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The development of polygonal fractures due to contraction: A disorder to order transition

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ABSTRACT

The formation of three-dimensional polygonal fractures in two-layered materials during surface cooling is numerically investigated to study the disorder to order transition mechanism of such fractures. The heterogeneity of the breakdown threshold in a brittle solid is modeled using a probability distribution at the mesoscopic level, and the cracking behavior of meso-elements is modeled using continuum damage mechanics. A finite element method (FEM) is used to obtain the thermal stress distribution. Then, the damage threshold is determined based on the maximum tensile stress criterion. The polygonal fracture behavior, including the initiation and propagation of microcracks and the formation of approximately equal-area surface cracks, are captured well by the numerical results. The impact of thermal conductivity on cracking patterns is discussed. The quantitative results indicate that the polygon sizes and fracture spacing are independent of the material heterogeneity while the thermal conductivity significantly affects the failure patterns of layered materials subjected to thermal shrinkage. Furthermore, the effect of the bond strength between the overlay and substrate is studied. For a high bond strength, the cracks initiate in the overlay and propagate into the interface. However, for a low bond strength, debonding is observed. The modeling results shows that heterogeneity of the brittle solid is the main reason for disordered initiation of cracks and that local energy minimization at a location and time is the key factor affecting polygonal fracture failure patterns.

1. Introduction

Polygonal fracture patterns are common in both natural and man-made materials and occur as these materials contract upon cooling or losing water. These patterns are broadly observed in clayey soils [1,2], basalt [3–6], starch slurry [7] and ceramic coating [8,9]. Fig. 1 shows some examples of polygonal fractures, and Fig. 1(a) is from Wikipedia [10]. In layered material, low material conductivity or rapid cooling/drying on the material surface generates steep thermal/moisture gradients between the surface layer and subsurface, increasing potential differences in contraction at the surface level. These processes often cause large tensile stress on the surface and compression stress in the subsurface, causing surface cracks. The crack patterns are generally parallel and equally spaced two-dimensional (2D) arrays or three-dimensional (3D) fractured polygon patterns. Cracks tend to propagate in the gradient direction of the material and thus affect the removal rate of the diffusing quantity. Notably, an initially disordered network can become more ordered as cracks propagate through the material. This can lead to, for example, the formation of hexagonal columnar joints in cooling basaltic lavas [11].

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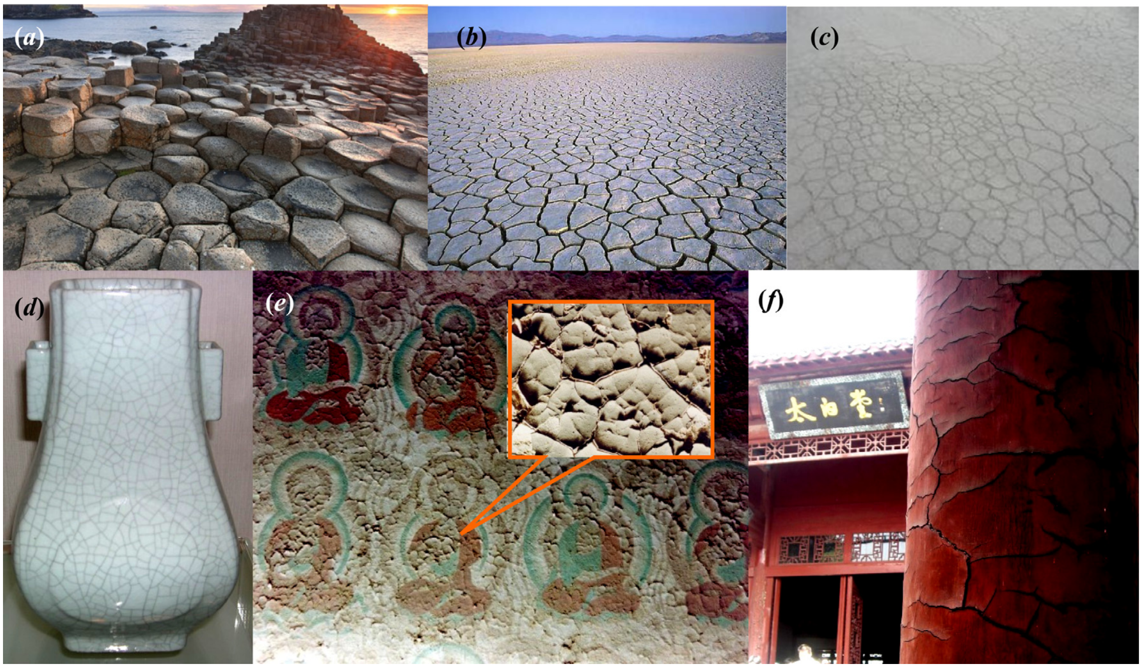

