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Original Research Paper

Predicting breakage behavior and particle size of bronze and cast iron machining chips pulverized by jet milling

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ABSTRACT

It has been proposed that the breakage behavior of particulate materials can be described by two material parameters f_{mat} and W_{min}. f_{mat} describes the resistance of the material to fracture in impact pulverization and W_{min} characterizes the specific energy which a particle can absorb without fracture. It is shown in this study that this concept can be used to quantify breakage behavior of bronze and cast iron chips in jet milling process and also to predict particle size of the jet milled product. Different tin bronze and cast iron chips with varying initial size were pulverized in a target plate jet mill with different velocity. f_{mat} was found to be in the range of 0.06–0.09 and 0.18–0.25 for bronze and cast iron alloys, respectively. For the cast iron alloys f_{mat} increased with increasing content of carbon and silicon. Similarly, for the bronze alloys, f_{mat} increased with increasing tin content. An equation was developed to predict mean particle size of the jet milled chips as a function of the kinetic energy, initial chip size and material parameters. The experimental results of various alloys confirmed that the mean particle size after single and multiple impacts were accurately predicted.

1. Introduction

Machining is one of the most important processes used for manufacturing semi-finished and finished products. In the process of machining parts, large quantities of chips are produced. Considering the enormous amount of chips created in different sections of industries, the development of proper methods to recycle and reuse the manufacturing scraps is economically, strategically, and environmentally important [1]. One method of recycling of machining chips is pulverization to produce metallic powders to make sintered components [2–5].

Recently it has been shown that jet milling process can be used as a viable pulverizing technique to produce metallic powders [3,6]. Emadi et al. [3] employed target jet milling to convert grey cast iron machining chips into powder and used it successfully to produce sintered powder metallurgy parts. Lu et al. [7] investigated, in detail, the preparation and characterization of TiAl alloyed powders using fluidized bed jet milling from the pre-crushed ingot. Rama Rao and Hadjipanayis [8] conducted a detailed study on the effect of jet milling conditions on particle size and magnetic properties of MnBi alloy. Afshari and Ghambari [6,9] studied production and characterization of bronze powder obtained from machining chips using jet milling process. Li et al. [10,11] utilized fluidized bed jet milling to control particle size, size distribution and morphology of tungsten powder, successfully.

It has been shown that industrial machining chips like bronze and cast iron chips could be converted to powder by jet milling. For detailed understanding of the breakage behavior, optimization of the process for industrial production and prediction of the particle size, modeling could be a useful tool [12]. Despite widespread use of jet milling process and numerous experimental studies, theoretical information in this field is few [13]. This leads to the situation that the milling conditions have to be determined for each material using pilot-scale trials. This is both material and time consuming [13,14].

Although, material properties are crucial for the fundamental understanding of the breakage phenomena, for breakage kinetics and for determination of operational conditions, current understanding of the influence of material properties is very limited [15]. Few attempts have been made so far to correlate the milling behavior of particles with their properties. Material dependence on a milling process can be characterized using various approaches. The most common methods are measuring the mechanical properties of the material such as hardness, fracture toughness, and elastic modulus [16].

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Although various methods have been developed to determine mechanical properties of particulate materials, nevertheless it is not possible to measure these parameters, accurately. One method is to prepare compacted samples of a powder with different porosity and determine properties such as yield stress and Young's modulus and Critical stress intensity factor. The mechanical property of the particles at zero porosity can be determined by extrapolation [17,18]. However, the material property obtained using this method refers to the bulk material rather than the particle. Another method to analysis mechanical properties is the indentation technique. However, current indentation techniques are generally limited to low strain rate conditions. In contrast, industrial milling systems operate well beyond the quasi static strain rate regime. Thus, the mechanical properties determined from indentation may not be applicable to the actual process [18]. There is also the limitation of requiring smooth surfaces for conducting a good indentation. Due to these shortcomings, recent developments are based on inferring the material properties from the impact breakage propensity of various materials [19–22]. Using this concept, Vogel and Peukert [21,22] developed a model for quantifying the impact breakage behavior using material parameters which could be determined experimentally by single particle impact tests. In the single particle device that they used, particles were transported from a feeder into a disk-shaped rotor. In the rotor, particles were accelerated by the centrifugal force. They emerge from the rotor and hit the target ring at an angle of 90 and the particle impact speed was controlled by the number of revolutions of the rotor. Later, this model was used for the pulverization of minerals [23] and pharmaceutical powders [24,25] utilizing the jet mill process, successfully. The aim of this study was to verify the application and validity of this model for breakage of bronze and cast iron machining chips in a jet mill. In addition, a model to predict a mean particle size of the jet milled chips after different numbers of impact cycles was developed.

