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On the failure pattern of sandstone impacted by high-velocity water jet

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ABSTRACT

Impingement of rocks by high-velocity water jets causes the erosion of structures, yet is also the principal process for non-traditional drilling and cutting methods, such as hydrodemolition, hydrodynamic fragmentation and cavitating drilling. The failure patterns of rocks subjected to water jets with different velocities vary greatly. Based on the theoretical studies, lots of experiments were conducted selecting water jets with velocities ranging from 157 ± 1 m/s to 774 ± 1 m/s. Scanning electron microscopy (SEM) was used to examine the fracture morphology in order to better understand the damage mechanism of sandstone. It's indicated that it will experience three different failure patterns in the bulk of sandstone under different jet velocities: (i) the center broken pit surrounded with a circumferential crack on the surface when the jet velocity is above a threshold value between 157 m/s and 316 m/s; (ii) the internal fractures constituted of circumferential fractures, radial fractures and the conical fractures; (iii) the macrocracks on the side surface, which change from transverse cracks to split-like cracks with the increment of jet velocity.

1. Introduction

The initial researches of high velocity liquid impacting target focused on some important practical situations, such as erosion of blades in a steam turbine, erosion of forward-facing components on an aircraft, and erosion of hydraulic machinery including ships propellers [1–3]. Based on these theoretical and experimental studies, the water jet technology has made rapid progress. Applying water jet to impinge rock have several operational advantages, such as low cutting forces, selective removal capability, high efficiency, dust-free, heat-free and vibration-free performance [4,5]. Due to the unique characteristics, the high velocity water jet is widely used in rock cutting, mining, oil and gas drilling and some other related engineering fields. During the past decades, high velocity water jets have been applied to hydrofracture, which means to develop interconnected cracks inside rocks and to make the channel for oil and gas. As a result, to study the generation and expansion of cracks in the rock subjected to water jet becomes especially important.

Bowden and Brunton [6] noted different failure patterns in brittle, rigid materials (glasses, ceramics) and in metals. The main damage feature noted in brittle materials was an undamaged central area surrounded by a system of discrete cracks and this damage feature was confirmed by Momber [7] after a lot of experiments. Bowden and Brunton [8] were probably the first to systematically describe the types of failure in materials subjected to high velocity liquid impact. They distinguished the following types of deformation and failure: circumferential surface fracture; subsurface flow and fracture; large-scale plastic deformation (for ductile materials only); shear deformation around the periphery of the impact zone; failure due to the reflexion and interference of stress waves. Furthermore, Bowden and Field [9] discussed the formation of ring cracks in greater detail and found that they were the result of the interaction of Rayleigh waves which generated during the collision between liquid and target. Field [10] summarized lots of impinging experiments and found that erosion resistance is characterized by determining its absolute damage threshold velocity ADTV. This is the velocity below which, for a given water jet size, the sample will never experience any damage regardless of the number of impacts to which it is exposed. Momber [11] noticed that if stresses generated during the impact of liquid to solid exceeded certain threshold values, drop impact contributes to the erosion. This process may in particular be critical to pre-cracked

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materials, namely: rocks and cementitious materials. Then, he selected four rock samples to study damage threshold velocity DTV in detail. It's indicated that critical liquid jet velocities are rather low for soft rocks, such as limestone (92 m/s), and sandstone (200 m/s); but high for hard rocks, such as granite (1250 m/s) and basalt (1662 m/s) [11]. Andrei Kaliazine et al. studied the failure patterns of brittle materials subjected to high velocity gas jet analytically and numerically and the proper material failure criteria were developed [12]. The previous researches concentrated mainly upon the damage threshold velocity (DTV) of different rocks. However, the failure pattern of rocks subjected to water jet with different velocities has remained elusive.

