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Effect of Temperature and Frequency on Removal of Nano-Dimensional Contaminants

Vetrimurugan[1], J. Michael Goodson[2], Terry Lim[3]

Cleaning Development Manager, Crest Ultrasonics, Penang, Malaysia[1]

CEO, Crest Ultrasonics Corporation, USA[2]

Executive Vice President (Asia) of Crest Group Inc, Malaysia[3]

Abstract: This study investigates the effect of temperature on removal of sub-micron particles from metal surfaces for various frequencies. The frequency used for this study was 25 kHz, 40 kHz, 58 kHz, 58/132 kHz, 132 kHz, 360 kHz, 470 kHz and 1 MHz. The temperature studied ranging from 30 ^{o}C - 70 ^{o}C. The parts are washed with various frequencies and temperatures and then the parts are subjected to Liquid Particle Counter (LPC) analysis. The size of the particles reported for this study was >0.2 um counts. The result shows that the particle count decreases with increase of temperature hence higher cleaning efficiency until 50 -60 ^{o}C and then the particle count start increases. The removal efficiency for various frequencies increases with increase of temperature until 50 -60 ^{o}C and then it start decreases. The effect of temperature on cavitation intensity for various frequencies (measured by ppb probe) was also carried out. The aluminium foil test was also carried out to see the effect of temperature for various frequencies. The result shows that the cavitation intensity decreases with increase of frequency and temperature. The aluminium foil study shows that the erosion rate is high for 30 ^{o}C compared to 70 ^{o}C. The erosion rate decreases with increase of temperature and also found more uniform dents on the aluminium foil for higher temperature. The result also shows that the erosion rate is high for 25 kHz compared to other frequencies tested. This is due the fact that the energy released during bubble implosion is significantly more for low frequencies compared to higher frequencies.

Keywords: Ultrasonic, Megasonic, Liquid Particle Count, Removal Efficiency, Cavitation Intensity, Erosion rate

I. INTRODUCTION

Cleanliness requirements for precision cleaning industries such as hard disk drive, medical, aerospace and other associated industries are getting more and more stringent [1-3]. In order to achieve higher cleanliness optimization of ultrasonic cleaning process is so important. There are several parameters affects the performance of ultrasonic cleaning process which includes frequency, sonication power, basket orientation, basket material, temperature, re-circulation rate and so on. So, for every material, it is necessary to find the optimum parameters to achieve higher cleanliness. Among all the parameters, temperature is the most important single parameter to be considered in maximizing cleaning performance. This is because so many liquid properties affecting cavitation intensity are related to temperature. The changes in temperature result in changes in viscosity, the solubility of gas in the liquid, the diffusion rate of dissolved gasses in the liquid, and vapor pressure, all of which affect cavitation intensity [4-5].

A moderate increase in the temperature of a liquid brings it closer to its vapor pressure, meaning that vaporous cavitation is more easily achieved. Vaporous cavitation, in which the cavitation bubbles are filled with the vapor of the cavitating liquid, is the most effective form of cavitation. As the boiling temperature is approached, however, the cavitation intensity is reduced as the liquid starts to boil at the cavitation sites [6-8]. Traditional ultrasonic theory suggests that the best temperature for use in an ultrasonic cleaning system is typically 65% of the boiling point of the solution [9]. Although this formula has been used as a general guideline to determine optimum temperatures for decades, in reality it rarely plays a role in determining optimum temperatures for any given application. Temperatures are usually related more to the effectiveness of the cleaning agent in use rather than the effectiveness of the ultrasonic cleaning system. Each cleaning fluid may have an optimum temperature at which it performs best.

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In this paper, the effect of temperature and frequency on particle removal was studied. The cavitation intensity and aluminium foil test was also carried out for various temperatures and frequencies.

