Quantitative Electrode Design Modeling of an Electroadhesive Lifting Device Based on the Localized Charge Distribution and Interfacial Polarization of Different Objects

Kisuk Choi,† Ye Chan Kim,‡ Hanna Sun,§ Sung-Hoon Kim,† Ji Wang Yoo,∥ In-Kyung Park,† Pyoung-Chan Lee,† Hyoung Jin Choi,†∥ Hyouk Ryool Choi,† Taesung Kim,∥ Jonghwan Suhr,∥ Young Kwan Lee,†∥ and Jae-Do Nam*†∥§

§School of Chemical Engineering, Department of Polymer Science and Engineering, ‡Department of Energy Science, Program of Interdisciplinary Material Science and Engineering, and Department of Mechanical Engineering, Sungkyunkwan University, Suwon 16419, Republic of Korea
∥Korea Automotive Technology Institute, Cheonan 31214, Republic of Korea
*Department of Polymer Science and Engineering, Inha University, Incheon 22212, Republic of Korea

ABSTRACT: Electroadhesive devices can lift materials of different shapes and various types using the electrostatic force developed at the interface between the device and the object. More specifically, the electrical potential generated by the device induces opposite charges on the object to give electrostatic Maxwell force. Although this technology has a great deal of potential, the key design factors based on the fundamental principles of interfacial polarization have yet to be clearly identified. In this study, we identify that the lifting force is quantitatively related to the total length of the boundary edges of the electrodes, where the induced charges are selectively concentrated. We subsequently propose a model equation that can predict the electrostatic lifting forces for different object materials as a function of the applied voltage, impedance, and electrode-boundary length. The model is based on the fact that the amount of induced charges should be concentrated where the equipotential field distance is minimal. We report that the impedance magnitude is correlated with the electroadhesive lifting forces by analyzing the impedance characteristics of objects made of different materials (e.g., paper, glass, or metal), as attached in situ to the electroadhesive device.

INTRODUCTION

As an alternative to the mechanical gripper, which usually requires strain or stress controlling units to avoid damage while picking up of fragile and/or soft objects,1–3 the electroadhesive picking tool is considered attractive because it could intrinsically avoid damage to objects, without using such stress/strain control units. This electroadhesive picking tool adopts an interfacial electrostatic force, which is developed only at the interface of the objects in the shearing mode.4–6 The electroadhesive device is capable of adhering to almost any shape of any type of object made from steel, glass, paper, wood, concrete, and so forth, so long as these materials could allow the induced charges to be formed at the device–object interface.7–10 It subsequently makes the electroadhesive device quite attractive as an ideal picking technology that can be used11–14 in such areas as the warehouse industry,15 semiconductor manufacturing,16 robots, and so forth.17 Despite its attractive features, it has been pointed out that the lifting force is often short of the utilization requirements; and more importantly, the key controlling factors of the lifting force for different object materials have yet to be clearly identified.18–20 This is likely due to the fact that the electroadhesion process contains structural and electrical complexity, where the electrical voltage is applied to the in-plane electrodes, but the electrical potential fields propagate in the perpendicular direction, and, as a result, generate the induced charges on the attached object.

The electroadhesive force being generated on the insulating substrate is mainly derived from electric fields and polarizations.21 More specifically, the interfacial polarization and orientational polarization is the main contribution of generating electroadhesive force.22,23 Note that the “interfacial polarization” specifically occurs in heterogenous systems and consists two or more phases. The space-charge build-up is observed at the macroscopic interfaces from the difference in permittivities and conductivities of constituents.24,25 The electroadhesive device uses the induced polarization of molecules or accumulation of charged particles (ions or charged moieties) formed at the interface between the object and the device. Subsequently, the induced polarization...