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Effect of thermal-induced microcracks on the failure mechanism of rock specimens

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Abstract. It is seldom possible that geotechnical materials like rocks and concretes found without joints, cracks, or discontinuities. Thereby, the impact of micro-cracks on the mechanical properties of them is to be considered. In the present study, the effect of micro-crack on the failure mechanism of rock specimens under uniaxial compression was investigated experimentally. For this purpose, thermal stress was used to induce micro-cracks in the specimens. Several cylindrical and disk shape specimens were drilled from granite collected from Zanjan granite mine, Iran. Some of the prepared specimens were kept in room temperature and the others were heated by a laboratory furnace to different temperature levels (200, 400, 600, 800 and 1000 degree Celsius). During the experimental tests, Acoustic Emission (AE) sensors were used to monitor specimen failure at the different loading sequences. Also, Scanning Electron Microscope (SEM) was used to distinguish the induced micro-crack by heating in the specimens. The fractographic analysis revealed that the thin sections heated to 800℃ and 1000℃ contain some induced micro-fractures, but in the thin sections heated to 200℃, 400℃ and 600℃ have not been observed any micro-fracture. In the next, a comprehensive experimental investigation was made to evaluate mechanical properties of heated and unheated specimens. Results of experimental tests showed that induced micro-cracks significantly influence on the failure mode of specimens. The specimens kept at room temperature failed in the splitting mode, while the failure mode of specimens heated to 800℃ are shearing and the specimens heated to 1000℃ failed in the spalling mode. On the basis of AE monitoring, it is found that with increasing of the micro-crack density, the ratio of the number of shear cracks to the number of tensile cracks increases, under loading sequences.

Keywords: failure mechanism; micro-crack; thermal stress; acoustic emission

1. Introduction

Failure analysis of rock is a fundamental aspect in rock engineering projects. Micro-cracks, damage zone and flaws are an inseparable part of natural materials such as rocks (Jaeger *et al*. 2007, Cai *et al*. 2002) and certainly have an influence on the failure mechanism of rocks because of stress concentration on the micro-crack tips (Ghazvinian *et al*. 2013). The macroscopic deformation and failure of rock is a dynamic, gradual and cumulative process of nucleation, growth, propagation, coalescence of micro-cracks, which is a non-equilibrium, non-linear evolutionary process. The deformation and failure of rock is its macro-response to accumulated intrinsic micro-damage and cracking (Cai and Liu 2009).

The subject of rock failure analysis is becoming an interesting research area since 1960s and many valuable research works have been performed to evaluate the mechanisms of deformation and failure of rock or rock-like materials (Hoek and Bieniawski 1965, Bieniawski 1967, Wawersik and Fairhurst 1970, Hallbauer *et al*. 1973, Sprunt and Brace 1974, Batzle *et al*. 1980, Shen 1995, Wong and Chau *et al*. 1998, Bobet and Einstein 1998, Sagong and Bobet 2002, Li *et al*. 2005, Mughieda and Khawaldeh 2006, Cai and Liu 2009, Park and Bobet 2009, Chen *et al*. 2011, Imani *et al*. 2017). There are three separate phases in the failure analysis of intact rocks including: (1) initiation of micro-cracks (2) propagation of micro-cracks and (3) micro-crack coalescence.

Some new procedures for evaluation of failure mechanism of rocks have been developed in recent years. Cai and Liu (2009) investigated the failure mechanisms of rock under compressive shear loading using real-time laser holography. They found that the real-time laser holographic interferometry is helpful and powerful for real-time observation of the process of deformation and failure of rock. Hence, it can play a role of a bridge to connect macroscopic study and meso-microscopic study on deformation, failure and other behaviors of the rock.

Pan *et al*. (2012) studied the mechanism of the intermediate principal stress effect on rock failure behavior through a numerical method using the EPCA3D system and concluded that for a brittle rock specimen, a moderate intermediate principal stress delays the onset of failure propagation, which leads to the increase of the rock strength.

Pu and Ping (2012) assessed the influence of fissure inclination angle and distribution density on the failure characteristics of rock-like specimens. They showed that the fissure inclination angle was the major influencing factor on the failure modes of fissure bodies.

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Basu *et al*. (2013) studied the failure modes of granite, schist, and sandstone under uniaxial compression, Brazilian, and point load tests in relation to corresponding strengths. They showed that Granite and sandstone specimens failed mainly following central or central multiple type of fracturing whereas schist specimens principally failed by layer activation in combination with either central or non-central fractures over the entire range of determined Brazilian tensile strength.