II. EXPERIMENTS

The experiments are conducted using Crest standard tanks and Crest Console systems with various frequencies. All experiments were performed in a Class 100 Cleanroom of the Advanced Ceramics Lab, Malaysia. The cavitation intensity for various frequencies was measured by using ppb ™ cavitation meter. The frequency used for this study was 25 kHz, 40 kHz, 58 kHz, 68 kHz, 132 kHz, 58/132 kHz (Patented Technology), 360 kHz (Megasonic Sweep Technology), 470 kHz (Megasonic Sweep Technology) and 1 MHz (Megasonic Sweep Technology). The ranges of temperature studied for each frequency was 30 - 75 ^{o}C. The parts used for this study was E-Coated DSP. This is one of the hard disk drive components. The parts were washed with different frequencies, temperatures and then subjected to LPC extraction to find the residual particles in the parts. The component used for this study was come from the same batch of material so that the initial cleanliness was approximately the same. It is also important to note that these parts had been pre-cleaned at their respective vendors. For each frequency the experiments were repeated three times and the average of this value was taken to plot the temperature vs particle counts.

The frequency used for final extraction was 132 kHz with 60 watts/gallon. The ultrasonic extraction method utilizes ultrasonic energy to extract particles from a part and the particle concentration in the extraction solution was measured using liquid particle counter (LPC). The particle counter used for this study was particle measuring system (PMS^{TM}) and LiQuilaz SO2. This counter can measure the particle sizes from 0.2 um to 2 um. The size of the particles reported for this study was >0.2 um.

Aluminium foil test was also carried out to find the effect of temperature and frequencies on removal of material. In this study, a strip of thin aluminium foil with 15 x 22 cm was suspended in the water and subjects to sonic for 5 min. The material loss due to various frequencies and temperature was measured.

The effectiveness of various temperatures at final rinse in removing submicron and nano-dimensional particles from disk drive component E-coated DSP was studied. After washing and rinsing with various temperatures, the parts were subjected to 132 kHz extraction and the particles in the extracted solution were measured using liquid particle counter. The experimental flow used for this study was as shown below.

Flow 1: Washing with 58 kHz, 1% CC 2000x, 50 ^{o}C → DI rinsing with 132 kHz, 30 ^{o}C → DI rinsing with 360 kHz, 30 ^{o}C → LPC extraction

Flow 2: Washing with 58 kHz, 1% CC 2000x, 50 ^{o}C → DI rinsing with 132 kHz, 50 ^{o}C → DI rinsing with 360 kHz, 50 ^{o}C → LPC extraction

Flow 3: Washing with 58 kHz, 1% CC 2000x, 50 ^{o}C → DI rinsing with 132 kHz, 70 ^{o}C → DI rinsing with 360 kHz, 70 ^{o}C → LPC extraction

The surfactant used for this study was 1% CC 2000x. The cleaning efficiency is quantified and presented in terms of its dependence on acoustic frequency for particle size >0.2 um.

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III. RESULTS AND DISCUSSION

1. Effect of temperature on cavitation intensity

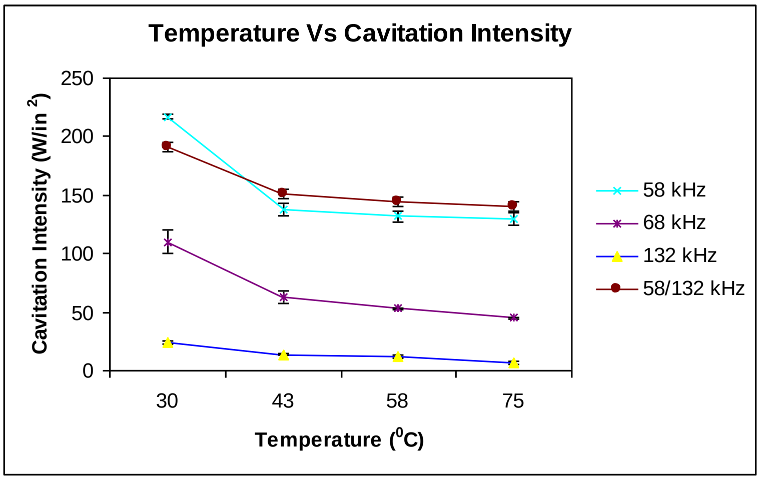

Fig.1 Effect of temperature on cavitation intensity for various ultrasonic frequencies

