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Mechanics of Micro-Damage at Contact Portion of Two Grains
두 입자의 접촉면에서의 손상역학 해석

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Abstract/요약

To better understand the fundamental problems of the true micro-damage in medium-grained granite under uniaxial compressive stress, micro-damage localization, initiation and propagation have been observed in a great detail in contact portion of two grains such as quartz and feldspar. For this purpose, new experimental system allowing us to observe the micro-damaging process continuously was developed. Earlier studies used the specimens of unloaded state and it is difficult to visualize stress-induced microcracks under unloading state. Thus, direct observation under loading state is very important for understanding the true micro-damage process. The results explain well the mechanism of micro-damage at two grains, and mechanics of the micro-damage is clarified well by Hertzian fracture mechanics.

응력하에서 암석 및 암반의 변형특성의 원인이되는 손상발달에 대한 이해는 지질공학 및 토목공학에 있어서 매우 중요하다. 지금까지의 연구에서 보면 실험전과 후의 관찰로서 응력하 미소손상발달에 대한 연구는 아직 미비한 실정이다. 그러므로 응력하에서 손상과정을 직접 관찰하는 것은 매우 중요하다. 본 연구에서는 응력하 중립질 화강암의 미소손상에 대한 보다 정확한 이해를 위해 미소손상집중, 발생 및 진전등이 석영과 장석의 접촉면에서 새로이 개발한 실험장치에의해 상세히 관찰되었다. 그 결과는 두입자의 elastic mismatch 와 Hertzian fracture mechanics에 의해 잘 설명된다.

INTRODUCTION

Granitic rock, as a most natural, is characterized by microstructures including microcracks and microcavities whose evolution and interaction, called the micro-damaging process, determine macroscopic, mechanical response. Granite commonly involves complex composite microcrack system which are caused by different geologic processes under varying conditions (Kranz, 1983).

Microcrack studies are of increasing interest in geophysics and engineering geology related to underground space development and radioactive waste disposal. Numerous recent studies have shown that the physical properties of rocks are affected not only by the constituent minerals and their preferred orientation (Olsson, 1974;Schrodt et al., 1983;Wong, 1990) but also by the microcracks (Bombolakis, 1973;Sprunt et al., 1974;Hadley, 1976;Batzle et al., 1976;Richter et al., 1977;Kranz, 1979a;Nemat-Nasser et al., 1982;Sammis et al., 1986;Yukutake, 1989;Gottschalk et al., 1990;Ahrens et al., 1993).

Microscopic studies of cracks in postloaded samples have been made using scanning electron microscope (SEM) in order to reveal interactions between microcracks and relationships between the concentrated microcracks and macroscopic failure (Friedman et al., 1970;Mardon et al., 1990). For damage propagation in particular, Chelmsford granite specimens were loaded to various levels, unloded, cut lengthwise into halves and then observed by Peng et al. (1972). These experimental studies have shown that macroscopic fractures grow from grain-scaled microcracks, which are abundant in crystalline rocks. However, these works have the drawback of having been performed only under zero stress conditions using thin or cut sections after an experiment, or under artificially fractured conditions.

Recently, experimental observations of acoustic emission (AE) locations during shear fracturing in cylindrical specimens of Westerly granite and Berea sandstone were conducted by Lockner et al. (1992). By using an array of piezoelectric tranducers, they recorded arrival times of AE events resulting from the impulsive growth of microcracks during deformation of initially intact rocks. These resulrs may provide a number of important clues regarding the process of brittle shear fracturing, which are not obtained by a direct observation method.

Microcracking during complex loading could result from stress concentration around flaws such as grain boundary microcracks, intracrystalline microcracks and microcavities. Therefore, a detailed knowledge of microcracks may also substantially improve our understanding of damaging process, microcrack-induced dilatancy and failure in intact rock.

To better understand the fundamental problems of micro-damage initiation and propagation in granite, we have observed the actual micro-damage behavior during the deformation of granite specimens. Experimental studies of damage process in intact medium-grained granite specimens under uniaxial compressive stress were carried out with a newly developed experimental system. This experimental system allows one to observe continuously the damaging process under loading.

EXPERIMENTS

The microcrack formation and subsequent damage propagation examined in this study were produced in a series of compression tests using medium-grained granite under nominally dried condition at room temperature. Average rate of loading of 0.02 MPa/s was applied in this experiment.