Hamdi *et al*. (2016) used the finite-discrete element method (FDEM) to model microcrack heterogeneity by introducing into a model sample sets of microcracks using the proposed micro discrete fracture network (μDFN) approach. They concluded that the tensile strength is influenced by the presence of microcracks, with a reduction in tensile strength as microcrack intensity increases.

Nazerigivi *et al*. (2017), Najigivi *et al*. (2017) evaluated the nano-silica and steel fiber on the failure mechanism of concrete specimens and found that the addition of nano-silica particles could modify failure and micro-crack growth behavior of concrete specimens.

Also effect of thermal heating on geo-material has been investigated in several studies. Zhang *et al*. (2015) proposed a meso-scale approach to modeling thermal cracking of concrete and showed that the random distribution of concrete mechanical parameters and the temperature gradient near water-cooling pipe have a significant influence on the pattern and failure progress of temperature-induced micro-cracking in concrete.

She *et al*. (2016) developed both two- and three-dimensional numerical model to analyze the heat transfer mechanisms through the porous structures of cellular concretes and a correlation derived between the results of the 3D and 2D models.

Peng *et al*. (2017) conducted an experimental and numerical study on temperature gradient and thermal stress reinforced concrete and proposed some temperature gradient curves to obtain the thermal stress induced in the concrete.

Irrespective of model size, fractures significantly affect the mechanical behavior and failure mechanism of rocks and concretes. The mechanical behavior of laboratory small scale specimens was influenced by weak grain boundaries and micro-defects. Micro-cracks in rocks are produced when the local stress exceeds the local strength and usually observed in rocks in two forms of natural and stress-induced micro-cracks (Hamdi *et al*. 2015, Lee and Jeong 2015). Under the loading sequences, micro-cracks propagate and coalesce and create macro-cracks, which are responsible for the final breaking of rock specimens.

In the present study, it is intended to experimentally investigate the effect of microcracks on the failure mechanism of granite specimens in a new view. The specimens were heated to different level of temperatures to induce various amounts of micro-cracks in the prepared samples. Also Acoustic Emission (AE) sensors were used to monitor specimen failure at the different loading sequences.

2. Experimental investigation

2.1 Specimen preparation

Granite is an igneous rock with medium to coarse grain size which form by crystallization of slow cooling of magma. The main minerals of granite are quartz, plagioclase feldspars and alkali feldspar, and some amount of biotite, muscovite and/or hornblende (Farndon 2010). Granite is including heat-producing radioactive isotopes (K, Th, U), and is thus commonly associated with temperature anomalies and elevated geothermal gradients within the crust. Therefore it is a suitable geothermal reservoir rock. Furthermore granite is extremely low permeable and high strength rock, which also is a good potential storage site for nuclear waste (Shao *et al*. 2015).

The granite which used for experimental investigation in this study was mined from Zanjan, Iran, and the composition of the Granite under study was summarized in Table 1. Some cylindrical and disk shape specimens were prepared for uniaxial compression and Brazilian tests, respectively. Some cylindrical specimens with 135 mm in length and 54 mm in diameter were prepared for uniaxial compression tests. Also some disk shape specimens of granite with 54 mm in diameter and 42 mm in thickness were provided for Brazilian tests.

Some of the prepared specimens were kept in room temperature and the others were heated by a laboratory furnace to different temperature levels (200, 400, 600, 800 and 1000 degree Celsius). The heating rate in furnace is 10℃ per min and after reaching the desired temperature, the furnace temperature was kept constant within 30 min to occur a proper heat transmission to the inside of specimens. Then the Furnace was turned off and allowed the specimen to cool down in the furnace. This is because to prevent the fast cooling of specimens and creation of a thin damage zone near the outside of the specimens.

The matrix color of unheated specimens is grey and changed to light cream color for heated and cooled specimens. Different colors of specimens at different temperatures were shown in Fig. 1. The heating temperature was increased from right to left side of Fig. 1.

