Effects of Tensile Strength and Tensile Breakup Energy on Mulling Processes of Wet Powders

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Abstract

The dynamic mixing power required for mulling process of green mold sands was measured by using various types of kneaders and binding materials. A series of tensile tests for the green mold sands were carried out. The surface structures of the sands were also observed by a scanning electron microscope.

The state of mulling of the sands was found to be successfully correlated with the tensile strength, the tensile breakup energy and the compression characteristics of the sands. It was also found that the completeness of mulling process could be assessed by observing the steadiness of the power for mulling, and that it could be evaluated in terms of the tensile breakup energy. The more the power for mulling was required, the better the state of mulling was.

1. Introduction

Mixing of wet powders in the pendular and funicular states is usually achieved by mulling operation. This operation is extensively utilized not only in chemical industry but also in various kinds of other industries such as food, ceramics and foundry. Despite its considerable importance from the engineering point of view, few studies on mulling engineering have been reported. Suitable design of mulling process, choice of kneaders and analysis of their operational data may be facilitated by a standardization of the methods for evaluating various properties of solid-liquid systems and mulling power requirement.

The author and his co-workers conducted a series of tensile tests on the solid-liquid systems in pendular, funicular and capillary states, and reported the characteristics of the wet powders in terms of the breakup displacement-moisture content relations. They also analyzed the relationship between the tensile strength and the mixing torque of the wet powders. At the present stage, however, the state of mulling in wet powders is still evaluated in terms of the degree of mixing by human sensory judgement or rheological morphology, and these methods permit only a qualitative assessment. It can also be said that the relationship between the power requirement for mulling and the tensile breakup energy of the mixture product has not become clear yet.

In this study, the mixing torque or the mixing power for mulling of green mold sands (silica sand-bentonite-water system) widely used in foundry, was measured to know the effect of moisture content on the tensile breakup characteristics of the green mold sands by using various types of binders and kneaders. The surfaces of green mold sands were observed by a scanning electron microscope to examine the state of mulling. This paper describes the interrelationships among the state of mulling, the tensile strength, the tensile breakup energy, the compression characteristics, the moisture content and the power requirement for mulling of the green mold sands.

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2. Materials and methods

A vertical cylindrical mixer with pitched paddles (Fig. 1(a)) and a Simpson mill (Fig. 1(b)) were used as kneaders. The vertical cylinder was made of methacrylic resin and had the inside diameter of 140 mm and the height of 260 mm. Two pitched paddles were attached crosswise to a vertical rotating shaft with the attack angle of the upper paddle of 60° and that of the lower one of 120°. The paddles (8) were driven by an SCR motor (1) which was controlled to maintain a constant rotational speed against load changes. The mixing torque was measured by a strain gauge torque meter (3) (capacity: 5 Kg·m). The mixing performance of this kneader had been already obtained4).

The Simpson mill shown in Fig. 1(b) had a fixed pan with scrapers sweeping the pan wall and bottom. The rotational speed of the wheels of the mill was $N=0.62s^{-1}$. The power requirement for mulling was measured by the electric current intensity fed to the driving motor. Kneading was also carried out by hand to compare with the above result.

Figure 2 illustrates the outline of a hanging type adhesiveness tester used for testing of the tensile strength of binding materials and milled mixtures (green mold sands)1-5). This tester was of a split cell type with vertical compression and horizontal tension mechanism. The movable cell (2) was hung by three phosphor bronze plates (6). The cell measured 50 mm in inside diameter and 20 mm in height. The tension velocity was $3.33 \times 10^{-4}$ m/s. The relationship between the tensile stress $\sigma_x$ and horizontal displacement $\delta_x$ was determined with a strain gauge (3) and a differential transformer (4) and recorded on an X-Y recorder. This tester was equipped with an operational amplifier (7) to subtract the stress due to bending of the phosphor bronze plates so that only the tensile stress exerted onto the powder bed could be recorded. The porosity $\varepsilon$ of the powder bed in the cell was adjusted by changing the precompression load from 1.6 to 16.6 kPa. The tensile breakup testing was performed after release of the precompression load.
Table 1 Properties of powders tested

| Sample                      | Particle density $\rho$ (kg/m$^3$) | Apparent density $\rho_a$ (kg/m$^3$) | Angle of repose $\Phi_r$ (rad) |
|-----------------------------|--------------------------------------|--------------------------------------|-------------------------------|
| Silica sand (Australia)     | 2610                                 | 1479                                 | 0.600                         |
| Na-Bentonite (U.S.A)        | 2370                                 | 832                                  | 0.742                         |
| Coal powder (Japan)         | 1370                                 | 523                                  | 0.723                         |

The used powder consisted of the base material (silica sand) 100, the binder (bentonite) 7, the secondary binder (coal powder) 1.5 and the water 3, all in mass units. This composition was the same as that of the green mold sands employed in foundry industry. For mixing and mulling of the powder, the binder was first added to and mixed with the base material. A coal powder was then added to and mixed with the mixture, to which water was finally added at one time (refer Fig. 3). The powder was mixed in the same manner throughout the experiments regardless of the type of kneaders and kind of binders used.