2. Water jet–solid impact theory

2.1. Determinations of pressure produced by water jet impact on sandstone surface

Water jet impacting solid target includes two main stages. Initially, the liquid jet behaves in a compressible manner to generate the so-called “water-hammer” pressures. These extremely high pressures are responsible for most of the damage resulted from liquid impact and these high pressures will continue when the edge of the contact area between the impacting jet and the solid moves super-sonically with respect to the shock speed in the liquid [13–15]. As pointed out by Lesser [14], the water hammer pressure at the central area of solid is given

$$P_{\mathrm{wh}} = \frac{v\rho_{\mathrm{w}}c_{\mathrm{w}}\rho_{\mathrm{s}}c_{\mathrm{s}}}{\rho_{\mathrm{w}}c_{\mathrm{w}} + \rho_{\mathrm{s}}c_{\mathrm{s}}}, \tag{1}$$

where v is the impacting velocity and ρ_{w}, ρ_{s}, and c_{w}, c_{s} are the densities and the shock velocities of the water and the sandstone, respectively. Ref. [16] gave the shock wave velocity by a relationship

$$c = v_{\mathrm{s}} + \phi v, \tag{2}$$

where v_{s} and ϕ are the acoustic speed and the numerical parameter, respectively. For water with the velocity up to 1000 m/s, ϕ is set to be 2. For sandstone, a formula of ϕ values is delivered

$$\phi = 11.61 \Big/ v_{\mathrm{s}}^{0.239}. \tag{3}$$

However, the duration of the initial stage is short usually in a few microseconds. As a result, this stage is usually ignored. The duration can be defined as

$$\tau = \frac{Rv}{2c_{\mathrm{w}}^2}, \tag{4}$$

where R is the diameter of water jet. Once the steady impact is established, the pressure on the central axis falls to the much lower Bernoulli stagnation pressure

$$P_{\mathrm{s}} = \frac{\rho v^2}{2}, \tag{5}$$

According to Eqs. (1), (4) and (5), the water hammer pressures and the stagnation pressures induced by jet impact are figured out shown in Table 2.

Table 1
The physical and mechanical properties of the rock samples.

Parameters	Yellow sandstone	Gray sandstone	Cyan sandstone
Bulk density (kg/m^3)	2370	2510	2130
Uniaxial compressive strength (MPa)	68	72	62
Brazilian test strength (MPa)	2.17	5.54	1.91
Secant Young modulus (GPa)	57.62	52.37	64.75
Poisson's ratio	0.23	0.21	0.25
Acoustic speed (m/s)	4354	4387	4316

2.2. Stress wave distribution

It is certain that when a body is impacted by a water jet with a curved front, the disturbance is transmitted throughout the body through the stress waves, which include longitudinal wave, transverse wave and Rayleigh surface wave [8,17,18]. Both the longitudinal wave and the transverse wave propagate inside the material while the Rayleigh wave propagates at the surface shown in Fig. 1. The position of the longitudinal wave front and transverse wave front is in accordance with the boundary of the contact area, because both the two waves are still attached to the edge of the loading area. However, the longitudinal wave separates from the transverse wave due to the speed difference inside the material and propagates more deeply into it. The propagation velocities of longitudinal wave and transverse wave can be expressed:

$$C_l = \sqrt{\frac{E(1-v)}{v(1-2v)(1+v)}} \tag{6}$$

$$C_t = \sqrt{\frac{E}{2v(1+v)}} \tag{7}$$

where E and v are the Young's modulus and Poisson's ratio.

It is known that the longitudinal wave propagates within the solid in a compression–tension manner, which will cause radial tensile stress when the wave front expands forward rapidly. However, the particle motion in transverse wave is perpendicular to the propagation direction, which will cause shear stress and circumferential tensile stress in solid. The Rayleigh surface wave, with vertical component and horizontal component, will cause

Table 2
Summary of the test constant and variables.

Test constant							
Length: 1829 mm		Width: 2946 mm		Height: 2413 mm		Work area: 737 mm × 635 mm	
Jet velocity range: 100 m/s–1000 m/s				Standoff distance: 3 mm		Jet diameter: 2 mm	Impact time: 30 s
Rock core dimension: Φ50 × 50 mm							
Test variables							
Rock specimens: yellow sandstone (YS), gray sandstone (GS), cyan sandstone (CS)							
Jet velocities (m/s)	157	316	447	547	632	707	774
Water hammer pressure (MPa)	239.5	559.3	879.4	1157.6	1416.9	1662.8	1895.9
Stagnation pressure (MPa)	12.3	49.9	99.9	149.6	199.7	249.9	299.5
Water hammer pressure duration (ns)	49.9	72.2	80.7	83.9	85.2	85.6	85.5