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Some Features of Cleavage Cracks in Rocks and Metals

Peter Panfilov[1,2,*], Roman Korovin[1], Maxim Mezenov[1,2], Dmitry Zaytsev[1,2], Nikita Efremovtsev[3]

[1] Institute of Natural Sciences and Mathematics, Ural Federal University, Lenin ave. 51, 620083, Ekaterinburg, Russia
[2] Department of Physics, Ural State Mining University, Kuibyshev str. 30, 620144, Ekaterinburg, Russia
[3] Research Institute of Comprehensive Exploitation of Mineral Resources (IPKON) of RAS, Kriukovskii tupik 4, 111020, Moscow, Russia

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Abstract

The cracking of some rocks, namely granite, serpentinite and sandstone under tensile stress is examined in details. Brazilian testing or diametral compression, three points bending and explosion testing are used as the loading schemes in air at room temperature. Morphology of cracks in the model rocks are compared with cracks in silicon crystals, as the standard of a brittle crack, with cleavage cracks in iridium single crystals and with cracks in gallium-covered aluminum single crystals. The comparison of cracks between themselves has shown that there is additional channel for stress accommodation in the model rocks. This channel does not lead to transformation of a rock into a macroscopically ductile material, but it causes the arrest of the dangerous crack in it under tensile stress. Its influence causes transition from the brittle crack to the pore-like crack on the microscopic scale. The most probable mechanism of this transition is the dislocation emission from crack, which becomes possible in such a natural covalent solid as a rock due to Rehbinder's effect.

Keywords: Deformation behavior; Fracture; Cracks; Rocks; Metals

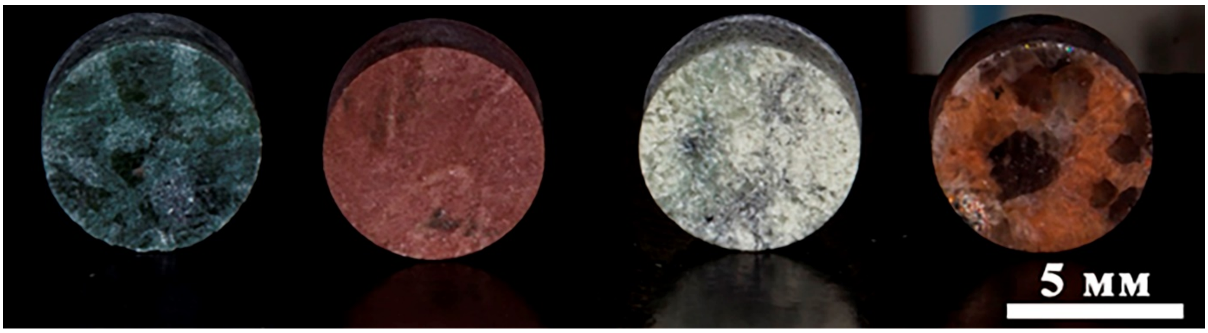
1. INTRODUCTION

Briefly, a rock could be determined as an inorganic solid of geological genesis with covalent interatomic bonding [1]. It means that rock should exhibit the brittle deformation behavior under mechanical loading [2]. Indeed, in majority of cases mechanical behavior and mechanical properties of rocks could be characterized in frames of the elastic solid state mechanics [3]. It is logical to suppose that fracture behavior of rocks are also ruled by the elastic solid state mechanics as it should be for a brittle solid. However, as experience has shown, cracks in rocks could stop and be stable under mechanical loading and, hence, their growth do not obey elastic fracture mechanics [4]. Indeed, everybody can observe stopped stable cracks in rock massives of mountains (Figs. 1a,b), in walls of mountain quarries, mines and even buildings (Fig. 1c), as well as in laboratory samples of rock materials (Fig. 1d). Long term observations have shown that such cracks could be stable under mechanical loading including so extreme conditions such as earthquakes and industrial explosions [1]. The similarity of crack morphology in rocks on different scales should be especially noted. But the shape of cracks in rocks is distinctively different from cracks in glasses and covalent crystals, such as silicate glasses, silicon, etc, which are accepted as the standard of a brittle solid.

Why does it happen like this? Could we consider a rock as a specific case of covalent solid, whose fracture behavior is not brittle? Or this is a phenomenon induced by an external cause, for example, impurities or influence of an environment, for example water? Another possible cause of this effect may be the scale difference of cracks in rocks that is mentioned above with cracks in covalent crystals and ceramics, which have been studied in details on the micro- and macro- scales only [5]. Examination of the morphology of cracks in the laboratory samples of rocks on macro- and micro- scales and comparison of the findings with cracks in other inorganic solids on the same scales could allow finding the cause of mentioned above feature of fracture behavior of rocks. The aim of this paper is the study of the morphology of cracks that advance in small sized laboratory samples of some rocks under tensile

* Corresponding author: Peter Panfilov, e-mail: peter.panfilov@urfu.ru

Fig. 1. Cracks in rocks and rock materials: a – island (satellite image); b – crack appeared after earthquake; c – crack in the brick wall of building; d – cracks in the laboratory sample of concrete under compression.



a b c d

Fig. 2. Small sized tablet shape samples of rocks for Brazilian testing in the initial state: a – green serpentinite, b – jasper, c – grey serpentinite, d – rose granite.

stress including explosive testing and comparison of the findings obtained with cracks in inorganic materials exhibiting brittle fracture. Granite, serpentinite, jasper, basalt, quartzite, sandstone, anthracite, nephrite, covalent crystals (Si and MgO), single crystals of brittle FCC-metal iridium and gallium-covered aluminum crystals are chosen as model materials in this work.

2. EXPERIMENT

Diametral compression or Brazilian esting and three-point bending are the deformation schemes usually used for application of tensile stress to brittle materials, including rocks, ceramics, glasses, etc. [1,4]. In these cases, samples never squeeze in grips of testing machine under loading, while applied stress is the main factor that rules a trajectory of a dangerous crack. Explosive testing is the additional method that allows inject cracks in brittle materials including rocks and minerals. Therefore, these loading schemes were chosen for the examination of crack growth in model rocks (granite, serpentinite, jasper, basalt, quartzite, sandstone, anthracite, nephrite).

The small-sized samples for Brazilian testing had the tablet shape with the diameter of 6 mm and the height of 3 mm (Fig. 2). Samples for 3-point bending were cut from the work-piece of gray granite in the shape of a bar with the size of 80×8×4 mm^3. Mechanical tests under Brazilian testing and 3-point bending were carried out on Shimadzu™

