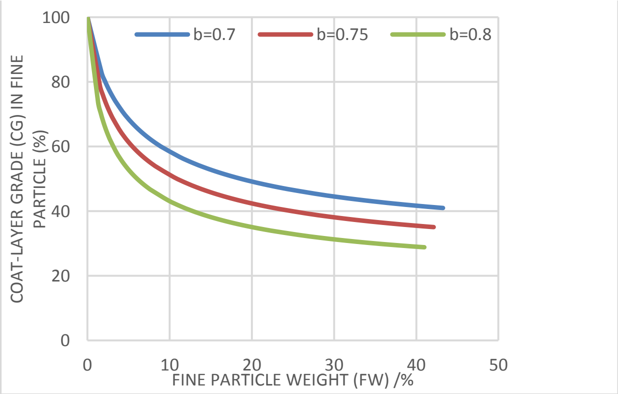

Figure 9. Calculation results showing the coat-layer grade of the fine particles, *CG*(t), versus the ratio of fine particles, *FW*(t) (k_c=0.75, m=0.25, b=0.75 and n=0)

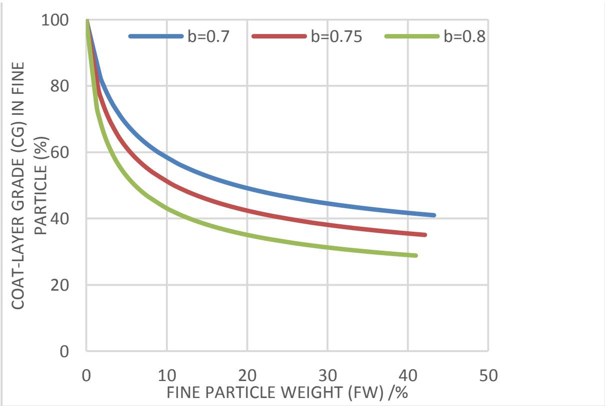

Figure 10. Calculation results showing grade of coat-layer in fine particle, *CG*(t), versus the ratio of fine particles, *FW*(t) (k_c=0.75, m=0.25, a=4, and n=0)

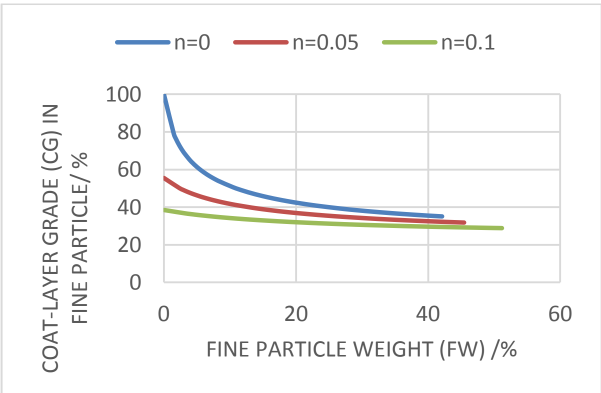

Figure 11. Calculation results showing grade of coat-layer of fine particles, *CG*(t), versus the ratio of fine particles, *FW*(t) (k_c=0.75, *m*=0.25, *a*=4, and *b*=0.75)

3- The effect of the initial characteristics of the sample, parameters *a*, *b* and *n*, on the *CG-FW* curve are shown in Figs. 9-11. The results indicate that the parameters influenced the *CG-FW* curves significantly: the curves shift to the top right at (1) higher ratios of the coat-layer to substrate attritions, (2) higher grades of the coat-layer feed, and (3) lower initial "active" mass of cordierite.

These results indicate that the grinding condition can affect the attrition rate but cannot change the grinding mechanisms, which were determined by the feed sample characteristics, including the shape, the initial grade of the coat-layer, and the ratio of the attrition rates of the compositional two phases.

Fig. 12 shows the experimental results and theoretical curves of Models A and B between the *FW* and *CG*. Experimental data were obtained from attritor grinding for each feed fraction. The numbers "0.2", "0.5" and "0.8" represent the mean ratios of the sample volume to the total volume. Here, the curves of Model A were calculated by (2), and the curves of Model B were determined by the least-squares regression method. the coat-layer of each product fraction obtained by two-stage crushing was fed into the attritor grinder: 29 wt.% of small particles, 24 wt.% of middle particles, and 21 wt.% of large particles. The initial weight of substrate, *n*, is known for the calculation of Model A and the fitting of Model B: 0.71 for small-sized feed particles, 0.76 for middle-sized feed particles and 0.79 for large feed-sized particles.

