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22. *Some Experiments on Thermal Shock Fracture of Rocks.*

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Summary

Thermal shock resistance and thermal strain are examined experimentally on basaltic rocks: thermal strain was created in the sample, cylindrical in shape having a coaxially drilled inner hole, by suddenly pouring hot molten metal into its inner hole. It was observed that the thermal strain (tensile) measured on the outer surface of the sample increases with the increase in the temperature of the poured metal. When the thermal strain reached the critical strain, fracture was observed. The temperature of the poured metal when it causes a fracture was in the present case about 800°C onwards.

1. Introduction

Brittle materials fracture when they are subject to quick changes in temperature. Fracture in such cases is called thermal shock fracture. This phenomenon is most commonly experienced when one pours hot water into a glass, and has been much studied on ceramic materials[1),2)] for its technological importance. Evidently the fracture takes place when the magnitude of the thermal stress[3),4)], developed in the material by the non-uniformity in temperature, surpasses the critical breaking strength σ_c. The magnitude of the thermal stress may generally be expressed as,

$$\sigma=\frac{E\alpha T_1}{1-\nu}\times S \tag{1}$$

1) *J. Amer. Ceram. Soc.*, **38**, No. 1 (1955).

2) W. D. KINGERY, *Property Measurements at High Temperatures* (1959), John Wiley.

3) S. TIMOSHENKO and J. N. GOODIER, *Theory of Elasticity*, Maple Press, York, PA., (1951).

4) *loc. cit.*, 2).

where the notations are ;

σ...thermal stress,

E...Young's modulus,

α...coefficient of thermal expansion,

T_1...change in the surface temperature,

ν...Poisson's ratio,

S...function of the time t after the first change in the temperature, the space variables in the material, the size and shape and the thermal properties of both the material and surroundings.

The lowest value of T_1 to cause a fracture in the above formula may be called the thermal shock resistance factor of the test material. Putting $E=5\times10^{11}$, $\alpha=1\times10^{-5}$, $\nu=0.3$ and $\sigma_c=1\times10^{8}$ (all in c. g. s.)[5),6)], the thermal shock resistance of rocks would be,

$$T_1=(1/S)\times 12^\circ\mathrm{C}\ . \qquad (2)$$

S being dependent on various factors in a complicated manner, the thermal shock resistance factor is not a material constant. It may be expected that, if the temperature change at the surface is ideally instantaneous and the contact thermal resistance is ideally small, the thermal shock resistance factor of rocks would be fairly small. It appears however that not much has been published, to the authors' knowledge, on this aspect of rocks.

Some geophysical interest may be found in the thermal shock resistance of rocks, as it would be related to the problems such as the possibilities of fracture of the crustal rocks due to magma intrusion, the formation of cracks and joints in an igneous mass when it cools or the weathering of surface rocks due to solar radiation and so forth.

2. Experiment

The experimental procedures are simple and illustrated in Fig. 1. The test samples are the cylinders, 4 *inches* in diameter of compact basalt, taken from the bore-hole near the outer somma of volcano Mihara, Oshima Island. They were supplied by the Dowa Mining Company which owns the hole. A coaxial inner hole one inch in diameter was drilled by a diammond drill in each sample. The thermal shock was given by suddenly pouring in molten metal of known tempera-

5) F. BIRCH, ed., *Handbook of Physical Constants* (1954), *Geol. Soc. Amer.*

6) K. MOGI, to be published in this Bulletin.

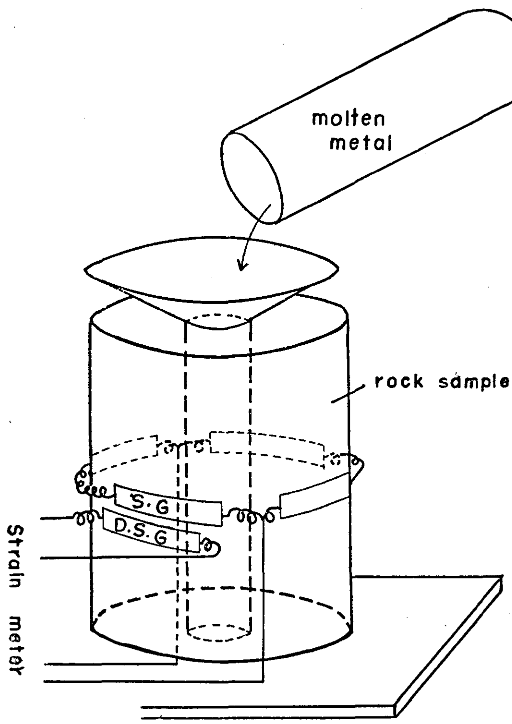

Fig. 1. Experimental procedures.
S. G.....metal wire strain gauge,
D. S. G.....dummy strain gauge.

