Impact of the rate of input of specific energy on the ball milling of aluminium in a planetary mill

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Abstract. In the present study, the effect of the rate of the input of comparable amounts of energy into the material being processed on the particle size and on the value of specific surface area of the particles was analysed. It was shown that, irrespective of the rate of the energy input into the material, the resultant particles have similar characteristics, including their size and shape, and the value of the specific surface area. A more intense action exerted by the grinding bodies on the particles in the material being processed is accompanied by a sharp increase of temperature throughout the entire system. The heated particles plasticize, thus undergoing to a rolling-type granulation process.

1. Introduction

In powder metallurgy, one of the main processes is the mechanical processing of powders, including that in planetary-type ball mills. This process affects the size of the particles and their shape depending on the physical properties and chemical composition of the material. The aim of powder processing is to obtain particles with a minimum size, with a maximum specific surface area, and with the bulk density of the material at the minimal consumption of activation energy [1-6]. The use of high-energy attritors for powder treatment allows not only performing the mechanical processing of powders but, also, their mechanical activation [7].

Ball milling of powder mixtures is accompanied by an intense mechanical action exerted on the particles. At the initial moment of the treatment, a considerable dispersion of the initial components occurs. Then, during the mechanical processing, due to the high surface activity of ultrafine particles those particles form the so-called "layered composites" (mechano-composites), or powder agglomerates in the case of a monophasic chemical compound [8-12]. As a result of the intense plastic deformation occurring in the formed agglomerates, the area of the inter-particle contacts many times increases, and there forms a high concentration of non-equilibrium defects and internal stresses, which process leads, for instance, to an acceleration of exothermic reactions and an increase in the SHS synthesis temperature [9, 11, 12].

When a grinding body interacts with a particle, the kinetic energy is spent on the plastic deformation of the particle proceeding with the release of a large amount of heat, up to 95% [13]. In [14], it was shown that the temperature in contacts, which arises due to the sliding friction, can reach the melting point of one of the materials. In this connection, the current studies of the influence of the energy input by grinding bodies on the material being processed, aimed at establishing the optimum
regimes of material processing, are presently quite topical ones. For instance, the study of [15] was devoted to obtaining a FeNi-alloy based powder in a ball mill, where the influence of the kinetic energy of the balls on the microstructure and particle size of the powders was investigated. In [16], low- and high-efficiency regimes of ball milling of powders (Cu, Ni and Fe) were preliminarily determined. The work [17] was devoted to the study of the doping of metallic Cu and Fe particles with ceramic Al2O3 and SiC nanoparticles. It was shown in [18] that the final structure of the doped Cu50Zr43Al7 alloy obtained by mechanical processing depended on the processing conditions. A low-energy planetary mill with a specific-energy input of 1440 J/g yielded a solid solution with a high copper content and, on increasing the rate of specific-energy input to 4320 J/g on a Spex ball mill (shaker), a nanostructured solid solution with a high Cu content and intermetallic compound Zr2Al3 formed. In [19], a study of the effect of the ball diameter on the crystal size, on the induced deformation, and on the diffusion of atoms in the system of immiscible Cu - 50%Fe alloys was performed. In [20], an analysis of the ball kinetics during the mechanical processing of copper powder was performed.

In publication [21], the processes occurring during ball milling between the grinding bodies and the material being processed were analyzed. High impact energies can be implemented using either large ball diameters or a high density of grinding bodies in combination with a high speed of their rotation [22, 23]. Very ductile materials (Ni, Zn, Cu, Al, Nb, etc.) require softer grinding conditions at lower temperatures and at lower impact energy.

The aim of the present work was to experimentally study the influence of the rate of specific-energy input into the grinded material during the ball milling of aluminum powder.

2. Experimental procedures

In the study, ball milling process ASD-1 grade aluminium powder was investigated. The histograms of the volumetric and number distributions of particles were obtained using an LS 13 320 (Beckman Coulter). Morphology of particles was determined using scanning electron microscope Evo MA15 (Carl Zeiss). The classification of powder particles in terms of their sizes was performed on a vibro-bench provided with a set of analytical sieves. The Activator-2SL planetary mill [27] had two cylinders, each having a volume of 250 ml. The inner radius of the cylinders was 42.5 mm; the mass of the loaded balls, 160 g for each cylinder; the acceleration of the grinding bodies, 117 g; and the mass of the material load to be processed, 30 g. The maximum rotational speed of the central axis was 1045 rpm, and that of the cylinders, 1550 rpm. Steel balls with a diameter of 3, 5, and 8 mm were used as the grinding bodies.

The specific power needed per unit weight of processing material in the ball mills was calculated using the following empirical formula [6]

$$N = \frac{8}{4\pi A} \left( \frac{a}{g} \right)^{3/2} R^{3/2}$$

In formula (1), $A = 0.03 m$ is an empirical parameter, $M_b$ is the mass of the balls, $m_p$ is the mass of the loaded powder, $a = 4\pi^2 n^2 R$ is the ball acceleration, $R$ is the inner radius of the cylinders, $n$ is the number of revolutions per second, and $g$ is the free-fall acceleration.

