Powder Technology 305 (2017) 396–404

Contents lists available at ScienceDirect

Powder Technology

journal homepage: www.elsevier.com/locate/powtec

Covering ability of aluminum pigments prepared by milling processes

Tomáš Svěrák, Pavel Bulejko *, Ondřej Krištof, Pavel Kejík, Josef Kalivoda, Jaroslav Horský

Heat Transfer and Fluid Flow Laboratory, Faculty of Mechanical Engineering, Brno University of Technology, Technická 2896/2, 616 69 Brno, Czech Republic

ARTICLE INFO

Article history:
Received 26 May 2016
Received in revised form 29 August 2016
Accepted 5 October 2016
Available online 07 October 2016

Keywords:
Milling
Aluminum powder
Pigment
Surface active agent
Hiding power

ABSTRACT

This paper deals with the influence of milling regimes on the development of a lamellar structure of aluminum pigment particles. A group of parameters describing the degree of fineness and morphology of the pigment particles were monitored simultaneously. The experiments were carried out using a semi-pilot milling plant with a vibrating mill and a ball mill. Based on the experiments, a criterial non-dimensional relationship was outlined. The relationship generalizes the influence of milling process conditions on the lamellar structure of pigment particles. At the same time, an equation which limits milling time used for the milling process was outlined. This equation solves the problem posed by the risk of destroying the lamellar structure of the particles over time. The theory of metal working was applied as an analogical base for establishing the efficiency of the milling process with respect to energy demand. In addition to basic process parameters, the significant influence of surface active agents on pigment lamellar structure was studied.

1. Introduction

Milling processes are among the most basic unit operations in chemical engineering. These processes are common in many industrial sectors, including mineral resource processing [1,2], high-tech pharmaceutical production [3–5] and the preparation of nano-composite materials [6–11]. One of the most interesting and, in fact, atypical technologies in milling operations is the production of aluminum (Al) powders [12–14]. These are used to produce porous concrete construction elements [13,15], coating compositions and varnish media, printing inks [16] and fingerprint detection compounds [17]. Last but not least, they are used in chemical and pyrotechnical production [18–22]. The basic raw material for producing ground Al powders is an Al particulate material with a high fineness and ball-shaped particles (Fig. 1A) called Al granulated powder. This material is usually obtained by spraying a hot Al melt, followed by granulometric screening [23].

The Al powder milling differs significantly from common disintegration processes which are encountered, for example, in the silicate industry. In Al milling, very fine round Al particles are first flattened to a lamellar shape and then beaten into separate plates with a higher aspect ratio [13]. At the same time, the particles are shredded into smaller flakes as shown in Fig. 1B, see also [13,16,18,24–27]. A wet or dry grinding regime is used depending on the quality requirements for the specific Al powder product. This typically takes place in ball mills [13,24,26] using various additives. Surface active substances play a significant role in Al powder milling and provide for the following:

- Transferring normal and tangential forces in the ground stock in a way which allows the Al flakes to be beaten into the required form and being torn into pieces of smaller dimensions within the defined range of sizes.
- Preventing the retroactive aggregation of the flakes into larger groups allowing effective screening of the final Al particles.
- Defined removal of surface charges from the ground stock which determines both the surface reactivity and production safety.
- Bulk properties and dispersion characteristics of the Al powder which conditions its processability [28].

This paper focuses on the changes in qualitative properties of Al powders used primarily as pigments, depending on the duration and specific milling conditions. The influence of surface active agents was studied and a comparison of dry and wet milling on milling efficiency and covering ability was performed. Based on the experiments, a criterial non-dimensional relationship was outlined. Finally, this process with respect to classical milling theories is discussed.

2. Theoretical background

2.1. Morphology of Al pigment particles

When evaluating pigments, opacity properties are very often the key quality factor. These properties are especially dependent on the ability of pigment particles to cover as much surface as possible by unit weight of the pigment. This is related to the fineness and lamellar shape of the pigment particles with the least possible thickness. The dimensional aspect ratio k_{ar}, i.e. the ratio of the greatest length dimension of a single

---

* Corresponding author.
E-mail addresses: sverak@fch.vut.cz (T. Svěrák), Pavel.Bulejko@vut.cz (P. Bulejko).