The effect of temperature on cavitation intensity for various frequencies is shown in Fig. 1. From Fig.1, it can be observed that the cavitation intensity decreases with increase of temperature for various frequencies. The cavitation intensity also decreases with increase of frequency. The cavitation intensity is inversely related to ultrasonic frequency. As the ultrasonic frequency increases, the cavitation intensity decreases because of the smaller size of the cavitation bubbles and their resultant less violent implosion. Increasing temperature can causes a reduction in the intensity of ultrasound required for the formation of cavitation bubbles. This is probably due to reduction in surface tension and/or viscosity of the liquid, either of which would lead to a reduction in the cohesive forces within the fluid and the energy required to tear it apart. However, near a liquid's boiling point, the high temperature causes a significant increase of vapor pressure. The presence of liquid vapor within the bubble leads to a cushioning of the implosion during the compression cycle. So, the cavitation implosion becomes less intense at higher temperature.

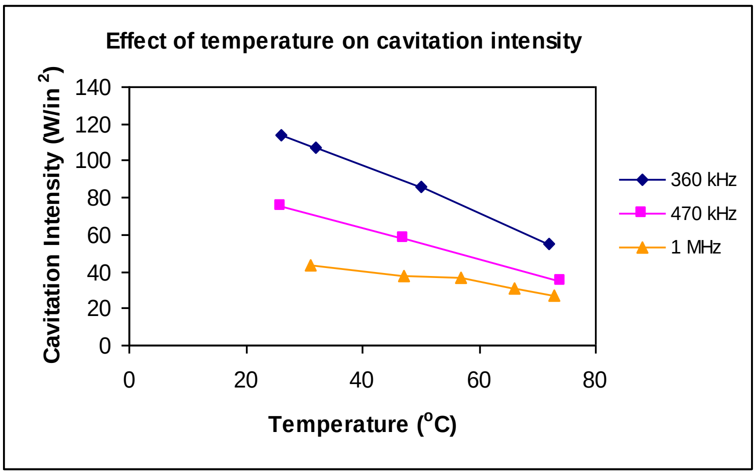

Fig.2 Effect of temperature on cavitation intensity for various megasonic frequencies

The effect of temperature on cavitation intensity for various megasonic frequencies is shown in Fig. 2. From Fig. 2, it can be observed that the cavitation intensity decreases almost linearly with increase of temperature.

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30 °C 50 °C 70 °C

Fig.3 Visualisation of cavitation pattern on aluminium foil for 25 kHz

The cavitation pattern obtained for various temperatures is shown in Fig.3. From Fig.3, it can be observed that the increase in fluid temperature will improve the distribution of ultrasonic cleaning action in the tank. As the temperature increases around 50 °C, the scrubbing action of ultrasonic is more evenly distributed and less powerful than at lower temperature. As the temperature increases, sonic takes longer time to make holes in the aluminum foil. However, the foil appears to be more evenly attacked by the ultrasonic and also large holes in the foil are replaced by smaller more evenly distributed holes.