Granite Specimen

All specimens were taken from a block of medium-grained granite from Geochang, Korea, by arranging the cut-planes in the same direction. The specimens consisted mainly of 36.5 % quartz, 56.3 % feldspar and 7.2 % biotite. The mean size of quartz grains, determined by the linear intercept method, is 3500 ㎛. The bulk density and apparent porosity of the granite are 2.58 g/cm^3 and 0.83 %, respectively.

The dimensions of a typical specimen are shown in Fig.1. The parallel and perpendicular degree of the end planes of the specimen is about 4/1000 and all surfaces were polished with 1000 grain. emery powder for easy observation by a stereoscopic microscope.

Experimental Procedures

The design of the specimen assembly and experimental system is shown in Fig.2. It consists of three subsystems a)

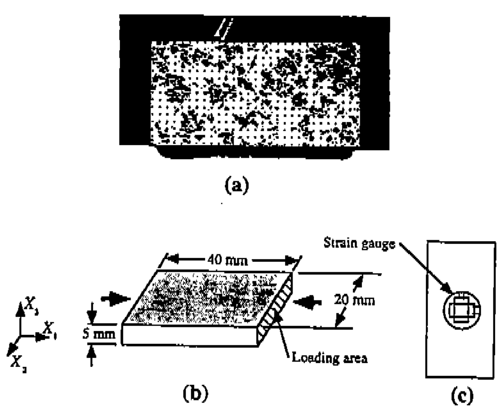

Fig.1 Description of specimen ; a)photograph of granite specimen, b)dimensions of specimen, axis of compression is X_1, and c)location of strain gauge.

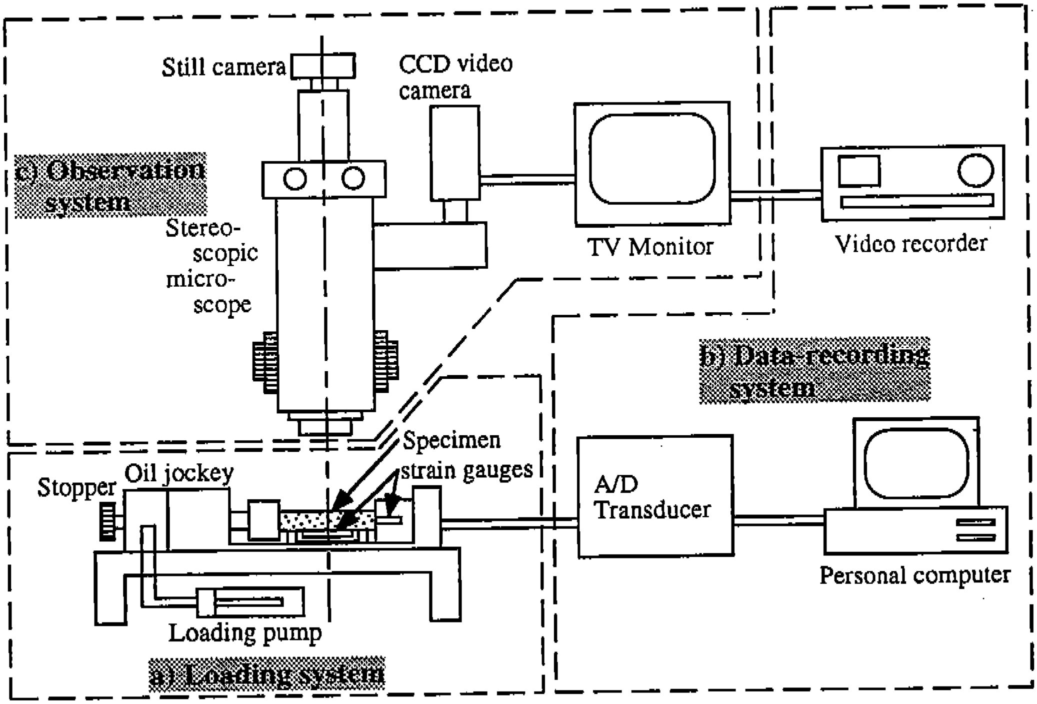

Fig.2 Schematic diagram of experimental system : a)loading system, b)data-recording system and c)observation system.

loading system, b)data-recording system and c)observation system. The loading system is illustrated in Fig.3.

