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Aspects of Asperity–Surface Interaction and Surface Damage of Rocks during Experimental Frictional Sliding[1])

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Summary – Mechanisms for the dissipation of energy during the frictional sliding of rocks includes brittle fracture, plastic deformation, frictional heating, and elastic distortion. The first three energy sinks are manifested by surface damage during frictional sliding. Normal load, temperature, and the velocity of the sliding surfaces as well as surface roughness and hardness all influence the nature of surface damage which includes the generation of structures such as wear grooves, gouge, and welded particles.

Key words: Friction; Frictional Heating; Surface damage.

1. Introduction

Several physical processes may occur during the sliding of rocks. These processes are the source of frictional resistance and the cause of wear or surface damage during frictional sliding. All processes stem from the mismatch of sliding surfaces in which an asperity, attached to one surface, encounters either another asperity or a relatively flatter area attached to the opposite surface. In this context an asperity refers to any roughness, bump or other projection on a sliding surface.

To study the relationship between physical processes during sliding and the frictional properties of rocks, sliding surfaces may be examined. The deformation processes accompanying slip of an asperity on a flat area are observed to be brittle fracture, plastic deformation, and frictional heating. A final product of these processes is fault gouge which also contributes to the frictional resistance by deformational processes.

2. Asperities

One source of frictional forces between rocks is the resistance between asperities and a sliding surface. An initial attempt to document the contribution of asperities to rock friction was made by BYERLEE (1967a, 1970) who, upon viewing surface damage,

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The deformation of asperities and surfaces depends on the relative scratch hardness of the surface and asperity (ENGELDER, 1976; ENGELDER and SCHOLZ, 1976). When quartz (Moh's hardness = 7) and feldspar (Moh's hardness = 6) in Westerly granites slide on each other three types of frictional wear tracks may be observed on the sliding surface. The tracks result from the sliding of a quartz asperity on feldspar, a quartz asperity on quartz, a feldspar asperity on feldspar, and a feldspar asperity on quartz. Quartz asperities plough into the feldspar causing brittle fracture, making a groove into the feldspar. Feldspar asperities sliding on quartz leaves a track of 'softer' feldspar which adheres to the quartz and is sheared much like graphite from a pencil which adheres to paper as the pencil point is pushed over the surface. Quartz asperities sliding on quartz surfaces leave a trail of release fractures which propagated as a sliding asperity presses into the quartz surface. Friction is higher for an asperity ploughing than sliding on the surface (ENGELDER and SCHOLZ, 1976).

OHNAKA (1975; Table II) recognized four mechanisms for frictional forces between rocks: shear of adhesion, ploughing, interlocking and plastic flow. Again these mechanisms depend on the scratch hardness of the minerals composing the rocks.

The frictional properties of a rock subject to extensive surface damage is likely to conform to BYERLEE's Law (see BYERLEE, 1977, this volume). There are detailed studies of friction associated with a flat surface. Laws of time-dependent friction reflect the growth of contact area and, hence, shear strength with time (SCHOLZ and ENGELDER, 1976). Deformation associated with the asperity pressing into an opposing surface depends on the normal load across the real area of contact (ENGELDER and SCHOLZ, 1976). Furthermore, frictional heating released during slip is critically dependent on the normal load across the real area of contact as well as asperity velocity (JAEGER, 1942).

TEUFEL (1976) and LOGAN and FRIEDMAN (1976) both determined the asperity contact area by measuring the width of bands within thermal dyes which had changed color in response to frictional heating by slip of an asperity on a surface. The contact area was calculated assuming the width of the band was the diameter of a circular contact area. The real contact area was from 1 to 16 percent of the total area of the sliding surface. ENGELDER (1976) and ENGELDER and SCHOLZ (1976) determined asperity contact area by measuring the width of wear grooves on sliding surfaces. They also assumed that the width of the wear groove was the diameter of a circular contact area. In ENGELDER's (1976) experiments the contact area was less than 1 percent of the total area of the sliding surface, whereas ENGELDER and SCHOLZ (1976) report on an experiment in which the real contact area equals the total area of the sliding surface.

