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Extrusion, slide, and rupture of an elastomeric seal

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ABSTRACT

Elastomeric seals are essential to two great technological advances in oilfields: horizontal drilling and hydraulic fracturing. This paper describes a method to study elastomeric seals by using the pressure-extrusion curve (i.e., the relation between the drop of pressure across a seal and the volume of extrusion of the elastomer). Emphasis is placed on a common mode of failure found in oilfields: leak caused by a crack across the length of a long seal. We obtain an analytical solution of large elastic deformation, which is analogous to the Poiseuille flow of viscous liquids. We further obtain analytical expressions for the energy release rate of a crack and the critical pressure for the onset of its propagation. The theory predicts the pressure-extrusion curve using material parameters (elastic modulus, sliding stress, and fracture energy) and geometric parameters (thickness, length, and precompression). We fabricate seals of various parameters in transparent chambers on a desktop, and watch the seals extrude, slide, rupture and leak. The experimentally measured pressure-extrusion curves agree with theoretical predictions remarkably well.

1. Introduction

Seals—along with tires, bearings, and medical gloves—are among the most significant applications of elastomers (Gent, 2012). In daily life, elastomeric seals are ubiquitous in plumbing joints, bottle caps, and pressure cookers. In engines and hydraulics, elastomeric seals enable fluid-tight, reciprocating motion of pistons in cylinders (Nau, 1999). Attributes of elastomeric seals include high sealing pressure, light weight, and low cost. Elastomeric seals are inexpensive, but their failure can be costly. The explosion of the space shuttle Challenger, for example, was traced to the failure of an O-ring (Rogers et al., 1986).

Our own interest focuses on elastomeric seals used in the oil and gas industry. These seals are commonly known as packers, and are used to isolate fluids in gaps between pipes and boreholes (Al Douseri et al., 2009; Ezeukwu et al., 2007; Kleverlaan et al., 2005). The packers achieve sealing either by mechanical mechanisms (mechanical packers) (Coronado et al., 2002), or by imbibing fluids (swellable packers) (Cai et al., 2010; Druecke et al., 2015; Lou and Chester, 2014). Seals are essential to the two great technological advances in oilfields: horizontal drilling and hydraulic fracturing (Davis and McCrady, 2008; Gavioli and Vicario, 2012; Miller et al., 2015; Yakeley et al., 2007).

Elastomers can sustain essentially arbitrarily high pressure, so long as the pressure has the same magnitude in all directions and in all places (i.e., hydrostatic and homogeneous pressure). The function of a seal, however, is to sustain a *drop of pressure*. The

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inhomogeneous pressure inevitably leads to shear and tensile stress, which causes the elastomer to deform and possibly rupture. When a seal is used to enable hydraulic fracturing, the pressure at one end of the seal must be high enough to fracture rocks, and the pressure at the other end of the seal can be as low as that in the ambient. These requirements correspond to a drop of pressure up to 70 MPa (Nijhof et al., 2010). Such a large drop of pressure is remarkable, considering that the elastic modulus of an elastomer is on the order of 1 MPa. Fracture mechanics has not been systematically applied to study the rupture of seals, although cracks are commonly observed in postmortem examinations. In practice, seals are tested in assembled parts, which are opaque and make the processes leading to leak unobservable.

Here we describe a method to study an elastomeric seal using its pressure-extrusion curves (i.e., the relation between the drop of pressure p and the volume of extrusion of the elastomer Q). We introduce a model sealing system that enables theoretical analysis and experimental observation. The theory calculates the finite elastic deformation of the seal and the energy release rate of the crack. The theoretical results are in analytical forms, and relate the pressure-extrusion curve to material and geometric parameters. We fabricate seals of various parameters in transparent chambers on a desktop, watch the seals extrude, slide, rupture and leak, and measure their pressure-extrusion curves. We then use independent experiments to determine elastic moduli, fracture energies, and sliding stresses (Appendix A, B, C), and use them to calculate the theoretical pressure-extrusion curves. The pressure-extrusion curves recorded in the experiment agree well with those calculated using the theory.

2. Modes of failure

The deformation of the elastomer is essential to both the function and failure of a seal. When the elastomer seals the fluid in a gap between stiff mating parts, the deformation of the elastomer enables it to adapt to unpredictable variations, such as the height of the gap, the misalignment of the mating parts, the roughness of their surfaces, and the change in temperature. Consequently, neither the seal nor the mating parts need be designed with high precision, which could be costly or impractical. However, the deformation of the elastomer may also lead to failure. The fluid pressure can cause the elastomer to extrude, which may lead to rupture, loss of contact, or even escape from the sealing site.

Incidentally, deformation of soft materials under constraint is also important in biology and medicine. For example, to measure

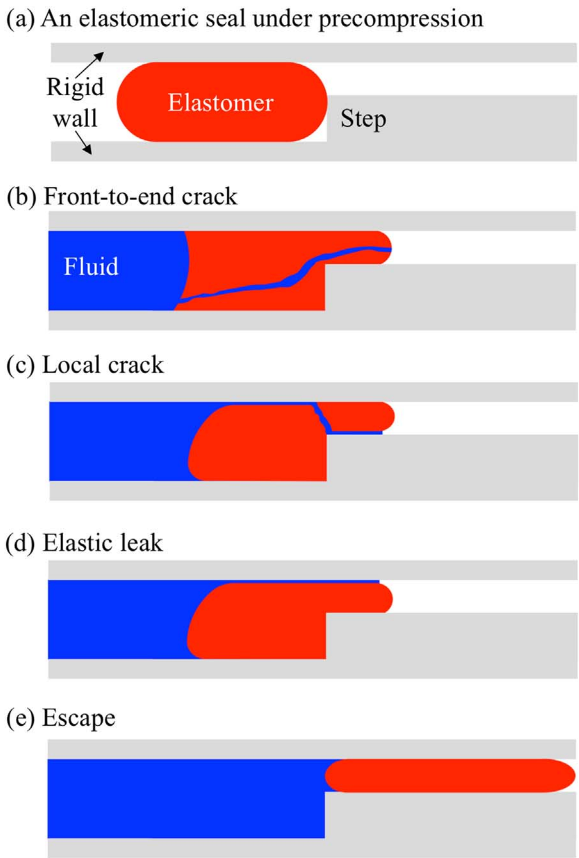

Fig. 1. Modes of failure of an elastomeric seal. (a) Prior to the injection of the fluid, a seal is in a state of precompression between two rigid walls, and a step in the bottom wall defines the sealing site. (b) A crack initiates from the front of the seal and propagates through the length of the seal. (c) A crack forms at the end of the seal and cuts the extruded elastomer. (d) Elastic leak without damage. Fluid penetrates into the interface between the elastomer and rigid wall. (e) Seal escapes from the sealing site.