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Effect of surface temperature on adhesion of nanoparticle-coated microparticles

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ABSTRACT

Toner microparticles are coated with silica nanoparticles for modulating their adhesiveness to optimize two competing requirements in the electrophotographic process: low adhesion for facilitating particle transport and high adhesion with deposited substrates prior to high temperature fusing. In addition to the adhesion effect of nanoparticle coating, nanoparticle-coated toner microparticles are subjected to various thermal fields during utilization. Understanding the effect of temperature on particle adhesion properties has the potential to improve energy efficiency, process predictability and print resolution. In current work, the effect of surface temperature on the adhesion bond between single nanoparticle-coated toner microparticles and a silicon substrate is investigated in a non-contact/non-invasive manner by monitoring the rocking dynamics of acoustically excited single microparticles on a silicon wafer surface. In the reported spectral experiments, at a range of substrate temperature levels from 15 to 30 °C, the work-of-adhesion values of the surface-particle bond are evaluated from the acquired rocking resonance frequencies of the single toner microparticles. Rayleigh Surface Acoustic Waves (SAW) are employed to generate highly controllable surface motion to excite the vibrational modes of deposited microparticles, through which the out-of-plane transient responses of their apexes are acquired using a laser vibrometer. In addition to surface temperature, the effect of coating nanoparticle spatial distribution on the adhesion properties of the microparticle is observed and explained by proposing possible contact configurations, depending upon how silica nanoparticles are accumulated in and around the particle-surface contact zone. Finally, it is observed and reported that the relative humidity (RH) can play a significant role in microparticles rocking motion dynamics and adhesion.

1. Introduction

In a wide spectrum of industrial processes and natural phenomena, both microparticle adhesion force prediction and its statistical variation are critically essential for process optimization. In recent years, precise control over the microparticle size and shape distributions has been achieved using production techniques for electrophotography (e.g. Emulsion Aggregation (EA) technology [1]) and additive manufacturing (e.g. plasma spheroidization). Therefore, understanding the effects of adhesion force distribution on the surface of an individual microparticle has become more relevant for developing processes to obtain narrower property distributions, leading to improved deposition performance. In electrophotographic printing/copying, electrostatic forces are utilized to move and transfer charged toner particles from a reservoir to a surface for the purpose of producing high-quality images, so accurate adhesion characterization is essential for process optimization. Various microparticle adhesion methods which primarily employ centrifugal, electric field detachment, aerodynamic (air gun), hydrodynamic, pendulum impact-separation, and ultrasonic vibrations techniques have been reported for microparticles [2]. Due mainly to limited accuracy and spatial resolution of adhesion methods, disagreements over the relative importance of electrostatic and non-electrostatic contributions to toner adhesion have been reported [3]. For instance, the results of Hays et al. [3,4] indicate that toner adhesion is dominated by electrostatic forces, while the analyses of Rimai et al. [5] appear to show that toner adhesion at micro-scale is mainly as a result of van der Waals forces. Some investigations such as those of Gady et al. [6] suggest that both van der Waals and electrostatic forces can play significant roles in microparticle adhesion. In addition to contributors of adhesion force, our recent experimental results [7,8] indicate that their spatial distribution over the surface of the individual particle must be understood for more precise prediction of production control parameters. However, the temperature dependency of adhesion in microparticles attracted rather limited

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attention, even though many processes expose microparticles to large temperature variations.

Numerous simulation-based computational studies have been conducted to predict the temperature effect on adhesion energy. The surface energy dependence on the surface temperature, for example, was computationally estimated for solid nickel [9] for the surface temperature range 27–1327 °C (300–1600 K) using molecular dynamics (MD) simulations and for copper using Monte Carlo simulations in the broad range of −273–927 °C (0 − 1200 K) [10]. Changes in the surface energies of amorphous carbon films were reported for the relatively narrow temperature range of 20–95 °C (293–368 K) employing a contact angle-based experimental method [11]. The effect of temperature on the surface energy of diamond-like carbon and tetrahedral amorphous carbon (ta-C) coatings considered as a protective layer for biological implants owing to their superior biocompatibility [12] were also investigated and reported [11].

The focus of current work is to understand and evaluate the surface temperature effects on nanoparticle coated toner microparticle adhesion. Progress in the area could lead to energy efficient optimized processes and increased process predictability as well as high-resolution images. In the reported study, based on a non-contact measurement approach, the surface energy dependence of the adhesion bond between a single nanoparticle-coated toner microparticle and a silicon substrate on the substrate surface temperature is quantified. Emulsion Aggregation (EA) nanoparticle-coated toner microparticles are utilized in the experiments for studying the effect of surface temperature on their adhesion properties. EA is a chemical process used to grow near-perfect spherical microparticles with narrow diameter distributions from submicron sized precursors. EA toner particles are often coated with nanoparticles in order to modulate their adhesiveness as bare particles have high adhesion energy compared to milled microparticles and surface area coated toner particles [13]. High surface energy of bare toner particles make the particle transport process in printing/copying machines a challenge, therefore understanding the properties of coated toner particles is important for process optimization. In reported experiments, the decrease in the surface energy of the substrate (silicon) with the increase in surface temperature is investigated by studying the work-of-adhesion of microparticles for a temperature range of 15–30 °C. The microparticle–substrate adhesion is evaluated using a non-contact/non-invasive approach based on ultrasonic excitation and interferometric motion sensing techniques similar to those reported in [14]. Experimental data demonstrating the effect of surface temperature on the work-of-adhesion of the microparticle–substrate interface is presented and discussed.

