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A physical model of shear deformation in brittle-plastic transition regime; coexistence of junction slip and asperity flow

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A layer of granular NaCl was sandwiched between steel forcing blocks and sheared in a biaxial apparatus at room temperature. Experiments were done over a wide range of normal stress (NS) (10-250 MPa) and shear rate (SR) (0.01- 10 micrometer/s) conditions. As earlier studies (Shimamoto, 1986) have suggested from the SR and NS dependences of steady-state shear resistance, frictional sliding seems to be the dominant deformation mechanism in low NS and high SR conditions, while plastic flow seems to be the dominant mechanism at high NS and low SR conditions. In the present study, we exploit acoustic transmissivity (AT) measurement, which is expected to reflect the real contact area of the interface, in addition to the mechanical measurements. Also, instantaneous positive effect of SR on shear resistance, known as direct effect (DE) in frictional regime, was evaluated upon the imposed step change of SR because this quantity is expected to reflect the microscopic deformation mechanism, not complicated by the effect of real contact area, which has a hysteretic dependence on SR. Transition from friction to flow mechanism has been depicted in following observations.

1)Loss of NS dependence of shear resistance in high NS conditions above about 160 MPa coincides with the loss of NS dependence of AT. Both increase approximately linearly with NS at low NS and level off at high NS, suggesting that full contact is achieved at these high stress levels.

2) DE for the low NS below about 160 MPa and high SR (above about 0.1 micrometer/s), takes a roughly constant value when normalized by NS to remove the effect of NS-dependent contact area. The constant value is a small one typical of frictional mechanism suggesting that the most likely site of the deformation in this regime is thought to be the frictional junctions.

3) At low SR below about 0.1 micrometer/s, DE normalized by NS is much greater than the typical frictional value, suggesting that the responsible mechanism is of flow type less sensitive to driving stress. In addition, up to NS of about 120 MPa, the normalized DE is independent of NS, suggesting that the driving stress is independent of NS, as in the case of frictional mechanism. Therefore, we propose that the most likely site of deformation in this regime is the asperities backing frictional junctions, where the stress magnification is second greatest. Effective cross section of such asperities is thought to be roughly proportional to the real contact (i.e. frictional junction) area at least up to a certain NS level. In addition, it was observed that the difference of DE from the frictional value is more pronounced as SR goes further lower. Hence, the observed regime is thought to be still in the midst of transition from friction regime to flow regime.

4) DE is roughly independent of NS at experiments at high stresses above about 160MPa, as expected from the achievement of full contact. However, the increase of the magnitude of DE for low SR was observed also in such experiments at high NS. The magnitude of DE for high SR was of typical friction value. Hence, we infer that junctions intrinsically weaker than the surroundings remain even under full contact conditions, where frictional mechanism can still prevail for high SR.

In order to frame these rather rich observations, we propose a conceptual physical model where the local shear stresses on asperities and frictional junctions are related to the macroscopic applied shear stress through two area parameters representing the effective cross sectional area of asperities and the real contact area composed of junctions, respectively. Explicit involvement of the former parameter is first done in the present study. This model well explains the qualitative behavior of whole system over different regimes except for the full-contact frictional regime, which requires material properties for junctions to be different from the rest.