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콘포컬 레이저 현미경을 이용한 불연속면의 거칠기 측정 연구

A Study of Roughness Measurement of Rock Discontinuities Using a Confocal Laser Scanning Microscope

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요약 / ABSTRACT

새롭게 개발된 레이저 콘포컬 현미경을 이용해 암석 불연속면의 거칠기를 측정하였다. 레이저의 파장은 488 nm이며, 현미경은 두 개의 galvano-meter scanner mirror를 이용한 광 편광법에 의해 제어된다. 레이저 반사를 통한 자동 초점기능은 관찰대상을 빠르고 정확하게 측정할 수 있다. 이 현미경은 기존의 다른 콘포컬 현미경에 비해 광축방향의 해상도를 크게 개선하였고, 특수 제작한 현미경 스테이지를 이용해 최대 10 × 10 cm 까지 크기의 시료를 측정할 수 있다. 측정간격은 x와 y 방향으로 2.5 μm씩이며, z방향의 최대 측정해상도는 10 μm로서, 다른 방법에 비해 훨씬 정확하다.

조립질과 세립질의 입도가 다른 화강암을 대상으로 인장시험(Brazilian test)를 통해 인공절리를 생성시켰고, 생성된 좌우의 절리면에 각각 3개씩의 측선을 설정하였다. 각 측선을 따라 측정한 높이는 1차원은 물론 거칠기의 세밀한 양상을 보여주는 2차원과 3차원의 디지털 이미지로 표현된다. 조립질 화강암의 1차원 단면은 세립질보다 불연속면의 기복이 더 심함을 잘 보여준다. 거칠기를 정량적으로 특성화하고 거칠기를 구성하는 성분 중 가장 큰 영향을 미치는 성분을 파악하기 위해 고속퓨리에 변환(FFT)를 이용한 스펙트럼 분석을 실시하였다. 스펙트럼 분석결과 저주파 성분이 큰 시료의 경우 거칠기의 기복변화가 심하고 긴 파장을 나타내는 경향이 있음을 구명하였다.

주요어 : 화강암, 거칠기, 콘포컬 레이저현미경, 고속퓨리에 변환, 스펙트럼분석

Fracture roughness of rock specimens is observed by a new confocal laser scanning microscope (CLSM; Olympus OLS1100). The wave length of laser is 488 nm, and the laser scanning is managed by a light polarization method using two galvano-meter scanner mirrors. The function of laser reflection auto-focusing enables us to measure line data fast and precisely. The system improves resolution in the light axis (namely z) direction because of the confocal optics. Using the

CLSM, it is possible to measure a specimen of the size up to 10 × 10 cm which is fixed on a specially designed stage. A sampling is managed in a spacing 2.5 μm along x and y directions. The highest measurement resolution of z direction is 10 μm, which is more accurate than other methods.

Core specimens of coarse and fine grained granite are provided. Fractures are artificially maneuvered by a Brazilian test method. Measurements are performed along three scan lines on each fracture surface. The measured data are represented as 2-D and 3-D digital images showing detailed features of roughness. Line profiles of the coarse granites represent more frequent change of undulation than those of the fine granite. Spectral analyses by the fast Fourier transform (FFT) are performed to characterize the roughness data quantitatively and to identify influential frequency of roughness. The FFT results suggest that a specimen loaded by large and low frequency energy tends to have high values of undulation change and large wave length of fracture roughness.

Key words : Granite, Roughness, Confocal laser scanning microscope, Fast Fourier transform, Spectral analysis

INTRODUCTION

Fracture roughness is one of the important factors to determine characteristics of groundwater flow and mechanical properties of rock mass. Recent studies introducing concepts of aperture variation and channel flow emphasize importance of surface roughness for conductive fractures (Rasmuson et al., 1986; Tsang and Tsang, 1987; Tsang et al., 1988; Berkowitz and Braester, 1991). Roughness has various features depending on the rock type, size and observation scale. In most of cases, different methods of measurements give different results for the same specimen. Therefore, it is necessary to measure the roughness with an appropriate method and to represent it quantitatively with a mathematically adequate method.

Many researches have been concerned with discontinuity roughness measurement. In early studies a surface profilometer was used (ISRM, 1978; Brown and Scholz, 1985). Brown and Scholz (1985) tried to measure a variety of roughness with an experimental profilometer and field apparatus. Many works were reported by using the profilometer (Power et al., 1987; Keller and Bonner, 1985; Durham and Bonner, 1993; Kulatilake et al., 1995; Power and Durham, 1997; Lespinasse and Sausse, 2000; Plouraboue et al., 2000). In recent, an improved and accurate method was developed, which is applicable for various sizes of specimens (Schmittbuhl et al., 1995). Lee et al. (1990) used mechanical equipment, which is designed to measure height of fracture surfaces. They reported the relationship between JRC grade and fractal dimension.

Photographic techniques were also applied to measure the roughness. Krohn and Thompson (1986) used techniques of scanning electron microscope (SEM) photography to acquire microstructures of specimen surfaces. This method includes a series of process such as image digitizing, filtering, counting of surface geometry and fitting of feature histogram. Jesselle et al. (1995) succeeded in accurate measurement of fracture roughness using a photogrammetric technique. Maerz et al. (1990) applied a shadow profilometry method to record shadows due to roughness on videotape.