The area of asperity contact can vary several orders of magnitude (Fig. 2). From experiments the smallest documented asperity contact areas (10^{-6} cm^2) are associated with highly polished surfaces (ENGELDER, 1976). Asperity contacts of about 10^{-4} cm^2 have been observed on natural slickenside surfaces (ENGELDER, 1974). The upper opposite surface by brittle fracture. At low normal stress the material deformed plastically and the sliding was stable. BYERLEE (personal communication) pointed out, however, that polished surfaces of brittle materials have a thin surface layer which has a different structure than the underlying material (ARNOLD, 1952). This surface layer is probably composed of water molecules and ultrafine particles produced during polishing. BYERLEE suggests that only when the indenter penetrates the surface layer does brittle fracture and stick-slip occur.

The relative hardness of the opposite surface influences the normal stress across the sliding surface at the onset of stick-slip; the onset of stick-slip occurred at lower normal stresses when asperities slid on surfaces with lower penetration hardness. However, there is no evidence that the stable sliding to stick-slip transition takes place at a constant true normal stress for rocks with a variety of penetration hardness. But much smaller normal stresses are required across asperities for stick-slip, either at lower sliding rates on silica-bearing rocks (TEUFEL, 1976) or rock bearing large quantities of weaker materials such as calcite (LOGAN and FRIEDMAN, 1976). These latter experiments imply that other mechanisms than the brittle fracture of asperities also control the onset of stick-slip in some rocks.

To explain the onset of stick-slip LOGAN and FRIEDMAN (1976) introduced the concept of critical shortening rate. Their concept is based on the observation that static friction increases because the asperity contacts increase in size as a function of time-dependent inelastic deformation (ISHLINSKI and KRAGELSKII, 1944; SCHOLZ and ENGELDER, 1976). Basically, LOGAN and FRIEDMAN suggest that for any rock there is a slip rate which is so slow that the shear strength of the asperity-surface contact grows faster than the steady rate of application of shear forces. The shear strength of the asperity-surface bond grows as a function of the log of time (SCHOLZ and ENGELDER, 1976). With a steady rate of application of shear force the strength of the asperity will eventually be exceeded. The same stable sliding to stick-slip phenomenon holds true where asperity contact area increases as a function of normal stress rather than time. Again referring to Fig. 2, the contact area of asperities increases until the transition from stable sliding to stick-slip as observed by both ENGELDER and SCHOLZ (1976) and TEUFEL (1976).

3. *Gouge*

One consequence of the shearing of asperities is the generation of gouge between the sliding surface. The primary effect of gouge is to dampen the magnitude of stick-slip events and increase the normal stress of the stick-slip to stable sliding transition (BYERLEE and SUMMERS, 1976). BYERLEE and SUMMERS (1976) also pointed out that gouge-induced stable sliding is not indicative of lower friction. At high pressure the frictional strength of surfaces separated by a thick layer of material such as talc, chlorite, and a variety of clay minerals that are normally considered to be weak, is

4. Frictional heating

The partitioning of energy during the sliding of an asperity on a surface is the topic of intense debate among researchers in rock mechanics as well as seismology. Seismic efficiency for earthquakes is assumed to be relatively low (< 10 percent) (McKenzie and Brune, 1972) and this is most certainly the case for frictional sliding. Essentially most of the energy expended during frictional sliding must go into either deformation or heating. Engelder *et al.*'s (1975) calculation for the consumption of energy to create new surfaces during the generation of gouge, indicates that only a small fraction of the total work expended during the whole of frictional sliding goes into fracturing to create new surface area. Because little plastic deformation takes place, Engelder *et al.*'s (1975) calculation implies that a large fraction of the work expended during frictional slip must go into frictional heating.

