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Ultrasonic washing of textiles

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ABSTRACT

We present the results of experimental investigation of ultrasonic washing of textiles. The results demonstrate that cavitation bubbles oscillating in acoustic fields are capable of removing soils from textiles. Since the washing performance is mitigated in a large washing bath when using an ultrasonic transducer, we propose a novel washing scheme by combining the ultrasonic vibration with a conventional washing method utilizing kinetic energy of textiles. It is shown that the hybrid washing scheme achieves a markedly enhanced performance up to 15% in comparison with the conventional washing machine. This work can contribute to developing a novel laundry machine with reduced washing time and waste water.

1. Introduction

Before the advent of washing machines in the late 19th century [1], the laundry was done by the use of hands or tools such as clubs and bats. The laundry is still done in this manner in some less industrialized regions. In the manual laundry, mechanical forces are exerted on the dirt adhering to textiles by scouring, twisting, or beating. Washing machines use electric power to replace human labor for producing the mechanical forces. In particular, the rotation of washing bath induces a liquid flow to generate mechanical actions such as deformation and scouring of textiles, thereby removing the dirt [2,3]. In addition to the chemical effect of detergent loosening the dirt from textile surfaces, mechanical actions by washing bath are principally responsible for the textile washing.

Recently, attempts have been made to use acoustic cavitation for washing textiles. Ultrasonic cleaning has been widely employed to remove submicron-sized contaminant particles adhering to solid substrates (e.g., photomasks and wafers) in semiconductor industry [4,5]. Ultrasonic waves traveling in a liquid result in cavitation and thus produce bubbles [6]. The bubbles exhibit rich dynamic behaviors such as translation, oscillation, growth, and collapse in response to the varying acoustic pressure [6]. Moholkar et al. examined the effect of acoustic cavitation on washing textiles which were placed at pressure nodes and antinodes in a standing-wave field [7]. Their experiment showed that the textiles were exclusively cleaned at the antinodes where acoustic cavitation is mainly generated, suggesting that acoustic cavitation is a main factor for textile washing. Juarez et al. showed that the ultrasonic system with the acoustic intensity higher than approximately 0.4 W/cm^2 had better washing results in comparison to conventional washing machines [8].

However, ultrasonic washing has some critical weaknesses in terms of cleaning range [8]. The dynamic motions of cavitation bubbles occur through the interaction with acoustic waves, which are unduly inactive at the far fields due to the attenuation and reflection. Thus, the effects of ultrasonic washing are limited to the near field of the transducer, which has presumably impeded the development of ultrasonic washing machines for practical uses.

We here investigate the cleaning effects of acoustic cavitation for textiles. We theoretically analyze the detachment forces induced by acoustic cavitation, which are proved to be comparable with the adhesion forces of particles on the textile. The analysis is supported by the high-speed visualization of the particle removal from the textile by cavitation bubbles. We then develop an ultrasonic washing system combined with a commercial washing machine. Our experimental results demonstrate that the hybrid scheme can achieve enhanced cleaning performance.

2. Removal forces on a particle by an oscillating bubble

We estimate the adhesive force of carbon black particles on a standard specimen textile (EMPA 106, Testfabrics) made of cotton fabric. Fig. 1 presents SEM (Scanning Electron Microscopy) images indicating that nano-sized carbon black particles form aggregations sized on the order of 1 μm. We may thus assume an aggregation of carbon black as a single particle with a radius of approximately 1 μm. The strength of adhesion of a micron-sized

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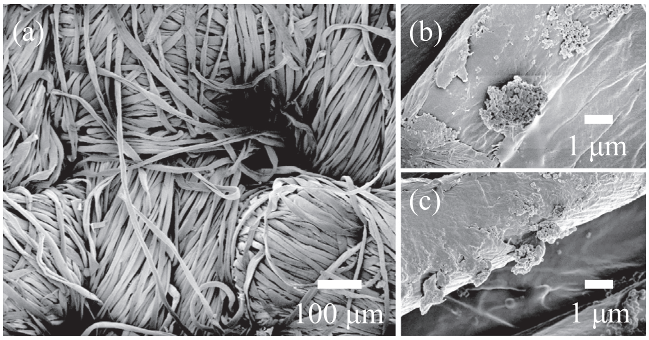

Fig. 1. SEM images of carbon black particles adhering to the textile. (a) Texture of the contaminated specimen textile. (b and c) Carbon black aggregations on the textile.