After digitizing of the recorded shadows, they separated shadow edges by image processing and represented roughness by calculating roughness parameters.

Gentier et al. (1989) and Gale (1987) developed a resin impregnation technique. An epoxy resin was injected into fracture aperture and the resin-filled fracture was sectioned after consolidation of resin. The cross section of fracture was digitized to measure surface roughness. This method can acquire roughness data for both sides of fracture surfaces. Since it is also available to conduct a permeability test simultaneously along fracture in the lab, it is possible to identify the fracture condition on the experiment.

3-D representations of measured data have been studied recently. Develi et al. (2001) designed a computer-controlled surface-scanning device and reported a 3-D representation method. The device is capable of 0.01 mm resolution in z direction. Moreover, its computer-aided automatic control of scanning reduces observation bias due to manual operation. The roughness measurement using a laser image makes it possible to acquire more accurate data than the previous methods (Huang et al. 1988; Brown, 1995).

In this study we use a newly developed confocal laser scanning microscope to acquire accurate digital data of surface roughness of rock specimens. Since this microscope provides confocal optics, the resolution is extremely improved in the direction of light axis. The computer system makes it easy to get 2-D and 3-D images including various fracture geometries such as length, aperture, spacing and mineral surfaces. Small scale features of roughness can be measured as well as large scale geometry of roughness. Moreover, the geometry data at geological aspect can also be obtained simultaneously under high magnification observation lens.

CONFOCAL LASER SCANNING MICROSCOPE

The equipment which we use to measure fracture roughness is Olympus OLS 1100 (Fig. 1). It is a confocal laser scanning microscope (CLSM) with high resolution and contrast in the light axis direction because of the confocal optics. It offers 2-D and 3-D images as well as a variety of other features including improvement of image quality, line width and shape measurements.

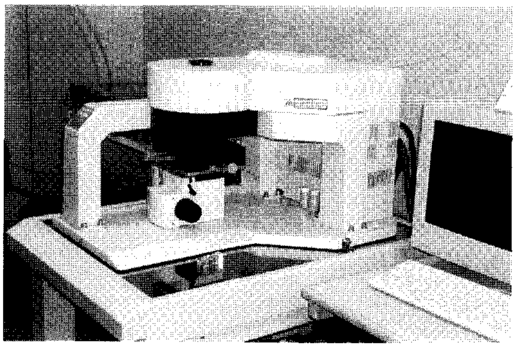


Fig. 1. Confocal laser scanning microscope, Olympus OLS 1100.

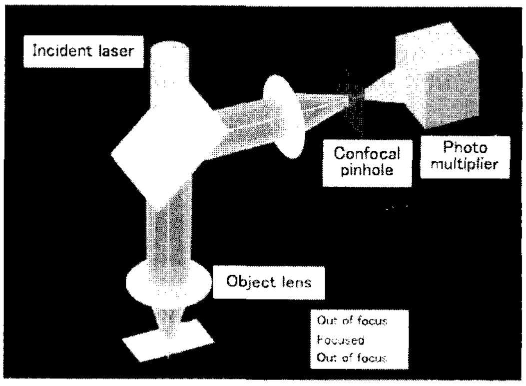


Fig. 2. Schematic description of measurement principle of OLS 1100.

The CLSM converges a laser beam into a small spot providing a pinhole at the confocal point to eliminate light from parts other than the focused position, and scans the specimen in the x-y directions. As a result, the part corresponding to the eliminated light is darkened in the image (Fig. 2). It outputs a clear image of the specimen on a computer monitor.

The scanning method of the CLSM is a light polarization using two galvano-meter scanner mirrors. Resonant galvano mirrors enable high resolution and high speed scanning of a wide area. A non-confocal observation provides images with a large focal depth without a focal effect while the confocal observation provides clear imageswith a shallow focal depth. The confocal and