An estimation of the maximum temperature from frictional heating can be made for Engelder *et al.*'s (1975) experiment. They observe that a thin layer of indurated gouge forms between deformed quartz gouge and a pre-cut surface of sandstone during stable sliding at 0.7 kb confining pressure. 0.168 cm^3 of indurated quartz gouge was formed during 0.1 cm of displacement where the slip rate was 10^{-3} cm/sec. During this slip 2.7×10^9 ergs were dissipated. If all of this energy is converted to frictional heat and liberated instantaneously in the indurated gouge, the temperature of the indurated gouge would be on the order of 600°C:

$$\Delta T = \frac{\Delta Q}{C} = \frac{(2.7 \times 10^9 \text{ ergs})/(4.186 \times 10^7 \text{ ergs/cal})}{(0.25 \text{ cal gm C}^\circ)\ (0.44 \text{ gm})}$$

However, the heat is generated at the rate of less than 0.02 cal cm^2 sec for about 100 seconds. The thermal conductivity of the intact rock and gouge is high enough to dissipate most of the thermal energy before appreciable heating takes place.

Jaeger (1942), Bowden and Thomas (1954), and Archard (1959) have all calculated or observed frictional heating caused by the slip of asperities of various materials on flat surfaces (Table 1). Their calculations show that for frictional heating of several hundred degrees in slip distances feasible in the laboratory both excessive speed ($> 10^2$ cm/sec) and excessive normal stresses (> 40 kb) are required. Neither this slip velocity nor normal stress is reached for conventional laboratory rock friction experiments.

Despite calculations showing that little frictional heating is likely to occur during room temperature frictional experiments, several experiments suggest that frictional heating may be significant. In early experiments, Griggs (1936) observed highly-slickensided shear surfaces coated with a shiny black substance which was 'too finely crystalline (probably colloidal) to produce an X-ray pattern'. Griggs entertained the idea that it was 'elemental silicon, liberated by the enormous shearing stress at rupture.' After shearing flat surfaces Jaeger (1959) noticed that they had a character-

Table 2

Gouge-Type	P_c (kb)	Shortening Rate (ε)	T°C	Characteristics	Reference
Welded Clumps	0.14 1.00	10^{-4}/sec 10/sec	24°C	Fragments of quartz embedded in and indurated by an isotropic matrix with a lower refractive index than quartz.	HUMSTON (1972), FRIEDMAN *et al.* (1974), JACKSON and DUNN (1974), TEUFEL (1976)
Fibrous Patches	0.5	10^{-4}/sec	260–416°C	1 micron long tapered fibers which root in welded clumps.	FRIEDMAN *et al.* (1974)
Welded Plates	4.0–5.0	10^{-4}/sec	24°C	A more extensive and thicker version of the welded clumps.	FRIEDMAN *et al.* (1974)
Indurated Gouge	0.67	10^{-4}/sec	24°C	Same characteristics as welded plates but completely covering sliding surface.	ENGELDER *et al.* (1975), ENGELDER and MCKEE (1973), JACKSON and DUNN (1974)
Charred Kerosene	1.00	10^{-4}/sec	24°C	Kerosene burns when introduced to sliding surface following a jacket leak.	HUMSTON (1972)

During discussion at the symposium on 'Experimental Studies of Rock Friction with Application to Earthquake Prediction' several questions were raised concerning use of thermal dyes to measure frictional heating. The change in color of the dye is caused by a phase change but it is not known how shear stress at the points of contact between the surfaces affect the transition temperature. Eirich and Tabor (1948) have demonstrated that where thin films are sheared rapidly there is a large increase in temperature of the film. If this phenomenon occurs during the shearing of the thermal dye, then the temperature of the dye may not be related to the temperature of the underlying material.

5. Conclusion

Asperity–surface interaction dissipates frictional energy by several processes which are manifested by structural changes on the sliding surface. Wear grooves associated with stick-slip indicate the important role of asperity indentation and ploughing as a mechanism of stick-slip. Welded gouge and features suggesting high temperatures plus calculation indicate that frictional heating is the major energy sink during frictional sliding.

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istic smell similar to that found near rock crushers and, sometimes, after breaking rocks in the laboratory. JAEGER suggests that the smell is associated with heating of rock powder during slip and, in fact, calculates that about 2.9 cal/cm^2 was liberated during slip. Assuming that heat was liberated into a small amount of crushed rock flour, JAEGER suggests that the transient temperature could be as much as 3000°C. More recently several workers have reported various surface and gouge features which have been attributed to frictional heating (Table 2).

