PARTICLE REMOVAL USING ULTRASONIC CLEANING

by

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Abstract

Removal of contaminant particles from silicon wafers presents one of the most challenging problems in the electronics industry today. Ultrasonic cleaning is an established method for removing micron-size or larger contaminants from hard surfaces. In this study, The effectiveness of ultrasonic cleaning technique in removing submicron particles is investigated. The effect of the particle size, concentration, and sonication time on submicron particle removal effectiveness is studied. The effect of moving the fluid in the sonication bath is also considered. The initial results indicate that the microstreaming effects produced by ultrasonics waves play the dominant role in the cleaning process. Cavitation damages to the wafer surfaces have been observed under certain conditions. Preliminary results indicate that the ultrasonic cleaning technique is capable of removing particle sizes of 0.3 microns or larger.

1 Introduction

Surface contamination on silicon wafers is a very large concern in the microelectronic industry today. Particulate surface contamination is directly responsible for the low yields in the industry. There is a great need to develop an effective technique for particle removal from flat surfaces. As line widths decrease further into the submicron range the situation will become that much more serious [1,2].

The objective of this study is to investigate and develop useful correlation particle removal effectiveness using ultrasonic cleaning techniques. Other objectives include establishing a criterion and procedure for microcontamination particle removal from silicon wafers surfaces using the ultrasonic techniques. The criterion will provide insight into the relationship between the particle size, concentration and the sonication process parameters.

Considerable work has been done by Olaf [3], Crawford [4], Rozenberg [5,6], and Flynn [8,9] to describe the mechanism of ultrasonic cleaning. The mechanism can be explained as follows: High frequency sound waves passing through a liquid produces a rapidly alternation compression and rarefaction (positive and negative pressures). In the region where the negative pressure is created, the liquid pulls apart creating minute bubbles and effectively concentrating energy. When the amount of energy concentrated becomes great, the bubble becomes unstable and implodes. It is the powerful implosions (cavitation) that scrub contaminants from surfaces immersed in the liquid. This cavitation action, however, will cause considerable damage (pits that range between 1-10 micron in size or larger) on the surface. For large parts (that do not have micron size features) cavitation will clean surfaces and the erosion may not be noticeable upon inspection.

Crawford [4] suggested that the major contributing factor in ultrasonic cleaning is the active cavitation within the cleaning fluid. He indicated that the intensity of cavitation is of greater importance than its distribution. Also, for ultrasonic cleaning the major factor must be the ability of the cavitation energy to produce a break up of boundary layers at solid/liquid and liquid/liquid interfaces or to produce a micro-erosion of solid surfaces suspended in the liquid [4].

Rozenberg [5] investigated the effect of the medium, time and temperature on cavitation erosion. Erosion was measured as the weight loss from a standard sample. In his measurement, he used an aluminum sample and an ultrasound frequency of 8 kHz. He found that the erosion increased slowly (initially) with sonication or irradiation time. He also showed that the liquid temperature had a significant impact on erosion. He showed that maximum erosion of aluminum in water occurred at 50 *C*. Minimum erosion was observed at -10 and 90 *C*. The maximum erosion temperature was different for other liquids. For example maximum erosion took place at 10 *C* for alcohol. Erosion was also higher for water compared with other tested liquids (kerosene, alcohol, acetone, benzene).

Rozenberg [6] indicated that sound at high density levels in gas and liquids is accompanied by stationary flows known as acoustic streaming. These flows occur either in a free non-uniform sound field or near various types of obstacles immersed in a sound field or near oscillatory bodies. Their velocity increases with the sound intensity but the velocity remains smaller than the particle velocity in the sound wave. Especially relevant here, according to Rozenberg, is the boundary streaming near the surface of obstacles in a sound field. This streaming, which perturbs the boundary layer, does much to explain a number of observed effects involving the acceleration of transport process under the influence of sound such as the heat transfer of heated bodies and the cleaning of contaminated surfaces.

