Fracturing of Brittle Materials in a Mixing Process with Water Jet

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Abstract. Procedures leading to the utilization of a *liquid jet* as a tool suitable for *material milling* are usually based on the suction of material particles or *loose material* of a suitable medium size into the mixing chamber and the focusing tube. In this system, called a cutting head, physical processes take place, which cause, or may cause, damage to the particles of material. The determination of an extent of changes in the size of particles induced in the cutting head, both theoretical and experimental, is the main objective of the article. The analyses are based on studies of fracturing processes that take place during impingement of the water jet onto the sucked *brittle particle*. Resulting knowledge of sizes of particles at the exit from the cutting head is fundamental for studying of the subsequent processes that are to support the milling effect of liquid jet. Among them the impingement of a jet containing material particles on a target of very resistant material or the collision of two such jets moving in the opposite directions are the most important ones.

Introduction

One of the methods used for fining of loose materials is the milling process utilizing a high-speed water jet. Loose materials (namely abrasive particles) are sucked into the mixing chamber where the water jet is hitting the grains. The process is exactly described in [3], [4], [5] and [6]. These particles are usually brittle minerals. The destruction of these particles was investigated in our laboratory. The laboratory equipment is focused rather on cutting of materials. Nevertheless, disintegration of loose materials named *water jet milling* is the secondary objective of the research team. The up-to-date research was done for almandine. Nearly all almandine grains are the monocrystals. The water jet milling and present possibilities of the water jet based disintegration tool are outlined in this contribution.

Theory of Destruction of Loose Grains in Mixing Chamber

The first contact of grains with water jet happens upon their approach into the mixing chamber. The velocity of grains entering the cylindrical water jet is only several meters per second. In this moment the grains are hit by water with a dynamic pressure

$$\mu p = \frac{1}{2}\rho v_0^2, \tag{1}$$

where p is a pressure of water before the nozzle, μ is the discharge coefficient of the nozzle, ρ is the density of water and v_0 is a speed of water jet nearly behind the nozzle – it is approximately 660 m/s for parameter configurations used in presented experiments. The liquid (in our experiments water) is pressurized up to 400 MPa. On short distance, near to 30 mm, majority of grains achieve the speed of the mixture (used liquid and sucked material) decelerating the water flow. In fact, the resulting speed of the suspense converges to the value lower than the theoretical one determined from the law of conservation of momentum that is 600 m/s for the detached system. Hence, the interaction time for duration of the mixing process should be of the order 10^{-4}s. Fig. 1 shows the interaction process inside the mixing chamber schematically.

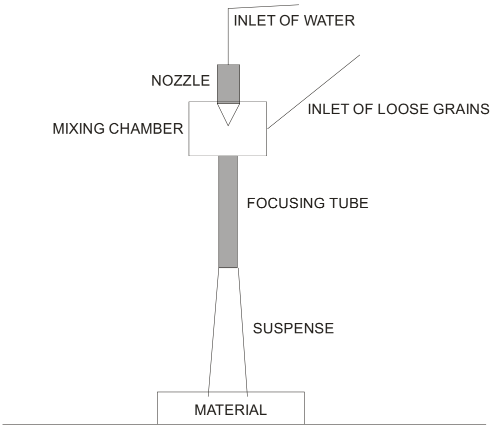

Fig. 1 Mixing process

The law of conservation of energy can be written, for the predominant brittle fractures, in the form

$$\frac{1}{2}q_{\mathrm{w}}tv_0^2 = \frac{1}{2}q_{\mathrm{w}}tv^2 + \frac{1}{2}q_{\mathrm{g}}tv^2 + \gamma\Delta S + \Delta u \tag{2}$$

while for the predominant plastic fractures the expression

$$\frac{1}{2}q_{\mathrm{w}}tv_0^2 = \frac{1}{2}q_{\mathrm{w}}tv^2 + \frac{1}{2}q_{\mathrm{g}}tv^2 + \gamma_{\mathrm{p}}\Delta S + \Delta u \tag{3}$$