particle to a flat substrate is generally given by the van der Waals force expressed as $F_v = AR/(6Z_0^2)$, where A is the Hamaker constant, R the aggregation radius, and Z_0 the distance between the aggregation and the surface [9,10]. When the particles deform and adhere to a substrate, the total adhesion force F_{ag} increases to $F_{ag} = F_v(1 + a^2/RZ_0)$, where a is the contact radius [9]. Neither the deformed shapes of carbon black particles nor the surface geometry is easily determined on the basis of the SEM observations. However, when a particle adheres to a solid surface, the contact radius is usually given by the Johnson–Kendall–Roberts (JKR) theory, $a \sim [6\pi W R^2(1/E_1 + 1/E_2)]^{1/3}$, where W is the surface free energy of solid surface, and E_1 and E_2 are the elastic moduli of the particle and solid substrate, respectively [11]. The surface free energy of cotton fabric is of the order of 2×10^{-2} J/m^2 [11], and the elastic moduli of cotton fabric and carbon black are 30 [12] and 27 GPa [13], respectively. Therefore, we obtain the contact radius of approximately 30 nm. In addition, we assume that $Z_0 \sim 1.6$ nm and $A \sim 3.3 \times 10^{-20}$ J, which correspond to a carbon black particle on cellophane immersed in water [14]. Consequently, our analysis yields a rough estimation of the adhesion torque $\tau_{ag} \sim aF_{ag}$ of the order of 10^{-16} N m.

The dynamic motion of an acoustic bubble is responsible for the particle removal [9]. Recently, our group characterized the motions of cavitation bubbles in ultrasonic field and classified into four modes: volume oscillation, shape oscillation, splitting, and chaotic oscillation [15]. Depending on the radius of a bubble and acoustic pressure, a specific oscillation mode is predominant. The pressure field around an oscillating bubble is the most powerful in the chaotic oscillation mode, and followed by those in splitting, shape oscillation, and volume oscillation modes.

The chaotic oscillation of an ultrasonic bubble occurs at a relatively high acoustic pressure if the radius of the bubble is comparable to that of a resonant bubble, which is given by Minnaert's formula $R_b = (3kP_0/\rho)^{1/2}/\omega$, where k is the adiabatic exponent, P_0 the ambient pressure, ρ the liquid density, and ω the angular frequency [16]. Because the dominant contents of bubbles are oxygen and nitrogen, the adiabatic exponent k is approximately 1.4 [9]. In our ultrasonic system with an acoustic frequency of 20 kHz, R_b is approximately 100 μm. It has been experimentally observed that a chaotically oscillating bubble induces the localized liquid flow with a speed v of ~10 m/s, which generates a dynamic pressure $\rho v^2 \sim 10^2$ kPa [15], thereby resulting in the removal torque $\rho v^2 a^3 \sim 10^{-13}$ N m. A chaotically oscillating bubble entails a liquid jet with a speed of ~10^2 m/s, which induces a water hammer pressure $\rho cv \sim 10^2$ MPa, and shock waves with a pressure on the order of 10^2 GPa [17]. Therefore, the removal torque by chaotic oscillation greatly exceeds the adhesion torque.

We examine that the aggregated carbon black particles can be removed by the volume oscillation of the bubble, the weakest mode. The volume oscillation is observed when the acoustic pressure is relatively low or when the bubble radius is significantly different from the resonance radius. An radially oscillating bubble with an angular frequency ω and radius R_b produces the radial velocity field given by $v \sim \omega R_b(R_b/r)^2$, where r is the radial distance from the center of bubble. The dynamic pressure $P \sim \rho v^2$ decreases with the distance from the bubble. Therefore, the pressure gradient is scaled as $|\partial P/\partial r| \sim \rho\omega^2 R_b(R_b/r)^5$ near a resonant bubble, and this pressure gradient exerts a thrust of the order of $R^3|\partial P/\partial r|$ on a particle sitting near the bubble. Accordingly, the detachment torque due to the dynamic pressure can be expressed as $\tau_d \sim (8\pi/3)\rho\omega^2 R^4 R_b{}^6/r^5$, so that the detachment torque τ_d is on the order of 10^{-16} N m near the bubble interface where $r \sim R_b$, which is comparable to the detachment torque.