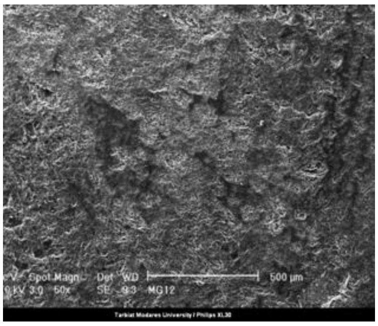
2.2 SEM microfractography

The scanning electron microscope (SEM) is one of the

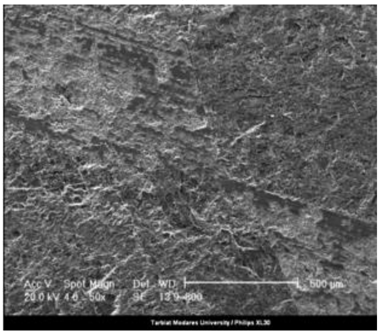
Table 1 Composition of the Granite under study

Mineral Type	Percent
SiO_2	67.02
AL_2O_3	19.60
MgO	0.00
Na_2O	11.51
CaO	0.31
TiO_2	0.00
FeO	0.15
MnO	0.01
Cr_2O_3	0.00
K_2O	0.1
Sum	98.70

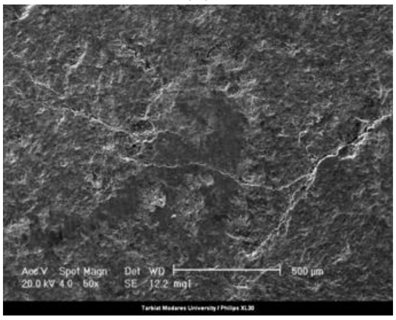
Fig. 1 Prepared specimen for experimental tests



(a)



(b)



(c)

Fig. 2 SEM images of granite: thin section (a) at room temperature; (b) heated to 800°C; (c) heated to 1000°C

most suitable instruments available for examination and analysis of micro-structural characteristics of rocks due to its high resolution. In this section of study, SEM was used to distinguish the micro-crack induced by heating in the specimens. For this purpose, some thin sections from all heated and unheated specimens were prepared and evenly coated with a thin layer of gold to create a conductive layer on the surface of specimens. Conductive layer on the samples prevents charging, reduces thermal damage and improves the secondary electron signal required for topographic examination in the SEM.

The fractographic analysis revealed that the thin sections heated to 800°C and 1000°C contain some induced micro-fractures, but in the thin sections heated to 200°C, 400°C and 600°C have not been observed any micro-fracture. Fig. 2 shows SEM images of granite thin sections in different temperatures.

2.3 Mechanical characteristics of specimens

A comprehensive experimental investigation was made to evaluate mechanical properties of heated and unheated specimens. Ultrasonic test, uniaxial compression test and Brazilian test were performed in accordance with procedures outlined by International Society for Rock Mechanics commission on testing (ISRM 1981).

2.3.1 Ultrasonic test

Ultrasonic test is a method to determine the velocity of propagation of elastic waves in laboratory rock testing (ISRM 1981). High frequency ultrasonic pulse technique was used for determination of *P*-wave velocity (V_p) in NX specimens. The ultrasonic test was carried out on the specimens before and after heating in furnace. The corresponding velocities for all specimens were recorded and decay factor (DF) of heated specimens were calculated as follows:

$$DF = \frac{V_P - V_P'}{V_P} \times 100$$

Where V_p and V'_p are *P*-wave velocity in specimen before and after heating, respectively. Fig. 3 illustrates variation of DF with heating temperatures and shows that decay factor of specimens increases with increasing the heating temperatures. For example, the specimen heated to 1000°C possesses a decay factor more than 67% which indicates a significant destruction of specimen.

2.3.2 Uniaxial compression test

Uniaxial compression test was conducted on heated and unheated specimens in an identical condition. The loading rate was kept at 0.5 MPa/s during uniaxial compression test. It is *precisely* expected that strength and elastic modulus of

