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Research paper

Fracture mechanical model for tensile strength of particle reinforced elastomeric composites

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ABSTRACT

The tensile strength of particle reinforced elastomeric composites (PRECs) was studied as functions of the particle volume content (loading) and particle size. The measured tensile strength increased with increasing particle loading and decreased with increasing particle size. The measured fracture toughness increased with increasing particle size. A fracture mechanical model to predict the tensile strength was developed to better understand the reinforcing effects of the particle and to provide a criterion for a better composite. Using a body center cubic (BCC) crystal system, the elastic energies of the undamaged and damaged cells were obtained. The tensile strength as a function of the measured fracture toughness (J value) and the modulus of the matrix can be calculated by comparing the energies. The predicted tensile strength decreased with increasing particle size in a similar manner to the experimental results. The analytical model predicted that the size of the poor interface up to 30° of the debonded angle on the tensile strength becomes less severe as the particle size is decreased. In addition, the specimen with smaller particles (<30 μm) should have a higher tensile strength than that of the experimentally measured values. The conglomeration and non-uniform distribution of smaller particles, and the entrapped void within the agglomerates while mixing and fabricating can be one reason.

1. Introduction

Particulate-reinforced elastomeric composites (PREC) have been used extensively in a range of fields because of their low production cost and ease with which they can be formed into complex shapes. The broad use of PREC as structural materials relies on an understanding of its reinforcing and damage mechanisms, which depend on many variables. Among these variables, the particle size, particle spatial distributions, particle–matrix interface adhesion, and particle loading are of significant interest. Recently, nano-materials, such as clay, silica, CNTs, and various inorganic particles have been used to reinforce a range of elastomers for better properties and wide functionality (Bertora et al, 2011; Frohlich et al, 2005; Chuayjuljit, et al, 2002; Ansarifar, 2007). On the other hand, very limited research on reinforcing or damage mechanisms depending on the particle size have been performed. Despite this, the results show that as the reinforcing particle becomes smaller and diversified, an understanding of these mechanisms of PREC as functions of the particle size and volume, interfacial conditions, etc. is very important for better PREC (Krause, 1965; Wolffand Wang, 1993; Suzuki et al, 2005; Park, 2005).

A number of studies have examined the dependence of the mechanical properties of particulate reinforced polymer composites (PRPC), including strength, rigidity, toughness, wearing resistance, etc., on the particle size and particle spatial distributions. Recently, Fu et al. (2008) reviewed the effects of the particle size, particle/matrix interface adhesion and particle loading on the stiffness, strength and toughness of particulate-polymer composites by comparing the published experimental results with theoretical models. They concluded that the composite strength and toughness are strongly affected by all three factors; particle/matrix adhesion, particle size and volume content. The mechanical properties of PREC is also affected by three factors. Since Hall–Petch [Anderson, 1995] reported that the strength of metals and composites was dependent on $d^{-1/2}$ (where d is the diameter of particles), many studies have been performed analytically and numerically to predict the strength of PRPC (Tzika, 2001; Quaresimin, 2014; Cho et al, 2006). In general, hard particles in PRPC have two effects: weakening due to stress concentrations and reinforcing due to crack growth barriers. Although in many studies, a prediction of the strength of these materials is difficult due to a range of parameters, such as interface adhesion, stress concentration and defects or cluster sizes, and their spatial distribution, etc., there is no universally accepted theory to predict the strength of PRPC.

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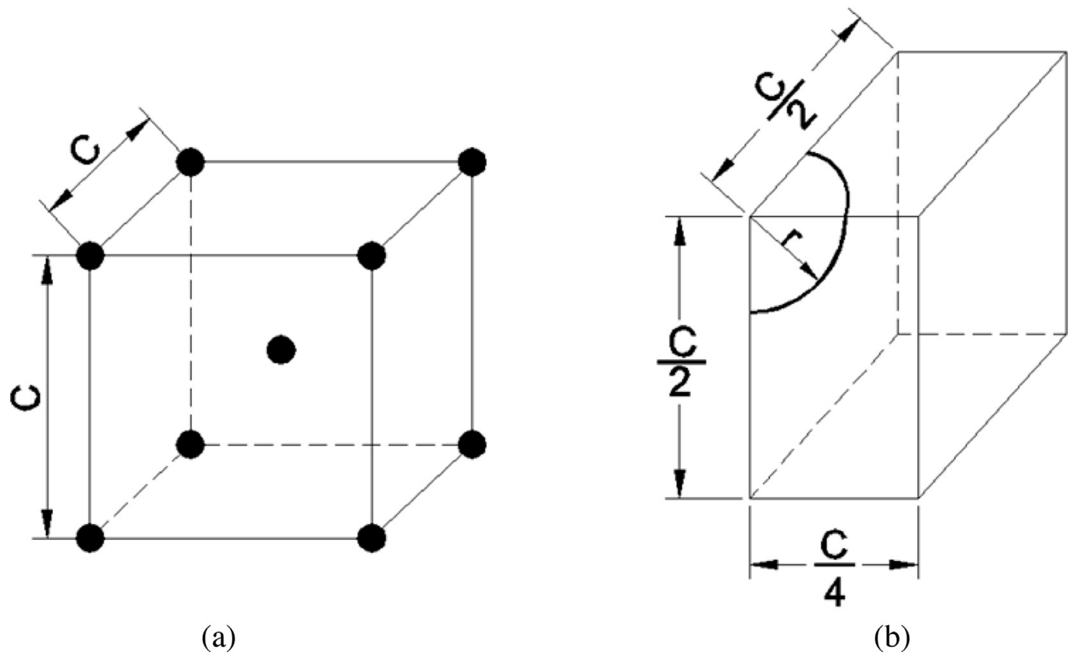