http://dx.doi.org/10.1016/j.powtec.2016.10.012

Nomenclature

a, b	(−) criterial relationship exponents
B	(m) width of the metal mirror in the hiding power test
C, C_{lim}	(−) empirical constant of the proportion of the suggested relationships
$C_{\mathrm{R\ (K,\ Ch)}}$	(−) Rittinger's (Kick's, Charles's) empirical constant of the grinding theory
d	(m) average diameter of grains after disintegration
d_{e}	(m) grinding element dimension
d_{50}	(μm) median particle size
D	(m) average diameter of grains before disintegration
D_{m}	(m) inner diameter of the mill
$e_{1\ (2,3)}$	(−) exponents of the calculation relationship
f	(−) coefficient of drag friction
f_{V}	(%) relative volume infilling of the milling cylinder - nominal
h	(m) average thickness of the lamellar particle of the Al pigment ground stock
k_{ar}	(m) aspect ratio of the particulate material
k_{A}	(kJ m^{-2}) surface energy coefficient of milling
k_{m}	(−) grinding ratio (grinding element weight to ground stock weight ratio)
k_{N}	(−) input coefficient of grinding regimes
l	(m) length of the mirror in the hiding power test
L	(m) length of the mill
m_{aa}	(%) amount of the surface active substance related to the weight of the ground stock
m_{e}	(kg) weight of the load of grinding elements
m_{m}	(kg) total weight of the ground stock at the beginning of the milling process
m_{s}	(g) weight of the sample for hiding power test
n	(s^{-1}) turns of the ball mill, frequency of vibrations of the vibrating mill
n_{cr}	(s^{-1}) critical turns of the ball mill
n_{p}	(kg^{-1}) number of particles in the ground stock in the unit of weight
N	(W) mill input
N_{spec}	(W kg^{-1}) specific input of the mill related to the unit of weight of the load
S_{cov}	(m^2 g^{-1}) hiding power
S_{spec}	(m^2 g^{-1}) specific surface of the ground stock
t	(°C) temperature of the ground stock
V	(dm^3) volume of the mill drum
V_{be}	(dm^3) total bulk volume of the grinding elements
V_{f}	(dm^3) volume of the liquid phase
V_{spec}	(m^3 g^{-1}) specific volume of the ground stock
$W_{\mathrm{f\ (ff,fs)}}$	(kJ kg^{-1}) total work (specific forming work, cutting work)
W_{m}	(kJ kg^{-1}) specific milling energy
Δ	(μm) average diameter of the lamellar particle of the Al pigment ground stock
ε_{e}	(%) void spaces of the grinding elements
$\sigma_{\mathrm{K(KS)}}$	(Pa) yield point (shear yield point)
ρ_{be}	(kg m^{-3}) bulk weight of the grinding elements
ρ_{bm}	(kg m^{-3}) momentary bulk weight of the processed material
ρ_{bmstart}	(kg m^{-3}) momentary bulk weight of the processed material at the beginning
$\rho_{\mathrm{e(m)}}$	(kg m^{-3}) specific weight of material of grinding elements (of processed material)
τ	(h) grinding time
$\tau_{\max}$	(min) maximal time value of the safe flake shape particle formation
T	(min) constant of the calculation relationship
φ_{e}	(%) relative infilling of the void spaces in grinding elements by ground stock

particle to the smallest one [29–31] is commonly used for evaluating lamellar features:

$$k_{\mathrm{ar}} = \frac{d_{\mathrm{lmax}}}{d_{\mathrm{lmin}}} \tag{1}$$

2.2. Grinding energy

Materials with a lamellar structure, such as soapstone or mica, are noted for the linear relationship between the work required to crush them and the newly formed surface. This linear dependence corresponds to Rittinger's classical theory [32–34]. According to this theory, when breaking down a cube-shaped particle with base dimension D to smaller cubes of size d, the surface increases and the deduced equation is as follows [32,35,36]:

$$W_{\mathrm{m}} = C_{\mathrm{R}}\left(\frac{1}{d} - \frac{1}{D}\right) \tag{2}$$

where W_{m} is the specific milling energy, C_{R} is Rittinger's empirical constant and D and d are the average diameter of grains before and after their disintegration, respectively. As Al pigment milling also forms particles with significant lamellar structures, it was worth studying whether this theory is applicable in this case as well. The lamellar structure of metal pigments during milling is formed due to the forming process in which the total volume of the particle must achieve the yield point. This is most likely a relationship between the grinding energy and the volume of the processed particles, as described by Kick's theory [32, 35–38]:

$$W_{\mathrm{m}} = C_{\mathrm{K}} \ln \frac{D}{d} \tag{3}$$

where C_{K} is Kick's empirical constant.

Generally, Charles' formula (4) can be used. Charles' formula generalizes most theories for grinding into a common differential form [36,37, 39]:

$$W_{\mathrm{m}} = C_{\mathrm{Ch}} \frac{\mathrm{d}D}{D^{m}} \tag{4}$$

where C_{Ch} is Charles' empirical constant and m is an experimentally established exponent that is a function of the grinding regime.

2.3. Ball mill input and dimensions of grinding elements

The necessary input of a ball mill N can be calculated using a modified version of Levenson's and Blank's formula [40]:

$$N = k_{\mathrm{N}} m_{\mathrm{e}} \sqrt{D_{\mathrm{m}}} \tag{5}$$

where k_{N}, m_{e} and D_{m} are the input coefficient of the grinding regimes, the weight of the grinding elements and the inner diameter of the mill drum, respectively. This is a rule-of-thumb formula which was derived for mills with a peripheral velocity corresponding to 75% of critical rotations.

The optimal diameter of the grinding balls depends on the size of the grains in the mill, on the required size of the product particles, on the mill diameter and on the grinding properties of the material to be ground [41]. To determine the grinding element diameter, an equation derived by Razumov can be used [42–44]:

$$d_{\mathrm{e}} = 28\sqrt[3]{D} \tag{6}$$