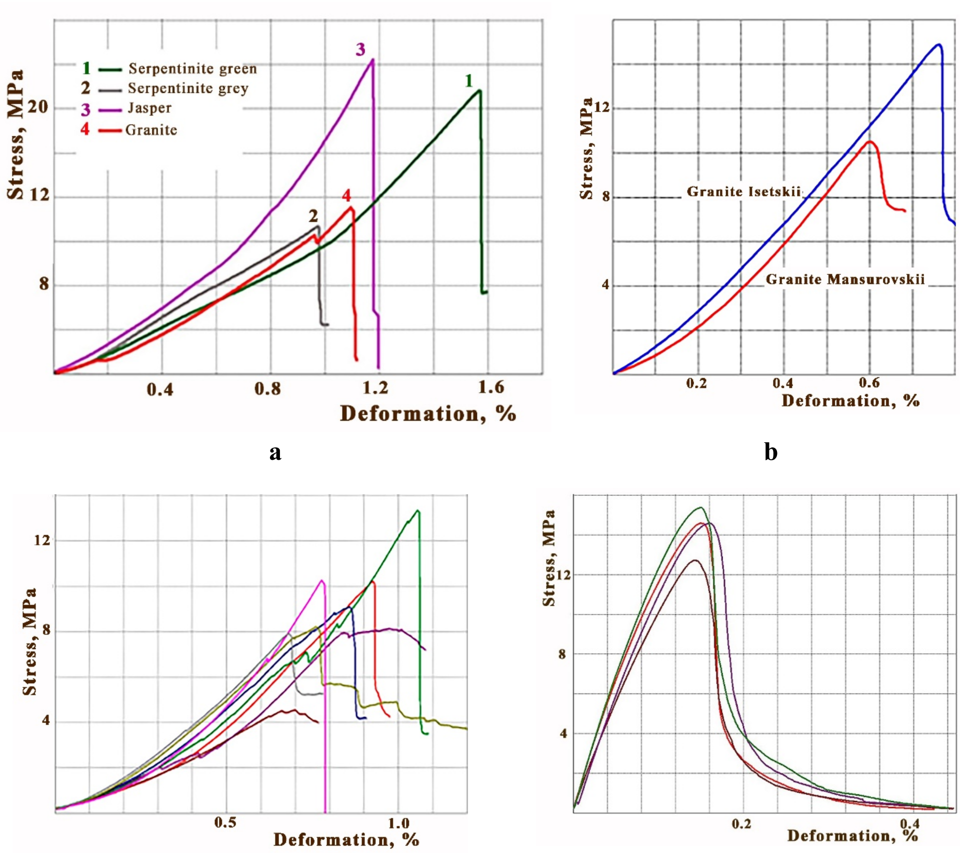


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Fig. 3. Deformation engineering curve for the model rocks: a – Brazilian testing (1 – green serpentinite, 2 – grey serpentinite, 3 – jasper, 4 – rose granite), b – Brazilian testing of grey granite from different deposits, c – Brazilian testing of grey granite containing cracks, d – 3-point bending of grey granite.

Autographs AG-X 50N testing machine (traverse rate is 0.1 mm/min). The deformation engineering curves were plotted and some mechanical characteristics were estimated for the model rocks with the help of Trapezium™ software. Evolution of cleavage cracks in metallic crystals (iridium and gallium-covered aluminum crystals) was studied under uniaxial tension and under bending. Cracks in covalent crystals (Si and MgO) were injected in samples using Vickers microindentation.

Cracks on the working surfaces of samples cut from rocks were examined with the help of an optical microscope under magnifications of x10, x100, and x500, while morphology of fracture surfaces of samples was attested with the help of a scanning electron microscope (SEM). Cracks in iridium single crystals, gallium covered aluminum crystals and the model covalent crystals (Si and MgO) were documented with the help of an optical microscope, a SEM and a transmission electron microscope (TEM).

3. RESULTS

Deformation curves of some model rocks are shown in Fig. 3. In all cases, deformation behavior of the samples under tensile stress should be estimated as brittle because the maximum deformation prior to the failure or the start of cracking is about 1%. At second, the course of these curves can be approximated as a linear dependence (Figs. 3a,b). The maximum stress of the model rocks under Brazilian testing varies in the limits of 10–20 MPa at the deformation of 0.5–1.6% that may also be considered as the feature of the brittle deformation behavior of inorganic solid [1,5]. However, in contrast with such brittle materials as silicate glasses or ceramics, an inflection on the engineering curve and the appearance of crack do not mean the momentary failure of the samples of the model rocks. Our testing has shown that only anthracite samples separate when an inflection appeared, while other rocks do not fail under both schemes of mechanical testing. Some of the grey granite samples contained cracks injected by explosion before the testing, however, these dangerous defects caused only some decrease in the deformation prior to an inflection of the curve (Figs. 3c), but they did not lead to momentary failure of the samples under loading. The brittle character of mechanical behavior of rocks, namely grey granite, does not change under 3-point bending including the ultimate stress (12–

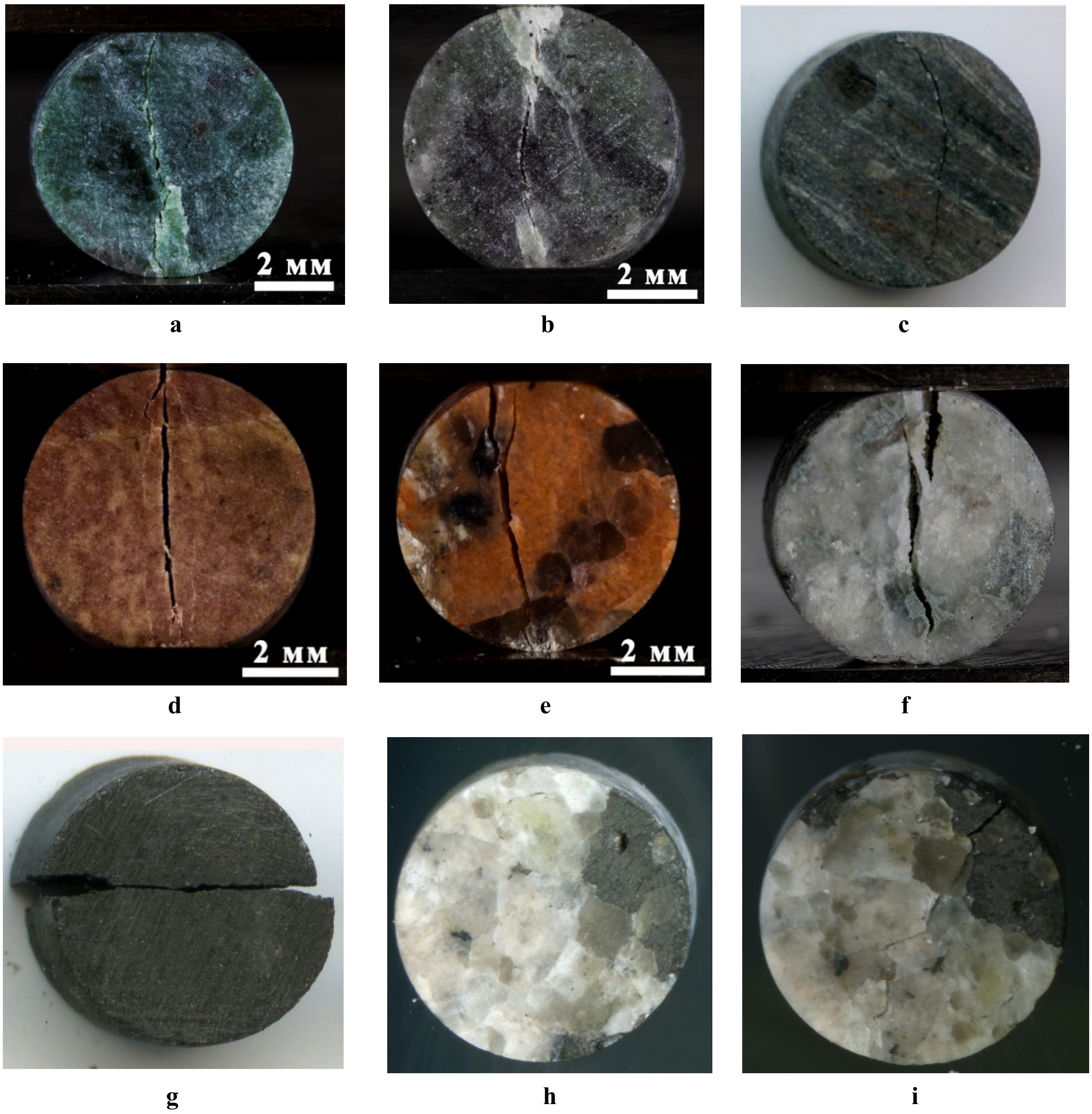
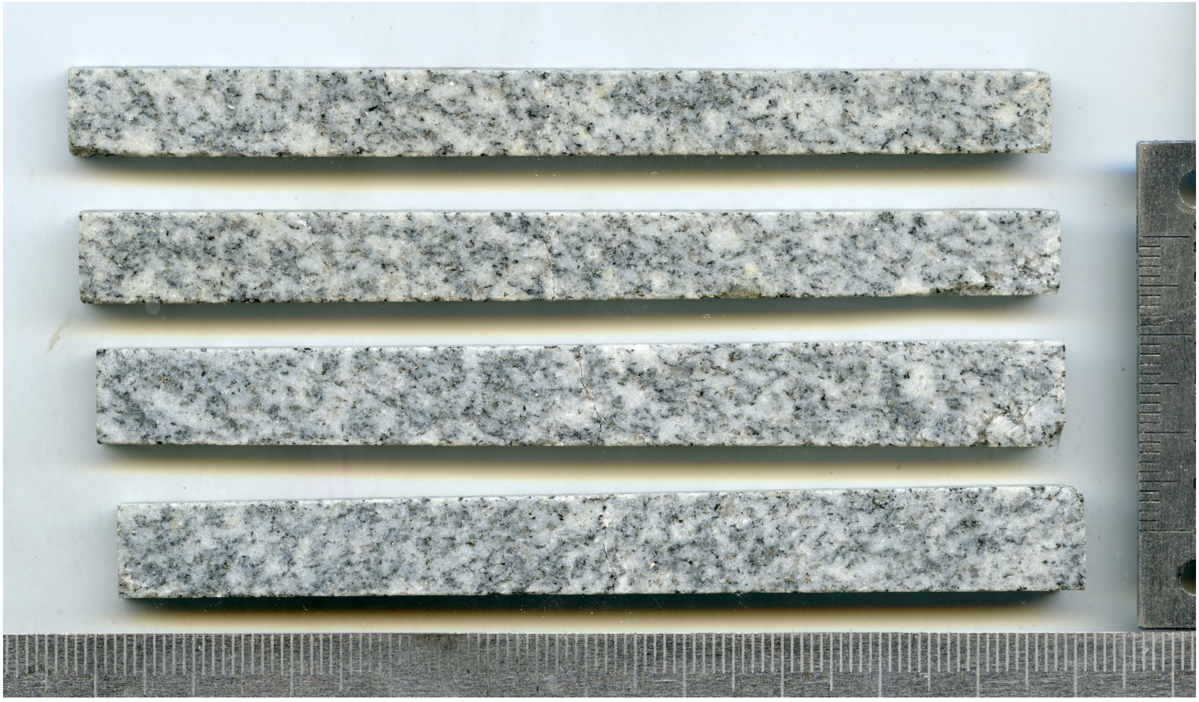