In his survey about ultrasound and its applications, Nyborg [7] explained that boundary layers exist when sound fields are applied in fluids such that motions occur tangentially to the solid boundaries. In addition, steady flow patterns of much smaller scale are observed near surfaces where those boundary layers exist [7]. In other words, sound fields give rise to time independent circulation (acoustic streaming near solid surfaces). Streaming (near oscillating bubbles) with a scale on the order of the bubble radius is called microstreaming. The particle velocity of a bubble wall (when the bubble radius is near the resonance value) is much higher than the particle velocity in the sound wave [7]. This streaming gives rise to a strong exchange of fluid near an obstacle which accelerates the removal of contaminants [7]. Streaming velocities can reach magnitudes of several meters per second. The direction of the streaming with respect to the solid surface depends on kinematic viscosity of the fluid and the sound intensity. For the case of water using high sound intensity (particle velocity amplitude of the bubble surface is 31-60 cm/sec) the streaming will be directed toward the surface [6]. This streaming appears as a jet directed toward the surface that removes contaminants without causing any surface damage.

J. Olaf [3] investigated the conditions for cleaning the surfaces by using ultrasonics in the frequency range of 15 *kHz* to 2.5 *MHz*. He shows that the cavitation can be increased and decreased by changing the hydrostatic pressure. Also, Olaf [3] concluded that the choice of liquid and the onset of cavitation has a large effect on the cleaning effectiveness.

Flynn [8,9] and Noltingk and Neppiras [10] have indicated that the presence of bubbles resembling transient cavities is a sufficient condition for the production of erosion by acoustic cavitation [8]. It seems now that erosion is caused by high speed jets arising from surface instabilities in the bubbles. Such instabilities can occur in stable or transient cavities [9,10].

Plesset and Chapman [11] studied numerically the collapse of an initially spherical vapor cavity in the neighborhood of a solid boundary. Figures 1 and 2 show that the

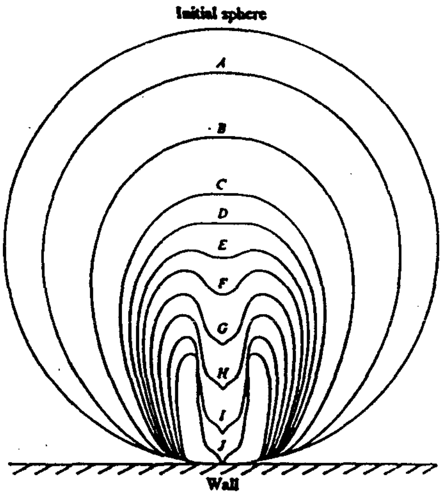

Figure 1: The Collapse of an Initially Spherical Bubble in Contact with a Solid Surface, from ref. [11]

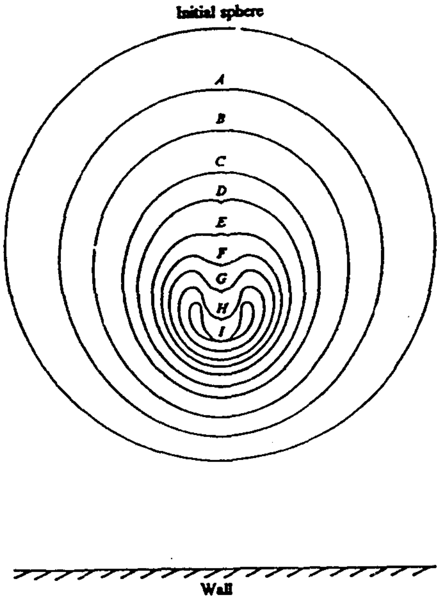

Figure 2: The Collapse of an Initially Spherical Bubble away from the Surface, from ref. [11]

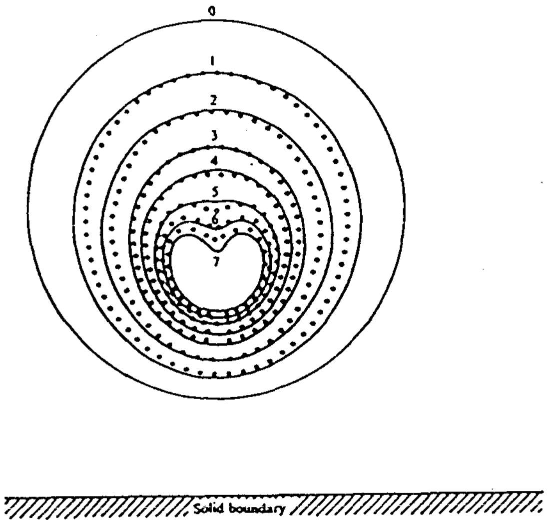

Figure 3: Comparison of Experimentally Determined Bubble Shapes (open circles) on Collapse of a Spherical Bubble near a Plane Solid Wall with Theoretical Results of Plesset and Chapman (solid curves), from ref. [12]