Fig. 1. BCC unit cell (a) and the actual model of one eighth unit cell (b) used in this study.

The failure of PREC is not clearly understand. Few studies have been performed to understand the reinforcement and failure mechanisms using single or double spherical beads in transparent elastomers (Gent and Park, 1984; Cho and Gent, 1988). Generally, the existence of two distinct failure phenomena, cavitation and debonding, has been demonstrated. In addition, these phenomena were strongly dependent on the diameter of the bead, which is in accordance with a Griffith-type relation when the bead is small. Although there have been many studies of polymeric material as the matrix, very limited works have been performed with rubber because of its many disadvantages, such as dilution effects, etc. (Lee and Ryu, 2010; Brown, 2002) On the other hand, it is necessary to understand the various failure and strengthening mechanisms of PREC for better elastomeric composites.

The range of particles, such as carbon black, silica, clay, etc., have been important reinforcing factors for elastomers since the 19th Century. Recently, silica has attracted considerable attention because it is an alternative non-black reinforcing filler that can be used widely to produce colored rubber products with excellent tear strength, high abrasion resistance and low rolling resistance (Leblance, 2002). In addition, with the increasing demand for the control of vibrations and noise, the importance of developing damping materials with silica is becoming vital in many industries (Tomozawa, 2001). Silica, however, is less compatible with some elastomers and small-sized silica is difficult to disperse. Therefore, an understanding of reinforcing and failure mechanisms is critical to maximize the potential of silica as a reinforcing filler and expand the applications of the elastomers.

This study examined the effects of the particle size and volume content on the tensile strength of PREC and developed a micromechanical model to better understand the effects of the particle volume, size and interfacial conditions on the tensile strength and failure phenomena. In addition, this simple model can provide a tool to better understand the failure mechanisms of PRPC and help develop improved PRECs.

2. Analytical modeling

In the body-center cubic(BCC) model, a PRC is represented by atoms located at all eight corners and a single atom at the cubic center, as shown in Fig. 1a. Two atoms in total represent the hard sphere of absolutely rigid particles embedded in an elastic rubber with a tensile modulus, E_m. By simplifying this model with symmetry, Fig. 1b shows the actual unit cell element consisting of one-eighth of an atom at the corner. When a tensile stress, σ_1, is applied to a unit volume of such a composite, an average composite tensile deformation, ε_1, is produced. Because the matrix is much softer than the particle, all the deformation will be concentrated locally in the matrix. In addition, all polymeric composites experience failure initiation due to debonding (β) between the matrix and particles that appeared mostly at the pole of the spherical particle in the direction of the applied tension (Fig. 2).

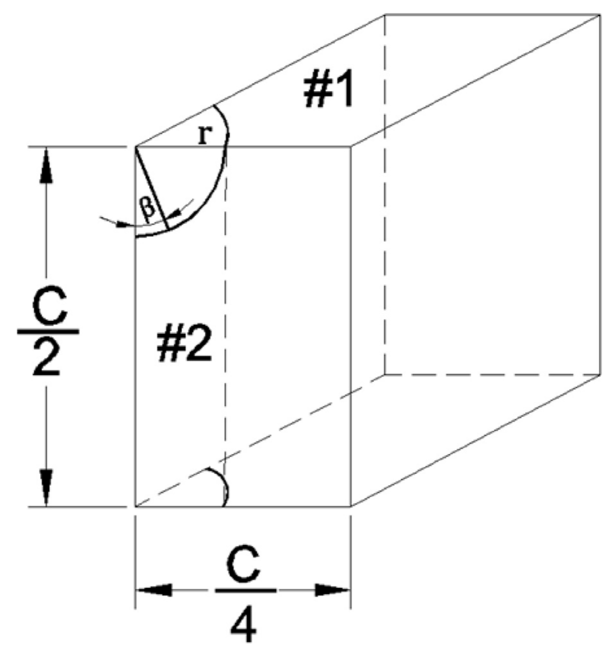

Fig. 2. Unit cell geometry with the debonded angle(β).