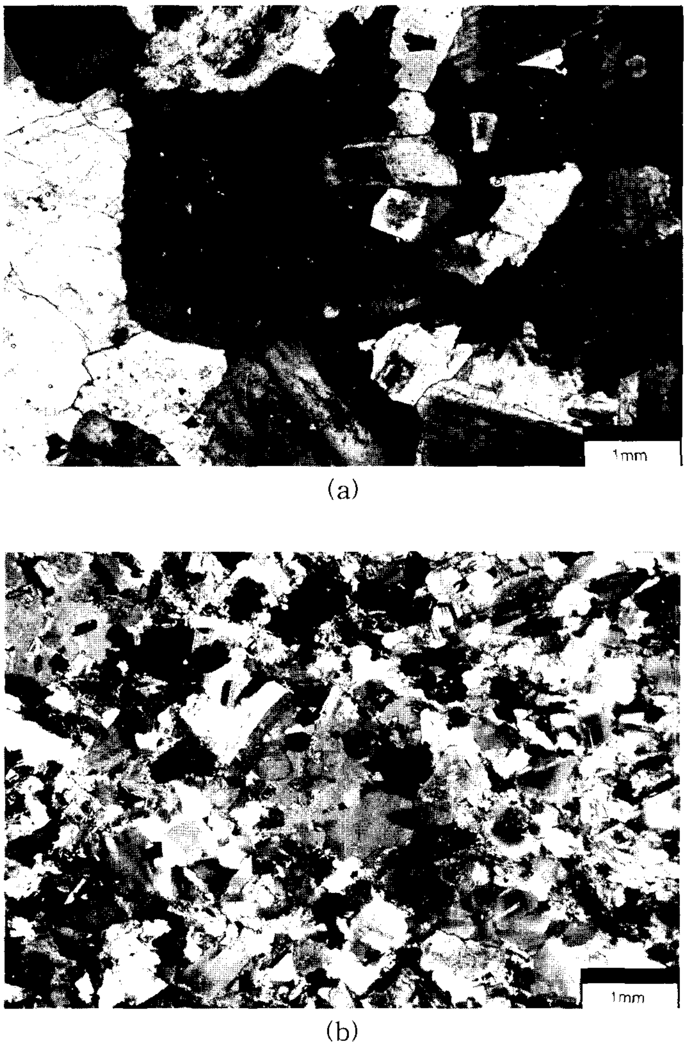
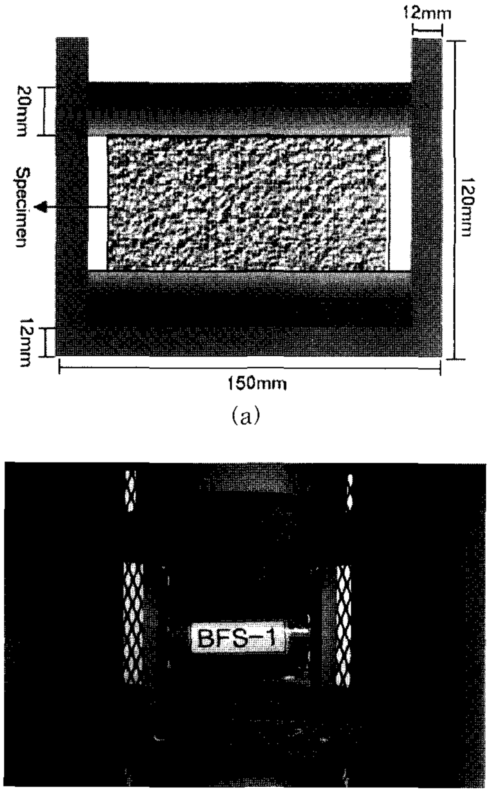


Fig. 3. Images of thin sections which were observed under a polarization microscope. Crossed nicol. (a) Coarse granites, (b) Fine granites.

non-confocal observations can be switched over easily.

The microscope can measure a specimen of the size up to 10 × 10 cm on a specially designed stage. Sampling spacing is 2.5 μm in both x and y directions. The highest resolution of z direction is 10 μm, which is more sensible than the previous methods. Note that other measurement methods usually need data conversion to a digital format providing for another analysis. However, the data by the CLSM can be utilized directly as input for a numerical modeling since they are acquired as a digital format.



(a)

(b)

Fig. 4. (a) Schematic cross section of the specimen loading frame. (b) A Photograph showing the specimen loading frame on a uniaxial compressive test machine.

MEASUREMENT OF ROUGHNESS

Preparation of specimens

Rock specimens are composed of coarse- and fine-grained granites which are acquired from rock cores drilled at two sites in Korea. Two specimens from each coarse-grained and fine-grained granite, four specimens in total, are made from intact and fresh cores. Size of a specimen is 10 cm in length and 55 mm in diameter. Observation of thin sections is conducted under a polarization microscope to identify mineral composition (Fig. 3).

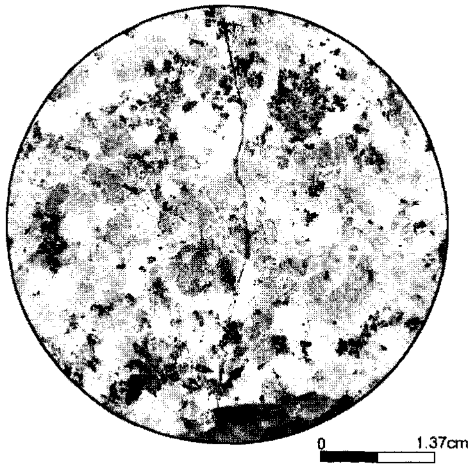


Fig. 5. A single fracture produced by a Brazilian test in a coarse granite.

An artificial fracture is introduced in a specimen by a Brazilian test. We make pentagonal steel rods of the size 130 × 16 × 20 mm and a specimen loading frame (Fig 4 a). The purpose of the pentagonal rods is to increase effect of linear loading to introduce a single fracture in a specimen. The size of the specimen loading frame is 150 × 70 × 12 mm for the lower frame and 120 × 70 × 12 mm for both sides. There are shallow grooves to fix the pentagonal rods in the frame. The loading frame is put on a uniaxial compressive machine and a normal stress is loaded through the frame (Fig. 4 b). Fig. 5 shows a specimen with single fracture developed by a Brazilian test.

Procedure of roughness measurement

Before measuring 2-D and 3-D configurations of roughness, a 1-D analysis for the measured data is required to evaluate accuracy of the microscope.