3. Visualization of particle removal

We visualize the effects of acoustic cavitation on particle removal. We constructed the experimental apparatus consisting of a transparent bath filled with water, a flow-horn type transducer (UP400S, Hielscher), an upright microscope (Olympus BX-51M) with a water immersion objective lens (Olympus LUMPLEL 10XW), and a high-speed camera (Photron SA1.1), as shown in Fig. 2. We visualized the cleaning process at a rate of 10,000 frames per second. The transducer with a diameter of 2.2 cm produces ultrasonic waves with a frequency of 20 kHz and an intensity of 40 W/cm^2. To visualize the process of contaminant removal, we used the microparticles (IDC Latex particle, Life technology) with 4 μm in diameter because the nano or submicron sized carbon black particles cannot be clearly shown with the optical lens. The microparticles were attached on a textile by placing a drop of the ethanol solution of microparticles. We waited 30 min to regulate the adhesion force before immersing the textile in the bath.

Fig. 3 shows the sequential images of the microparticle removal by an acoustic bubble. The microparticles adhering to the textile are trapped between the fibers, and detached by a chaotic bubble. This is the first visualization result, to the authors' knowledge of the particle removal from textiles due to an acoustic bubble.

4. Washing performance depending on distinct washing schemes

We proceed by analysis of the dependence of the performance of the ultrasonic washing on the acoustic intensity and the volume of washing medium. We placed the same transducer shown in Fig. 2 in a small beaker filled with the detergent (AHAM HLW-1 Formula III) solution with a mass concentration of 3000 ppm. The

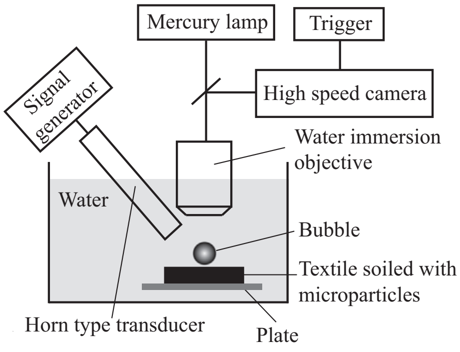

Fig. 2. Schematic illustration of the visualization apparatus.

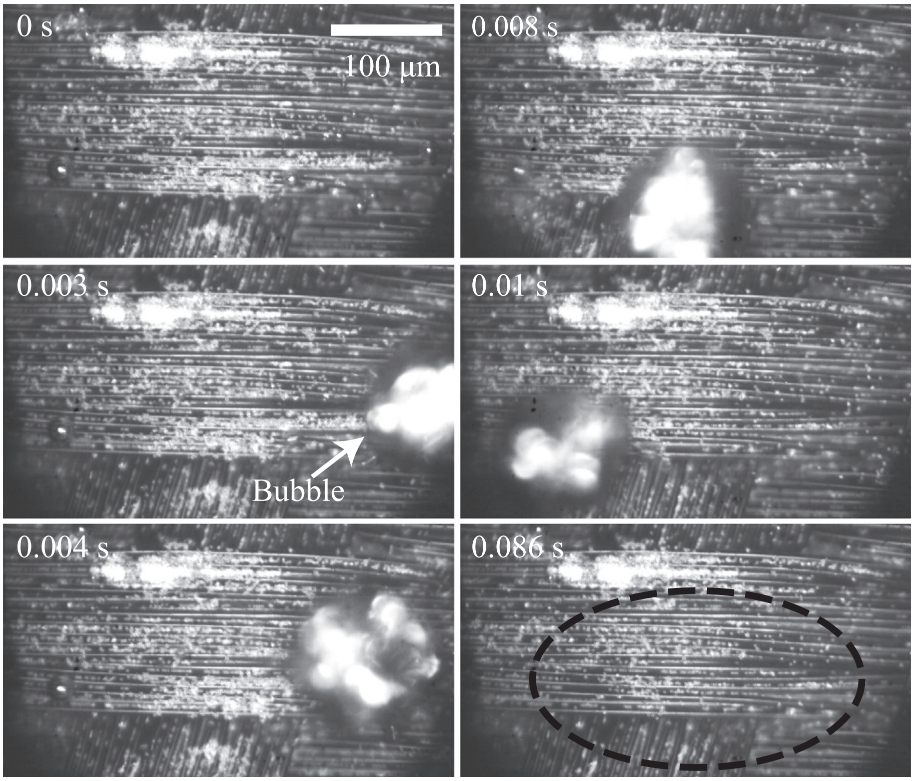

Fig. 3. High-speed images of the particle removal by an acoustic bubble. The dashed circle indicates the cleaned region. The bubble is blurred because the focus of the objective lens was given to the particles. See also Supplemental data available online.

detergent is composed of various chemicals including linear sodium alkyl benzene sulfonate, ethoxylated fatty alcohol C12-18, sodium soap, and anti-foam DC2-4248S. We tested the washing results of the textile soiled with carbon black particles after washing for 10 min. A needle hydrophone (Precision Acoustics HPM1/1) is used to measure acoustic intensity.

