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Universal Method for the Prediction of Abrasive Waterjet Performance in Mining

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ABSTRACT

Abrasive waterjets (AWJs) can be used in extreme mining conditions for hard rock destruction, due to their ability to effectively cut difficult-to-machine materials with an absence of dust formation. They can also be used for explosion, intrinsic, and fire safety. Every destructible material can be considered as either ductile or brittle in terms of its fracture mechanics. Thus, there is a need for a method to predict the efficiency of cutting with AWJs that is highly accurate irrespective of material. This problem can be solved using the energy conservation approach, which states the proportionality between the material removal volume and the kinetic energy of AWJs. This paper describes a method based on this approach, along with recommendations on reaching the most effective level of destruction. Recommendations are provided regarding rational ranges of values for the relation of abrasive flow rate to water flow rate, standoff distance, and size of abrasive particles. I also provide a parameter to establish the threshold conditions for a material's destruction initiation based on the temporary-structural approach of fracture mechanics.

1. Introduction

The need to increase the efficiency of mining machines and extend the field of their application has come to a head. Special attention is also required in the creation and development of mining equipment that provides an increase in technical and economic performance along with secure labor conditions. Waterjet technologies are one of the most promising solutions to meet these needs. These technologies are based on the usage of the energy of high-speed water streams to create stress within a destructed material that is higher than the strength of that material, leading to the propagation of cracks and to erosion [1,2]. Waterjet technologies are currently in broad usage in highly technological industries [3–5] due to their advantages, which include high machining versatility, the ability to contour, no thermal distortion, and a small cutting force. They also provide the possibility to cut difficult-to-machine materials such as ceramics, marbles, and layered composites. In mining, waterjet technologies allow an increase in productivity by permitting advancement to occur several times faster, and permit the destruction of hard rocks without dust formation but with explosion, intrinsic, and fire safety [6,7]. For these reasons, waterjet technologies can be exceptionally useful in extreme mining conditions and for the destruction of hard rocks.

The effectiveness of these technologies increases sharply with the addition of an abrasive to the water stream [6,8–11]. For rock destruction, the most common usage of abrasive waterjets (AWJs) is in the processing of natural stones, especially marbles and granite [12,13]. Possible ways of applying AWJs in underground mining have also been considered [6,14–16]. For the purpose of increasing the efficiency and safety of the working processes in mines, it is reasonable to use AWJs in the following operations:

- Dismantling works (i.e., cutting metal structures, armored cable, steel cord conveyor belts, etc.);
- Contouring the face preparatory workings when installing fasteners;
- Repairing excavations and restoring the area of their cross-section;
- Weakening hard rock with discharge slots, with further destruction by mechanical tools;
- Cutting rock and solid materials, including high-strength metals in extreme conditions (in areas of geological faults, fractured rock mass, etc.); and
- Drilling gas drainage holes in order to prevent outbursts in coal mines.

As seen from this list of mining conditions, it is necessary to effectively cut not only rock, but also metals, concrete, and other solid materials with different physical and mechanical properties.

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2. Basic principles of abrasive waterjets

There are two ways in which abrasives are mixed with water to form AWJs: the direct pumping system and the entrainment system. In a direct pumping system, abrasives are pre-mixed with water to form slurry, which is then pumped and expelled through a nozzle. In an entrainment system, a high-pressure waterjet is first formed by an orifice; next, abrasives are entrained into the waterjet to mix with it and form AWJs. For mining conditions, entrainment systems are more convenient because of their relative cheapness and compactness, and their lower requirement for a specific quantity of metal to be cut [17].

To be more precise, AWJs in entrainment systems are formed as follows: A high-pressure pump compresses water to a high (140–420 MPa) or ultra-high (over 420 MPa) pressure. A water supply system then delivers water to a cutting head, where a waterjet forms. This waterjet goes to a mixing chamber. Abrasive is also transported to the mixing chamber from a container using a special delivery system. In the mixing chamber, the waterjet mixes with abrasive particles to form slurry. The slurry then goes to a convergent section of the mixing chamber and further to a collimator, where the final forming of the AWJ occurs.

In most of the calculations associated with this technology, it is possible to neglect the influence of the water, since its main function is to accelerate the particles within the formed AWJs and then carry them off the surface of the destructed material. The destruction of materials with AWJs is caused mainly by the impact of abrasive particles in the stream [6]. Thus, this process can be described as an interaction between the abrasive particles and the material's surface. This type of interaction depends on the type of destructed material—that is, on whether the material is ductile or brittle. This division is due to a modern conception about the toughness of materials, which is based on fracture mechanics. In this conception, destruction is considered to be a form of erosion, which consists of simultaneous deformations, such as elastic and bound deformations and cracking.