First, a granite specimen with a mounted strain gauge was placed on a concave-shaped steel block in a vessel and various portions in the central region of the specimen were photographed. Next, stress was applied to the specimen by a piston actuated through a manually controlled loading pump. Axial stress and strain were recorded in a personal computer.

In order to observe directly the initiation and propagation pattern of micro-cracks which are developed in feldspar, pre-existing grain boundaries and intra-

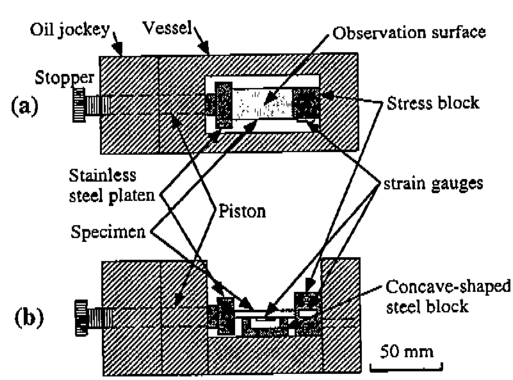

Fig.3 Specimen and each part assembly of loading system.

crystalline microracks in quartz, a stereoscopic microscope (Nikon,SMZ-U) with a magnifying power of 110 times is used. A video monitoring system was used for continuous recording and a still camera for intermittent recording.

Stress-Strain Relations

Axial stress versus axial and lateral strain curves were similar for all tests. A representative curve shown in Fig.4 is characterized by various stages such as closing phase of pre-existing microcracks (Stage 1), linear elastic phase (Stage 2), dilatancy initiation phase (Stage 3) and shear fracture development phase (stage 4) up to the peak strength.

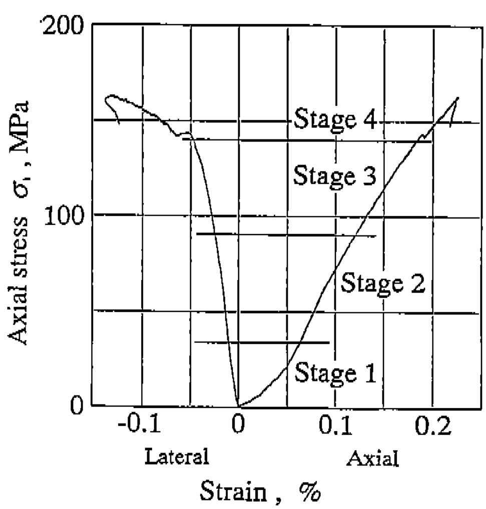

Fig.4 Typical axial and lateral strain versus axial stress.

MICROSCOPIC OBSERVATIONS OF DEFORMED SPECIMENS

Microcracks consisting of healed cleavages, pre-existing intracrystalline microcracks and grain boundary microcracks were traced on stereoscopic photomicrographs under gradually increased stress at various portions of the specimen.

Pre-Existing Microcracks

Before specimens are loaded, many healed pre-existing microcracks are observed in quartz grains, and some longish microcavities with blunt ends are observed in feldspar (Fig.5).

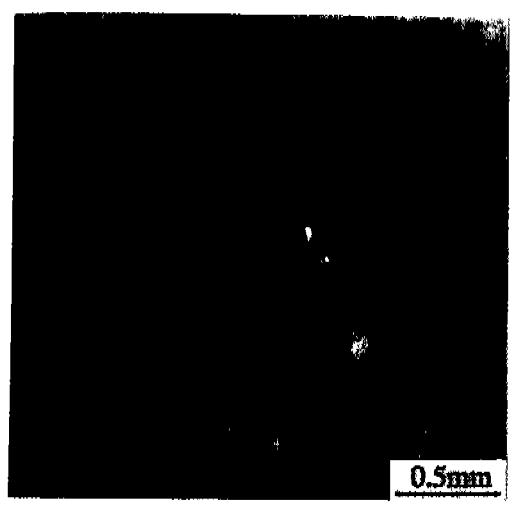

Fig.5 Photomicrograph showing that pre-existing microcracks are well developed in various directions in quartz (Q), but those in feldspar(E) are very few.

