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International Journal of Rock Mechanics & Mining Sciences 43 (2006) 473–482
International Journal of Rock Mechanics and Mining Sciences
www.elsevier.com/locate/ijrmms

Precursors for rock fracturing and failure—Part I: IRR image abnormalities

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Accepted 7 September 2005
Available online 24 October 2005

Abstract

There are many precursors, including the abnormality of infrared radiation (IRR), for rock fracturing and failure. As the comprehensive effect of rock thermoelasticity and rock friction, the study of the IRR abnormality of loaded rock, as one of the important issues of remote sensing rock mechanics (RSRM), is facilitated by the fast development of IR remote sensing imaging technology. In view of energy input and consumption by the loading system, comprised of loader, rock and air, the mechanism of surface IRR from loaded rock is studied. The concepts that surface IRR is the comprehensive effect of a series of physical–mechanical processes inside loaded rock and that the thermoelastic effect and the frictional–thermal effect are two of the main mechanisms are presented here. Based on retrospective investigation of the fundamental experiments on RSRM during the past decade, it is concluded that there are two kinds of IRR abnormality as precursors of rock fracturing and failure: IRR image abnormality and IRR temperature curve abnormality. The spatial–temporal evolution of abnormal surface IRR images of loaded rock in a condition of uniaxial stress, compressive shear, biaxial stress, frictional slide and impact is systematically analyzed. The fact that large IRR can occur in the fracturing center of compressively loaded and shearing fractured strong and brittle rock is also revealed. Finally, the relation between rock stress and IRR temperature are studied based on thermomechanical coupling theory for solid materials. It is concluded that IRR image abnormalities are important precursors for rock fracturing and meaningful for the forecast of rockbursts and tectonic earthquakes.

Keywords: Remote sensing rock mechanics; Infrared radiation image; Abnormality; Thermomechanical coupling; Rock fracturing and failure; Precursor

1. Introduction

Rock fracturing is a natural phenomenon in geosciences and in rock engineering and includes tectonic earthquakes, rockbursts, rock slopes, rock pillar failure and coal pillar failure. The mechanism and the precursors of rock fracturing and associated 'catastrophe' are two important issues in rock mechanics, seismology and mining science. Many kinds of radiation signal, including acoustic emission [1,2], electromagnetic radiation [3], RF emission [4] and light radiation [3,5], emitted from fracturing rock, are able to provide important and useful information for interpreting and for predicting the behavior of rock fracturing, as well as the possibility of more severe rock catastrophe.

Luong [6] firstly studied the infrared radiation (IRR) of concrete in the process of loading and fracturing with thermal imaging technology. Based on real time and non-destructive detection with a thermal imager, Luong [7–9] studied the production and development of micro-fissures in the process of rock and concrete loading, fatiguing, fracturing and damaging. Geng et al. [10,11] showed the existence of IRR abnormality before rock fracturing in experiments for investigating the mechanism of satellite IRR abnormality before tectonic earthquakes [12,13]. Wu and Wang [14] found from thermal IRR imaging experiments on uniaxially loaded coal and sandstone specimens

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1365-1609/$ - see front matter
doi:10.1016/j.ijrmms.2005.09.002

that there are three kinds of abnormal features for IRR thermal image and IRR temperature as precursors of rock failure, and that a stress level of around $0.79\sigma_c$ could be taken as a 'precaution index' for the stability monitoring of coal and rock. Later, a large amount of IRR imaging experiments on rock fracturing was conducted in China [15–23]. A new inter-disciplinary topic, remote sensing rock mechanics (RSRM), which takes remote sensing, rock mechanics, rock physics and informatics as its scientific and technical disciplines and serves for geosciences, rock mechanics and rock engineering, originated in the 1990s [10,15].

Many IRR abnormal images and IRR abnormal temperature data were recorded, and their meanings for rock fracturing and failure were studied. Aiming to compare the IRR abnormalities as precursors for different rock fracturing and failure, the abnormal IRR images from IRR detection experiments on rock samples in conditions of uniaxial loading, biaxial loading, compressive-shear loading and Hopkinson impacting bar are analyzed. Based on the physical mechanism discussions on IRR from loaded rock, this paper emphasizes systematical analysis of the spatial–temporal evolution of IRR images and the large amount of IRR which occurs in the fracturing center of rock samples. For theoretical interpretation, the relation between rock stress and IRR temperature is studied based on thermomechanical coupling theory for solid materials.