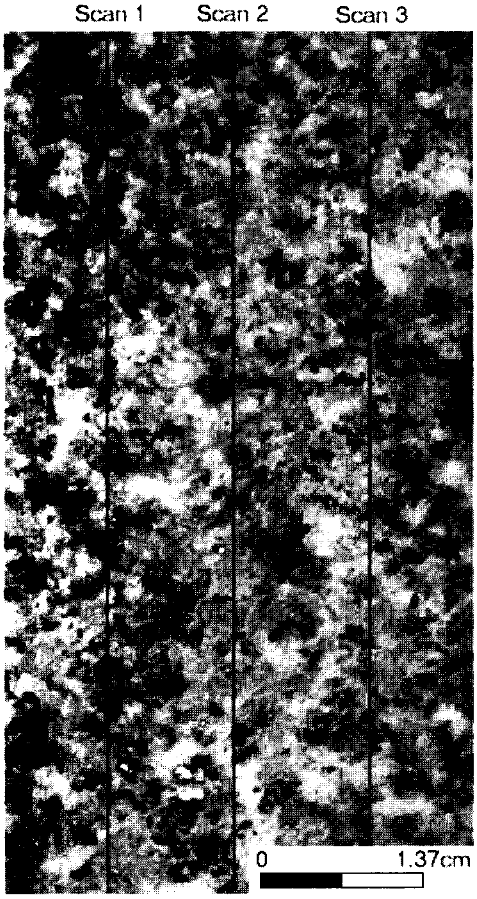


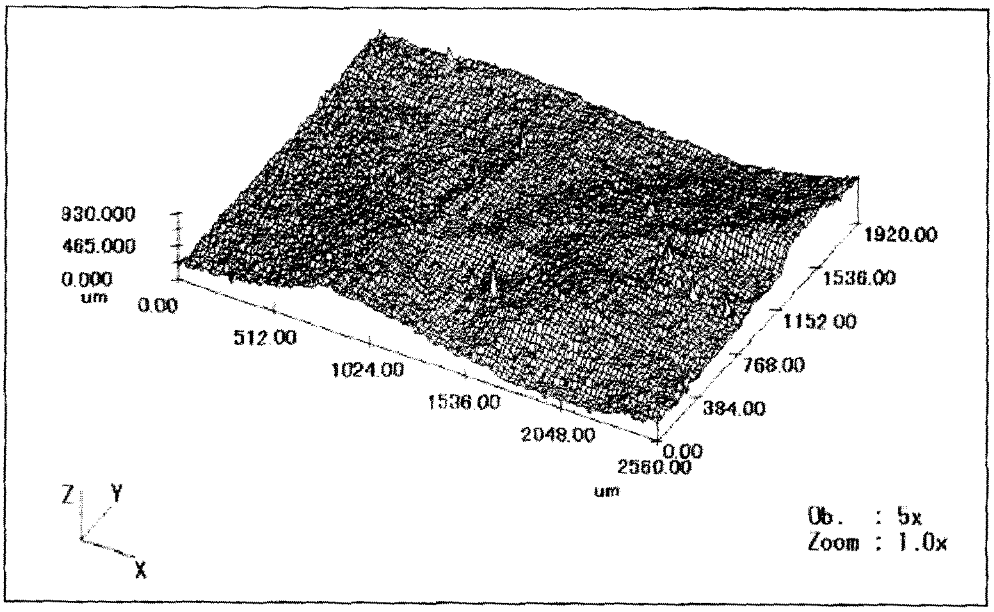
Fig. 6. Array of three scan lines on a fracture.

The major focus, therefore, is to measure and analyze 1-D roughness using a scan line method. The measurements are conducted along three scan lines on each fracture surface. As shown in Fig. 6, one scan line (Scan 2) is set at the center of fracture surface 5.5 cm in wide. Two other scan lines (Scan 1 and Scan 3) are set at 1.5 cm distanced from the center line. The length of a scan line is 10 cm. On the opposite side of a fracture surface the same array of scan lines are also set. These symmetric arrays make it possible to compare with roughness features of both sides. The total number of measured scan lines is 24.

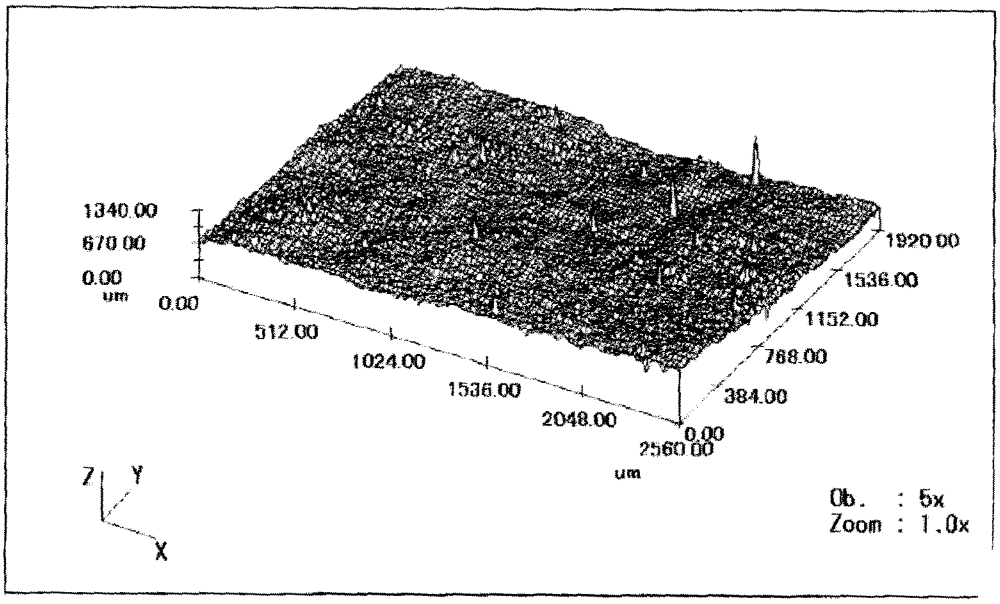
Various observation lenses can be attached for our measurement of the CLSM. We use the lowest magnification lens, 5×. The resolution of x and y directions is fixed as 1,024 × 768 pixels (2.56 × 1.92 mm in area) and the resolution of z direction is 10 μm. The measured data are shown as 3-D or 2-D digital image. 1-D roughness data are acquired from a scan line on the 2-D digital image. The scan line on the 2-D digital image can be selected easily both x and y directions. The 1-D roughness profiles are given as height data on each pixel.