It is now possible to define the type of material under certain loading and environmental conditions at the atomic level, using the temporary-structural approach of fracture mechanics [18]. Brittle fracture is related to the rupture of chemical bonds, whereas ductile fracture is due to the shift of atomic planes along slip planes. For this reason, most materials with isotropic features, which are characterized by a random arrangement of atoms, demonstrate brittle fracture. In contrast, solids with a crystalline structure, in which jointing is difficult because of the elimination of local stresses by elastic deformations, mostly demonstrate ductile fracture. Thus, hard rocks under normal conditions are always brittle, whereas most metals are ductile.

3. Method to predict abrasive waterjet performance

Although the destruction of hard rock is considered to be the main application for AWJ in mining, this technology can also be used (as mentioned above) to cut non-rock materials. Therefore, there is a need for a method to predict the efficiency of cutting with AWJs that is highly accurate irrespective of material. This problem can be solved using energy conservation modeling. This approach is based on the assumption that there is proportionality between the material removal volume and the kinetic energy of AWJ. This approach has led to the development of several semi-empirical methods that allow the depth of cut to be determined for various materials.

The first of these methods was developed by Blickwedel et al. [19], and takes into account the exponential character of traverse speed and its influence on the depth of the cut, d:

$$d = C_{\mathrm{s}} \frac{P - P_{\mathrm{c}}}{u^{f}} \tag{1}$$

where C_{s} is the empirical parameter, which depends on the material's properties; f is the empirical parameter, which describes the energy losses of the jet within a cut slit; u is the traverse speed of the AWJ; P_{c} is the minimum water pressure required to initiate destruction; and P is the current water pressure.

Parameter f is determined by the following equation:

$$f = 0.86 + \frac{2.09}{u} \tag{2}$$

This approach was developed further by Chen et al. [20] for cutting aluminum ceramic, which is a brittle material. The main feature of this method is the introduction of the abrasive flow rate, m_{a}:

$$d = 0.0101 \frac{m_{\mathrm{a}} P}{u^{0.78}} \tag{3}$$

Subsequent development of this approach was done by extending the number of parameters included; the approach was then applied to various materials. For example, Wang [21] added the jet diameter, d_{j}, and the water density, ρ_{w}, to this method and used it to predict the cutting efficiency of polymer matrix composites, which are ductile materials.

$$d = 0.6267 \frac{m_{\mathrm{a}}^{0.407} P}{d_{\mathrm{j}} u^{0.637} \rho_{\mathrm{w}}} \tag{4}$$

Although the exponents for traverse speed in Eqs. (3) and (4) are distinct from those in Eq. (2), the former are more reliable and can be considered as constants, for a certain type of destructed material [6]. Thus, for brittle materials, the exponent is approximately equal to 0.78, whereas for ductile materials, the exponent is about 0.64.

The constant values before the fractions in both equations are the coefficients of machinability for a certain material. The following formula, which comes from Ref. [4], can be used for the primary assessment of this coefficient:

$$C_{\mathrm{s}} = 3.626 \times 10^{-8} \exp(-2.448 \times 10^{-8} \sigma_{\mathrm{c}}) \tag{5}$$

where σ_{c} is the uniaxial compressive strength.

Although Eq. (5) is quite useful, it is preferable to detect the machinability factor for a particular material of interest using the regression method, which requires experimental studies.

It is known that effective cutting angles depend on the material's type [22–24]. The most effective destruction of a brittle material occurs when the cutting angle, φ, is 90°, whereas for ductile materials, the optimum cutting angle is about 20°. In order to take into consideration the influence of the angle of a waterjet attack on cutting efficiency, a new coefficient, k_{φ}, is enacted, which can have a value between 0 and 1. Such a coefficient was determined [22] by approximating functions built on generalized experimental data [6,22–24].

For brittle materials:

$$k_{\varphi} = 0.99 \exp\left(-0.5 \left|\frac{\varphi - 90}{28.4}\right|^{1.77}\right) \tag{6}$$

For ductile materials:

$$k_{\varphi} = 8437 \sin\left(\frac{\varphi}{68049}\right) \exp\left(\frac{-\varphi}{20.5}\right) \tag{7}$$

Eq. (6) operates for values from 0° to 180°, and Eq. (7) operates for values from 0° to 90°.

The next point that should be discussed is the abrasive flow rate. Studies on this parameter [25–28] have shown that its increase leads to an increase in cutting efficiency, until it reaches

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