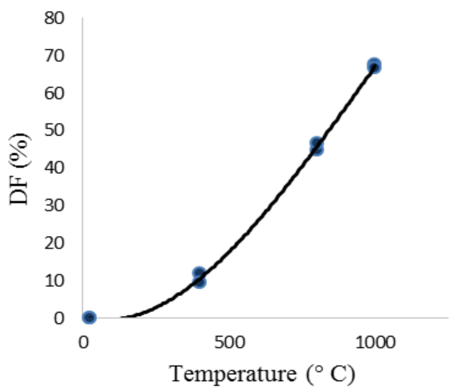


Fig. 3 Variation of DF with heating temperature

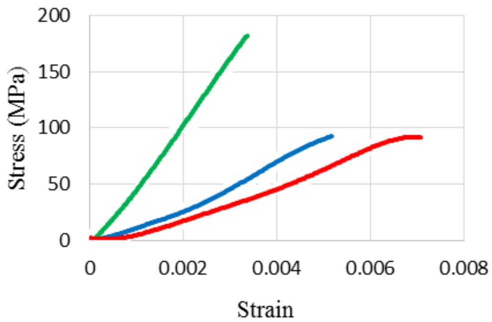


Fig. 4 Stress-strain curves of specimens at different heating temperatures

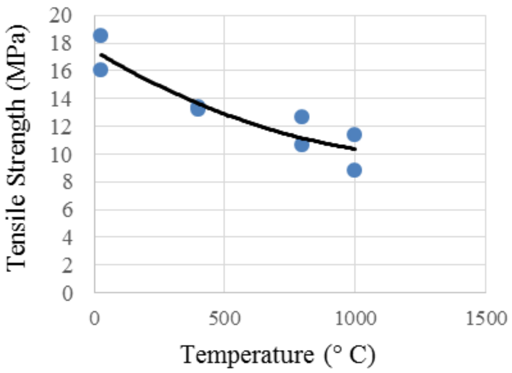


Fig. 5 Variation of tensile strength with heating temperature

specimens reduce with increasing the heating temperatures. Fig. 4 shows stress-strain curves of specimens at different heating temperatures.

2.3.3 Brazilian test

Brazilian test was performed to determine tensile strength of specimens indirectly. Fig. 5 illustrates variation of tensile strength of specimens with heating temperature with continuously decreases with increasing the heating temperature. The loading rate was kept at 200 N/s during Brazilian test.

2.3.4 Brittleness

Brittleness is an important rock property which affects the rock fracturing process. By definition, ductile materials are always accompanied by a significant amount of plastic deformation under loading, while brittle materials are characterized by little plastic deformation. Both types of materials have distinctive features on macro and micro levels (Nejati and Ghazvinian 2014).

Although some extrinsic parameters like temperature, state of stress, and loading rate have substantial influences on the material brittleness, to a large extent, ductility and brittleness depend on the intrinsic characteristics of materials such as mechanical composition and microstructure (Broek 1986).

It should be mentioned that ductile fracturing hardly ever occurs in rocks and usually is shown in metals. However, rocks can be categorized in different brittleness classes based on the demonstrated plastic deformation.

Despite the influence of brittleness on failure mechanism of rocks is significant, but still there is not a

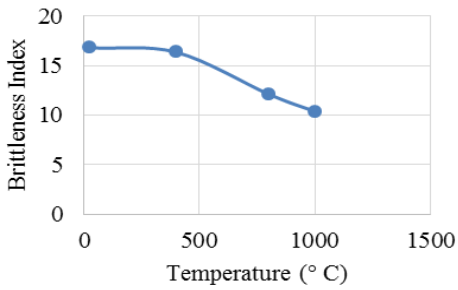


Fig. 6 Variation of brittleness index with heating temperature of specimens

standard method for measurement of rock brittleness. However, a large number of indices have been proposed for estimation of rock brittleness in the literature (Protodyakonov 1963, Hucka and Das 1974, Blindheim and Bruland 1998, Altindag 2000, Nejati and Moosavi 2016).

Hucka and Das (1974) proposed a strength-based index as a ratio of compression strength to tensile strength (σ_c/σ_t) which is popular index in rock mechanics research works. In the present study, σ_c/σ_t was considered as a brittleness index and its variation with heating temperature of specimens was evaluated (Fig. 6). As shown in Fig. 6, specimen brittleness decreases with increasing the heating temperature.

3. Acoustic emission monitoring

In recent decades, the acoustic emission (AE) technique has extensively been adopted, as an excellent diagnostic tool, to monitor fracture damage of geo-materials (Young and Martin 1993, Moore and Lockner 1995, Zietlow and Labuz 1998, Nasseri *et al*. 2006, Aggelis *et al*. 2011, Shah and Kishen 2012, Nejati and Ghazvinian 2014).