Fig. 4. Small sized tablet shape samples of rocks after Brazilian testing: a – green serpentinite, b – grey serpentinite, c – black quartzite, d – jasper, e – rose granite, f – grey granite, g – anthracite, h – grey granite with cracks in the initial state, j – grey granite with cracks after testing.

14 MPa), but the deformation is considerably lower (0.2%) (Fig. 3d). However, in this case, the appearance of inflection on the deformation curve also does not lead to the separation of the sample.

This feature of rocks under tensile stress is unusual for brittle solids [2], while it gives an opportunity to examine in details the morphology of cracks that appear and advance in the samples on macro- and micro- scales. The dangerous cracks in small-sized samples of the model rocks are shown in Fig. 4. No problems exist for the registration of cracks on the working surfaces because of their considerable width, which is unusual for brittle fracture. The dangerous crack crosses over the sample along diameter directed parallelly to the compression axis. On the other hand, the crack tips were sharp and the width of cracks in vicinity of their tips were considerably smaller than in other parts of dangerous crack. The geometry of Brazilian testing determines the trajectory of the main crack in the samples, i.e., it develops along the rectilinear line connecting the contact points of the tablet sample and the hard plates of testing machine [5]. At that, majority of cracks starts on one of contact points, but never reaches another point. As a rule, the dangerous crack in the sample for Brazilian testing deviates a little from this straight line, while it always consists of few cracks having a broken profile (Figs. 4a–c). Sometimes, cracks on the line between contact points could shield one another preventing their junction into the sole dangerous crack in the sample (Figs. 4d–f). Anthracite is an exception from this tendency, whose samples fail either under testing or during



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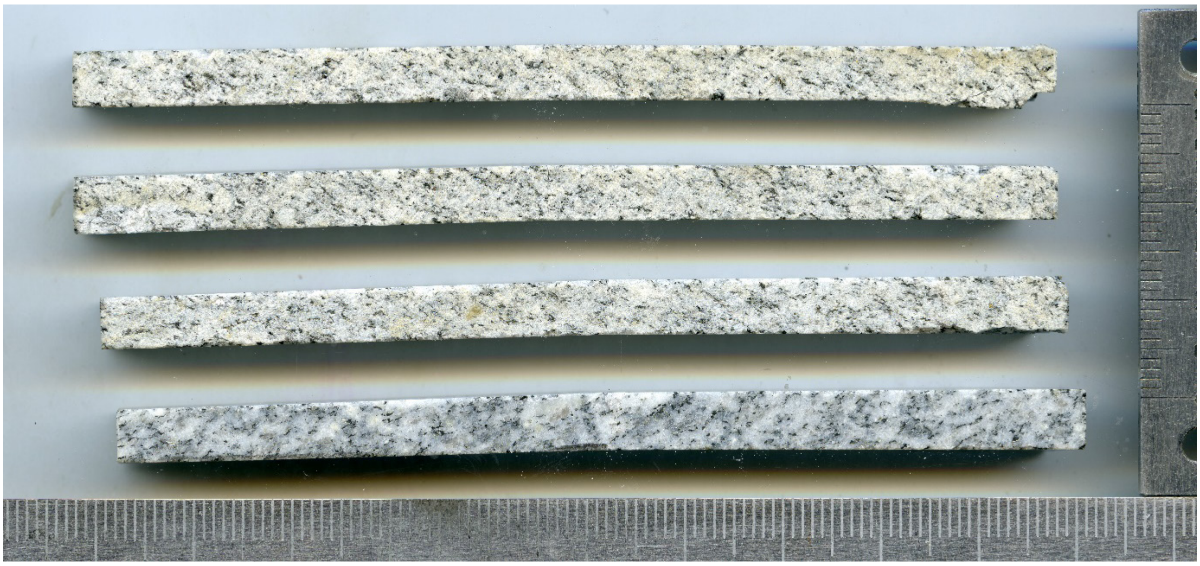


b

Fig. 5. Samples of grey granite after 3-point bending (cracks are situated in the middle parts of the samples): a – working surface, b – end surface (scale unit is 1mm).

installation of tested samples on the table of microscope (Fig. 4g). Indeed, experience has shown that anthracite is the most brittle among the model rocks [1]. The grey granite samples with injected cracks fail similarly. Existing cracks in the samples prior to the testing look like thin lines situated either on the granite grains or crossing over the grains (Fig. 4h). Despite these cracks, the dangerous crack always appears in the contact point between the sample and the hard plate of testing machine, while its trajectory obeys the loading geometry. The dangerous crack starts to develop from existing crack only in the case when it is situated in vicinity of the contact point with the hard plate of testing machine (see Fig. 4j). This agrees with the fact that sometimes granite sample with cracks exhibits the same behavior to the granite sample without injected cracks.

The samples of grey granite after 3-point bending are shown in Fig. 5. The dangerous cracks are situated in the middle part of samples where the bending prism touches the sample and, hence, the tensile stress is maximal. They