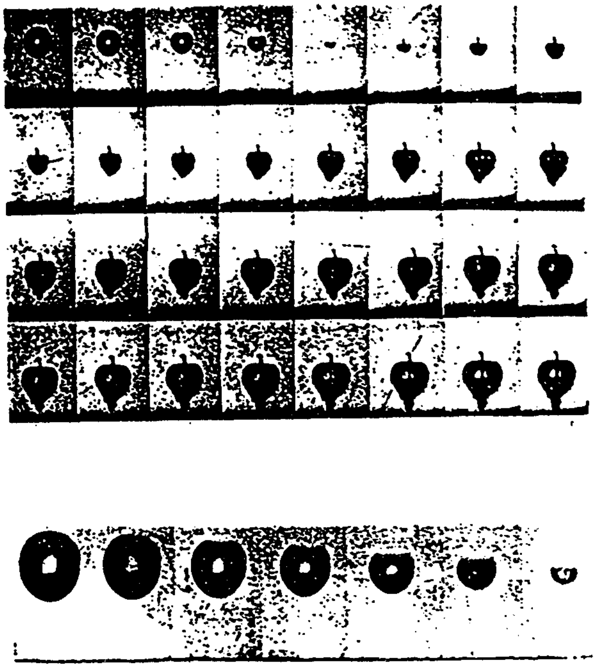

Figure 4: Bubble Collapse and Rebound near a Solid Boundary, from ref.[12]

bubble develops a jet directed toward the boundary during its collapse time. Jet velocities up to 130 m/s have been calculated in water at atmospheric pressure. Bolle and Lauterborn [12] have investigated experimentally the collapse of cavitation bubble in the neighborhood of a solid boundary. The numerical calculations by Plesset and Chapman have been quantitatively confirmed by Bolle and Lauterborn [12]. High speed photography was used to capture the bubble collapse as shown in Figures 3 and 4. Suslick [13] has reported that high pressures up to 500 atm and temperatures of about 5,500 C can be reached inside the bubble. Also, jet velocities up to 400 km/hr have been reported [13]. Such velocities and the associated pressures and temperatures are of magnitudes that can explain the cavitation damage.

2 Experimental

All experiments are performed in the Microcontamination laboratory's class-10 Clean Room at Clarkson University.

Ultrasonics cleaning is achieved using the J.M.NEY company proSONIK process control system model 40-PRO-0506N. The system consists of an ultrasonic generator, transducers, and stainless steel tank. The system is capable of controlling the band width, sweep time, quiet time, burst time, train time, degas time, and liquid temperature. The system center frequency was 40 kHz. The wafer is dried before post-scanning using a photo-resist spinner (Headway Research).