Monitoring and analyzing of the AE response during a loading sequence makes it possible to detect the occurrence and evolution of stress-induced cracks. In fact, cracking is accompanied by the emission of elastic waves which propagate within the bulk of the material (Antonaci *et al*. 2012). Amplitude of the *AE* signals, *A*, is the greatest recorded voltage in a waveform and is measured in either V or dB. Generally, the amplitude corresponds to the scale of fracture, since small scale fracture emits waves with low amplitude and large scale fracture generate signals with higher amplitude (Aggelis *et al*. 2011).

Aggelis *et al*. (2013) studied acoustic signal of different fracture modes and revealed that tensile cracking incidents show a preference to higher frequencies and shorter waveforms, unlike shear events. In other words, tensile micro-cracks produce an acoustic wave with high frequency and low Raise Angle (*RA*) while the waves emitted due to shear micro-cracks possess low frequency and high *RA*.

An experimental setup including a servo-hydraulic testing machine with a data acquisition system and an *AE* monitoring system was employed to monitor the failure sequence of specimens. The threshold amplitude of the *AE* signals was adjusted at 38.5 dB. Cumulative distribution of *AE* peak amplitude exhibited by the tested specimens is

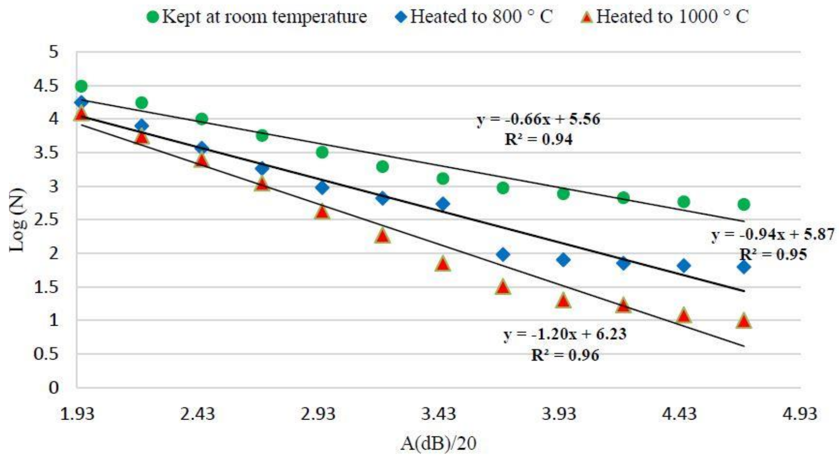


Fig. 7 Cumulative distribution of *AE* peak amplitude

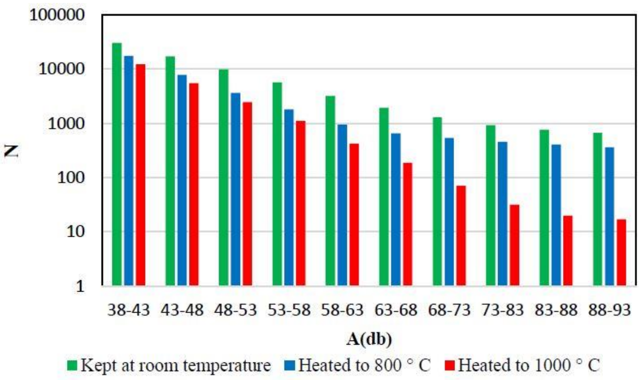


Fig. 8 Variation of number of *AE* hits with amplitude (dB)

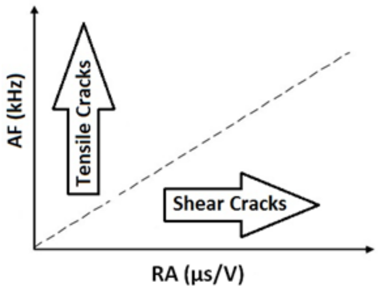


Fig. 9 Classification of crack type based on the characteristics of AE signals

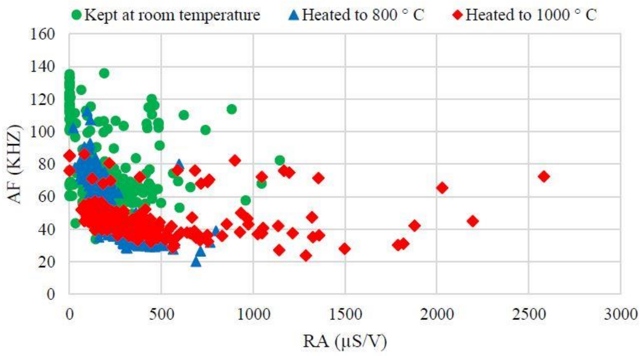


Fig 10 Variation of *AF* with *RA* for the three different groups of specimens

shown in Fig. 7. N is the number of *AE* hits or events with amplitude greater than A_{dB}. Each distribution includes all of the events recorded during the test. In order to demonstrate the trends, a straight line was fitted for each of the tested samples.