Table 1 is the list of the properties of the base material, the binder and the secondary binder used in experiments. The base material was Australian silica sand ($\sigma_g = 1.36$, $D_{50} = 345$ $\mu$m). The secondary binder was Japanese coal powder ($\sigma_g = 1.69$, $D_{50} = 120$ $\mu$m). Bentonite produced in Wyoming, USA (Na, $D_s = 7.2$ $\mu$m) was used as a binder. All the powder samples were dried at 110°C for 24 hours before experiments.

3. Results and discussion

3.1 Mixing torque and tensile process curves of the mulled mixture during mixing and mulling processes

Figure 3 shows an example of the mixing torque $T$, changing with time during a mulling process of the mixture. The mixing torque $T$, after its monotonic increase with an addition of water as a mulling process proceeded reached a constant value $T_\infty$ (Regardless of the type of kneaders and the kind of binders used, the mulling operation was continued considerably long even after the mixing torque reached a steady value $T_\infty$). To evaluate the state of mulling in the mixture, a portion of the mulled mixture in the kneader was randomly sampled during a course of mulling and its tensile break-up moisture content was measured.

Figure 4 shows an example of breakup process curves (the relation between the tensile stress $\sigma_x$ and the horizontal displacement $\delta_x$) of the mulled mixture. The porosity $\varepsilon$ shown in this figure was obtained by evaporation of
the moisture contained within the mixture. As can be seen from Fig. 4, the tensile stress \( \sigma_x \) rapidly increases at the start of tension loading and a breakup occurs at a certain horizontal displacement \( \delta_{x,T} \) showing the tensile strength \( \sigma_{x,T} \). For an evaluation of state of mulling in the mixture, two factors, the tensile strength \( \sigma_{x,T} \) and the tensile breakup energy \( W_t \) (refer to Fig. 4) were taken into consideration.

3.2 Relationship between the mixing power (or mixing torque) and the tensile strength or standard deviation of the moisture content in samples.

Figure 5 shows a change in the mixing power \( P \) (effective value) with time during a mulling process. This figure also shows the tensile strength \( \sigma_{x,T} \) and the standard deviation \( S \) of the moisture content in the samples of mulled mixture taken at an arbitrary mixing time. It can be said that the lower the value of \( S \) is, the better the state of mulling is, since a small value of \( S \) means a uniformness of the moisture distribution in the mulled mixture. Namely, the value of \( S \) is equivalent to the degree of solid mixing. As is clear from Fig. 5, the mixing power \( P \), after its monotonic increase with the progress of mulling, shows a constant value \( P_s \) (at \( t \geq 420 \, \text{sec} \)). The tensile strength \( \sigma_{x,T} \) of the mulled product also increased with the mulling time and reached a constant value at \( t \geq 420 \, \text{sec} \). The standard deviation \( S \) also showed a constant value at \( t \geq 420 \, \text{sec} \). This indicates that the mulling is possibly completed when the mixing power is stabilized.

Figure 6 shows examples of scanning electron microscopic pictures of the mulled mixture. At the mulling time \( t = 150 \, \text{sec} \) (Fig. 6(a)), the mulling was incomplete because of agglomerate sticking of the binding material, bentonite, to the particle surface of the base material (silica sand). On the other hand, at \( t = 600 \, \text{sec} \) when the mixing power \( P \) reached a steady value (Fig. 6(b)), the state of mulling was excellent as noted from the individual particles (silica sand) uniformly coated with the binder which could be seen as whitish cobweb in the photograph. It is further noted that, in the state of complete mulling, bentonite appears to be an inter-particle binder (Fig. 7).

Figures 5 and 6, therefore, demonstrate that the constancy of the mixing power reflects the completeness of mulling macroscopically as
well as microscopically.

Figure 8 shows the relation among the mixing torque $T$, tensile strength $\bar{\sigma}_{x,T}$ and standard deviation $S$ to the mulling time $t$ obtained in the vertical cylindrical mixer. It was also found that a completion of mulling was not obtainable until the mixing torque reached a constant value $T_{S}$.

3. 3 Comparison of the kneader performances

Figure 9 shows the relationship between the tensile strength $\bar{\sigma}_{x,T}$ and the standard deviation $S$ of the mulled mixture obtained by different mulling methods. The mixture was collected at 120 seconds later after stabilization of the mixing torque (or power) for tensile tests and moisture measurement. The figure also shows the tensile strength of silica sand-water mixture, dried bentonite and dried coal powder. As can be seen from the figure, the tensile strength $\bar{\sigma}_{x,T}$ of green mold sands (open circle) obtained by manual mulling is five times as large as that (open square) of the silica-water mixture. This difference may reflect the binding effect of water-impregnated bentonite. The value of tensile strength $\bar{\sigma}_{x,T}$ of the mulled mixture (green mold sands) decreased in the order of Simpson mill > hand mulling > vertical cylindrical mixer. The value of $S$ is also smaller, when the tensile strength is larger. This, therefore, indicates that the Simpson mill provides excellent mulling of the mixture, which may be due to the effective contribution of the kneading, smearing and spatulate actions by the wheels.