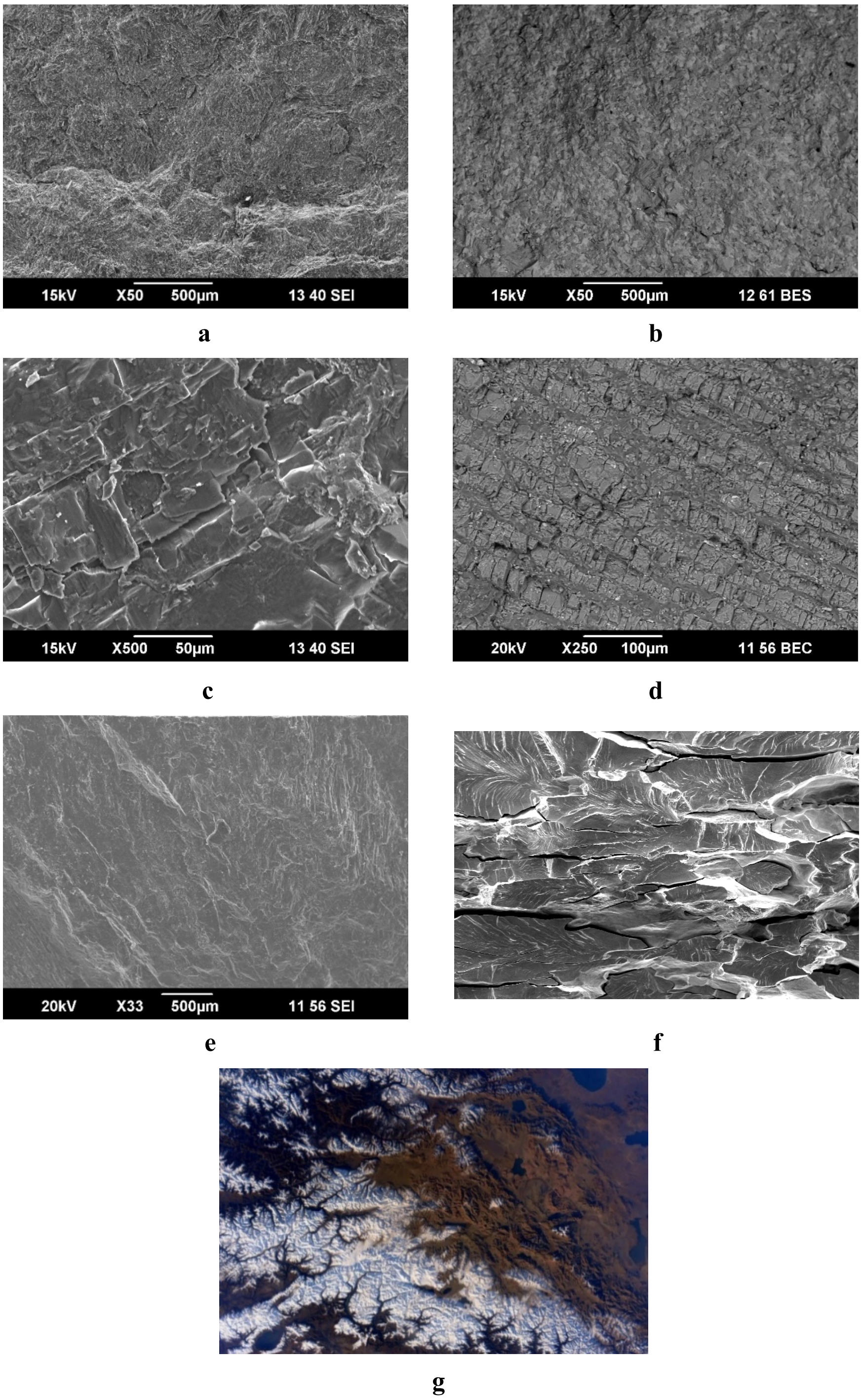
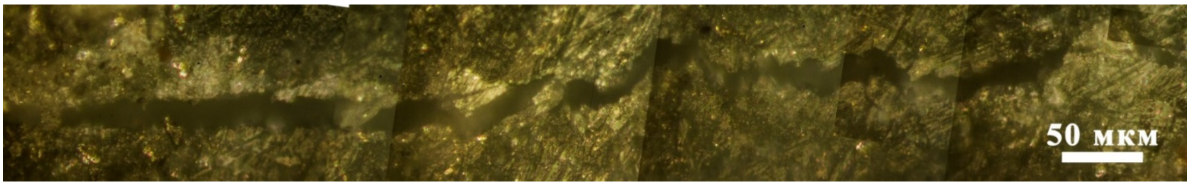


Fig. 6. Morphology of fracture surfaces of the model materials, which cleave: a – green serpentinite (SEM), b – jasper (SEM), c – rose granite (SEM), d – chondrite Chelyabinsk-2013 (SEM), e – anthracite (SEM), f – polycrystalline iridium (SEM), g – Alps (satellite image).

look like thin lines crossing over the working surface of samples from edge to edge (Fig. 5a), while they start on the edge with the maximum deformation and never reach another edge on the end surfaces (Fig. 5b). It means that the geometry of 3-point bending governs the trajectory of dangerous crack growth in grey granite. The difference between deformation prior to the failure of grey granite under Brazilian testing and 3-point bending (0.5–1.5% and 0.2%, respectively) correlates with the width of dangerous cracks in these schemes. It should be note that this difference can reach several times that is very unusual for brittle covalent material [2].

Fracture surfaces of some model materials are given in Fig. 6. They are SEM images, except for the image of mountains taken from satellite. The fracture surfaces were flat and oriented normally to the direction of tensile stress



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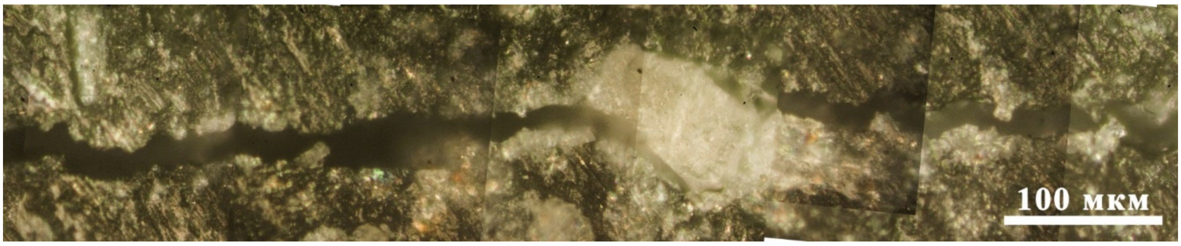

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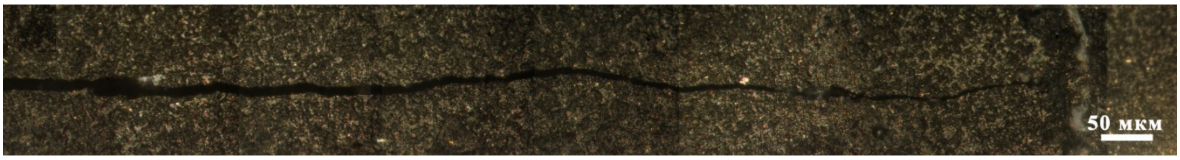

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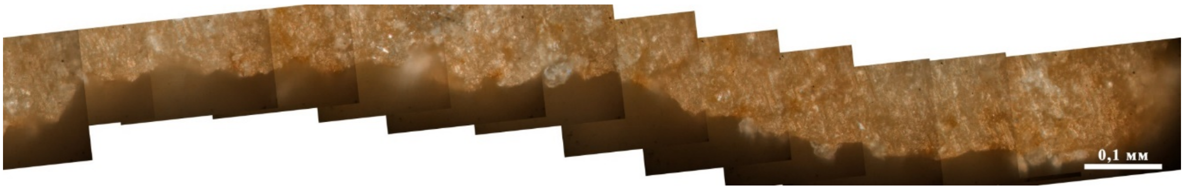


d

e

Fig. 7. Cracks on the working surfaces of rocks under Brazilian testing: a – green serpentinite, b – grey serpentinite, c – rose granite, d – jasper, e – sandstone.

applied to the sample. Briefly, morphology of these surfaces can be estimated as the brittle transcrystalline fracture with some elements of intergranular fracture [6]. River patterns or cleavage facets are the morphological features of the fracture surfaces, while sometimes intercrystalline cracks are clearly detected. This is surprising, but the morphology of the satellite image of mountain massive looks similar to fracture surfaces of the model materials despite the differences in genesis and scale.

Examination of cracks in the model rocks under Brazilian testing on the microscopic scale has shown that they have rough edges, whose "degree of roughness" depends on genesis of a rock (Fig. 7). It is clearly visible that the dangerous cracks in serpentinite consist of pore-like microcracks, some of them not merging with each other (Fig. 7a). The average length of such pore-like microcracks in serpentinite is 50–100 μm, while their width is 2–3 times smaller. Sometimes, an inclusion of other