The non-contact Surface Acoustic Wave (SAW) based ultrasonic approach reported in this work can be applicable to various other applications dealing with microparticles and temperature variations, such as biological cells (e.g., platelets, red blood cells) [15] and the coatings of biological implants [12] as well as toner particle adhesion in copying/printing applications [14,16].

2. Experimental approach and materials

Experiments were designed and performed to evaluate the effect of surface temperature on the dynamic and adhesion behavior of single toner microparticles fully covered with silica nanoparticles. The toner microparticles are deposited on a silicon substrate affixed on top of a stack of Peltier thermoelectric coolers (Fig. 1). Deposited microparticles were acoustically base-excited by a Rayleigh Surface Acoustic Wave (SAW) field driven by a commercial ultrasonic transducer with a central frequency of 1.0 MHz (A103R, Panametrics, Waltham, Massachusetts, USA) affixed to an acoustic wedge for a range of substrate surface temperature levels (T_s) (Fig. 1). It was previously reported that the temperature of the substrate decreases the surface energy of the substrate

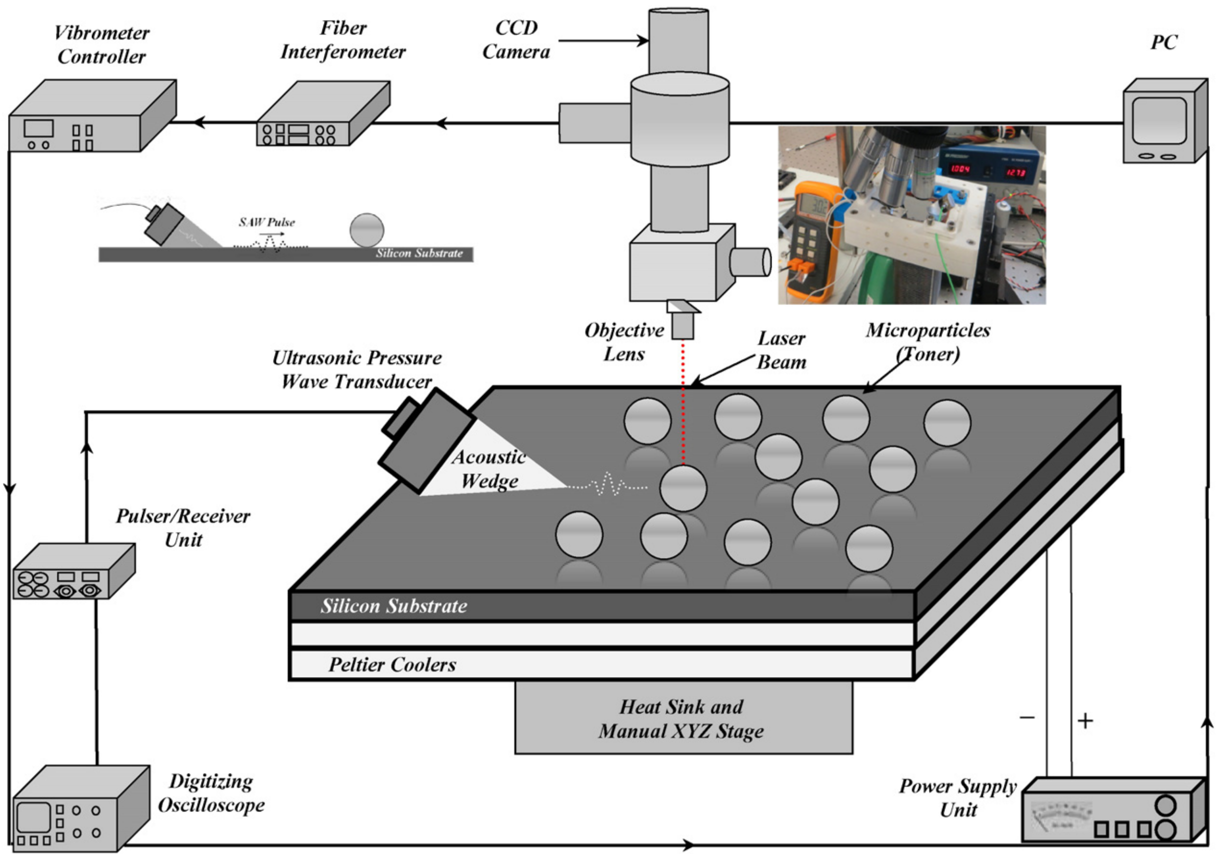

Fig. 1. Instrumentation connectivity diagram of the experimental set-up for SAW-induced microparticle rocking and rolling (not-to-scale), the schematic of the SAW wave pulse and the close up image of the experimental are shown in the inset.