Since it is not possible to cover the whole area of fracture surface simultaneously under 5× observation lens, the specimen must be moved on a microscope stage. For this purpose, a specially designed stage is introduced to control the movement within 20m. We acquire 1,024 data which are spaced at even intervals along axis. The 1,024 data correspond to the line length 2.56 mm. However, there is an overlap region as much as 560 μm (224 pixels), because the specimen displaces as 2.0 mm at a time. The overlapped data are used for checking the accuracy of measurement, then they are removed. Consequently, 800 data are acquired for each measurement section and totally data can be obtained for the whole of a scan line.

However, rock specimens involve irregularly chipped parts at the edges of the



(a)



(b)

Fig. 7. Examples of 3-D images of fracture roughness measured by the confocal laser microscope. (a) Coarse grained granite, (b) Fine grained granite.

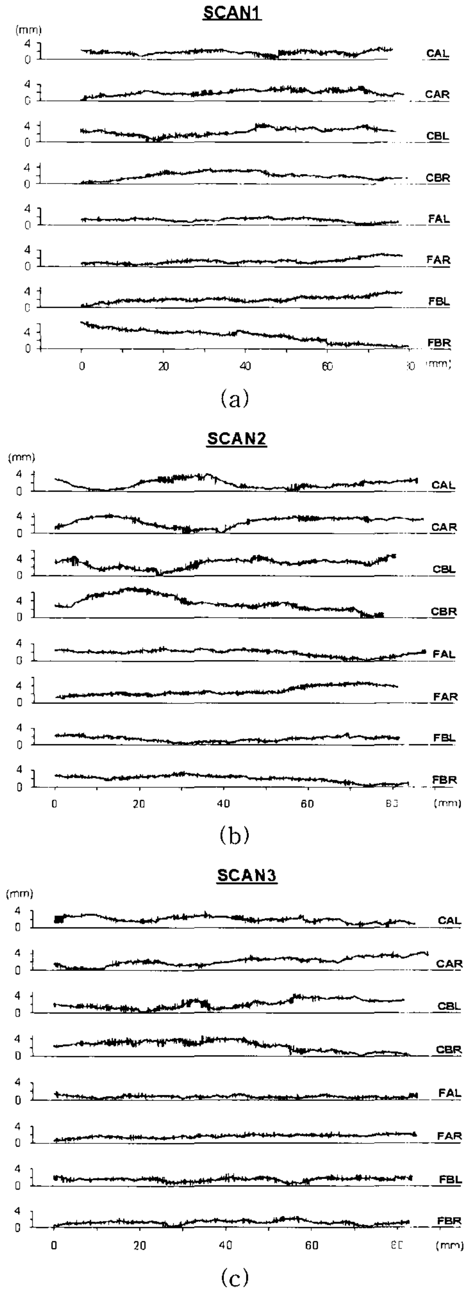
cores. Although these parts cannot be observed with our naked eyes, they induce high noise at the edges under the CLSM observation. These data are excluded in our analysis. Consequently, we analyze roughness data for approximately 8 cm long in each specimen.

RESULTS OF ROUGHNESS MEASUREMENT

Measurement results of 1-D roughness

The observed roughness shows various features because measurement resolution is very high. The 3-D images of fracture roughness of each measurement section also show roughness features very well (Fig. 7). Due to the high resolution, the 3-D images provide information of detailed changes of roughness as well as overall geometric features. Therefore, we can observe local change of roughness on a mineral surface as well as roughness itself.

As mentioned above, 1-D roughness data are acquired along a scan line of x direction chosen from the 2-D and 3-D images (Fig. 8). The 1-D roughness profiles also show detail features and changes of roughness in both small scale and large scale. According to the characteristics of roughness on each scan line, waviness on coarse-grained granite shows relatively large fluctuation and roughness is also of high value along the scan line 1. Fine-grained granite represents planar features with less rough surface due to smaller change of waviness (Fig. 8). The data of scan lines 2 and 3 show the similar features to those of scan line 1. It was reported that micro cracks are initiated from pre-existing defects of grain boundaries or interfaces of dissimilar minerals such as biotite or quartz (Tapponnier and Brace, 1976;



(a)

(b)

(c)

Fig. 8. Results of 1-D roughness measurement. (a) Scan 1, (b) Scan 2, (c) Scan 3. 'C' in the name of the specimens such as CAL means coarse grain. 'F' represents fine grain. 'A' and 'B' are different kinds of specimens. 'L' and 'R' mean left part and right part of a discontinuity, respectively.