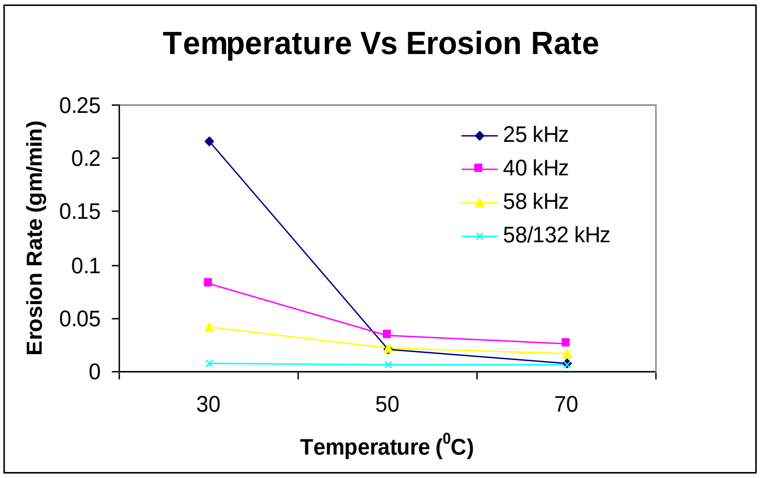

Fig. 4 Effect of temperature on erosion rate

The effect of temperature on erosion rate obtained for various frequencies is shown in Fig.4. The result shows that the erosion rate decreases with increase of temperature and frequency. The erosion rate is significantly low for 58/132 kHz (Crest patented technology) compared to other frequencies tested.

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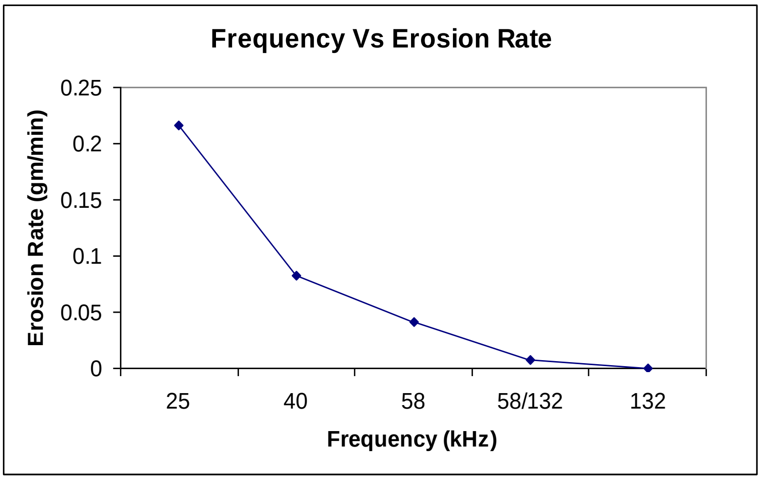

Fig.5 Effect of frequency on erosion rate

Fig.5 shows the effect of frequency on erosion rate. The erosion rate decreases with increase of frequency. As the frequency increases the number of cavitation bubbles increases but the size of the cavitation bubbles decreases [9]. Hence, higher cavitation intensity (low frequency) makes bubble implosions more violent as compared to lower cavitation intensity (high frequency).