3. Results and discussion

For comparison of data concerning the input of energy by grinding bodies into the powder particles, the regimes of mechanical processing were calculated using formula (1) (see Table 1).
Table 1. Processing regimes of aluminium powder.

| Processing regime of the powder | Specific energy, J/g | Parameter of ball milling 1: M₀/m₀ (160/30); a = 117g | Parameter of ball milling 2: M₀/m₀ (80/30); a = 117g | Parameter of ball milling 3: M₀/m₀ (160/30); a = 4.58g |
|--------------------------------|----------------------|--------------------------------------------------|--------------------------------------------------|--------------------------------------------------|
| Regime №1                     | 71                   | 15 c                                             | 30 c                                             | 31 min                                           |
| Regime №2                     | 142                  | 30 c                                             | 60 c                                             | 1 h 3 min                                        |
| Regime №3                     | 284                  | 60 c                                             | 120 c                                            | 2 h 5 min                                        |
| Regime №4                     | 426                  | 90 c                                             | 180 c                                            | 3 h 7 min                                        |

After mechanical processing, the powder was divided into two fractions, with the sizes of powder particles being smaller and greater than 90 μm. The separation of particles into the two fractions was due to the fact that the particles of the main fraction, with sizes less than 90 μm, are widely used ones, in particular, in gas-thermal, detonation, and cold gas-dynamic spraying [24-27]. The particles larger than 90 μm in size and shaped as deformed disks can be treated in a plasma jet to obtain a powder that consisted of spherical particles of micron and decamicron sizes [28, 29]. Such particles are currently in demand as they are widely used in additive technologies [30, 31], laser cladding [32], and in other powder-metallurgy areas.

Using the results of the study of the dispersed composition of the initial and treated aluminum particles, we have plotted the curves characterizing the changes in the mean particle size and in the main-range boundaries \(d_{10}\) to \(d_{90}\) as dependent on the input of energy into the processed material (Figure 1). The initial aluminum powder particles had a spherical shape with the mean size of the main fraction of 18 μm.

Figure 1. Size composition of the initial and mechanically processed aluminum powders.
1 – parameter of ball milling No 1; 2 – parameter of ball milling No 2; 3 – parameter of ball milling No 3.

Thus, it was shown that, irrespective of the rate of input of comparable amounts of energy into the processed material, the sizes of the particles and their specific surface areas had rather close values. The energy input intensity affects only the weight content of particles larger than 90 μm in the ball milled material. Figure 2 shows the successive changes in the surface morphology of the mechanically processed particles. It should be noted here that the behavior of aluminum particles during the mechanical processing was typical of the mechanical processing of ductile metallic materials in planetary mills irrespective of the regime of specific energy entry into the material [15, 33].
Figure 2. Evolution of the surface area in particles greater in size than 90 μm for four regimes at the parameter of ball milling No.1. Treatment duration: a) 15 s, b) 30 s, c) 60 s, d) 90 s.

At fixed mass of the grinding bodies loaded into the mill cylinder, a decrease in the ball diameter leads to an increase of the number of the balls (Table 2). Accordingly, at fixed velocity the kinetic energy of one ball decreases in proportion to its mass. Consequently, for the ball-particle interaction system a decrease in the ball diameter leads to a decrease in the degree of deformation of the particle and to a less pronounced heating of its volume. Taking into account the fact that with a decrease of ball diameter the curvature of the ball surface increases, the kinetic energy of the ball impinging on a particle is transferred to a smaller contact area with a sharp increase of local temperature occurring at the interaction site. Afterwards, sintering occurs over the hot-spot area during the interaction of powder particles. The reduction in the curvature of the surface (due to the increased ball diameter) leads to an increase of the contact area. As a result, the sintering leads to the formation of larger particles with a corresponding increase of the diameter of processed Al particles for a given operating mode of the planetary mill (figure 3).

Table 2. Characteristics of the grinding bodies.

| Ball diameter, mm | Mass of one ball, g | Number of the balls for load of 160 g |
|------------------|---------------------|-------------------------------------|
| 3                | 0.11                | 1470                                |
| 5                | 0.50                | 318                                 |
| 8                | 2.05                | 78                                  |
Figure 3. General view of the surface of the particles processed during 90 seconds at parameter No.1. Particles obtained by the interaction with the balls of diameter: a) 3 mm, b) 5 mm, c) 8 mm.

4. Conclusion
In the present study, it was shown that, irrespective of the rate of input of comparable amounts of energy into the material being processed, the particle size and the specific surface area of particles had similar values. The rate of energy input affected only the mass fraction of the particles larger than 90 μm in the mechanically processed material. The study of the influence due to the ball diameter at fixed mass of the load and at fixed rotation speed of the mill cylinders showed that the dynamics of particles and their deformations were similar. An increase in the ball diameter leads to an increase of the average diameter of the processed aluminum particles with a similar external structure.

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