To quantify the washing results, we used a graphic software (Adobe Photoshop CS6). We recorded the average gray scale of the pictures of the whole surface of the washed specimen. The gray scale ranging between 1 and 255 quantifies the brightness of a pixel of images, so that black and white pixels have the value of 1 and 255, respectively. Since carbon black particles darken the surface of the specimen, the higher gray scale indicates the better washing results. We define the washing efficiency as $\eta = (G_{\text{washed}} - G_{\text{soiled}})/(G_{\text{unsoiled}} - G_{\text{soiled}}) \times 100\%$, where G_{soiled} and G_{washed} are the gray scale of specimens before and after washing, respectively, and G_{unsoiled} is the gray scale of the specimen that has not been soiled with carbon black particles. Our measurements indicated that G_{soiled} and G_{unsoiled} were 104 and 252.

Fig. 4 presents the efficiency of the ultrasonic washing. The results indicate that the washing efficiency of the textiles increases with acoustic intensity (Fig. 4a). When the textile is washed in a volume of 0.3 L of water, acoustic intensity higher than approximately 20 W/cm^2 exhibits the better washing performance than the conventional washing machine (DWD-M300WA, Dongbu Daewoo Electronics). However, the washing efficiency significantly decreases with the volume of water, as shown in Fig. 4b. The strong ultrasonic waves are effectively present only in a region near the transducer due to the attenuation of acoustic waves [8], and acoustic bubbles thus become unduly inactive in far field.

We thus propose a novel hybrid scheme by combining the ultrasonic washing with the conventional washing method to enhance washing performance in a large volume of washing medium. The washing performance of the hybrid system is compared with those of the simple ultrasonic system and the conventional washing machine. Fig. 5a shows the schematic of the washing machine which is combined with the transducer. The washing machine has a drum bath with a diameter of 40 cm. A hole

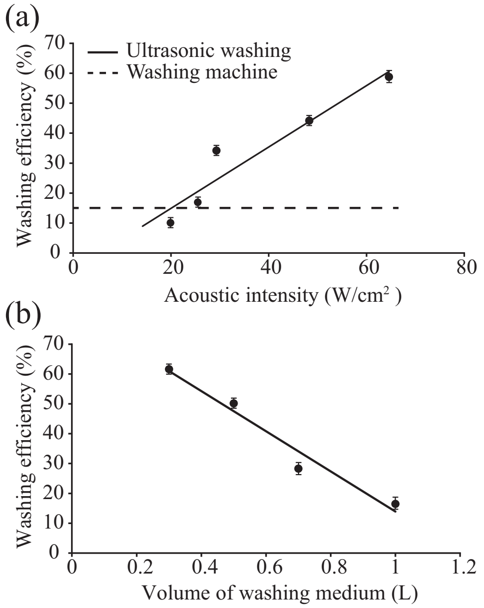

Fig. 4. The washing efficiency of the simple ultrasonic system. The efficiency decreases with increasing (a) acoustic intensity and (b) volume of water. The volume of water and the acoustic intensity are fixed as 0.3 L in (a) and 65 W/cm^2 in (b), respectively. The bars indicate the average efficiencies from three experimental tests, and the error bars denote the max and min.

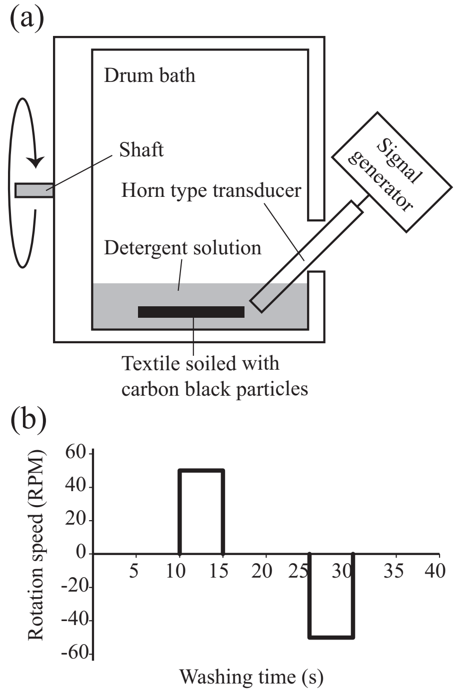

Fig. 5. (a) Schematic illustration of the washing machine combined with the ultrasonic system. (b) Operation cycle of the washing machine.