ture to fill the inner hole. The melting of the metals was conducted by heating the pieces of metal in an alumina crucible. Metals such as tin, lead, zinc, aluminium and copper were tried and among these non-noble metals, aluminium and lead were found to be convenient for the purpose. The temperature of the molten metals was measured just before the pouring either by a Pt-PtRd thermocouple or an opitical pyrometer: the accuracy of the measurements seems to be no better than $\sim$20°C.

The strains caused by the thermal stresses were measured on the outer surface of the sample by means of an ordinary metal wire strain gauge apparatus. Four metal strain sensitives were attached to the outer surface of the samples following the ordinary techniques and the readings were taken mannually with a commercial apparatus, or recorded by a penwriting oscillograph. It is obvious that the type of strain measurement employed here is not the best, since the electrical resistance of the metal wires is essentially dependent on temperature. Although a dummy gauge was always used to eliminate the effect of change in the ambient temperature, the rapid and non-uniform variations in the temperature which were unavoidable in the present experiments caused spurious readings a few minutes after the pouring in of hot metal. When the temperature in that part of the specimen, where the wire-gauges are attached, changes, the apparent reading will be the superposition of the various effects such as, the thermal change in the electrical resistance of the wire-gauges, the thermal expansion of both the specimen and the genuin thermal strains. Therefore, the readings after the time when the temperature change at the inner hole surface has propagated to the outer surface by conduction, would be very complex. In fact, it was found that a temperature change of some 10°C would upset the measurement. But during the first one to two minutes when the temperature of the outer surface remains unaffected the results seemed fairly reasonable as will be shown in Figs. 3 and 4.

Mathematically, the experiment may be approximated by the case where a hollow cylinder $a<r<b$, with zero initial temperature, is heated internally by changing the surface temperature of the hollow by $T_1 (T_1>0)$ stepwise at $t=0$. For small values of t, the boundary conditions may be simplified as, disregarding the cooling of the molten metal and the heating of the outer surface,

$$T=T_1 \quad \text{at} \quad r=a\,, \tag{3}$$

$$T=0 \quad \text{at} \quad r=b\,, \tag{4}$$

The temperature distribution and the thermal stress distributions for such a case were given by Jaeger[7] under more general boundary conditions. Jaeger's solution simplified to the present boundary conditions may be shown to be, denoting the radial and tangential stresses and thermal diffusivity by σ_r, σ_θ and κ,

$$T(r,\ t)=T_1\frac{\log b/r}{\log b/a}-\sum_{s=1}^{\infty} e^{-\kappa(S_s/a)^2 t}\, F(S_s/a)C_0(S_s r/a) \tag{5}$$

$$\begin{aligned}\frac{(1-\nu)\,\sigma_r(r,\ t)}{E\alpha}=&\frac{-T_1}{2\log b/a}\left\{\frac{b^2(r^2-a^2)}{r^2(b^2-a^2)}\log b/a-\log r/a\right\}\\ &-\sum_{s=1}^{\infty} e^{\kappa(S_s/a)^2 t}F(S_s/a)\left\{\frac{b(r^2-a^2)C_1(S_s b/a)}{r^2(b^2-a^2)S_s/a}\right.\\ &\left.-\frac{C_1(S_s b/a)}{(r/a)S_s}+\frac{2(b^2-r^2)}{\pi(b^2-a^2)S_s^2(r/a)^2}\right\}\end{aligned} \tag{6}$$