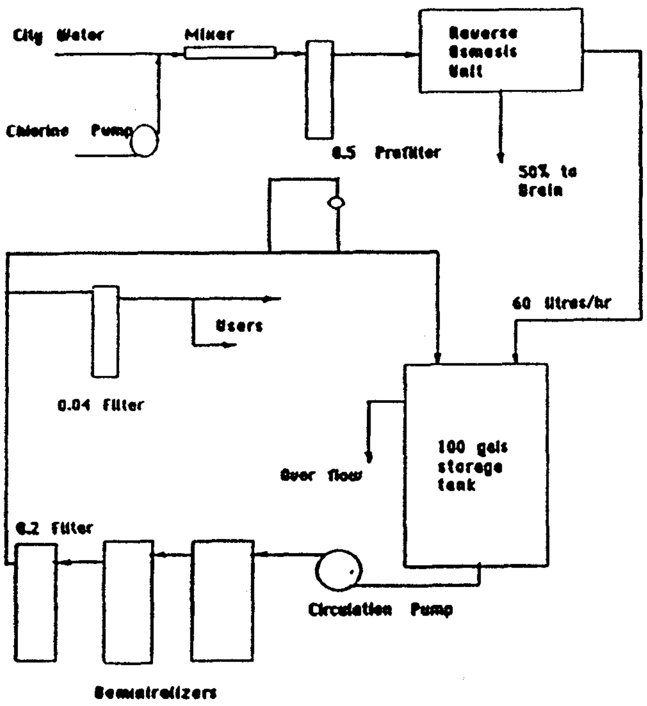

Figure 5: DI Water System Used in the Clean Room

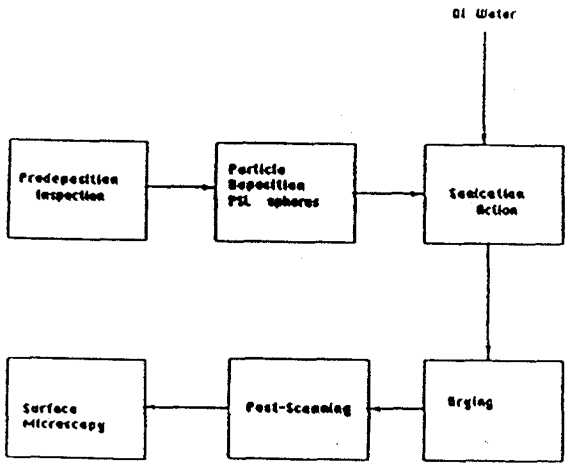

Figure 6: Schematic Diagram of the Ultrasonic Cleaning Process

The drying time is 120 *s* at 3000 *rpm*. The DI water supply system is shown in Figure 5.

Polystyrene latex (PSL) spheres (produced by Duke Corporation) of sizes 0.3μm, 0.5μm, 0.7μm, 0.8μm, and 1.0μm. used in this investigation. Surface inspection is carried out using the Surface Analysis System PMS model SAS-R. Also, surfaces are inspected for cavitation damages particularly after sonication has been applied. For this purpose an optical microscope is used (Olympus BH2-MJL-2001) in addition to a scanning electron microscope.

2.1 Experimental Procedure

A schematic of the experimental procedure is shown in figure 6. The procedure can be summarized as follows:

1. A clean silicon wafer is passed through an initial predeposition and surface defects inspection to reveal surface contamination which remains despite conventional cleaning.
2. Particles (PSL spheres) are then deposited on the wafer The wafers are then scanned to obtain the particle count before the ultrasonic cleaning is applied.
3. The wafer is immersed in a water tank and then exposed to ultrasonic vibrations. The wafer is then dried before post-scanning.
4. The wafer is then scanned to obtain the surface defects and particle count and distribution.

3 Results and Discussion

All results are obtained using the following sonication parameters: Center frequency=40 kHz, Bandwidth=0.5 kHz, Sweeptime=0.5 second, Train time=1 second, Degas time=0.5 second, Burst time=10 Millisecond, Quite time=5 Millisecond, water temperature=20 *C*.

Figure 7 shows the removal efficiency for different particle diameters. The figure shows that the removal efficiency increases with the particle diameter up to 95% at 4 μm. The interest lies, however, in the submicron range. For particles below 0.5 μm the removal efficiency averages about 75%. The ultrasonic cleaning method was found to be capable of removing particle sizes of 0.3 μm or larger. The initial particle concentration for the shown experiments in figure 7 is high (on the order of 20,000 to 30,000). Results for low initial concentration is shown in figure 8.

Figure 8 shows the removal efficiency versus particle diameters using a low initial particle concentration. The figure shows that the removal efficiency increases with the particle diameter up to an average of 90% at 1 μm. For particles below 0.5 μm the removal efficiency averages about 65%.

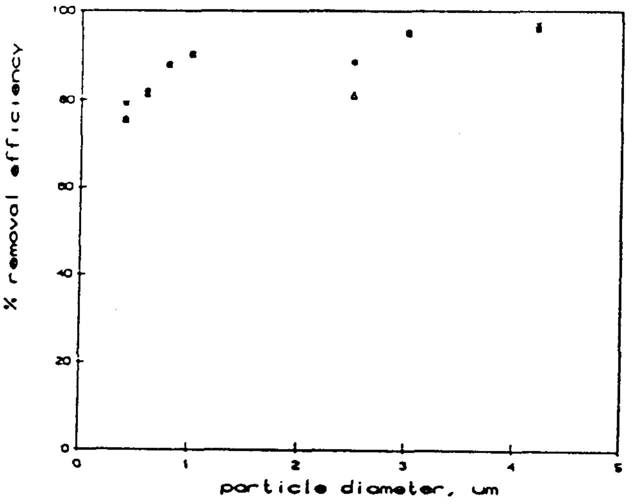

Figure 7: Removal Efficiency versus the Particle Diameter (for high initial concentration