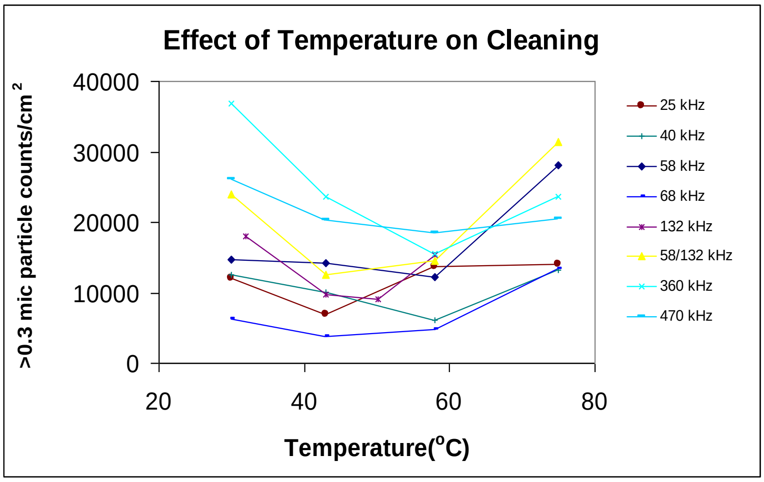

Fig.6 Effect of temperature on cleaning for various frequencies

The parts are cleaned with different frequencies and various temperatures and then it was subjected to 132 kHz LPC extraction. The particle count obtained for various frequencies with different temperature is shown in Fig. 6. From Fig. 6, it can be observed that the particle count decreases with increase of temperature until 60 ^{o}C (Maximum cleaning efficiency) and then it starts increases (cleaning efficiency drops). This is due to the fact that the temperature around 50 – 60 ^{o}C the adhesion force mainly due to Van der Waals force between the particles and the substrate weakens and therefore the particles attached to the surface can easily be removed. Once the temperature reaches 60 ^{o}C the particle count starts increases (drops in cleaning efficiency). This is due to the fact that the high temperature causes a significant increase of vapor pressure. So, whilst high temperature favors the nucleation of cavities and the presence of liquid vapor within the bubble leads to a cushioning of the implosion during the compression cycle. Hence stable cavitation is favored and the impact of ultrasound is reduced, as the shock wave released on cavity implosion becomes less intense. So, the particle removal efficiency is also reduced for temperature above 60 ^{o}C.

Increase in temperature makes it easier to go below the point of vaporization so the cavitation initiate with less energy. The number of cavitation events will increase as the temperature is increased but the energy being stored in the cavitation bubble will decrease. As the temperature increases the cavitation intensity steadily diminishes and cease or becomes ineffective for most cleaning applications at the boiling point of the liquid. So, the balancing of temperature and cavitation is important to achieve higher cleaning efficiency.

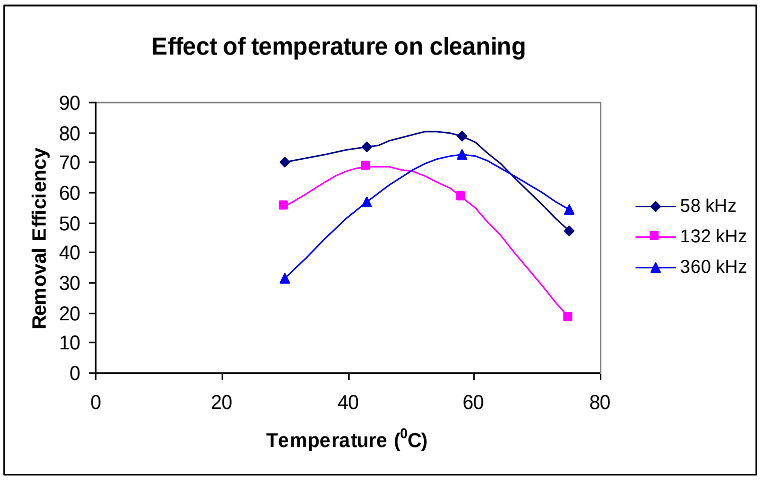

Fig.7 Effect of temperature on cleaning efficiency

The cleaning efficiency obtained for various frequencies is shown in Fig.7.

The percent removal efficiency, η (%), can be calculated as follows;

$$\eta(\%) = \left[\frac{N_{cb} - N_{ca}}{N_{cb}}\right] \times 100 \qquad (1)$$

Where, N_{cb} is the number of particles in the extracted solution before cleaning and N_{ca} is the number of particles in the extracted solution after cleaning. For any particular operating condition, three experiments were run, three removal efficiency values were measured, and their average was calculated. From Fig.7, it can be observed that the particle removal efficiency increases with increase of temperature until 60 ^{o}C and then it start decreases with increase of temperature. The particle removal efficiency is maximum at 50 – 60 ^{o}C. The variation of cleaning efficiency for different frequencies is higher at 30 ^{o}C and the variation is getting lower when the temperature reaches 50 ^{o}C. The particle removal efficiency is high for 58 kHz compared to all other frequencies tested.