is valid. The variables q_{w} and q_{g} are mass flow rates of water and loose grains respectively, t is a time, v is a velocity of the suspense, ΔS is a change of surface of grains and Δu represents change of the inner energy of water. The difference between γ and γ_{p}, i.e. a specific surface energy for brittle fracture and a specific fracture surface energy for plastic deformation respectively, is present on the surface [8] of milled grains. The relations among these quantities can be described by equation

$$\gamma_{\mathrm{p}} = \gamma + \frac{\Delta u_{\mathrm{g}}}{\Delta S} \tag{4}$$

where Δu_{g} is a change of the inner energy of grains during milling process. The law of conservation of momentum is expressed in the form

$$q_{\mathrm{w}} t v_0 = q_{\mathrm{w}} t v + q_{\mathrm{g}} t v\,. \tag{5}$$

The equation (5) can be transferred to the form

$$v = \frac{v_0 q_{\mathrm{w}}}{q_{\mathrm{w}} + q_{\mathrm{g}}}\,. \tag{6}$$

Taking into account the quantities important in mixing process and the law of conservation of energy, equations (2) and (3), and the law of conservation of momentum (5), the relationship was derived for calculation of the mean size of particles produced during mixing process [2]. The equation

$$a_{\mathrm{n}} = \frac{24\rho\gamma c^2 a^3}{24\rho\gamma c^2 a^2 + C\pi a d^2 \mu^2 p^2 \chi^2} \tag{7}$$

shows relations between the pressure p of water before the nozzle and the grain size of sucked particles a as the independent variables and the grain size after milling process a_{n} in the mixing chamber as the dependent variable. Other variables are as follows: density of water under normal conditions - ρ, surface energy - γ, sound velocity in water - c, water jet head-shape coefficient - C, water nozzle diameter - d, nozzle discharge coefficient - μ, the coefficient based on compressibility of water - χ. Comparison of grain sizes calculated for three water pressures from relationship (7) – the curves – with experimental data – points – shows Fig. 2.

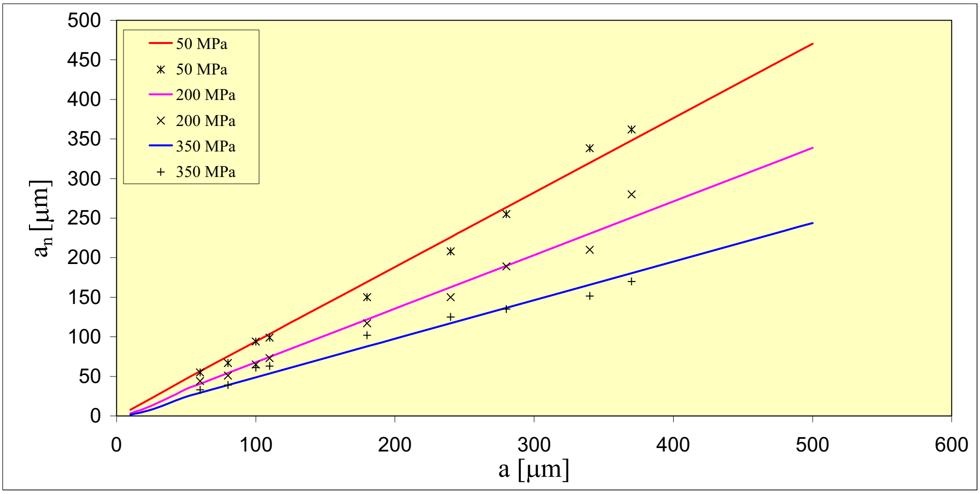

Fig. 2 Disintegration of almandine grains in the mixing chamber – theoretical (curves) and experimental (points) results

The transfer of energy of water jet is described by a semi-empirical relationship (8) derived from the conservation laws and the Newton´s relationship for a resistant force. The relationship inherently includes some empiric effects. The amount of the energy W transferred from the high speed water jet into one grain of loose material is expressed by equation

$$W = C_{\mathrm{D}} \frac{\pi d^2 \mu^2 p^2 \chi^2 a}{4c^2 \rho}. \tag{8}$$

C_{D} is a drag coefficient, i.e. it characterises the resistance of material particle in the flow of liquid, d is the diameter of the nozzle, μ is a discharge coefficient of the nozzle, p is a pressure of water before the nozzle, χ is a coefficient based on compressibility of water, a is the initial medium grain size, c is sound velocity in water and ρ is the density of loose material grains.