2. Mechanism of surface IRR from loaded rock

As a relatively independent closed system, comprised of loader head, rock sample and environmental air, as shown in Fig. 1, rock deformation, rock fracturing and rock failure are a complex process of energy input and consumption. Without consideration of the possible chemical reactions and related energy changes inside loaded rock, the energy input to loaded rock includes two parts: the mechanical work of the loading actuator and the heat input through positive thermal exchange from the actuator head and environmental air. The energy consumption by the loaded rock is much more complex in that it includes the energy accumulation in the rock and energy dissipation from the rock.

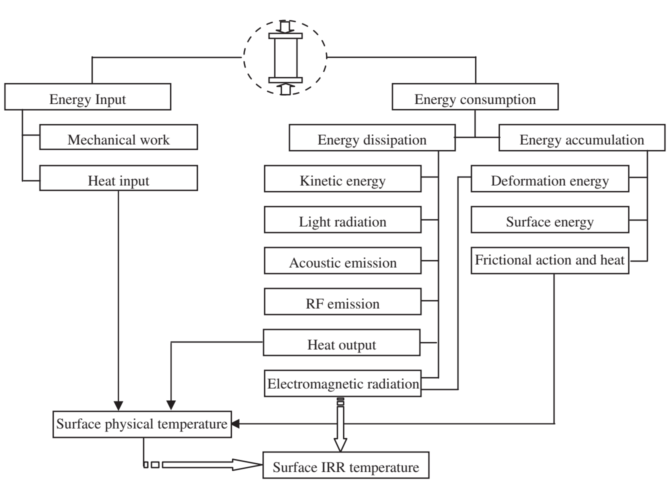

Fig. 1. IRR mechanism related to energy accumulation and consumption by loaded rock.

The energy accumulation in the loaded rock includes the positive elastic–plastic deformation energy of rock (the positive change of oscillation and rotation energy of mineral molecules), the surface energy of newly produced fractures or fissures, and the frictional actions between mineral molecules, grains, joints, fissures and fractures inside the rock as well as the produced frictional heat. The energy dissipation from the loaded rock includes the negative thermal exchange with the loader head and/or environmental air (i.e., heat output), the kinetic energy of flying fragments of fractured rock, light radiation, acoustic emission, RF emission and electromagnetic radiation including IRR and microwave radiation.

Since thermal exchange (heat input and output) and frictional action cause the loaded rock to change its heat state, the rock surface physical temperature, without consideration of the complex heat transfer process inside the rock, could be a direct index reflecting the heat state of the loaded rock. The Stefan–Boltzmann formula states that the IRR strength (radiation flux density) of any material, at temperatures above absolute zero, is biquadratic to its surface physical temperature. Crystal physics states that the energy jump of molecules oscillation and/or rotation due to the change of molecules distance, resulting from deformation, is an important mechanism of electromagnetic radiation. Hence, the rock surface IRR is a comprehensive effect of rock deformation and the physical thermal state of the rock surface. The rock surface IRR temperature could be an index reflecting the rock surface physical temperature and rock surface deformation field, which indicates the complex physical–mechanical process inside loaded rock.

In spite of thermal exchange and plastic deformation, the thermoelastic effect and the frictional–thermal effect [24] are two of the main physical mechanics of IRR production from loaded brittle rock. In the stage of elastic deformation, the thermoelastic effect is the main cause, while in the stage of plastic deformation or fracturing, the frictional–thermal effect plays a great role. At the moment of rock fracturing or failure, the friction-heat effect becomes more significant. The friction-heat effect depends on two factors: frictional force (decided by normal stress and frictional coefficient) and frictional speed. The larger the frictional force and the quicker the frictional speed, the stronger the frictional heat effect.

3. Spatial–temporal evolution of IRR image abnormality

3.1. Uniaxially loaded rock

Many rock samples of coal, ironstone, sandstone, marble, limestone, granite, granodiorite, gabbro and gneiss