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Fundamental aspects of the thermo-elasticity in the columnar joint formation

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Columnar joints form as a result of unidirectional propagation of cooling and the consequent thermal contraction. So far in interpreting the columnar regular structures at nature, two hypotheses are assumed about the fracture threshold and propagation direction: 1) fractures take place at a certain temperature, that is, at the isothermal surface corresponding to the yield strength (fracture threshold hypothesis). 2) fractures propagate perpendicular to the isothermal surface (propagation direction hypothesis). However, those hypotheses have not been proved on the basis of the thermo-elastic theory. In this paper, we analytically show, using the thermo-elastic theory in 2D, that these two hypotheses are correct under the specific circumstances. Firstly we derive the relation between the stress field and temperature field in terms of principal stress difference, stress invariant and temperature. From the relation, we understand that the principal stress difference contributing to the crack initiation is exactly equivalent to a certain temperature when the minimum principal stress is small enough. The temperature corresponding to the crack initiation, which is determined by the yield strength, defines the fracture isotherm or crack front. Secondly we derive the direction of maximum extension on the fracture isotherm as function of azimuthal angle. If the stress is completely released in the region where fracturing already occurred and cracks are present, that is, where temperature is less than fracturing temperature, then the shear stress on the fracture isotherm must be zero, and one of principal stress is perpendicular to the fracture isotherm and another principal stress is along the fracture isotherm. These geometric relations naturally mean that the direction of maximum extension is perpendicular to the fracture isotherm. Numerical calculations well explain morphological features derived from our analog experiments, indicating that two hypotheses work correctly in real systems.

Keywords: columnar joint, thermo-elasticity, thermal stress