Many friction experiments have produced an ultrafine amorphous gouge (ENGELDER and MCKEE, 1973; TULLIS and YUND, 1977). T.E.M. observations have failed to demonstrate that melting has occurred during sliding. It is apparent that this ultrafine material contains many fine crystalline fragments: however, sample preparation techniques make it difficult to isolate individual particles from crystalline neighbors for positive identification.

Using thermal dyes on sandstones, TEUFEL (1976) reports temperatures as high as 1177°C under asperities during laboratory friction experiments (Fig. 3). Theory and TEUFEL's (1976) experiments indicate that frictional heating increases with both normal load and slip rate. Near the melting point of silica (1150°C) this relationship breaks down. The thermal dyes indicate a much higher temperature than indicated using JAEGER's (1942) calculations which accounts for heat dissipation by thermal conductivity. One explanation is that the thermal mass of a surface or dyes is infinitesimally small and thus, easily heated, compared to the thermal mass of a layer of finite thickness.

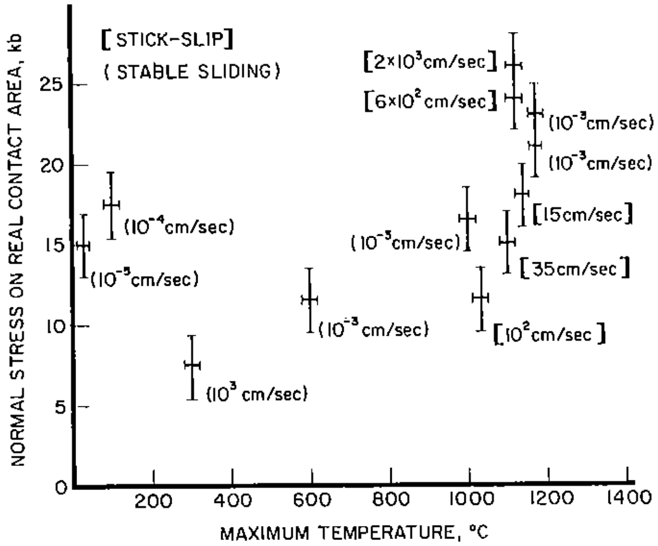

Figure 3
Maximum temperature versus normal stress for TEUFEL's (1976) friction experiments. Sliding velocity indicated for stable sliding and stick-slip.

Table 1

Material	Contact Radius (cm)	Thermal Conductivity (cal/cm–sec–°C)	Velocity (cm/sec)	Normal Stress (kb)	Friction (μ)	Maximum Temperature (°C)	Build-up Time (sec)	Slip (cm)	Source
Perspex	0.017	4.7×10^{-4}	114	107	0.17	85	—	—	Observed ARCHARD (1959)
Steel	0.057	0.11	380	43	—	700	4×10^{-3}	1.62	Observed BOWDEN and THOMAS (1954)
Steel	0.001	0.14	100	392	0.23	160	—	—	Calculated JAEGER (1942)
Earth	—	6×10^{-3}	0.4	0.25	0.5	1000	2.4×10^{4}	10^{4}	Calculated JEFFREYS (1942)
Earth	—	6×10^{-3}	1000	0.25	0.5	1000	4×10^{-3}	4	Calculated JEFFREYS (1942)
Earth	—	—	100	0.60	0.5	1000	2.6×10^{-2}	2.6	Calculated MCKENZIE and BRUNE (1972)

about the same as for clean surfaces of granite. Yet the mode of sliding is affected by the composition of the gouge. Where ENGELDER *et al.* (1975) documented stable sliding on quartz gouge, LOGAN and FRIEDMAN (1976) report that mixed quartz and calcite gouge produces stick-slip.

A set of structures commonly developed during slip on gouge are shear bands characterized by alternating layers of coarse and fine grained gouge (ENGELDER *et al.* 1975; LOGAN and FRIEDMAN, 1976). In cross section, the shear bands developed in quartz and calcite gouges strike across the gouge zones and intersect the intact surfaces, so that the acute angle between the band and the intact surface opens toward the direction of slip of the intact surface. In contrast, shear bands in NaCl gouge are oriented to give the true sense of shear of the intact rock. The acute angle opens away from the direction of slip of the intact surface. This difference in orientation of the sheared NaCl is attributed to plastic flow of the NaCl gouge where the entire layer is strained by simple shear. The strain history of gouge with shear bands opposing the slip vectors is much more complicated.