The important notion that inferred from the trend lines, illustrated in Fig. 7, is the slope of the lines, commonly referred to as the "*b-value*", which designates the frequency ratio of micro- to macro-cracks. *AE* of the specimen at room temperature presents a *b*-value equal to 0.66, while the *b*-value of the specimen heated to 800℃ and 1000℃ are 0.94 and 1.2, respectively. A smaller *b*-value indicates more *AE* activities with high amplitude. Therefore, in the specimen kept at room temperature, more highly energetic fractures were created compared to the heated specimens, during the loading sequence.

Variation in number of *AE* hits with amplitude is depicted in Fig. 8 and it is observed that the number of *AE* hits generated in the specimen kept at room temperature is more than the number of *AE* hits of heated specimens. This means that the frequency of induced fracture under monotonic loading in intact specimen is more than that in the fractured specimen by heating.

As mentioned before, mode of induced fractures under loading sequences influence on the characteristics of acoustic signals emitted from the specimen. Tensile micro-cracks produce an acoustic wave with high frequency and low *RA* while the waves emitted due to shear micro-cracks possess low frequency and high *RA*. Although there is not a certain frequency or *RA* for all specimens to precisely distinguish the tensile and shear fractures from each others, increasing in the frequency and/or decreasing in *RA* of *AE* signals indicate increasing in the number of tensile cracks in the specimens. Fig. 9 schematically shows classification of crack type with arrangement of average frequency (*AF*) and *RA*.

Fig. 10 illustrates variation of average frequency (*AF*) to raise angle (*RA*) for the three different groups of specimens. *RA* and *AF* of the emitted signals from the specimens were influenced by the micro-crack density in the specimens. The specimens kept at room temperature compared to the heated specimens possess higher *AF* and lower *RA*. Therefore, it is inferred that inducing micro-crack by heating can change

(a) (b) (c)

Fig. 11 Failure mode of specimens: (a) kept at room temperature (b) heated to 800℃ and (c) heated to 1000℃

the mode of fractures in specimens from tensile cracks to shear ones, and with increasing of the micro-crack density, the ratio of the number of shear cracks to the number of tensile cracks increases. Therefore, it is expected that failure mode and consequently failure mechanism of specimen changed with increasing the heating temperature.

4. Failure mode of specimen

Although uniaxial compression testing of rock is a simple technique for evaluation of rock strength, it contains a complicated failure pattern in the specimen which is influenced by various parameters (Fakhimi 2015). Numerous studies were conducted to investigate the effect of various parameters on failure mode of specimens under uniaxial compression.

Paul 1968 recognized three failure modes of (1) splitting, (2) shearing, and (3) spalling for heterogeneous materials under uniaxial compression loading.

Gramberg (1989) identified two main categories of (1) axial cleavage and (2) conjugate shear for brittle rock specimen subjected to uniaxial compression.

Szwedzicki and Shamu (1999) evaluated effects of strength on failure modes of rock samples and recognized five distinct modes of failure for cylindrical specimens under uniaxial compression loading as (1) simple extension, (2) multiple extension, (3) multiple fracturing, (4) multiple shear and (5) simple shear.

Basu *et al*. (2013) analyzed the failure modes of granite, schist, and sandstone under uniaxial compression tests in relation to corresponding strengths and observed six different failure modes of (1) axial splitting, (2) shearing along single plane, (3) double shearing, (4), multiple fracturing, (5) along foliation, and (6) *Y*-shaped failure.

In this section, effects of density of induced fractures on the failure modes of NX granite specimens under uniaxial compression loading were considered. For this purpose, the failure mode of specimen kept at room temperature was compared with the failure mode of specimens heated to 800℃ and 1000℃. Fig. 11 shows the failure mode of tested specimens at different heating conditions. As depicted in this figure, three different failure modes were distinguished at the specimen with different fracture density. The specimen kept at room temperature was failed in the *splitting* mode (Fig. 11(a)), while the failure mode of specimen heated to 800℃ is *shearing* (Fig. 11(b)) and the specimen heated to 1000℃ failed in the *spalling* mode (Fig. 11(c)).

