Diffusion induced stress in a cylindrical particle-binder system

Gaurav Singh[a] and Tanmay K. Bhandakkar[b*]

[a,b*]Department of Mechanical Engineering, Indian Institute of Technology Bombay, Mumbai, India

1. INTRODUCTION & OBJECTIVE

With the ever-growing focus on non-conventional energy sources and its storage mechanisms, Lithium (Li)-ion battery has emerged as one of the most promising option owing of its very high energy and power density[1]. In order to further improve its effectiveness, researchers are exploring the possibility of replacing graphite, the conventionally used anode material with high energy density materials like Silicon, Germanium, Tin, Aluminum [2]. A side effect of using these materials is the excessive volume expansion of electrode as compared to graphite during battery charging-discharging that cause high stresses in the electrode under constrained conditions. These stresses are referred to as diffusion induced stress (DIS) and are responsible for the subsequent failure and low cycle life of Li-ion battery. Amongst the many ways proposed to lessen the large DIS, one way is to use a relatively soft polymeric material termed as binder around the electrode particles which while maintaining the electromechanical integrity of the system offers reduced constraint to expansion and thus decreases DIS[3].

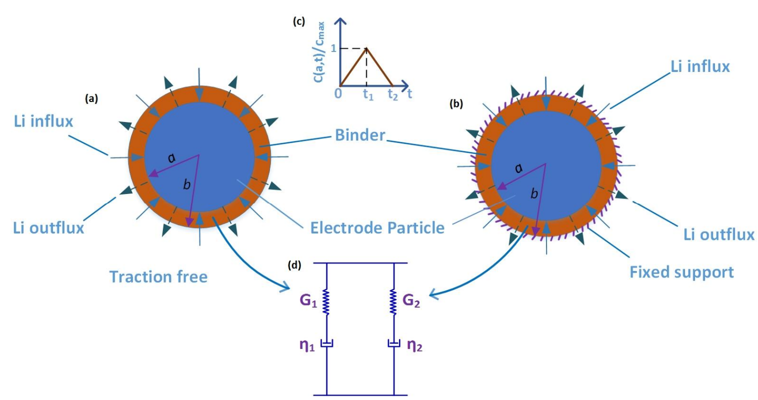

Fig.1 Schematic of an electrode particle binder system (PBS) comprising of a cylindrical electrode particle of radius *a* encapsulated by a hollow cylindrical binder of inner radius *a* and outer radius *b*. (a) Outer surface of the binder is traction free (TF condition), (b) Outer surface of the binder is constrained rigidly i.e. fixed constraint (FC condition), (c) Charging-discharging cycle for electrode in terms of time variation of concentration at the electrode surface. The linear nature of curve is just for illustration, (d) Arrangement of four elements comprising of two springs (Stiffness G_1, G_2) and two dampers (Viscosity η_1, η_2) which models the linear viscoelastic binder.

In literature, though there are many studies on calculation of DIS on isolated electrode particle, only a few studies include the electrode particle binder system (EBS)[4-7]. Recently closed form expressions were developed for DIS in spherical particle-binder system undergoing a charging-discharging cycle; to study the effect of binder on DIS[7]. The objective of current study is to extend the analysis to a cylindrical particle-binder system undergoing flux controlled charging-discharging cycle as shown in fig.1. During the charge-discharge process, electrode particle and binder are assumed to undergo infinitesimal plane strain deformation under quasi-static

* Further author information: (Send correspondence to Tanmay K. Bhandakkar)

[a] E-mail: singh_gaurav@iitb.ac.in, Telephone: 09167924077

[b*] E-mail: tbhanda2@iitb.ac.in, Telephone: (+91)-22-25767537, Address: Department of Mechanical Engineering, Indian Institute of Technology Bombay, Mumbai 400076, India

condition. The particle is assumed to be elastic-perfectly plastic material and the binder is modeled as a linear viscoelastic material. Using elastic-viscoelastic correspondence principle, closed form expressions of stresses in the particle as well as in the binder is developed as a function of radius and time. Polyvinylidene Difluoride (PVDF) a commonly binder material is adopted for the present work and is modeled as the combination of linear spring-dashpot system (see fig.1d).

2. RESULTS & HIGHLIGHTS OF IMPORTANT POINTS

The study calculates the limiting value of flux for initiation of plastic deformation on the surface of electrode. It is shown that the stress in binder is independent of the nature of the electrode deformation i.e. purely elastic or elastic-perfectly plastic. Similarly the stress in the binder remains unaffected whether effect of hydrostatic stress on concentration evolution in electrode is considered or ignored. Binder with low viscosity and stiffness are recommended for lower DIS. The study shows that the maximum stress occurs at the particle binder interface and is the likely location for crack initiation and propagation. It is shown that high mass ratio of binder to the electrode particle reduces DIS in the electrode–binder system but at the same time also reduces the energy and power density of the battery. Due to rate-dependent nature of deformation in binder, the present work concludes that rate of charging not only affects DIS through variation in concentration gradient but also influences the binder stiffness and in turn affects the DIS. The closed form solution for DIS in cylindrical electrode binder system can be used to benchmark numerical solutions. The small deformation assumption used in the present work provides an upper bound to the stresses experienced in electrode-binder system.

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