of 3 cm in diameter was drilled on the door to insert the transducer into the washing medium. The acoustic power of an intensity of 65 W/cm^2 was applied. The drum bath was filled with 1.5 L detergent solution, and three pieces of specimen were washed. The washing machine has a specific washing cycle programmed by the manufacturer, as shown in Fig. 5b. The drum bath rotates at 50 RPM for 5 s and stops for 10 s, and then rotates again reversely. This washing cycle was repeated for 10 min.

For the test of the performance of the conventional washing machine alone, the ultrasonic transducer was turned off. In the test of the simple ultrasonic system, the washing bath was off and stationary, but the transducer was activated during every time intervals of 10 s following the interruption of 5 s, such that total sonication time was 6.7 min out of the total washing time of 10 min. When we tested the hybrid scheme, the transducer and the washing bath were in action in such a way that the sonication was applied while the washing bath was stationary.

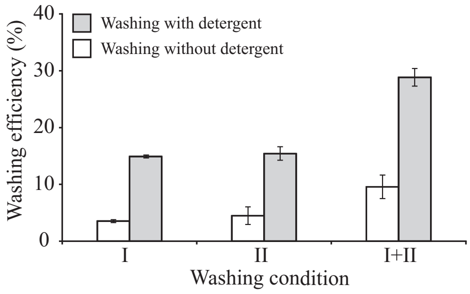

Fig. 6. The washing results of each washing conditions. I and II denote the washing machine and the ultrasonic system, respectively. The volume of water and the acoustic intensity are 1.5 L and 65 W/cm^2, respectively. The gray and white bars correspond to washing with detergent and washing without detergent, respectively. The bars indicate the average efficiencies from three experimental tests, and the error bars denote the max and min.

The washing performances of distinct washing schemes are presented in Fig. 6. The washing efficiency of the conventional machine is only 15% because the mechanical forces created by the drum rotation are insufficient to completely break the van der Waals interaction between the textile and the carbon black particles [3]. The washing efficiency of the simple ultrasonic washing is also approximately 15% because the simple ultrasonic washing is ineffective in a large volume of water despite the outstanding washing performance in a small washing bath. However, the hybrid scheme shows the washing efficiency of 30%, which significantly exceeds the washing results of both the conventional washing machine and the simple ultrasonic washing. The results suggest that during the wasted time interval when the drum rotation stops, ultrasonic power is effectively applied to the washing bath, yielding the synergy effects that the performance of the conventional washing machine is remarkably improved by the support of ultrasonic system. Note that the washing efficiency of hybrid scheme is only 10% for washing without detergent. It suggests that the detergent loosens the adhesive force of particles so that the ultrasonic bubbles can more easily remove the particles.

One may note that a simple ultrasonic system yields non-uniform washing because the straight propagation of ultrasonic waves causes the inhomogeneous ultrasonic field in a washing volume [18]. Although the hybrid scheme provides more uniform washing than the simple ultrasonic washing due to the uniform washing effects of the conventional washing machine, this problem definitely has to be captured for the practical development of the hybrid scheme. We thus expect that multiple ultrasonic transducers can achieve a homogeneous distribution of acoustic waves in a washing bath, thus yielding uniform washing results over the entire surface of textile.

5. Conclusions

We have estimated the adhesion torque of a carbon black particle and the removal torque by an acoustically oscillating bubble. Our analysis suggests that carbon black particles adhering to a textile surface by the van der Waals force can be removed by either the interfacial thrusts or the dynamic pressure gradient of acoustic bubbles. Such theoretical prediction has been verified by the high-speed visualization of the removal of microparticles by an acoustic bubble. We have experimentally investigated the washing performance of ultrasonic system combined with a conventional washing machine. The washing efficiency decreases in the simple ultrasonic system with the increasing volume of washing liquid, and the conventional washing machine shows impoverished washing performance of carbon black particles. However, the combination of both the washing systems is superior to the individual schemes, allowing us to start thinking about optimal designs of transducers and operating conditions for practical uses.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ultsonch.2015.07.018.

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