Determination of Surface and the Specific Surface

The quantity ΔS appears as a change of surface in relationships (2) and (3) and it can be evaluated from equation

$$\Delta S = q_{\mathrm{g}} t (S_{\mathrm{s2}} - S_{\mathrm{s1}}) \tag{9}$$

where S_{s1} and S_{s2} are the specific surfaces before and after the milling process respectively. All loose materials have, from the point of view of the *grain size d*, the log-normal function of the density of probability f [1], [7]. The example for our experimental material is presented in Fig. 3:

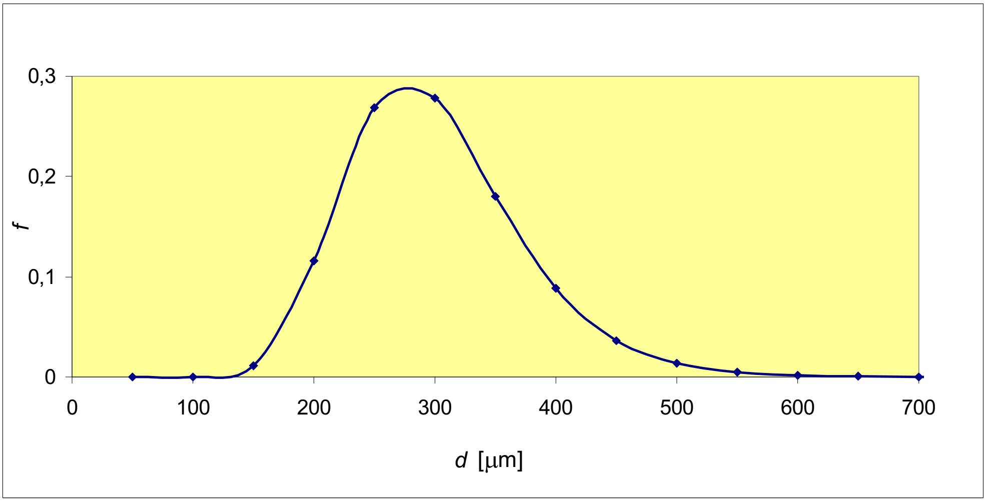

Fig. 3 The density of probability of loose grains (almandine) before the milling process

Transforming the grain size d_i using the function $\ln d_i$ the next equation originates

$$\mu = \frac{\sum_{i=1}^{n} \ln d_i}{n}, \text{ and } \sigma^2 = \frac{\sum_{i=1}^{n} (\ln d_i - \mu)^2}{n-1} \tag{10}$$

where μ is a transform mean value and σ^2 is a transform dispersion of grain sizes. Finally, the variable S_s $\left[m^2/kg \right]$ is written according to the theory into the form

$$S_s = \frac{6}{\rho \exp(\mu + 2{,}5\sigma^2)}. \tag{11}$$

The ρ is density of the grains. For the purpose of our analyses, the variable calculated from equation (11) is a macro-surface because the segmentation of a real surface was not monitored. The data for grain size d_i were obtained from laser device Analysette 22 using laser dispersion of light for determination of the sizes of grains or powders. The equation (11) is specified in [7]. The laser device is to be used two times - before and after milling process.