Although gouge tends to modify the large stress drops associated with stick-slip on rock surfaces without gouge, stick-slip still occurs. This suggests that there is still a common process accompanying frictional sliding on both fresh rock and on gouge: there is a mechanism for locking the surfaces. ENGELDER *et al.* (1975) first recognized that during stable sliding movement occurs by shearing along bands within the gouge, but during sudden slip the intact rock slips along its contact with the gouge layer. Subsequent experiments by LOGAN and SHIMAMOTO (1976) and BYERLEE *et al.* (1976) are consistent with this observation. In fact, BYERLEE *et al.* (1976) suggest that shearing of the gouge occurs while the fault zone is locked prior to a stick-slip event but, upon sudden slip, shearing occurs just at the margin between intact rock and gouge. In a review of previous work on deformed gouge LOGAN and FRIEDMAN (1976) suggest that three processes are most likely involved in stick-slip:

(1) Deformation during frictional sliding changes from shear strain within the gouge to slip along the boundary between the gouge and host rock.

(2) Surface asperities indent into the gouge almost to the full depth. The country rock-fault gouge system is locked primarily by the strengthening of gouge due to compaction and lithification, which prevent the movement of the surface asperities ploughing through the gouge.

(3) Stick-slip is produced by the sudden slip of the locked interface between the country rock and gouge, resulting in the breakage of some surface asperities and/or the gouge at the locked portion.

LOGAN and FRIEDMAN (1976) go on to say that the stick-slip behavior depends largely on the mechanical properties of severely deformed gouge near the country rock-gouge interface, and on the geometry and strength of surface asperities of the intact rock. Because the above mechanism is based mainly on the observations of deformed calcite and quartz gouge, its generality is still an open question. However, the important point is that the action of an asperity seems to be common to both intact surfaces and flat surfaces developed on gouge.

limit of the size of asperity contacts is probably some unknown fraction of the total area of crustal faults which themselves have areas in excess of 100 km^2.

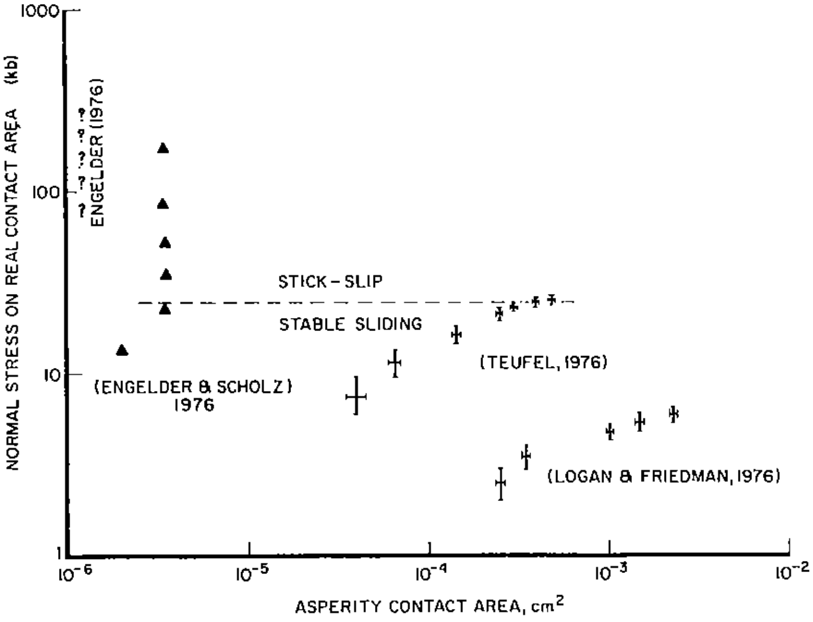

Figure 2

Asperity contact area versus normal stress for four suites of friction experiments. The stable sliding to stick-slip transition applies only to data on quartz materials from TEUFEL (1976) and ENGELDER and SCHOLZ (1976).