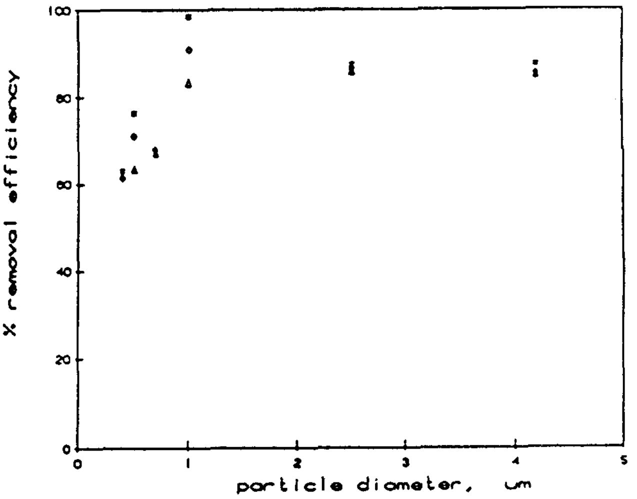

Figure 8: Removal Efficiency versus the Particle Diameter (for low initial concentration)

This shows that the removal efficiency is lower when low particle concentration is used (specially in the submicron range). At high particle concentration the particles tend to coagulate (agglomerate) which allows for higher removal efficiency. This is due to the weak bondage between the particles compared to the adhesive force between the particles and the wafer surface. The initial particle concentration for the shown experiments in figure 10 is low (on the order of 1,000 to 2,000).

Figure 9 shows the removal efficiency plotted against the sonication time for a particle diameter of 0.6 μm. The figure shows that the removal efficiency is a strong function of time. The figure exhibits the improvement or increase in removal efficiency (with respect to the last reading or point) at a time interval of five minutes (which means that the wafer is getting cleaner with time). The shown results are not cumulative.

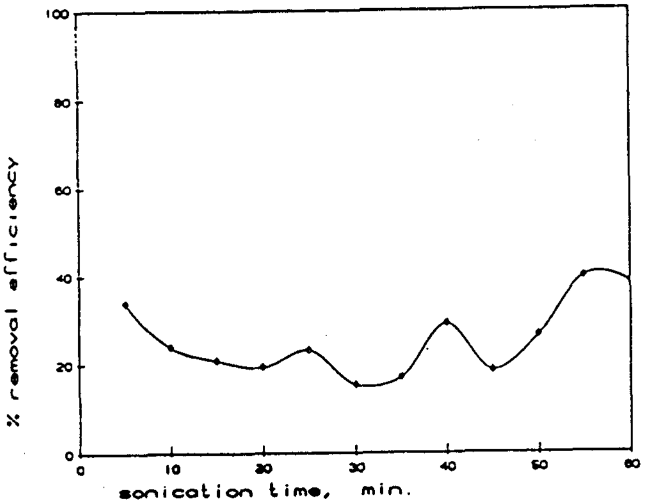

Figure 9: Removal Efficiency and Sonication Time for 0.6 μm Particle Diameter

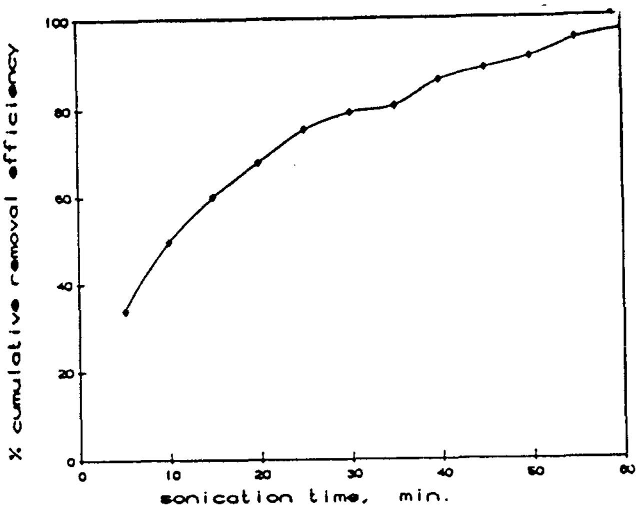

Figure 10: The Cumulative Removal Efficiency vs. Sonication Time for 0.6 μm Particle Diameter

The cumulative removal efficiency is plotted against the sonication time as shown in figure 10. The figure shows that the removal efficiency continuously increases with time. This indicates that the cleaning has not reached a maximum yet after one hour of cleaning. Removal efficiency results are based on the initial wafer particle count. The experiment was conducted using an initial high particle concentration.