Brittle or Plastic Fracture

Real complication of the milling process induces that it is impossible to derive the energy transferred into grains during mixing process exactly and, therefore, the equations (7) and (8) are only approximative. The sort of fracture, brittle or plastic, is to be considered in future investigation of the process. Nevertheless, short interaction times imply the conclusion that development of the plastic deformation is less probable. The quantity information about it can be acquired from computation of the specific surface energy γ or the specific fracture surface energy γ_L from equations (2) and (3). Specific surface energies can be approximated as $\gamma \approx$ several $\mathrm{J/m^2}$, according to [10]. Specific fracture surface energies expected for minerals seem to approach higher values - $\gamma_L \approx n \cdot (10^1 - 10^2)\,\mathrm{J/m^2}$. Moreover, the surface energies are not constant. The values of γ and γ_L depend on grain size because lower number of micro-cracks in volume of grains increases their values [9].

Milling in a Mixing Chamber and by Opposite Jet

Now, the difference between milling process inside the mixing chamber and by opposite jets can be demonstrated. The mixing chamber is space where collisions of high speed water jet and loose material grains proceed. The opposite jets are two high-speed (abrasive) water jets directed one against the other. It was expected that the chamber with opposite jets should be a better tool for disintegration of loose grains. This idea appeared to be correct as apparent from results presented in Fig. 4. The axis d is in a log-form and the y-axis represents density of probability for volume of grains, not for a grain size. The label "initial grains" means the volumetric size distribution of grains before milling process.

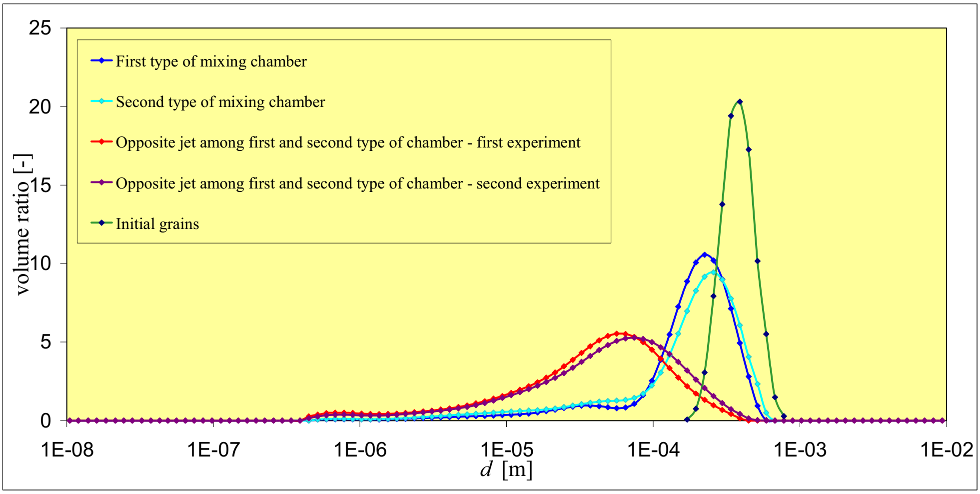

Fig. 4 Disintegration of almandine inside the mixing chamber and by opposite jets

The experimental conditions for experiments presented in Fig. 4 were: water pressure in water pump p = 400 MPa, water nozzle diameter inside each mixing head d_o = 0.15 mm, liquid medium - water, diameter of each focusing tube d_a = 0.5 mm, length of each focusing tube l_a = 51 mm.

Summary

The milling process was described inside the mixing chamber by laws of conservation. The semi-empirical relationships were derived for determination of the medium grain size of loose material flowing through the mixing head set-up. The theoretical results were compared with experiments. Some basic relationships for determination of specific surface of loose grains or powder particles were set up. The theory is based on the well-known log-normal distribution. A brief consideration of various aspects of grain fracturing in the mixing process was presented in the section Brittle or Plastic Fracture. At present state-of-the-art the question cannot be solved, which of the fracture mechanisms is predominant. Nevertheless, presented theory can be used for determination of some value of the specific surface energy from experimental results. By the end of the contribution the experimental comparison is presented for products of both the mixing chambers and the collision chamber of the opposite jets set-up through respective volumetric particle size distributions. The opposite jets improve the disintegration process comparing to self-sustaining mixing heads. Therefore, the work will be continued both on the better description of processes and parameters and experimental equipment modifications.

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