From their study of the origin of microcavities, Sprunt et al. (1974) concluded that many of the intracrystalline with high aspect ratio microcavities might have been sites of a residual fluid phase which remained after the crystallization of granite, and some could have been the sites of fluid inclusion. They also showed that long rows of bridged microcavities with low aspect ratio were most commonly associated with quartz grains. These long rows of microcavities can be described as healed microcracks with almost completely leaked fluid inclusion. They observed that, in granite, microcracks were preferentially developed in quartz, and most of them were intracrystalline, frequently starting at grain boundaries. Therefore, these microcracks might reflect the existence of pre-existing intracrytalline microcracks, and their systems may be considered as micro-cracks caused by internal stress due to change of pressure or temperature, or through mechanical loading during their early history (Jeong et al., 1993). Some isolated low aspect ratio microcavities within feldspar may represent healed cleavage microcracks which are sometimes bridged with rounded ends.

In quartz grains, pre-existing intracrystalline microcracks are well developed in various directions, but microcracks in feldspar grains were few. The higher microcrack densities within quartz grains compared with adjacent feldspar grains may indicate that the initiation of microcracking is generally related to internal stresses or difference of volumetric strains at grain scale.

Quartz grain in granite underwent a large volume change upon cooling from 600℃; about 4-5% compared to a value of 1-2% for most other common silicate minerals (Friedman et al., 1970). Thus quartz grain undergoes a greater contraction than the feldspar leading to high tensile stresses in the quartz. Therefore, the existence of these pre-existing microcracks is mainly due to differences in the thermo-mechanical properties of minerals (Table 1).

Table 1. Physical properties of quartz and feldspar
[from Skinner, 1966;Birch, 1966]

Minerals	$\alpha(\times 10^{-5}℃^{-1})$	$K(\times 10^{4}MPa)$	$\beta(TPa^{-1})$
Quartz	5.15	3.82	26.2
Feldspar	1.45	4.29	23.3

α : thermal expansion ratio
K : bulk modulus
β : compressibility

Almost all of the grain boundaries in granite used in this study, which mostly consist of medium-grained quartz and feldspar, observed to be open. The damage due to preparing specimens may be more severe because of mechanical stress during handling than before preparing of specimen. An indicator of the damage due to sectioning (i.e., cutting and polishing) is described in Peng et al. (1972). That is, if there are microcracks which run through a few grains, the damage may be due to sectioning. In the specimens used in the present study, such microcracks were absent under no stress condition.

Micro-Damage Localization

The location of stress-induced micro-damage initiation, growth direction and the relationship between pre−existing grain boundary microcracks and stress−induced microcracks was observed in a great detail with use of a stereoscopic microscope which enables continuous observation during loading.

Microcrack initiation at quartz-feldspar grain contact

Feldspar grains have cleavages of {001} and {010} plane. These cleavage planes generally have low bond density or strength, and low surface energy. Planes with defects such as microcavities show the lowest strength and surface energy stored in the grain. As a result, stresses tend to be relieved on these planes first, and the feldspar then tends to be microcracked.

The primary stress-induced microcrack in feldspar grains is initiated through the defective grain boundary (Fig.6) at a stress level of 30 MPa. At the same time, microcavities in feldspar are linked, and intracrystalline microcracks and non-coincident grain boundary microcracks parallel or subparallel to the axial stress direction are predominantly caused by

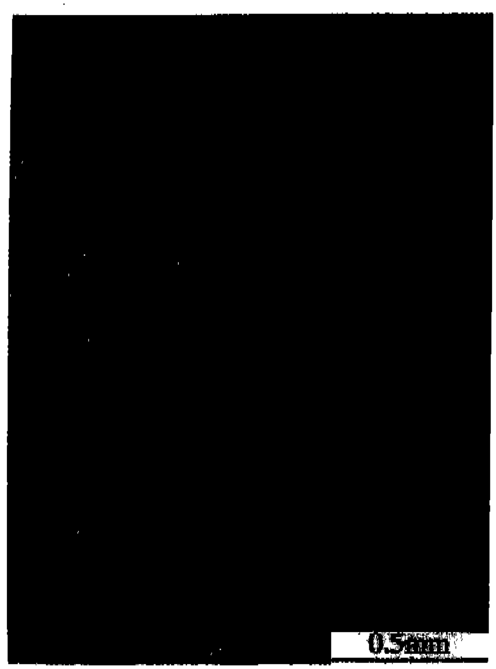

Fig.6 Stress-induced microcracks in quartz(Q) and feldspar(F).

tensile stress due to the Poisson effect in nature. Furthermore, local variation in elastic properties of different minerals or the presence of microcracks cause the stress to be concentrated, and the remote compressive stresses are converted to locally tensile stresses. Based on these facts, intracrystalline microcracks nearly parallel to the axial stress direction are initiated from pre-existing grain boundary microcracks between quartz and feldspar grain. Note that the compressibility of feldspar is lower than that of quartz grain. On the other hand, microcracks perpendicular and inclined to the axial stress direction are closed and sheared, respectively.

