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Heating behavior of ferromagnetic Fe particle-embedded thermoplastic polyurethane adhesive film by induction heating

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ABSTRACT

The heating behavior of micrometer-sized Fe ferromagnetic particle-embedded thermoplastic polyurethane adhesive (TPU) under induction heating is examined in this study. The effects of particle size and content, TPU film thickness, and output power of the induction heater were considered. According to this study, heat generation, including the heating rate and maximum temperature, is proportional to the size and content of Fe particles. Greater film thickness and output power also led to higher heat generation. The permeability of the micrometer-sized Fe particles is the most important parameter for higher heat generation of TPU films with larger Fe particles.

Introduction

Adhesive bonding in industrial production requires high speed and efficiency. A rapid and high-efficiency curing process is necessary in serial production, especially in the footwear industry due to large number of bonding processes. The adhesive bonding process in footwear is very complex and includes bonding between the outer sole and mid sole, the mid sole and insole, etc. It involves solvent cleaning, drying, and manual mechanical surface treatment. Convection oven curing is the most widely used process in industries, where the surrounding air is heated and transfers heat to the adherent. However, it has many disadvantages, including longer curing time, lack of selective curing resulting in heat deformation of unbonded structures, and high consumption of energy. Therefore, advanced curing technologies are required to improve the previous curing technology.

Induction heating is a method of heating conductive objects by means of electromagnetic induction. This heating method is of interest for the materials and manufacturing industries, because it is fast, precise, and controllable. Though an induction heating system may be more expensive, it is usually preferable to other types of processing methods such as open flame heating or chemical processes. In most cases, it is also the most efficient and precise heating method in practice today [1].

Thermoplastic adhesive fusion and curing of coating materials using induction heating are very attractive techniques for adhesive joining and repair of composite structures and coating curing processes [2–8]. The induction-based melting of susceptor-embedded thermoplastic composite materials has recently been enhanced in welding applications [3,4]. The electrical properties of the reinforcement are mainly used for matrix melting in this case. Induction heating has several features, including high efficiency and economic benefits. Induction heating of susceptor-embedded adhesives can provide selective, noncontact, and localized heating. Inductive heating can occur in susceptor-embedded adhesives due to three mechanisms: (i) eddy currents can form in susceptor materials, creating dielectric losses in the adhesive materials [2,6,7], (ii) eddy currents can form in conductive susceptors placed in adhesive materials, causing Joule heat losses [8], and (iii) hysteresis can occur in susceptors-embedded in adhesives, causing ferromagnetic domain wall motion and domain realignment losses [8]. Therefore, ferromagnetic and metallic particles are potential candidates for susceptor materials that offer hysteresis heating-based Curie temperature control for polymer processing [9–11]. Ferromagnetic particles generate heat upon application of a magnetic field until they reach the Curie temperature, where

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the magnetic state changes from ferromagnetic to paramagnetic and heat is no longer generated.

The total powder core loss at low flux densities is the sum of three frequency-dependent losses: hysteresis loss, residual loss, and eddy current loss. The core loss is calculated using Legg's equation (1). When a varying magnetic field passes through the powder core, eddy currents are induced. Joule heat loss by eddy currents is called eddy current loss. Hysteresis loss is due to the irreversible behavior of the hysteresis curve and is equal to the enclosed area of the loop. The other core loss is called residual loss.

$$\frac{R_{ac}}{\mu L} = aB_{\max} f + c f + e f^2 \quad (1)$$

Here, R_{ac} is the core loss resistance (Ω), μ is the material permeability, L is the inductance (H), a is the hysteresis loss coefficient, $B_{\max}$ is the maximum flux density, c is the residual loss coefficient, f is the frequency (Hz), and e is the eddy current loss coefficient.

Nickel is an attractive susceptor material for composite adhesion by induction heating because it is available in a variety of sizes at relatively low costs. Suwanwatana et al. studied the hysteresis heating behavior of nickel particulate polysulfone films and the influence of particle size on hysteresis heating behavior [12]. According to the results, heat generation in the Ni/PSU film was inversely proportional to the size of the nickel powder and is strongly related to the hysteresis loop of nickel powder. Various types of induction heating using different shapes of susceptors such as carbon fibers, metal foils, and metal meshes have also been reported [13]. Bayerl et al. examined the effects of various ferromagnetic particles on the heating behavior of HDPE in terms of amount of contents. They used ferromagnetic materials containing cast iron, magnetite, and nickel and electrically conductive materials such as carbon black. They observed the highest heating rates in the ferromagnetic material obtained from cast iron powder and magnetite in that order and relatively low heating rates in nickel power. Carbon black showed an insufficient heating rate by induction heating [14].