Jeong and Ichikawa, 1994; Seo et al., 2002). Growth of micro cracks results in fracture in meso-scale. Because the geometry of micro cracks is controlled by the size and arrangement of grains, difference of roughness in this experiment indicates that the geometry is influenced by growth of micro cracks dependent on grain size.

Although the measured data by the CLSM represent characteristics of roughness very well, some noises are included in the data (Fig. 8). The noises are induced by difference of physical properties and arrangement of minerals, and different reflection intensity of laser beam on mineral surface. Confocal images of microscope are used to identify the reason why the noises are occurred, that is, whether it is caused by actual high roughness of mineral surface or by difference of reflection intensity of laser beam (Fig. 9). For example, bright parts of the confocal image imply strong intensity of reflection on mineral surface. Therefore, it is needed to identify the true property of noises when using the CLSM. It is thought that most of the noises represent difference of small scale roughness on discontinuity or mineral surface. Due to the high resolution of measurement in z-direction, t is possible to measure very small difference of roughness. However, some of the noises can also be caused by difference of reflection intensity on mineral surface.

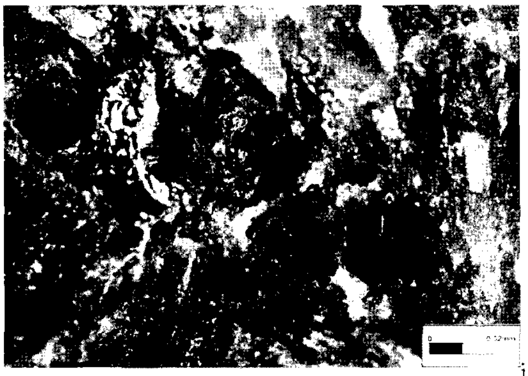


Fig. 9. Image of a fracture section taken by confocal optics of the microscope.

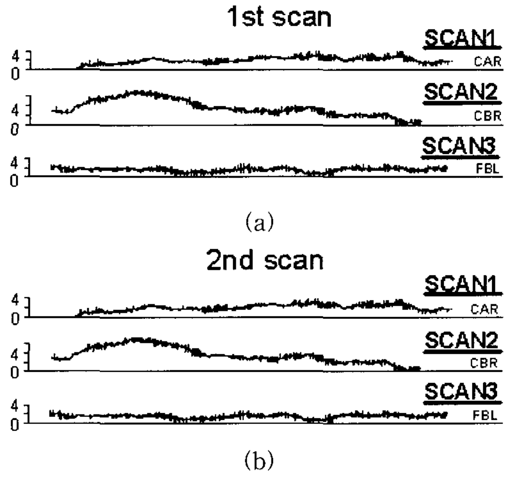
Confirmation of measurement accuracy

In order to test and confirm the measurement accuracy, we scanned three fractures repetitively among the total specimens. After complete scanning of a fracture, it was scanned again under the same condition of the previous scanning. We selected random samples such as CAR of scan 1, CBR of scan 2 and FBL of scan 3. For the acronym of the specimen, 'C' means coarse grain and 'F' represents fine grain of granite. 'A' and 'B' are different kinds of specimens. 'L' and 'R' mean left part and right part of a discontinuity, respectively. For example, CAR means right part of a discontinuity of coarse grained granite specimen A.

According to the repeated scanning results, they gave very identical roughness data and features (Fig. 10). The samples exhibit the same fluctuation patterns at the micro-scale roughness including noises as well as waviness at the meso-scale. These results confirm that the measurement method is very accurate and it does not have measurement bias during scanning. In other words, if there is no error encountered by the operator such as different loading of starting point on a specimen or inappropriate setting of scanning range between the upper and the lower limits in z-direction, we can acquire the same data for the same sample.

SPECTRAL ANALYSIS USING THE FAST FOURIER TRANSFORM

A Fourier spectral analysis is conducted to identify roughness characteristics quantitatively.



(a)