Displacement along grain boundary microcracks increases as the axial strain continues to increase. The circumference of these microcracks fails partly and tends to be very complex, with many fraction.

DISCUSSION

Rock and rock masses are composed of discrete elements of microstructures such as different grains and microcracks. Accordingly, instead of a simplified continuum approach, we must take into account the discrete structural elements and mechanical properties of various grains. Damage mechanics and fracture mechanics have been recently developed as effective methods to estimate these materials. Where the damage propagates from a pre-existing crack of mesoscale or macroscale, these methods are very effective. However, a number of studies (e.g., Peng et al., 1972;Lockner et al., 1992) have shown that a propagation, coalescence and increased density of microcracks cause mesoscale or macroscale cracks, and elastic and plastic properties of rocks are significantly affected by changes in these microstructures. From this standpoint, a precise understanding of the damage process of microscale in rocks is very important.

In the past, most of the attempts (e.g., Peng et al.,1972;Hadley, 1975;Kranz et al., 1979;Lockner et al., 1992) to observe damage initiation and propagation leading to shear fracture were carried out with thin or cut section or by a SEM observation method after unloading. These studies demonstrated microcrack damage of rock specimens only under no loading or unloading condition.

Through indirect methods such as AE observations, recently Lockner et al. (1992) demonstrated the ability to retard unstable fracture propagation so that quasistatic fault growth can be studied on a timescale of minutes to hours.

This ability is based on the technique of controlling stress to maintain a constant AE rate. The brittle fracture process was experimentally found to involve three stages; 1)distributed damage during loading of the specimen to peak stress, 2)fault nucleation after peak stress, and 3)fault propagation. Though the results can explain well the macro-damage growth, the first stage in the detailed description of micro-damage is not demonstrated sufficiently.

To clarify the true damage process of microscale in granite under uniaxial compressive stress, we have observed the process in considerable detail. Microscopic observations revealed that incipient micro-damage is generated from the two grain contact portions by the elastic mismatch and by the critical stress intensity factor of the two grains, and the direction of micro-damages is parallel or subparallel to the axial stress direction.

Mechanics of Micro-Damage

Since most grains are in contact with each other, we based our interpretation of the microcrack initiation and propagation at the contact of grains on the special nature of the inhomogeneous stress field of Hertzian loading (Frank et al., 1967;Wilshaw, 1971). The radius a, as shown in Fig.7, of the circle of contact between spherical two grains is formed from the Hertzian analysis:

$$a^3=\frac{3}{4}Pr\left[\frac{(1-\nu^2)}{E}+\frac{(1-\nu'^2)}{E'}\right] \quad (1)$$

where P is the normal load applied on the grain, E′ and E are the Young's

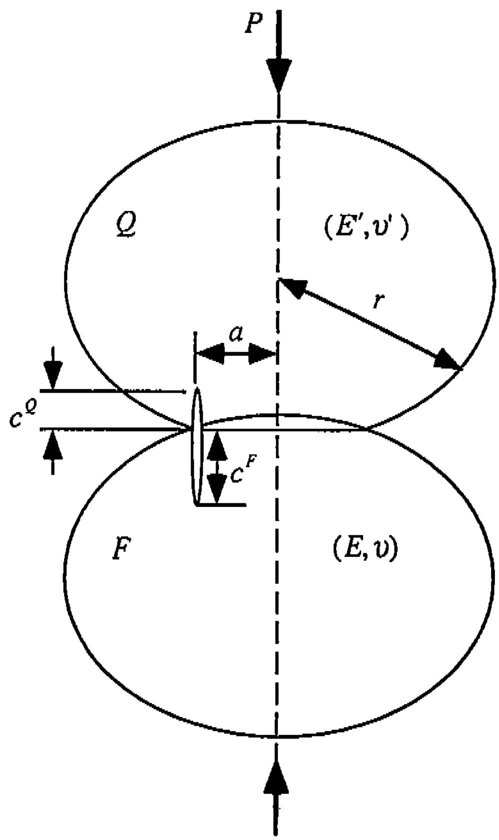

Fig.7 Hertzian loading arrangement showing a schematic array of a grain contact.

moduli of quartz and feldspar grains respectively, r is radius of the grain, and ν' and are the ν corresponding values of the Poisson ratio.