$$\begin{aligned}\frac{(1-\nu)\sigma_\theta(r,\ t)}{E\alpha}=&\frac{-T_1}{2\log b/a}\left\{\frac{b^2(r^2+a^2)}{r^2(b^2-a^2)}\log b/a-1-\log r/a\right\}\\ &-\sum_{s=1}^{\infty} e^{\kappa(S_s/a)2t}\ F(S_s/a)\left\{\frac{b(r^2+a^2)C_1(S_s b/a)}{r^2(b^2-a^2)S_s/a}+\frac{C_1(S_s r/a)}{S_s r/a}\right.\\ &\left.-C_0(S_s r/a)-\frac{2(b^2+r^2)}{\pi(b^2-a^2)S_s^2(r/a)^2}\right\}\end{aligned} \tag{7}$$

where

7) J. C. JAEGER, *Phil. Mag.*, **36** (1945), 418.

$$C_0(x)=J_0(x)Y_0(S_s)-Y_0(x)J_0(S_s)\ ,$$
$$C_1(x)=J_1(x)Y_0(S_s)-Y_1(x)J_0(S_s)\ ,$$
$$F(S_s/a)=\pi T_1\left[\frac{J_0^2(S_sb/a)}{J_0^2(S_sb/a)-J_0^2(S_s)}\right]\ , \tag{8}$$

S_s is the s-th root of

$$J_0(S_s)Y_0(S_sb/a)-J_0(S_sb/a)Y_0(S_s)=0\ . \tag{9}$$

Putting $a=1/2\ inch$, $a/b=1/4$, and $\kappa=10^{-2}$, the above formulas give the distributions of T, σ_r, and σ_θ in the cylinder as shown approximately in Fig. 2. As can be seen in the figure, while the radial stress is always small and compressive, the tangential stress is compressive at the inner part and tensile at the outer part. The greatest tensile stress is to be found on the outer surface of the cylinder at the instant when the heating in the inner hollow starts: the maximum of

$$\sigma_\theta(1-\nu/E\alpha T_1),$$

which is the value of S in (1), amounts to 1 on the inner surface and 0.6 on the outer surface. From these results it is expected that the fracture, in such an ideal case, would start from the outer surface inwards at the instant when the hot liquid is poured in.

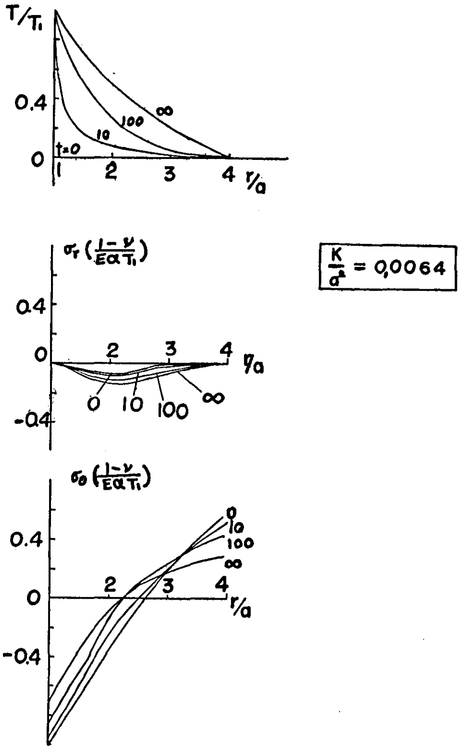

Fig. 2. Temperature and stress distributions in a hollow cylinder.

Figs. 3 and 4 are the examples of the strain (apparent) measurements. The ordinate is the reading of the strain-meter (Fig. 3) and the output signal of the strain-meter recorded by a pen-writing oscillograph (Fig. 4), and the abscissa is the time after the pouring of the metal. In all cases, the stress was found to be tensile, as expected. But, unlike the above expectation, the maximum of the tangential tensile stress took place one or two minutes after the pouring. This is considered as