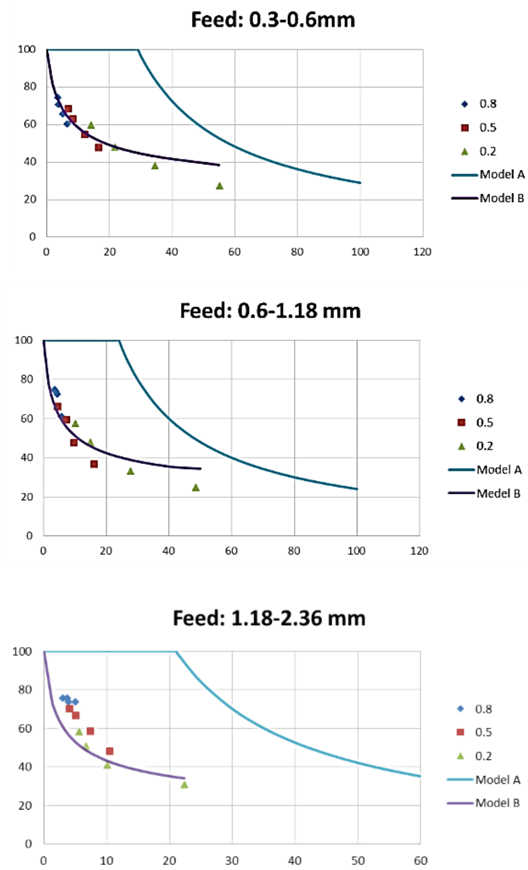

Figure 12. CG-FW distribution of fine particles (-75 µm) for each feed fraction, and the calculation results of Models A and B

The curves of Model B predict the experimental results more accurately than those of Model A. Therefore, the behaviour of attrition grinding more closely follows Model B. The *CG-FW* distribution was determined by the properties (e.g., shape, weight ratio, grindability) of the two compositional phases.

IV. CONCLUSIONS

In this paper, two types of kinetic grinding models were developed to describe the attrition grinding behaviour of double-decked materials. A new evaluation diagram of the *CG-FW* relationship was demonstrated. The findings are summarized as follows:

1- In the attrition grinding process, the outer coat-layer surface is gradually separated from the surface. Model A was not able to describe the practical behaviour. In Model B, fine particles were initially generated from the edges or corners of both phases. Attrition then gradually proceeds into both phases but at a different grinding rate. These results were in good agreement with the experimental data. The above results indicate that the attrition force was first applied to the sharp edges or corners of the sample, which was mainly composed of an alumina/ceria phase, resulting in the generation of fine particles with a high *CG* from the sample. The grade was gradually decreased with increasing grinding time.

2- Five parameters were introduced into Model B and divided into two groups: the Gwyn indices, k_c and m, and the indices of the original property of the two-component feed material, a, b, and n. The former group represents the rate of fine particle generation from the parent particles, and the values were mainly determined by the grinding conditions, such as the stirring rate and the volume ratio of the media ball to the sample. The latter group, a, b, and n, represents the ratio of the attrition grinding rates between the coat-layer and substrate, the initial weight ratio of the substrate and the initial weight of "active" substrate in the feed, respectively. These results show that the *CG-FW* relationship was mainly determined by the original feed properties (a, b, and n), whereas the grinding conditions (k_c and m) had no effect on this relationship.

V. APPENDIX

$CG(t)$: Grade of the coat-layer of fine product	[wt.%]
FW: Weight of fine product abraded feed particle	[wt.%]
FW_c: Weight of fine product abraded from coat-layer	[wt.%]
FW_s: Weight of fine product abraded abraded from substrate	[wt.%]
k_c: Constant of Gwyn attrition grinding equation for coat-layer	[-]
k_s: Constant of Gwyn attrition grinding equation for substrate	[-]
m: Exponent of Gwyn attrition grinding equation	[-]
t: Attrition grinding time	[s]
$W_c(0)$: Initial weight ratio of coat-layer	[wt.%]
$W_s(0)$: Initial weight of substrate	[wt.%]
$W_{s,a}(t)$: Active weight of substrate	[wt.%]
$W_{s,n-a}(t)$: Weight of substrate covered by the coat-layer	[wt.%]

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