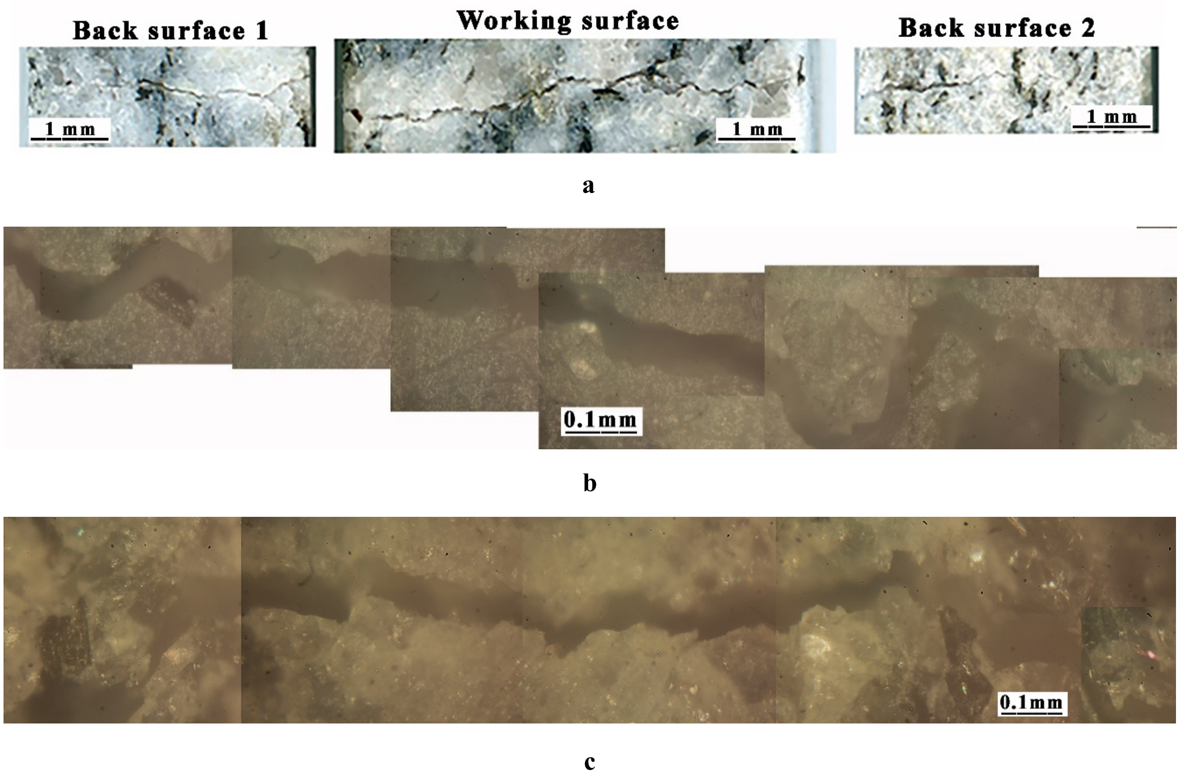


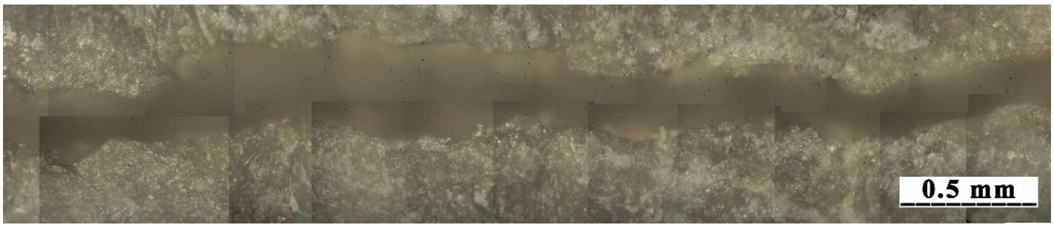
Fig. 8. Cracks appearing in the sample of grey granite after 3-point bending: a – cracks on the back and working surfaces on the macroscale, b – fragment of crack on the working surface on the microscale, c – fragment of crack on the back surface on the microscale.

phase in rock could stop the crack growth under Brazilian testing (Fig. 7b). The pore-like microstructure of dangerous crack could be hidden in other magmatic rocks, for example a rose granite. In this case, the crack edges are not rough and even almost smooth, but their width is too big for the crack in a brittle solid (Fig. 7c). It should be especially noted, that these differences in the morphology of cracks between serpentinite and rose granite do not lead to any differences in their mechanical behavior under Brazilian testing. The broken profile of the dangerous crack in jasper is caused by considerable part of the intercrystallite fracture in its fracture mode due to its genesis (Fig. 7d). Jasper may be called the most brittle model rock under Brazilian testing because all tablet samples of jasper were taken apart after testing procedure. The morphology of dangerous crack in sandstone is similar to serpentinite. The crack also consists of merged and almost merged pore-like microcracks, however their tips are sharp in contrast with pore-like microcracks in serpentinite (Fig. 7e).

Cracks appearing in grey granite under bending are shown in Fig. 8. The dangerous crack crosses over the working surface of the sample from edge to edge (Fig. 8a). It also starts from the edge of the end surface, where the tensile stress is maximum, but never reaches the opposite edge, where the tensile stress is minimal. The dangerous crack has a broken profile because it consists of merged and almost merged pore-like microcracks (Fig. 8b). At that, the zig-zag geometry of dangerous crack does not correlate directly with grain structure of grey granite. It should be noted that the sharpest edges and tips are observed in microcracks situated on the end surface of samples far away from the working surface, where the tensile stress level is minimum (Fig. 8c). It may be concluded that morphology of cracks appearing in grey granite under bending is similar to cracks in serpentinite under Brazilian testing, however their width is considerably smaller. Another feature of cracks in rocks under bending is that their tips are blunt and edges are smooth under tensile loading, despite rocks possessing covalent chemical bonding.

Cracks in the samples of some model rocks appearing under explosion are given in Fig. 9. In contrast with Brazilian testing and 3-point bending, the stress distribution in the samples under explosion is complicated that makes the estimation of crack morphology difficult. All examined cracks possess complicated profile, which could be estimated as smoothed broken profile. In spite of this, the trajectories of cracks under explosion are close to rectilinear (Fig. 9a). The deviation from the rectilinear direction can be caused by the features of crack growth under high rates of loading. The edge of crack in grey granite are smooth similar to the dangerous crack in grey granite on the working surface under bending, while no pore-like microcracks are detected in the dangerous crack (Fig. 9b). Cracks in basalt, which is also magmatic, but more brittle

a



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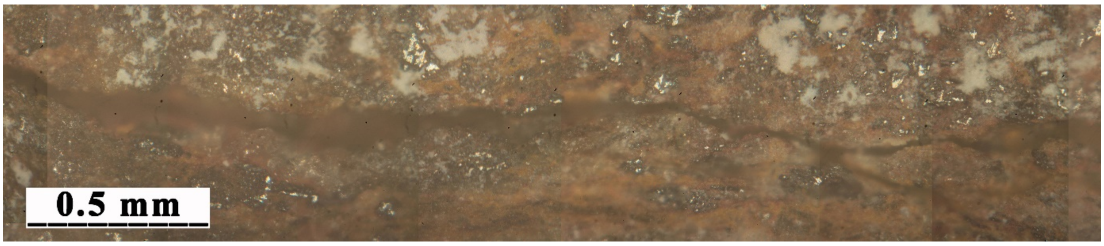

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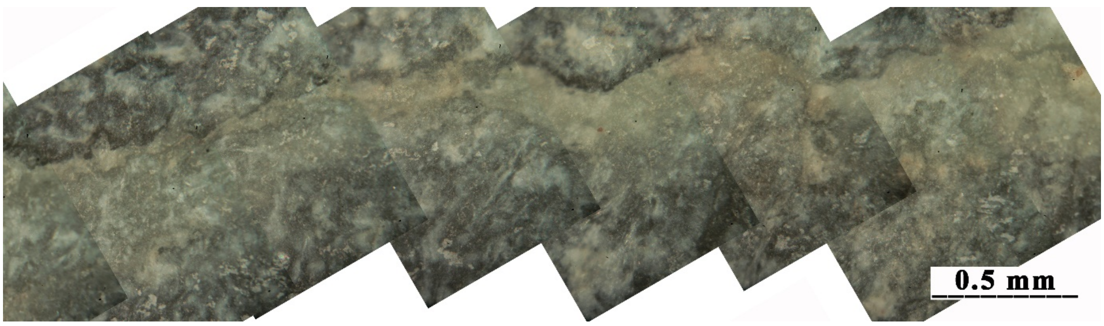


f

Fig. 9. Crack appearing in some model rocks under explosion: a – grey granite, view of crack on working surface of sample; b – grey granite, fragment of crack on the working surface of sample under high magnification; c – quartzite, view of crack on working surface of sample; d – quartzite, fragment of crack on the working surface of sample under high magnification; e – nephrite, view of crack on working surface of sample; f – nephrite, fragment of crack on the working surface of sample under high magnification.

silica-based rock, possess similar morphology to grey granite (Fig. 9c). The sole difference between cracks in basalt and grey granite is their width — 0.1 mm and 0.3 mm, respectively (Fig. 9d). The trajectory of crack in nephrite under explosion is close to one described for grey granite and basalt, while its width is considerably smaller than in brittle rock of basalt (Fig. 9e). This geometric parameter of crack is so tiny that it cannot be correctly estimated with the help of metallographic microscope at light field (Fig. 9f). Dark field regime of optical microscope has shown that crack width is about 10 μm.