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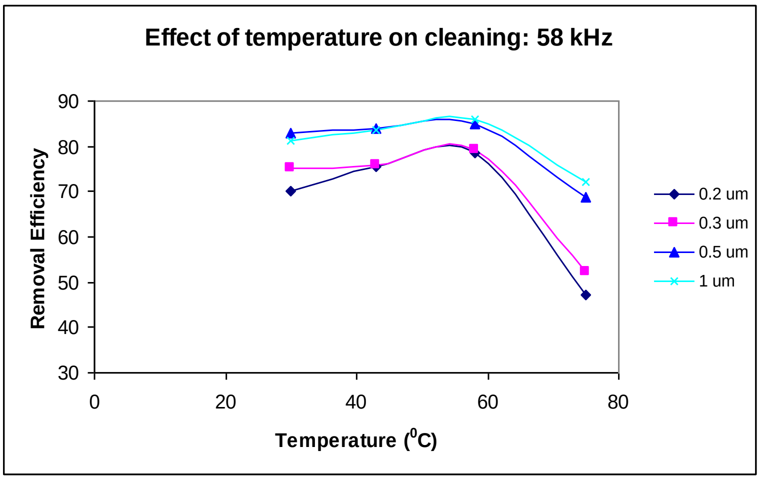

Fig.8 Effect of temperature on particle removal efficiency for 58 kHz

Fig. 8-9 shows the effect of temperature on removal efficiency for various frequencies and particle sizes. The removal efficiency is high for 1 um particles compared to 0.2 um particles. The removal efficiency drops more significantly after 60 ^oC for 0.2, 0.3 um particle counts compared to 0.5 and 1 um particle counts.

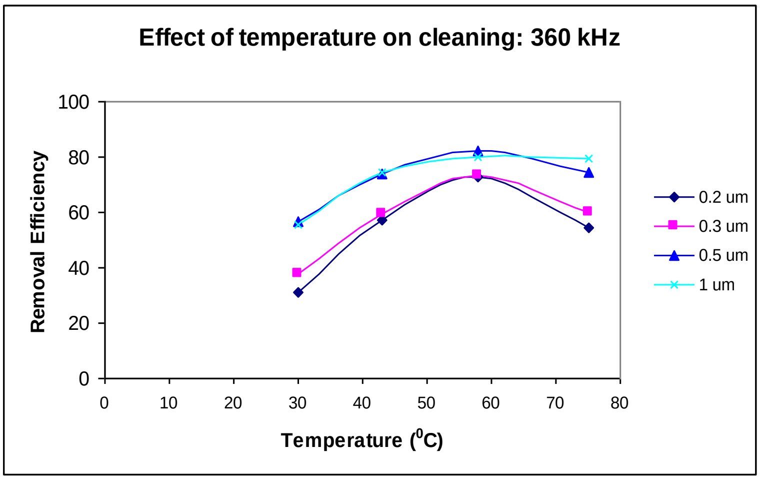

Fig.9 Effect of temperature on particle removal efficiency for 360 kHz

From Fig.9, it can be observed that the removal efficiency increases linearly with increase of temperature until 65 ^oC and then it become constant with increase of temperature. The trend obtained for 470 kHz frequency is also same [Fig.1]. In megasonic cleaning the cleaning mechanism is mainly by acoustic streaming compared to acoustic cavitation. So, the increase in temperature would leads to increase in acoustic streaming velocity. The increase in streaming velocity increases the removal efficiency of particles and also avoids the re-deposition of particles.