Fig. 1. Polygonal fracture patterns are found naturally in many materials and can be driven by thermal or desiccation contraction. This figure shows examples of polygonal fractures in (a) Giant's Causeway, Northern Ireland [10]; (b) a drying fracture in mud in Dalian, China; (c) a shrinkage fracture in pavement in Dalian, China; (d) cracked ceramics in a museum of Dalian University, China; (e) a crack in a Dunhuang fresco in China and (f) a crack in a painted pillar in Taibai Tower, Anhui, China.

Many studies have focused on the mechanism of polygonal fracture pattern generation. One study was determined that basalt columns originate from fracture propagation caused by the thermal contraction of solidified lava [4]. Aydin and DeGraff [3] suggested that the tetragonal networks at flow surfaces systematically evolve into hexagonal networks as the joints propagate inward during lava solidification. A study on fractures in a mud layer indicated that after a fracture has been established, it will rapidly propagate across the mud layer in a roughly straight line until it hits something or runs out of mud. Polygonal cracking continues until the polygons reach a characteristic size, which is proportional to the depth of the surface layer [11]. At that time, fracture saturation occurs and substantial stress widens existing cracks rather than starting new ones [12]. Furthermore, results have also suggested that polygonal fractures that start in a random distribution on a surface transform into a more regular polygonal configuration with mostly hexagons while propagating with depth. The random distribution of fractures (or failures) is a disorder process, whereas the regular polygon configuration is an order process. Therefore, the formation of polygonal fractures is a disorder to order transition process. The mechanisms of this process have been studied by several researchers. Goehring et al. [7] observed the polygonal fracture process using computer tomography, and Bahr et al. [4] observed this process using schematic drawings. Goehring and Morris [13] found that the column radius and stria size are proportional to each other and inversely proportional to the cooling rate of the lava; i.e., faster cooling led to narrower columns, and steeper gradients led to narrower striae. The maturation process of columnar joints was simulated with 2D models using a variation of Voronoi tessellation [5], using a 3D spring network model [14], and by minimizing an energy functional [6,15]. Jagla and his collaborators [6,16,17] presented the generation of columnar joints based on energy minimization, atomistic simulation, 2D analogues, and a finite element stress analysis. In general, materials such as rocks, ceramics and mud are inhomogeneous and significantly affect the mechanical behavior [18,19]. Tang et al. [20,21] studied the effects of temperature, the thickness of soil layer, wetting and drying cycles and soil types on the geometrical structure of surface shrinkage cracks in clayey soils. Their results showed that cracking mainly occurs in three stages: the main crack initiation stage, sub-cracks initiation stage and terminal stable stage. Hornig et al. [8] used considered a finite element model to analyze the fragmentation of a coating over a bulk material. They modeled the coating using an array of springs and accounted for the statistical inhomogeneities by assigning each spring a breakdown threshold taken from a given probability distribution (PD). They found that the fragmentation mode depends on the disorder's strengths. For small disorders (narrow PDs), the system fragments through crack propagation. For strong disorders (wide PDs), the cracks are formed by the coalescence of initially independent point defects.

Despite several decades of research regarding polygonal fracture patterns, the ordering mechanism, similar to many fracture problems, is not fully understood [7]. Numerical methods can be used to effectively calculate the stresses and strains in structures with complex shapes and even to predict the propagation process for a number of cracks. Modeling the fracture patterns in a layered material is generally a 3D problem that requires fracture analysis. Although some simulations of frac-