4. DISCUSSION

Obtained findings have confirmed once again that mechanical behavior of the model rocks under tensile stress is brittle that is inherent to materials with covalent chemical bonding [1,2]. Indeed, all of them exhibit very low macroscopic deformation prior to the failure and their deformation engineering curves are close to a straight line. These features suggest that a linear elastic deformation is the main channel for stress accommodation in the model rocks at the macroscopic scale [3]. The decrease of the deformation prior to the failure in some model rocks under bending in comparison with Brazilian testing is caused by the harsher conditions of tensile stress application under bending. However, the experimental fact that samples of the model rocks, except for anthracite, never separated when inflection appears on the engineering curves is rather unusual response for a brittle material. In other words, a crack appears in the model rocks under loading, but its growth is stopped despite not decreasing applied stress. It is direct indication to the existence of additional channel for mechanical stress accommodation in model rocks. The choice of such channels is not wide, it may be either non-linear elastic deformation or irreversible deformation. However, in both cases the contribution of this additional channel to deformation behavior of a rock should be comparable with the contribution of a linear elastic deformation, i.e., to be macroscopically small or less than 1% elongation. It may be supposed that this channel is active on the microscopic scale only.

Brazilian testing has shown that cracks crossing over the samples from edge to edge are observed in tested samples and their trajectories are governed by the geometry of applied loading. They are clearly detected on the samples due to their considerable width. These cracks are stable to external stress, except for cracks in jasper, which allows to carry out metallographic examination of the dangerous cracks in tested samples. The changing of deformation scheme from Brazilian testing to bending, does not change fracture behavior of the model rocks. There are stable cracks crossing over the working surfaces from edge to edge in the samples. The trajectories of crack are also governed by applied loading. However, their width is considerably smaller than the width of cracks under Brazilian testing. This is an expected finding because 3-point bending is the harder deformation scheme in comparison with Brazilian testing and, hence, the behavior of material should be more brittle, i.e., both deformation prior to the failure and width of cracks should be considerably smaller under bending than under Brazilian testing [5]. Thus, an influence of the additional channel for stress accommodation is higher under Braziilian testing than under bending.

Analysis of fracture surfaces morphology of the samples confirms that fracture mode of all model rocks is brittle fracture despite the details of their deformation behavior. It is the brittle transcrystalline fracture for majority of cases, but sometimes brittle intercrystalline fracture could be detected in the fracture surfaces, as it occurs in jasper [6]. At that, fracture surface morphology does not depend on neither chemical content of the model material, nor the type of interatomic bonding in material and even, which is especially intriguing, the scale of the image. Indeed, SEM images of rocks and iridium under x500 look like the satellite images of mountains.

The trajectory of crack in a brittle solid can deviate from a straight line, determined by the tensile stress distribution in the sample, however the magnitude of such deviation should be small [2]. All cracks in tested samples on the macroscopic scale meet this condition. Metallographic examination of cracks under Brazilian testing determined the cause of a complicated shape of the dangerous cracks in the model rocks on the microscopic scale. It was shown that the dangerous crack in serpentinite, grey granite and sandstone consists of merged and almost merged pore-like microcracks having length of 50–100 μm and width of 10–20 μm (Figs. 7a,b). These microcracks faces are microscopically rough, their tips sometimes are sharp, while their angles of opening are more than 5°. Typically, this parameter for a crack in a brittle solid is 1° or less. It sounds unusual, but these cracks looks like a dangerous crack in neck region of such plastic metals as aluminum or copper [7]. However, the dangerous cracks in some kinds of granites, basalts and quartzites after explosion possess smooth faces, where an observer cannot discover pore-like microcracks (Fig. 7c) unlike the previous case. The value of a crack opening angle for these rocks is close to a crack in a brittle solid. Dangerous cracks in them look like a crack in silicon glass except for their considerable width (5–10 μm). The broken profile of the dangerous crack in jasper (Fig. 7d) is caused by considerable portion of the brittle intergranular fracture on the fracture surface. This fact is the cause of the brittleness of this mineral. The dangerous crack in sandstone consists of fragments, where pore-like microcracks could

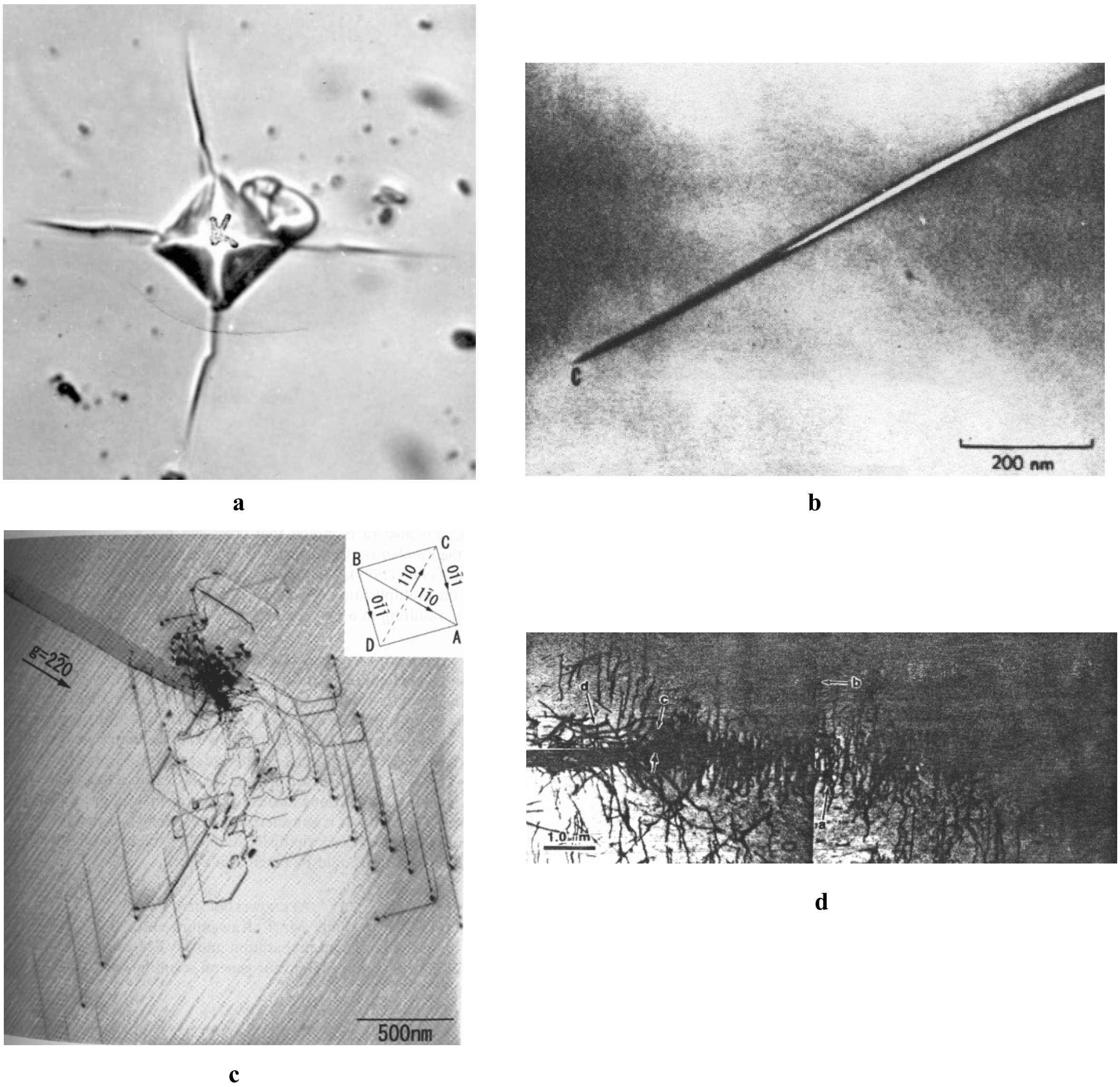
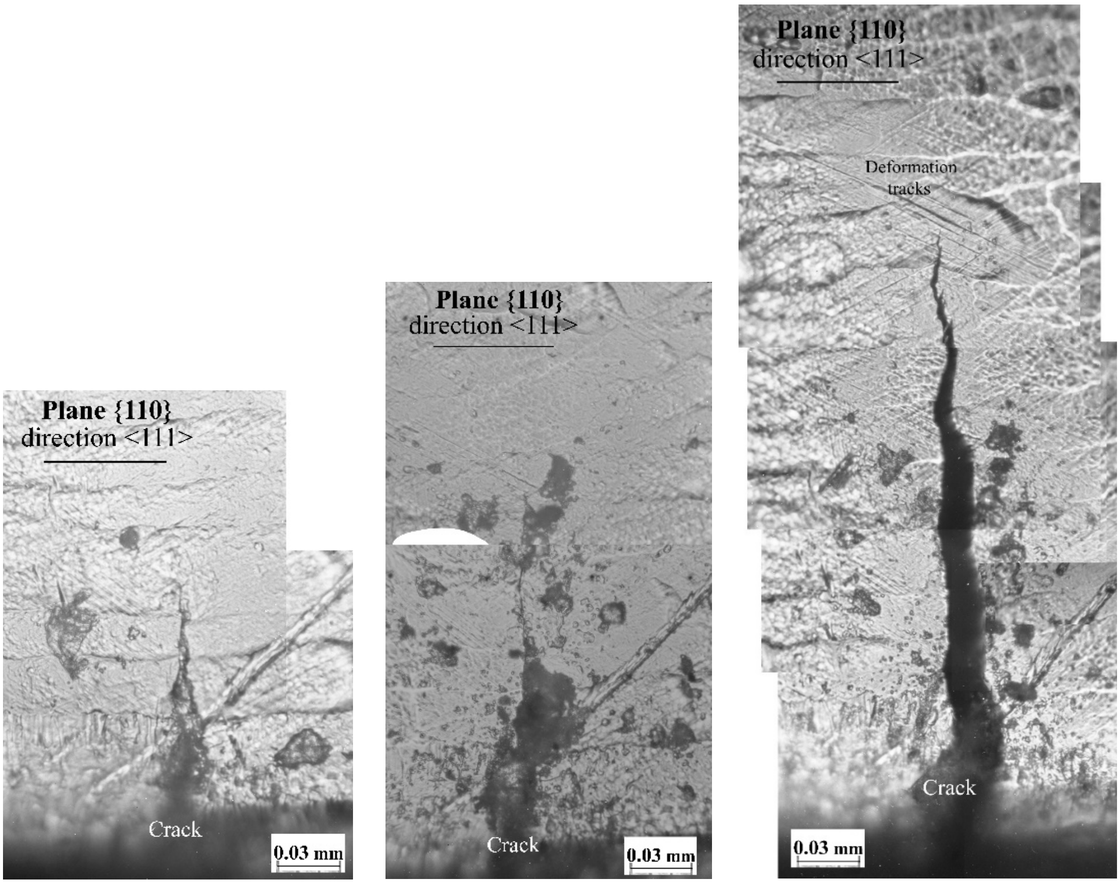