2. Fundamentals of Vogel and Peukert model

Vogel and Peukert [20–22] developed a model for quantifying the breakage behavior of various materials. The approach was developed on the basis of dimensional analysis suggested by Rumpf [26] and by applying fracture mechanics as previously done by Weichert [27]. They found that the breakage probability of a particulate material could be defined as follows:

$$\mathrm{S} = 1 - \exp\{-\mathrm{f}_{\mathrm{mat}}\mathrm{NX}\Delta\mathrm{W}\} \qquad (1)$$

where S is the breakage probability, X is the initial particle size, N the impact number, f_{mat} a material property which serves as a measure of the resistance of the material against fracture (larger the f_{mat} value, larger is the number of broken particles under the sieve cut size.) and ΔW is the net kinetic energy available within the particle for fracture which is defined as follows:

$$\Delta W = W - W_{min} = 0.5\left(v^2 - v^2{}_{min}\right) \qquad (2)$$

where W denotes the specific kinetic impact energy of the particles and W_{min} can be regarded as energy threshold which characterizes the specific energy a particle can take up without pulverization. v is the particle velocity and v_{min} is the particle velocity corresponding to the energy threshold. This energy threshold is size dependent; the product of particle size and energy threshold XW_{min} has been found to be constant [21]. According to the model assumption, f_{mat} and XW_{min} comprise all particle properties and should therefore describe the material influence on the pulverization result. In addition the situation of single and repeated impacts can be considered with the help of the N parameter.

For determination of the material parameters f_{mat} and XW_{min}, pulverization experiments are performed at different impact speeds. The obtained breakage probabilities are plotted versus impact energy, and a curve fitting using Eq. (1) yields f_{mat} and XW_{min}.

3. Materials and experimental procedure

3.1. Materials

Three different tin bronze alloys with different tin concentrations and three different cast iron alloys with different carbon and silicon concentration were sand cast in the form of rods. The chemical compositions of the alloys are shown in Tables 1 and 2 for tin bronze and cast iron, respectively. The rods were machined using a lathe to obtain machining chips. All the machining conditions, i.e. the cutting speed, the feed rate, the depth of cut, and the cutting angle, were kept constant for all alloys. The required quantity of chips of the desired starting size distribution was prepared using sieves of appropriate sizes, corresponding to a constant aperture ratio of $\sqrt{2}$ [28]. The chips were sieved and separated into discrete size ranges including 20–30 mesh (600–850 μm), 30–40 mesh (425–600 μm), 40–50 mesh (300–425) and 50–70 mesh (212–300 μm).

3.2. Experimental procedure

An experimental target-plate jet mill was used to pulverize the machining chips. The machining chips were transported into the mixing section, where they were accelerated by a nozzle using compressed air and were then impacted onto a target inside the grinding chamber. A detailed description of the setup is presented elsewhere [9]. The nozzle-to-target distance and impact angle were kept at their optimum values obtained via pre-experiments i.e a nozzle to target distance of 8 cm, and an impact angle of 90° [6]. The experiments were done at different impact speeds controlled by the initial air pressure.

It is reported that, if the volume fraction of the solid to the gas is lower than 1×10^{-4} the gas velocity and particles velocity would be close together [17,29]. Since, in this study the volume fraction of solid was in the range of $3.5–6.3 \times 10^{-5}$, the particles velocity assumed to be the same as the gas velocity. The gas velocity was calculated from the grinding pressure, the gas flow and the nozzle diameter. It should be noted, that the particle concentration was found to be sufficiently low to neglect particle to particle interactions during acceleration and impact. The air pressures used in this study along with the corresponding velocity and specific kinetic energy are listed in Table 3. The influence of multiple impacts was also tested up to 10 cycles at the constant pressure of 6 bar. To obtain reliable and reproducible data, all of the experiments were conducted at least three times.

The materials were sieved before the milling experiments, and narrow sieve fractions were used for the experiments as mentioned in Section 3.1. At the end of each milling cycle, the size distribution of the produced particles was determined by sieve analysis. After the analysis, the produced particles were again jet milled under the same conditions in order to determine the influence of multiple impacts. This procedure was repeated up to 10 times.

Size reduction during milling can be described by the breakage probability and the breakage function. The breakage probability is the fraction of particles broken after a certain stressing event, and the breakage function denotes the size distribution of the fragments [30]. It is suggested that, as an approximation for the breakage probability, the mass fraction of particles smaller than the feed

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