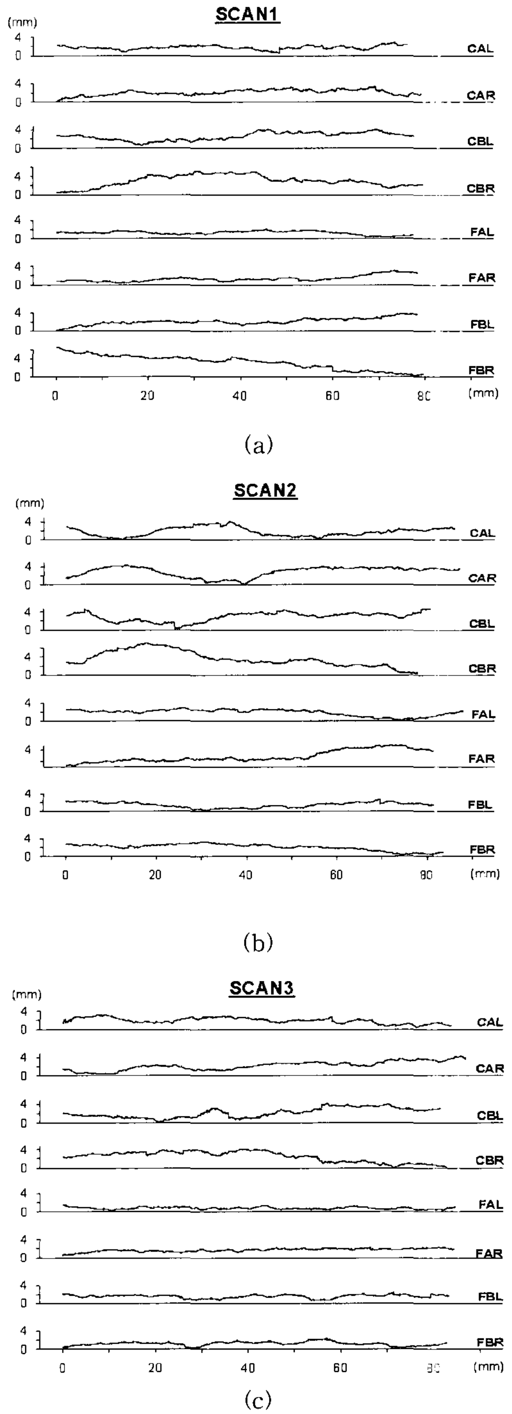
(b)

Fig. 10. Comparison of repeated scanning results. (a) Data acquired from the first scanning, (b) Data acquired from the second scanning. CAR; coarse grained granite, specimen A, right part. CBR; coarse grained granite, specimen B, left part. FBL; fine grained grainte, specimen B, left part.

A Fourier spectral analysis is conducted to identify roughness characteristics quantitatively. The spectral analysis provides information of intensity for each frequency which consists of a height signal data. Therefore, it is possible to identify composition of frequency and the most effective frequency in the signal data. In this study, the fast Fourier transform (FFT) is conducted to analyze roughness characteristics using the measured data.

Noise reduction

Because the measured data contain some noises as shown in Fig. 8, a noise reduction scheme selecting an appropriate noise filter is needed to analyze data accurately. We used a Savitzky-Golay (S-G) smoothing filter in this study, which is a type of low pass filter called as the polynomial smoothing filter or the least squares smoothing filter. It is a generalized form of FIR average filter which also



(a)

(b)

(c)

Fig. 11. 1-D fracture roughness after noise reduction by Savitzky-Golay FIR smooting filter. (a) Scan 1, (b) Scan 2, (c) Scan 3.

preserves high frequency components of signal data. Moreover, it is a good filter that can reduce noises effectively under maintaining original characteristics of the signal data.

Results of filtering with the S-G smoothing method show that the noises are reduced effectively under good preservation of overall roughness features between pre- and post-reduction of noises (Fig. 11). Consequently we can observe detailed parts of the roughness.

Spectral analysis of fracture roughness

Using the noise-reduced discrete data, a spectral analysis is performed by the FFT analysis which can identify frequency characteristics of the roughness signal data. Results of the FFT analysis show that frequency characteristics are dependent on the grain size. Most of low frequency components give a distribution of higher spectrum intensity (Fig. 12). This indicates that low frequency components control overall roughness characteristics in the specimens. In other words, waviness of a fracture surface is the more influential factor than the smaller scale of roughness in terms of the surface geometry characteristics.

For more detailed understanding of the results of spectral analysis, we focus on amplitudes between 0 and 0.5Hz of frequencies on each scan line. The amplitude patterns of each specimen are very different in the low frequency domain, especially in the near zero frequency domain (Fig. 13). In fact, the amplitude of coarse-grained granite shows higher intensity than that of fine-grained granite. The highest spectrum intensity is distributed at the second harmonic. According to the comparison results of the second harmonics on each scan line, the coarse-grained granite gives the average intensity 0.9853 and the fine-grained one does 0.6772 (Fig. 14). In general, the higher the intensity at low frequency domain is, the longer the wave length is, that is, the larger the fluctuation of waviness is. This is directly related with the roughness features that the coarse-grained granite shows a larger undulation of fracture surface than the fine-grained granite. It implies a specimen controlled by high intensity at a low frequency domain tends to show a large fluctuation of waviness, that is, a long wave length on the fracture surface.