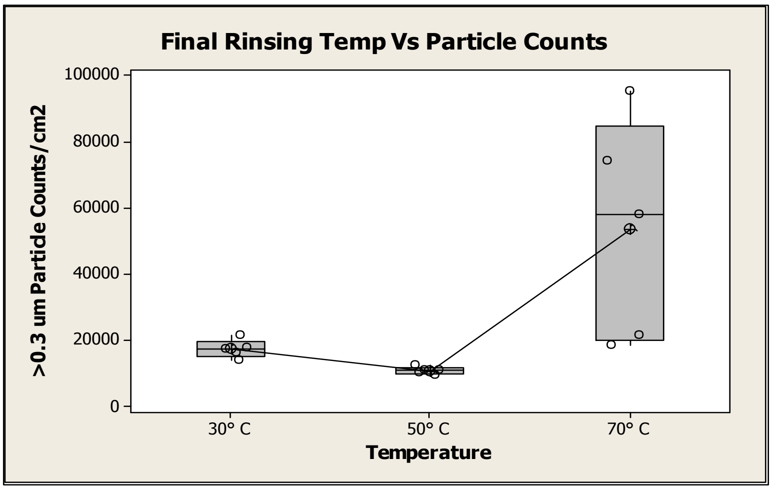

Fig.10 Effect of temperature on particle removal at final rinsing

The parts are washed with 58 kHz and rinsed with various temperatures and then the parts are subjected to 132 kHz LPC extraction with the watt density of 60 W/gallon. The results obtained are shown in Fig. 10. It can be observed that maintaining 50 ^{o}C at final rinsing gives lower particle counts hence higher cleaning efficiency than 30 ^{o}C and 70 ^{o}C. The reason for this was explained already. The run to run variation is also high for 70 ^{o}C compared to 50 ^{o}C and 30 ^{o}C.

V. CONCLUSION

The cavitation intensity decreases with increase of frequency and temperature. The erosion rate also decreases with increase of temperature and frequency. The particle removal efficiency increases with increase of temperature until 60 ^{o}C and then it start decreases with increase of temperature for all ultrasonic frequencies tested. In case of megasonic frequencies such as 360 kHz and 470 kHz, the particle removal efficiency increases with increase of temperature until 65 deg C and then it become constant. We also observed that the sonic energy is more uniformly distributed for the temperature around 50 – 60 ^{o}C. At higher temperatures around 70 ^{o}C the particle removal is not so consistent compared to particle removal at 30 ^{o}C and 50 ^{o}C. The optimum temperature obtained for cleaning of e-coated DSP was around 50 to 55 ^{o}C. So, the best ultrasonic performance should be roughly 60% of the boiling point of the liquid for effective removal of particles for most of the components. The temperature above 60% of the boiling point will decrease scrubbing force of the system thereby decrease the removal of particles. Overall, the balancing of cavitation and temperature is so important to achieve higher cleanliness for various components. In future, the experiments will be carried out for various conditions such as heating the parts and maintaining the washing liquid at room temperature, heating the washing liquid and maintaining the parts at room temperature and heating the parts and heating the washing liquid.

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BIOGRAPHY

Name: Vetrimurugan, Place: India, Educational background: PhD in Chemical Engineering, Indian Institute of Technology Madras (IITM), India. Degree awarded year: 2007. Major Field of study: Ultrasonic/Megasonic cleaning and Ultrasonic mixing

Past work experience: 1. Worked as a Research Officer for ISRO (Indian Space Research Organisation) project in IITM for 3 years 2. Worked as a Cleaning and Development Staff Engineer in Western Digital, Thailand for 4 years. 3. Currently working as a Cleaning Application and Development Manager in Crest Ultrasonics, Malaysia for past 3 years. Published more than 20 research papers in various journals and international conferences. Current work mainly involves development of cleaning process for various customers include process optimization, equipment selection, chemistry and waste minimization. Main research area: Applications of Ultrasonic and Megasonics in diverse areas.

Address: No.1536, Jalan Perusahaan, Bukit Mertajam, Penang.

Name: Lim Teong Kheng (Terry), Place: Malaysia, DOB: 31st August 1973, Education background: B. Eng (Hons), University Science Malaysia. Degree awarded year: 1996. Major Field of study: Mechanical Engineering.
Past work experience: 1. Sales Engineer in 3M, Malaysia. 2. Director in Ideal Dynamic (M) S/B, Malaysia. 3. **Executive Vice President (Asia) of Crest Group Inc.** Current work involves managing operations in Asia and cleaning application development with customers of various fields.

Name: J. Michael Goodson, Place: USA, CEO of Crest Ultrasonics Corporation.