Fig. 10. Cracks in covalent crystals: a – silicon crystal samples under Vickers diamond indenter, b – crack in silicon thin foil for TEM [8], c – crack in silicon thin foil for TEM at temperature higher than brittle to ductile transition temperature [9]; d – crack in MgO thin foil for TEM [10].

be selected (Fig. 7e). However, in contrast with pore like microcracks in serpentinite, they have sharp tips with small angle of opening. It should be noted that these microcracks possess morphology close to cracks in Fig. 1 in spite of different scales.

The analysis of crack morphology in the model rocks requires some information on the geometry of cracks in solids that cleave. The covalent crystals such as silicon are intrinsically brittle materials, where cracks can be treated as standard for brittle cracks. Cracks in single crystalline silicon at room temperature are shown in Figs. 10a,b on the microscopic scale (optical image) and nanoscale (TEM image), respectively. They have sharp tips and narrow width, while their trajectories are almost straight, especially on the nanoscale. No emission of deformation defects was observed from these cracks including dislocation emission from crack tips or crack edges. Cracks in silicon thin foils for TEM become the dislocation sources at temperatures higher than the temperature of brittle-to-ductile transition (Fig. 10c). However, this additional channel for stress accommodation does not change the geometry of cracks, which continue to be brittle at room temperature. Thin foils for TEM of ion crystal of MgO with low temperature of the brittle-to-ductile transition also contain sharp narrow brittle cracks, emitting a lot of dislocations (Fig. 10d). The comparison with obtained findings allows concluding that only cracks in nephrite under explosion (Figs. 9e,f) have the morphology close to a brittle crack.

The refractory FCC-metal iridium cleaves under tensile stress at room temperature after considerable elongation or macroscopic plasticity [11]. Therefore, the cleavage crack morphology in iridium single crystals under



a **b** **c**

Fig. 11. Cleavage crack growth in iridium single crystal under bending: a – first bending; b – second bending; c – third bending [11].

bending is another corner stone for the analysis of cracks morphology in the model rocks. The crack that grows in the iridium single crystal under bending is shown in Fig. 11. It is clearly visible that the crack appears on the strong stress concentrator near the crack edge. It also has the sharp tip, but its angle of opening is considerably higher than in silicon. As a result, the width of cleavage crack in iridium under bending is too large for a brittle crack. However, this circumstance does not reflect on the morphology of fracture surface, which looks similarly to the transgranular cleavage (Fig. 6f and Ref. [11]). Moreover, the cleavage cracks in iridium single crystal with abraded surface after elongation of 10–18% (Fig. 12) look like cracks in some rocks on the different scales (see Figs.1b–d and Figs. 5a,b,d–f).

Another case of the brittle fracture in plastic metals is the effect of liquid metallic embrittlement or the environmentally-induced brittle fracture [12]. Usually, this effect is connected with a drop of grain boundary cohesive strength under influence of liquid metal, but Lynch has shown that this effect takes place in single crystalline metal too, for example, in the pair of Al-Ga [13]. The transcrystalline crack evolution in the gallium-covered aluminum single crystal under tension is given in Fig. 13. The average elongation of the crystal prior to the crack appearance is about 5%, while its growth is documented at 8–10% of elongation. The rare case of V-shaped crack growth on the tip of the notch from the razor blade is shown in Figs. 13a,b. It is clearly visible that crack possesses a sharp tip, it grows without emission of octahedral slip bands, but its angle of opening is over 10° similar to cleavage cracks in iridium single crystals [14]. However, usually, crack growth in gallium-covered aluminum crystal is accompanied by the localization of plastic deformation near its tip and, as a result, the transformation of a sharp crack to a pore (Figs. 13c,d). It should be noted that initial V-shaped cracks propagate in the cleavage plane, while the secondary pore-like cracks grow in the octahedral plane. Therefore, the dangerous crack, whose growth causes the failure of the gallium-covered aluminum crystal, has the broken profile like the dangerous crack in the neck of aluminum sample in air. However, no necking was observed in the gallium-covered aluminum crystals under tension despite the deformation prior to the failure was about 20% of elongation.

This is really puzzling, when the gallium-covered aluminum crystal exhibits a brittle-like cracking, similar to iridium single crystals, on the initial stage of crack

Fig. 12. Cleavage cracks in iridium single crystal having abraded working surface under tension.