The primary stress-induced intracrystalline microcrack is initiated from the contact portion of two grains. While the crack is small and normal to the contact surface, the maximum tensile stresses σ_m^Q and σ_m^F in the quartz and feldspar grains are uniformly distributed along the microcrack. Moreover, the microcracking criterion is assumed equivalent to that for a single edge microcrack in tension (Wilshaw, 1971). The stress intensity factors K_I^Q and K_I^F, which are function of the stress and the microcrack length c^Q and c^F, are given by

$$K_I^Q = 1.12\sigma_m^Q(\pi c^Q)^{1/2} \quad (2)$$

$$K_I^F = 1.12\sigma_m^F(\pi c^F)^{1/2} \quad (3)$$

where

$$\sigma_m^Q = \frac{(1-2\nu')P^Q}{2\pi a^2} \quad (4)$$

$$\sigma_m^F = \frac{(1-2\nu)P^F}{2\pi a^2} \quad (5)$$

By substituting equation (4) and (5) into equation (2) and (3), we obtain the critical forces for the initiation of microcracks in quartz and feldspar grain as

$$P^Q_{critical} = \frac{2\pi a^2 K^Q_{IC}}{1.12(\pi c^Q)^{1/2}(1-2\nu')} \quad (6)$$

$$P^F_{critical} = \frac{2\pi a^2 K^F_{IC}}{1.12(\pi c^F)^{1/2}(1-2\nu)} \quad (7)$$

In this case, we should assume in the above analyses that the local stress field in the vicinity of the microcrack in solely due to the elastic contact between two grains (Zhang et al.,1990). This is a reasonable assumption in our microcrack initiation analysis, since the contact stress concentration is highly localized and the microcrack at the initiation of Hertzian fracture is short.

We may now evaluate the characteristics for microcrack propagation. Since at a contact portion of two grains, $P^Q_{critical}$ must be equal to $P^F_{critical}$, we obtain the following relation:

$$\frac{K^F_{IC}}{K^Q_{IC}} = \frac{(1-2\nu)}{(1-2\nu')} \cdot \left[\frac{c^F}{c^Q}\right]^{1/2} \quad (8)$$

where the critical stress intensity factors of quartz and feldspar have been measured by Atkinson et al.(1980) for several orientations, then we take their average critical stress intensity factors 0.383 $MPa\sqrt{m}$ for K^Q_{IC} and 0.364 $MPa\sqrt{m}$ for K^F_{IC}. The Poisson's ratios are obtained as $\nu' = 0.109$ and $\nu = 0.299$ by Birch (1961). By using these values, we obtain the microcrack propagation condition as:

$$c^F = 3.42c^Q \quad (9)$$

However, if open pre-existing intracrystalline microcracks are developed in quartz and feldspar grains, the Hertzian theory presented here is not applicable.

SUMMARY AND CONCLUSIONS

In order to better understand the fundamental problems of micro-damage localization and propagation and to clarify the true damage process of microscale in granite specimens under uniaxial compressive stress, we have observed the micro-damaging procedure in a great detail using a newly developed experimental system which allows continuous observation of the procedure.

The response of microcracks to compressive stress is more complex than to tensile stress. However, the mechanism of microcrack initiation in the granite specimen, used in this study under uniaxial compressive stress, may be considered in the case which two grains (i.e., quartz and feldspar) are in contact in the same direction with the applied axial stress. As the contact portions are normal to the axial stress direction, pre-existing grain boundary microcracks may close up to 30 MPa of the axial stress level, and at the stress level of 30 MPa, stress-induced microcracks are initiated.

Micro-damage mechanics of microcrack initiation and propagation is explained well by Hertzian fracture mechanics, and the mechanism can be also clarified by elastic mismatch of two grains.

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