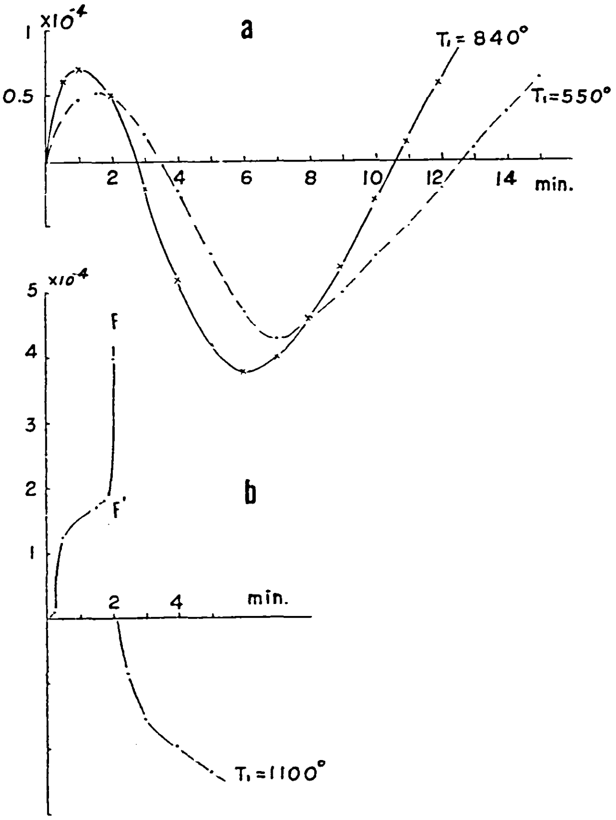

Fig. 3. Examples of strain gauge readings as dependent on time.

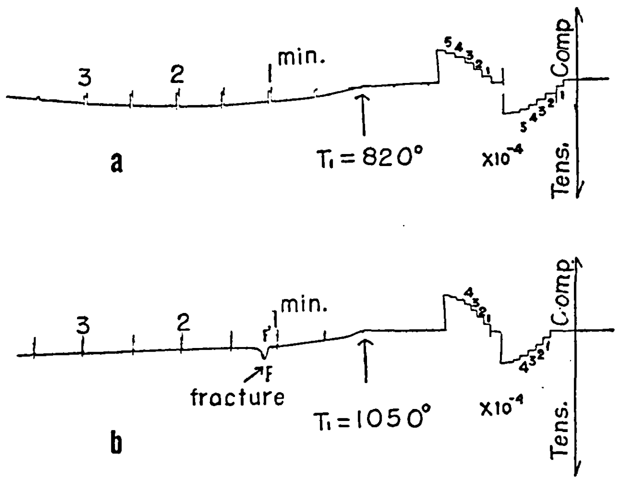

Fig. 4. Examples of strain-meter records.

being due to the fact that the temperature at the inner hole surface in actual cases did not change exactly stepwise so that the simplified boundary conditions (3) could not be met. After a few minutes, the strain decreased and became even compressive. It seemed, however, that this was only apparent because of the temperature disturbance in the strain gauge. Considering these, it may be appropriate to take the maximum value of the tensile strain (M in Figs. 3 and 4) as the thermal strain in our experiments.

In the cases of Figs. 3 (b) and 4 (b), thermal shock fracture took place. As shown in these figures, the strain suddenly started to increase just before the fracture. The actual fracture, detected by a sharp click, occurred at the pointed peak (F in the figures) of strain. The magnitude of the strain at fracture is in agreement with the critical tensile strain of rocks under ordinary strength testing.[8] There seems to be two ways of assigning the critical strain in our experiments, *i. e.* whether to take either F or F' in the figures. It may be possible that after F' the deformation is no longer ideally elastic and some kind of yield is taking place perhaps locally in the sample. If so, F' may be the true critical strain. The cracks formed by the fracture were more or less parallel to the radial plane and penetrated from the outer surface to the inner one. In most cases the crack was a single plane: occasionally three planes *ca.* 120° apart from each other were formed.