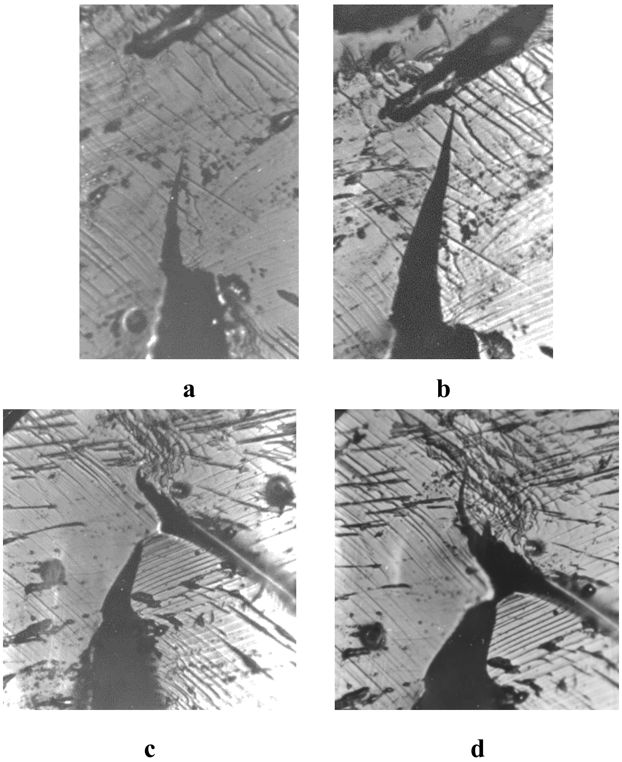
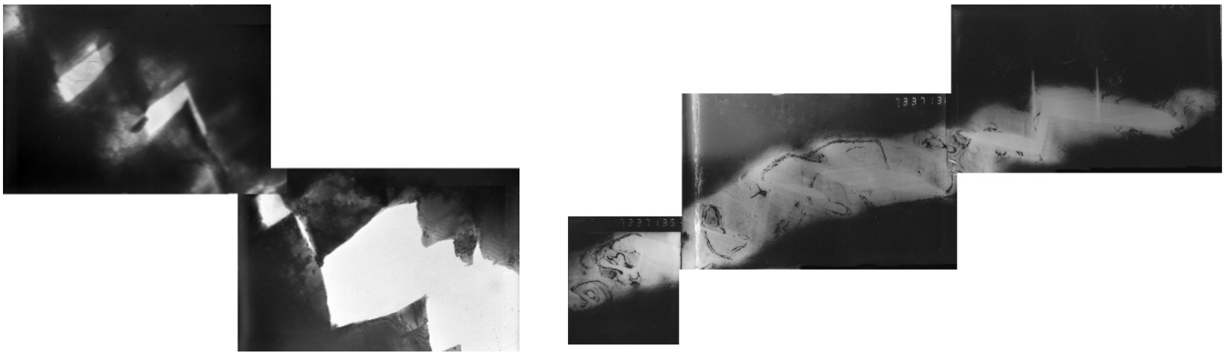


Fig. 13. Crack growth in gallium-covered aluminum single crystal under tension: a – crack 1, first tension; b – crack 1, second tension; c – crack 2, first tension; b – crack 2, second tension [14].

evolution only, whereas on the other stages it behaves like a plastic metal before the start of necking. Examination of the dangerous crack in thin foils of iridium and aluminum under in situ tension in TEM has shown that both cleavable iridium and ductile aluminum show the same fracture mode in thin foil (Fig. 14), namely, the dragon teeth that is intrinsic fracture mode of ductile metals [11]. This finding allowed concluding that the inclination of iridium to the transgranular cleavage is the property of bulk samples of this refractory FCC-metal, while its thin foils for TEM behave like usual FCC-metal. Thus, it may be supposed that the brittle transgranular fracture is the macroscopic property of iridium and gallium-covered aluminum crystals, while they are normal FCC-metals on the micro- and nanoscales. In other words, the brittle transgranular fracture in these FCC-metals does not mean that they cannot exhibit a ductile response on the microscopic or lower scale levels.

Two kinds of brittle fracture of natural inorganic materials were considered, whose fracture surfaces look similarly (it is the brittle transgranular fracture in majority of cases). However, the crack morphology in the model materials can change from "inherent brittle" as in silicon single crystals to "almost ductile or semibrittle" as in gallium-covered aluminum single crystals. Cracks in the model rocks fall within these frames. Indeed, the dangerous cracks in granite, serpentinite and sandstone possess the broken profile because they consist of merged or almost merged pore-like cracks. Sometimes these cracks have sharp tips, but in spite of this their growth could be suppressed. It is puzzling, but similar fracture occurs in the neck regions of ductile metals under tensile testing [15,16]. Of cause, rocks and metals have considerable differences in interatomic bonding and deformation behavior on the microscopic scale. However, it does not mean that some similarity in the mechanical responses on the microscopic and lower levels should be absent. Both morphology of cracks in granite, serpentinite and sandstone on the microscale and the stability of cracks in the sample under tensile loading allow supposing that additional channel for stress accommodation should be active in these rocks on the microscopic level. It seems that the contribution of this channel to stress accommodation near cracks increases with the growth of applied stress. Indeed, the profile of dangerous cracks under explosion in the model rocks is smooth in comparison with cracks under Brazilian testing. The analysis of cracks in granite under bending confirms this conclusion. Cracks on the curved surface of the sample possess the smoothest profile and the largest width in comparison with cracks on the end surfaces, whose width drops to zero near concave surface of the sample.

In other words, the model rocks exhibit the brittle response on the macroscopic scale, but almost ductile one on the microscopic level. Dislocation emission from cracks is the more favourable additional mechanism for stress accommodation on the nanoscale, which may be helpful for analysis of the observed effect [17–19]. Indeed, many models describe this process in initially brittle materials, such as silicon [20–22]. Usually, the main condition for the start of dislocation emission from crack tip in silicon is heating of samples over the temperature of brittle to ductile transition. It should be especially noted that this transition does not mean that the silicon sample becomes macroscopically ductile material. However, in the case of rocks it may be reasonably supposed that the dislocation emission becomes possible due to a water inside the sample because of Rehbinder's effect [23]. This mechanism cannot induce the ductile response in a rock on the macroscopic level, but it can lead to transition of initially brittle



a b

Fig. 14. Fragments of dangerous cracks propagating in thin foils of FCC-metals under in-situ tension in column of TEM: a – iridium single crystal, b – coarse-grained aluminum [11].

crack to a pore and, hence, become the cause for the dangerous crack arrest in a rock.

5. CONCLUSIONS

The comparison of crack morphology in some rocks (granite, serpentinite, sandstone) with the brittle fracture in silicon single crystals, iridium single crystals and gallium-covered aluminum crystals has shown that there is additional channel for stress accommodation in these rocks. This channel does not lead to transformation of a rock into a macroscopically ductile material, but it causes the arrest of the dangerous crack in it under tensile stress. Its influence causes transition from the brittle crack to the pore-like crack on the microscopic scale. The most probable mechanism of this transition is the dislocation emission from crack, which becomes possible in such a natural covalent solid as a rock due to Rehbinder's effect.

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Об особенностях трещин скола в горных породах и металлах

П.Е. Панфилов[1,2], Р.Д. Коровин[1], М.Е. Меженов[1,2], Д.В. Зайцев[1,2], Н.Н. Ефремовцев[3]

[1] Уральский федеральный университет, Екатеринбург
[2] Уральский государственный горный университет, Екатеринбург
[3] Институт проблем комплексного освоения недр РАН, Москва

Аннотация. Подробно рассмотрено растрескивание некоторых горных пород, а именно гранита, серпентинита и песчаника, под действием растягивающих напряжений. В качестве схем нагружения на воздухе при комнатной температуре используют бразильское испытание или диаметральное сжатие, трехточечный изгиб и испытание на взрыв. Морфологию трещин модельных пород сравнивают с трещинами в кристаллах кремния как эталона хрупкой трещины, с трещинами скола в монокристаллах иридия и с трещинами в монокристаллах алюминия, покрытых галлием. Сравнение трещин между собой показало, что в модельных породах имеется дополнительный канал аккомодации напряжений. Этот канал не приводит к превращению породы в макроскопически пластичный материал, но вызывает остановку опасной трещины в ней под действием растягивающих напряжений. Его воздействие вызывает переход от хрупкой трещины к пористой трещине в микроскопическом масштабе. Наиболее вероятным механизмом этого перехода является выброс дислокации из трещины, который становится возможным в таком природном ковалентном твердом теле, как горная порода, благодаря эффекту Ребиндера.

Ключевые слова: деформационное поведение; разрушение; трещины; горные породы; металлы