Previous research has shown that Fe particles are a good candidate material as the susceptor for induction heating given their heating rate, low cost, and abundant availability in various sizes. In industrial applications, a rapid and high-efficiency curing process is very important for productivity. Therefore, optimum heating rate control in the adhesion process is necessary. In the application of Fe particles in adhesive curing by induction heating, however, the effects of size, content, adhesive film thickness, and output power on the heating behaviors of Fe particle-embedded adhesives have rarely been investigated.

The research objective of this work was to develop a thermoplastic polyurethane adhesive film by adding ferromagnetic Fe particles and then to examine the effects of the particle size, contents, adhesive film thickness, and output power on the heating behavior of the Fe particle-embedded thermoplastic polyurethane adhesive film. The results will be applied to the footwear adhesion process, and further tests, including adhesion, weathering and thermal stability tests, will be carried out and reported.

Experimental

Materials and preparation of a TPU adhesive film

Thermoplastic polyurethane (DS-5190TF, supplied by Dongsung Tech, South Korea) was used as the adhesive material, and methyl ether ketone (MEK, supplied by Aldrich, USA) was used as a solvent.

Fe particles with an average diameter of 8 and 43 μm were purchased from Alfa Aesar, and particles with an average diameter of 74 μm were purchased from Metal Player (South Korea). The Fe particle sizes used in this study were observed by SEM, as shown in Fig. 1.

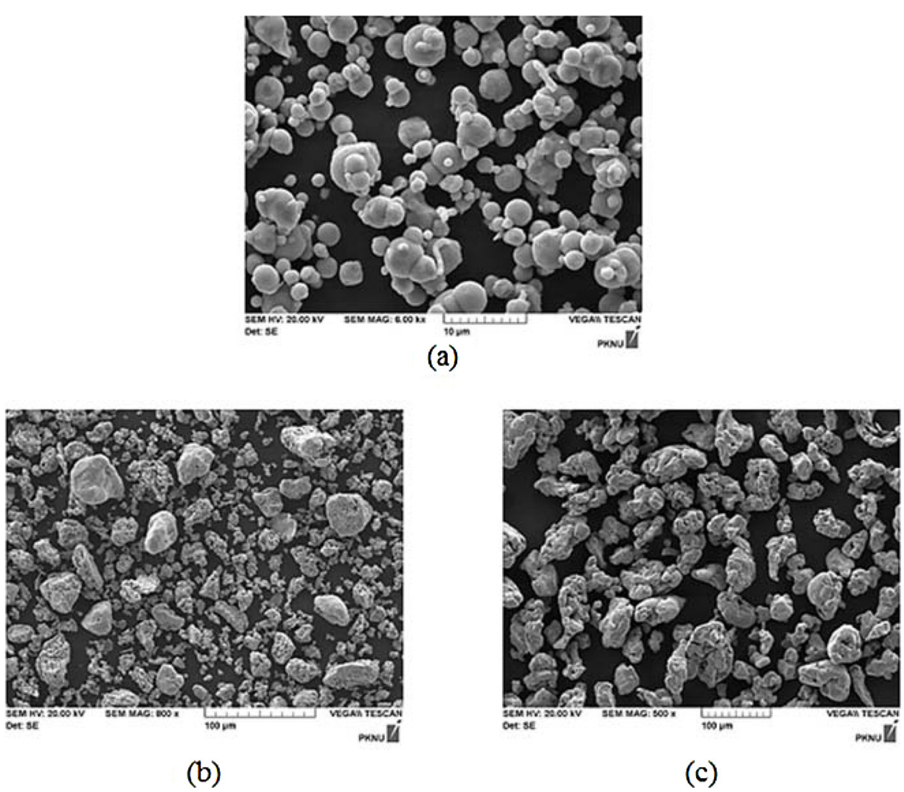

Fig. 1. SEM images of Fe particles: (a) 8 μm, (b) 43 μm, and (c) 74 μm.