The splitting failure mode is specimen breaking into a number of columns, parallel to the direction of compression loading, shear failure mode is one or two inclined fracture planes which split the sample into two pieces, and finally, spalling failure mode is flakes of rock due to existence of cracks below the specimen surface.

5. Results and discussion

Brittleness is an important characteristic of rocks, which has a strong influence on the failure process no matter from perspective of facilitating rock breakage or controlling rock failure when rocks are being loaded (Meng *et al*. 2015). In the case of uniaxial compression of rock specimens, two main failure mode of axial splitting and shearing failure mode can be recognized. Indeed, the third failure mode or splling failure mode is a combination of axial splitting and shearing failures. Axial splitting contains some axial cracks which are commonly known as tensile cracks. Therefore, rock specimens with high brittleness usually fail by axial splitting mode due to high ratio of compressive to tensile strength. In other words, in the specimen with high brittleness, tensile cracks initiated and propagated much more than the shear cracks. With increasing the fracture density in the specimens, the index of brittleness reduces (Fig. 6) and consequently the probability of nucleation and propagation of shear cracks, under uniaxial compression, increases. This is the main cause for changing of the type of specimen failure mode from axial splitting to shearing.

Monitoring of rock failure process using *AE* technique revealed that with increasing of fracture density in the specimens the mechanical stress-induced shear cracks increases (Fig. 10). Hence, the results of *AE* technique precisely confirm that the specimens with lower brittleness include more shear cracks under loading sequences and then fail by shearing mode. Szwedzicki (2007) emphasized that different modes of failure are due to the microscopic discontinuities in rock samples and confirmed that splitting failure mode occurred in the specimens which are relatively free of microscopic fractures.

Also, it is demonstrated that b-value are strongly influenced by rock brittleness. Nejati and Ghazvinian (2014) showed that brittleness affects density of micro- and macro-cracks generated during the loading sequences. An increase in rock brittleness increases the frequency of induced cracks, and ratio of micro- to macro-crack density decreases with increasing rock brittleness. In other words, during a loading sequence, a high brittle rock creates more highly energetic fractures compared to a low brittle rock.

Spalling failure mode is also known as tensile surface splitting and peeling (Andreev 1995). Therefore, spalling and splitting failure modes have the same mechanism of action, but the rock slabs or pieces that spalled from the specimen are generally thin due to existence of cracks below the specimen surface. Axial splitting failure generally occurs along a few main fracture planes, while spalling take places in much more axial planes compared to the splitting failure mode. Therefore, failure for the axial splitting specimen changes to shearing and then spalling, with increasing of the induced fracture density.

However, there is a transitional evolution between the failure modes where combined failure modes are present. For example, a specimen exhibiting shear failure may also contain elements of both spalling and axial splitting but the dominant failure mode is shear failure (Hudyma *et al*. 2004).

6. Conclusions

This study reports an experimental research work on the effect of micro-cracks on failure mechanism of granite rock specimens. The results of this study can be summarized as follows:

The fractographic analysis on granite specimens revealed that the thin sections heated to 800℃ and 1000℃ contain some induced micro-fractures, but in the thin sections heated to 200℃, 400℃ and 600℃ have not been observed any micro-fracture.

In the specimens kept at room temperature, more highly energetic fractures were created compared to the heated specimens, during the loading sequence.

The number of *AE* hits generated in the specimen kept at room temperature is more than the number of *AE* hits of heated specimens. This means that the frequency of induced fracture under monotonic loading in intact specimen is more than that in the fractured specimen by heating.

RA and *AF* of the emitted signals from the specimens were influenced by the micro-crack density in the specimens. The specimens kept at room temperature compared to the heated specimens possess higher *AF* and lower *RA*. Therefore, it is inferred that inducing micro-crack by heating can change the mode of fractures in specimens from tensile cracks to shear ones, and with increasing of the micro-crack density, the ratio of the number of shear cracks to the number of tensile cracks increases.

The specimen kept at room temperature was failed in the splitting mode, while the failure mode of specimen heated to 800℃ is shearing, and also the specimen heated to 1000℃ failed in the spalling mode.

With increasing the fracture density in the specimens, the index of brittleness reduces and consequently the probability of nucleation and propagation of shear cracks, under uniaxial compression, increases. This is the main cause for changing of the type of specimen failure mode from axial splitting to shearing.

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