Fig. 5 summarizes the general results. In this figure, the abscissa is the temperature of the poured metal or the T_1 and the ordinate is the maximum thermal strain defined above. It is seen in the diagram

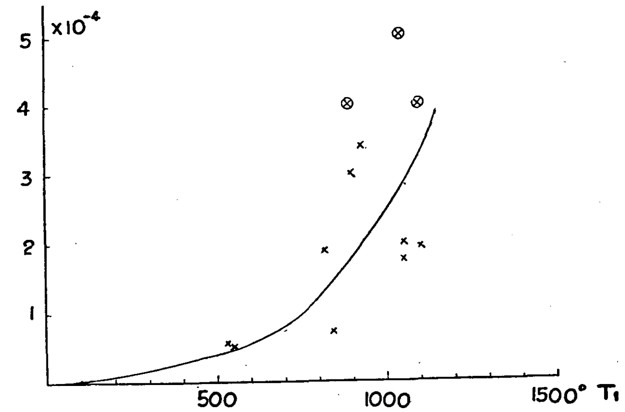

Fig. 5. Maximum observed thermal strain as dependent on the temperature of the poured metal.

that the thermal strain increases regularly with the increase in T_1. The increase however is not quite linear with T_1. The reason for this is not known. The circles with a cross correspond to the strains at F in Figs. 3 and 4 and the crosses right below each of them correspond to the strains at F'. As can be seen in the diagram, thermal shock resistance of the basalt under the present conditions seems to be about 800°C. This value is considerably higher than that expected from the simple ideal calculation described above.

3. Discussion

One of the authors (U. S.)[8] put forward a hypothesis, in order to explain the mode of temporary change in the local geomagnetic field on an occasion of major activity at volcano Mihara, that in the volcanic activity, the molten magma would rise rather slowly all through its journey from the depths to the surface. In the more orthodox view, the magma is believed to be stored in a "magma reservoir" several kilometres deep and to come out from there very quickly, through a more or less open vent. In the new hypothesis, it was postulated that the heat transfer in an active volcano would be very effective perhaps by virtue of some convective machanism, so that at the very beginning of each active period the hot magma wonld somehow have to make its way up through already cooled and solid mountain mass, which had provided a vent for the magma and had been heated during preceding activity some years before. If such is the case, the new fluidal magma would have to fill every available crack and fissure and create some new ones to make its way out. In addition to its ordinary mechanical force, the intruding magma will produce some thermal shock upon the wall rocks. Such thermal shocks may contribute to the crack-formation. The experiments described above would correspond to our own sphere of volcanological interest.

The temperature of the basaltic lava of volcano Mihara has been reported to be 1050–1100°C.[9),10)] Therefore, if the temperature of the mountain mass surrounding a fissure to be filled with the new magma should be less than say 200°C, formation of new cracks by thermal shock fracture would not be utterly impossible. Such a process is expected to proceed

8) S. UYEDA, *Bull. Earthq. Res. Inst.*, **39** (1961), 579.
9) R. TAKAHASHI and T. NAGATA, *Bull. Earthq. Res. Inst.*, **15** (1937), 1047.
10) T. MINAKAMI, *Bull. Earthq. Res. Inst.*, **29** (1951), 487.

almost instantaneously as compared with any process of heat transfer. Hence, the magma intruded into new cracks will meet practically non-heated wall rocks so that some further thermal shock fracture may be formed. This process would continue until the magma reaches the surface and by that time a fairly large portion of the mountain may have been penetrated with a resulting number of cracks and heated up to above 200–300°C. In the hypothesis referred to as 8), the heated portion is assumed to be a cylinder having a radius of 430 *m*.

In the experiment, however, the sample was of a very particular form. It is by no means guaranteed that the thermal shock resistance *in situ* would be the same as that obtained here. To make sure whether or not such thermal shock fracture would in fact play any significant rôle in volcanism, more realistic experiments as well as more exact knowledge regarding the state under the volcano would be required.

4. Acknowledgement

The authors would like to thank Dr. K. Mogi who allowed them to use his strain meter and to the Dowa Mining Company who put numerous pieces of rock-specimens at the authors' disposal.

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22. 岩石の熱衝撃破壊について

地震研究所 {上田 誠也
藪 武夫}

玄武岩の熱衝撃抵抗および熱歪を実験的に調べた．熱歪は，円筒状内孔を有する玄武岩柱に，種々の温度の熔融金属を注入して生ぜしめられた．標本表面に発生する引つ張り歪みは，ストレーンゲージによつて測定されたが，注入金属の温度とともに増大することが観られた．また破壊を起す場合の金属温度はほぼ 800°C 以上であつた．800°C 以上の温度差を有する高温岩漿が，地層岩石内に突然注入した場合には，熱衝撃破壊の発生が予想される．