BYERLEE (1967b) observed that for a loading system with a constant stiffness the mode of frictional sliding for Westerly granite changed from stable sliding to stick-slip when normal stress on the sliding surface exceeded a certain value. From two studies on quartzose materials, for which the asperity contact size is known, a stable sliding to stick-slip transition can be delineated as a function of normal stress across the contact area (Fig. 2). At about 25 kb normal stress, both ENGELDER and SCHOLZ (1976) and TEUFEL (1976) observed a change in sliding mode for materials with either fused quartz or quartz sliding at about 10^{-3} cm/sec. Because of the difference in machine stiffness between TEUFEL'S and ENGELDER and SCHOLZ'S experiments, Fig. 2 implies that machine stiffness has only a minor influence on the stable sliding to stick-slip transition. The reason machine stiffness seems to have little influence is a mystery; theories of stick-slip friction predict that the onset of stick-slip is critically dependent on machine stiffness (see DIETERICH, this volume).

The role of asperities in controlling the mode of slip is obscure. Using highly polished surfaces of quartz-bearing rocks ENGELDER (1976) demonstrated that stick-slip occurred only when wear grooves formed as a result of asperities penetrating the suggested that asperities on sliding surfaces became interlocked and subsequently sheared off. Further studies of structural damage showed that interlocking also occurs by the brittle or ductile penetration of sliding surfaces by the plowing of asperities, adhesion of asperities, or indentation by creep (COULSON, 1970; OHNAKA, 1975; ENGELDER, 1976; SCHOLZ and ENGELDER, 1976).

Asperity size or surface roughness affects friction. Combining data from BYERLEE (1976b) and ENGELDER (1976) on Westerly granite, it is evident that friction ($\mu_s = \tau/\sigma_n$) at the initiation of slip of rocks is highly dependent on the size of asperities (surface roughness) (Fig. 1). The smoother surfaces have a lower initial frictional strength. This is not to say that smaller asperities have an inherently lower friction but because they have lower shear strengths due to smaller cross-sectional area, the gross frictional strength of the surface is less. This would also suggest that the real area of contact is less for smooth surfaces. Others may say that the degree of interlocking is less. Both COULSON (1970) and OHNAKA (1975) demonstrated that the surface roughness – friction relationship is highly dependent on the rock. In addition, friction at the initiation of slip does not continue to increase with asperity size, as shown by OHNAKA (1975) for Solenhofen Limestone.

As surface damage increases after the initiation of slip the frictional coefficient usually approaches a value of 0.5 to 0.6 (BYERLEE, 1967, Fig. 3; OHNAKA, 1975, Fig. 11; and ENGELDER, 1976, Fig. 4). For surfaces with very small asperities (1 μm) friction seems to be low initially and increase, whereas for surfaces with relatively larger asperities (10–100 μm) the friction seems to be high initially and decreases.

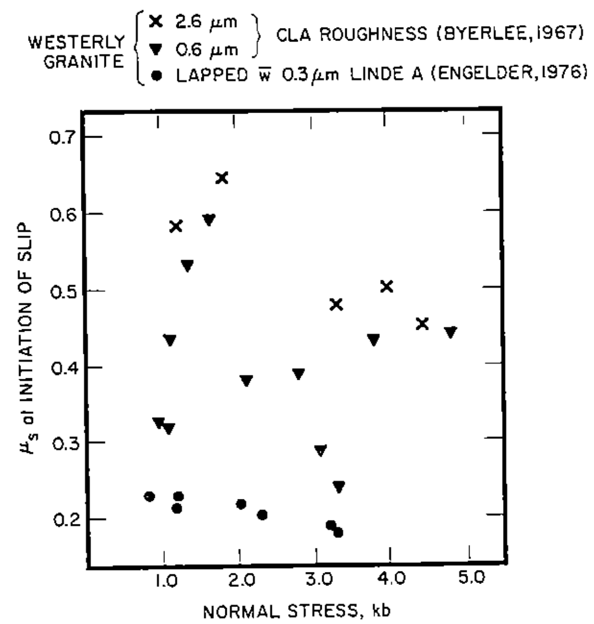

Figure 1
Effect of asperity size on friction.