Figure 10 shows the compression characteristics of the mulled mixture in terms of the vertical load $\bar{\sigma}_{z,w}$ and the porosity $\bar{\epsilon}$. At the vertical load of 15 kPa onto the mulled mixture, for instance, the porosity $\bar{\epsilon}$ indicates the values of approximately 0.506 for the mulled mixture obtained from the vertical cylindrical mixer and approximately 0.556 for that from
the Simpson mill. This suggests that the green mold sands kneaded by the Simpson mill are packed less tightly and thereby has a better permeability than that kneaded by the vertical cylindrical mixer.

The above findings demonstrate that the green mold sands obtained by the Simpson mill are sufficiently kneaded with a better permeability, thus satisfying the basic requirement for green mold sands. The data obtained by the tester may be interpreted to support the reasonableness of the wide-spread use of Simpson mill in industrial production of green mold sands.

3.4 Relation between the tensile breakup energy and mulling power requirement

The energy needed for the tensile breakup of the mulled mixture can be expressed by Eq. (1) and the mulling power requirement by Eq. (2) (refer to Figs. 4 and 8).

\[
W_t = \int_{\delta s}^{\delta x,T} \sigma_x d\delta x
\]

\[
E = \int_{0}^{t_s} T \, dt, \quad E_p = \int_{0}^{t_s} T \, dt/F
\]

where \( E_p \) is the energy per unit mulled amount, and \( F \) designates a mulled amount. Figure 11 shows the relation between the tensile breakup energy \( W_t \) and the mulling power requirement \( E_p \). It is noted that the breakup energy \( W_t \) for the mulled mixture produced by the Simpson mill is higher than that by the vertical cylindrical mixer. This indicates the effectiveness of mulling energy in the Simpson mill. Figure 12 shows the relation between the tensile breakup energy \( W_t \) and the mulling energy requirement for the mulled mixture (green mold sands) prepared in the Simpson mill with the bentonite calcined at various temperature conditions as a binder. The use of calcined bentonite was intended to evaluate the effects of a binder heated by molten metal on the tensile breakup energy and mulling power requirement, because the green mold sands are usually repeatedly used in industrial processes. As can be seen from Fig. 12, the mulling energy
(power) requirement increases with an increase in the tensile breakup energy irrespective of the calcining temperature. Hence, the mulling power requirement for green mold sands (wet powder) can be evaluated in terms of the tensile breakup energy.

4. Conclusion

The state of mulling could be estimated on the basis of the tensile strength, the tensile breakup energy, the compression characteristics and the scanning electron microscopic observations of the mulled mixture. A well mulled mixture showed higher values of tensile strength and tensile breakup energy and lower value of the standard deviation of the moisture content in the mixture. The Simpson mill was proven its popularity in industrial production processes of green mold sands over paddle type mixers. Tensile breakup test could be utilized for an assessment of the state of mulling. The completeness of mulling in mixers could be estimated by observing a change with time in and a steadiness of the mixing torque or power. It was also confirmed that the power requirement for mulling of wet powders could be evaluated in terms of the tensile breakup energy.

Nomenclature

- $D_s$: surface mean diameter [$\mu$m]
- $D_{50}$: 50%-radius particle size [$\mu$m]
- $E$: mulling power requirement [kJ]
- $E_p$: energy per unit mass of mulled amount [kJ/kg]
- $N$: rotational speed [sec$^{-1}$]
- $P$: mixing power [W]
- $P_s$: steady mixing power [W]
- $S$: standard deviation of moisture content in sample. $S = \sqrt{\frac{1}{15} \sum_{i=1}^{15} (C_i - \bar{C})^2}$ [-]
- $T$: mixing torque [N-m]
- $T_c$: calcinating temperature [K]
- $T_s$: steady mixing torque [N-m]
- $t$: mixing time [sec]
- $W_t$: tensile breakup energy [J/m$^2$]
- $\delta_x$: horizontal displacement [$\mu$m]
- $\delta_{x,T}$: tensile breakup displacement [$\mu$m]
- $\bar{e}$: porosity [-]
- $\rho$: particle density [kg/m$^3$]
- $\rho_a$: apparent density [kg/m$^3$]
- $\sigma_x$: tensile stress [kPa]
- $\sigma_{x,T}$: tensile strength [kPa]
- $\sigma_{z,w}$: vertical load [kPa]

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