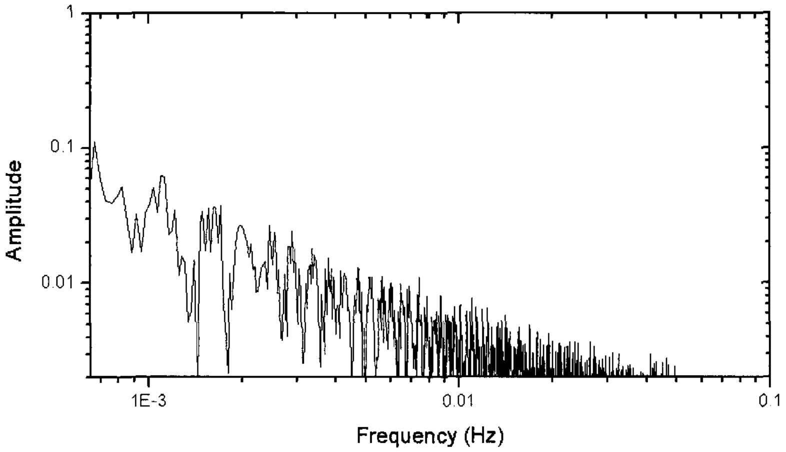
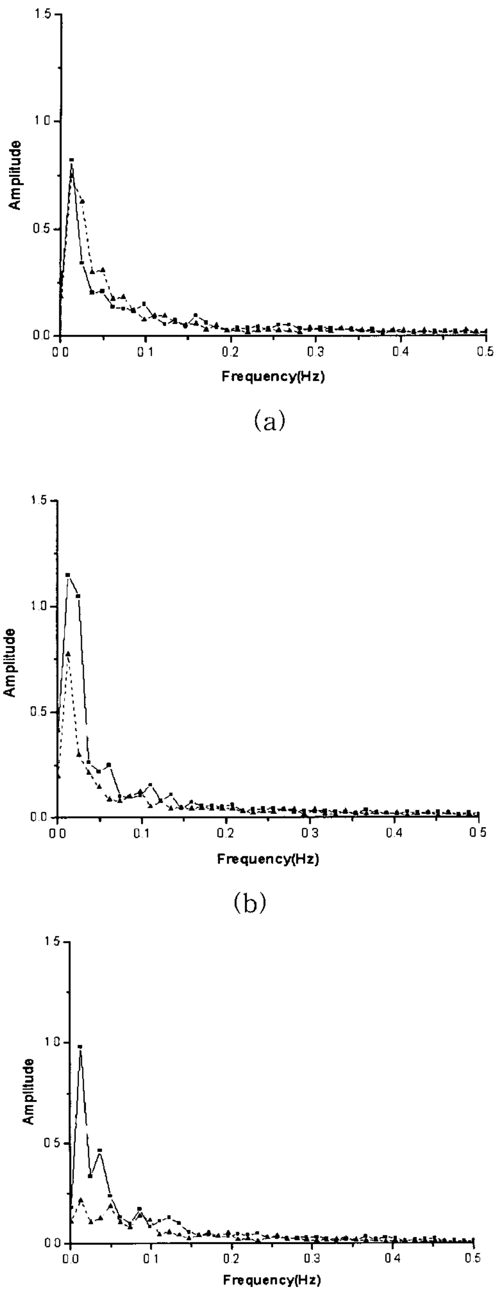


Fig. 12. An example of results of spectral analyses by the FFT.



(a)

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Fig. 13. Average amplitudes of each frequency for the whole specimens. Solid line is coarse granites and dotted line is fine granites. (a) Scan 1, (b) Scan 2, (c) Scan 3.

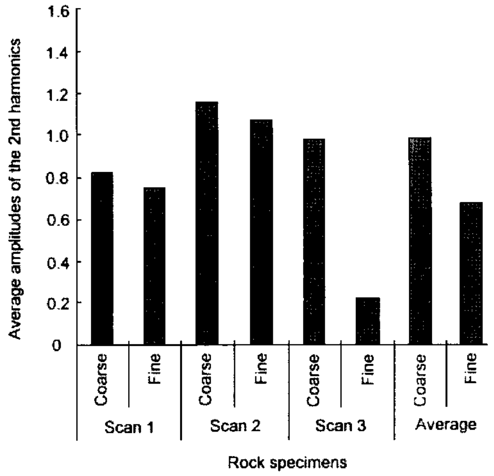

Fig. 14. Comparison of average amplitudes of the 2nd harmonics acquired by the FFT.

SUMMARY AND CONCLUSIONS

We first present a set of observation data of surface roughness of granite fracture by using a new confocal laser scanning microscope (CLSM) which can improve resolution of the height data. The computer program installed in the CLSM makes it easy to get 2-D and 3-D images. Scanning method of the CLSM is a light polarization using two galvano meter scanner mirrors. the CLSM can measure a specimen of the size up to 10 × 10 cm using a specially manufactured stage. Sampling spacing is 2.5m in x and y directions. The highest resolution of z direction is 10m, which is more improved and accurate than existing measurement methods.

Because the CLSM system can observe a specimen under high magnification lens, it is also possible to identify minerals and geometries in a sense of geology. Furthermore, we must usually convert the observed data into a digital form for a subsequent analysis in other methods, while the CLSM originally provide digital data.

An artificial fracture is introduced in a specimen by a Brazilian test. The roughness of the fracture surface is measured along three scan lines. The length of a scan line is 10 cm. On the opposite side of a fracture surface the same array of scan lines are also set. These symmetric arrays make it possible to compare with roughness features of both sides.

Results of roughness measurements show delicate features of roughness due to high resolution of measurement. The 3-D images excellently represent a small scale of roughness as well as a large scale of waviness. The 1-D roughness profiles show that coarse-grained granite involves larger undulation and rougher surfaces than fine-grained one.

A Fourier spectral analysis is conducted to identify roughness characteristics quantitatively. The spectral analysis provides information of intensity for each frequency which consists of a height signal data. The highest spectrum intensity is distributed at the second harmonic. Comparing the second harmonics on each scan line, the coarse-grained granite gives the average intensity 0.9853 and the fine-grained one does 0.6772. In general, the higher the intensity at low frequency domain is, the larger the fluctuation of waviness.

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