Particle Dia.	*Moving Fluid*	*Stagnant Fluid*
4.2 µm	82.10%	65.06%

Table 1: Table (1) Removal Efficiency for Moving and Stagnant Fluids

The effect of liquid motion near the wafer in the sonication bath have also been investigated. These results are presented in Table 1. The table shows that moving the fluid (without allowing fluid circulation in the tank) near the wafer improves the removal efficiency as compared to the stagnant liquid case. This can be easily explained by the fact that the removed particles are not allowed to redeposit on the wafer's surface.

Figure 11A and 11B shows the SEM images of wafer surfaces after being sonicated for 60 *min*. As it may be seen there are some specific areas on the wafer surface that are wavy in nature. These areas seem to be depressions as cannot be cleaned off. It is clear from figure 11B that a circular feature or depression (about 10 µm in diameter) is a surface pit. Since the wafer has been carefully scanned using a microscope before the application of the ultrasonic waves, it is believed that these damages are due to cavitation. These observations agree with those found by other researchers [6,8,9].

Flynn [8,9] explained that the hammer blows are caused by the impact of high velocity liquid jets generated by asymmetrical collapse of bubbles near a solid surface, see figures 1-3. Liquid jets have been observed photographically and recent calculations indicate that they have sufficient momentum to cause observed pitting [14]. Other researchers also suggested that high velocity jets forming during cavity collapse will cause damages upon impingement on the solid surface [15,16,17,18].

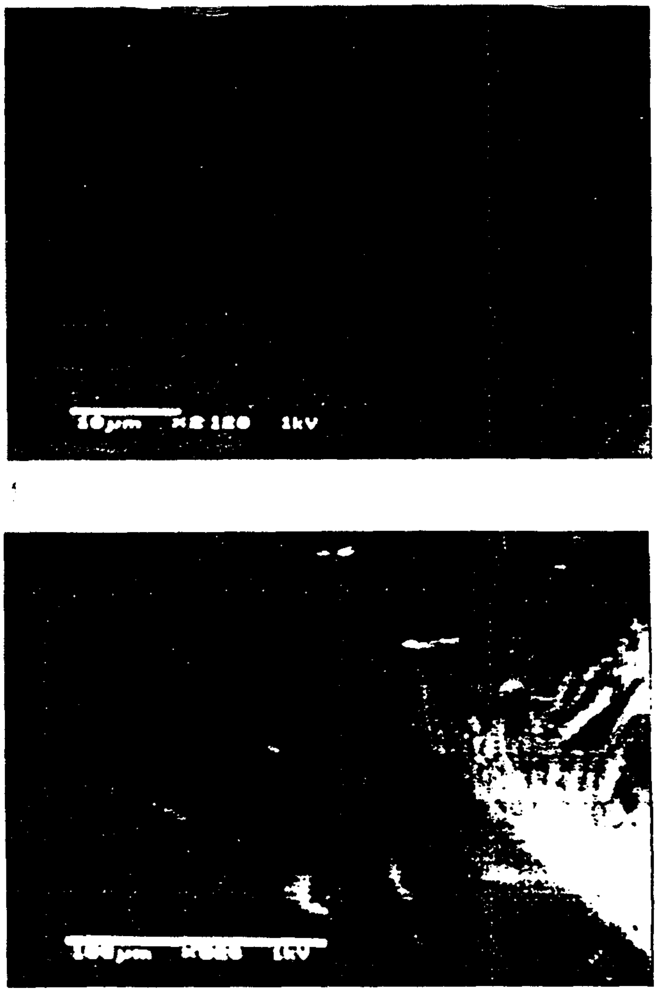

Figure 11: Surface Damage caused by Cavitation

4 Conclusions

The experimental cleaning method employed in this study is an effective means of surface cleaning. Preliminary results indicate that a high removal efficiency is obtained for large particle sizes of 1.0 µm or larger. For smaller sizes, a relatively lower efficiency is obtained. Results show that the ultrasonic cleaning method is capable of removing particles of sizes as small as 0.3µm in diameter with removal efficiencies in the range of 65-70%. The removal efficiency is shown to increase with the sonication time. Results indicate that initial high particle concentration produces high removal efficiency. Moving the liquid in the sonication bath is shown to improve the cleaning process significantly.

The ultrasonic cleaning method should be implemented with great care to avoid cavitation surface damage. This is established by avoiding cavitation erosion (bubble collapse near the surface) action altogether and utilizing acoustic microstreaming as the only cleaning mechanism.

Acknowledgment

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