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Oil Droplet Detachment from Metal Surfaces as Affected by an Applied Potential

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ABSTRACT

Removal of organic contaminants from metal surfaces submerged in an aqueous surfactant solution can be improved by application of an applied potential. Earlier work has shown that the detachment of organic droplets is noticeably affected by variations in the pH of the solution and charge of the surfactant. Modifications in solution pH result in modifications of the electrostatic charge of the solid surface, which, depending on the charge and nature of the surfactant, will improve or hinder adsorption of surfactant at the solid–aqueous interface. This adsorption of surfactant molecules is of great importance to the detachment of organic droplets and, consequently, on the determination of cleaning efficacy. It is proposed that modification of the surface charge through application of potential will also result in changes in

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the adsorption of surfactant and, as a result, will alter drop detachment. Experimental results from a battery of tests for the removal of industrial quench oil from a stainless steel surface with different applied potentials are shown. Additionally, several different surfactants were examined, and drop detachment times and cleaning efficiency by ultrasonication were measured. A mechanistic model describing the affect of potential on surfactant adsorption was proposed, and a correlation between detachment time and cleaning was developed for some of the surfactants.

INTRODUCTION

Recent experimental observations indicate that the use of applied potentials augmented the cleaning of metal surfaces by aqueous surfactant solutions. These applied potentials were observed to shorten the time required for contaminant removal from metal surfaces. The improvement to the cleaning of metal surfaces is of considerable interest to many metal machining industries. The various processes for the removal of contaminants that could otherwise be detrimental to the subsequent manufacturing steps potentially have environmental consequences that can be alleviated through the minimization of nonrecyclable wastes. These wastes include exhausted surfactant solutions, cleaning solvents, and the contaminants removed from the metals during cleaning.

Surface contaminants are grouped into categories of organic and inorganic, as well as particulate and liquid. Inorganic contaminants include rust, oxide residues, abrasive polishing compounds, dust, and metal-processing residues. Organic contaminants include carbon-based materials, such as mineral oils, cleaning and descaling residues, and lubricating oils. Organic liquid contaminants are the primary concern of the research presented in this article. Removal of these contaminants was historically performed using organic or halogenated solvents. Unfortunately, such solvents have been identified as potential causes of health and environmental concerns.[1] Recently, limitations imposed by the Clean Air Act and its amendments have significantly curtailed the use of such solvents.

Aqueous surfactant solution based cleaning agents are currently the favored replacement for these volatile cleaning agents. These solutions present fewer disadvantages for use when compared with the organic or halogenated solvents. Such cleaning solutions are comprised of water, one or more surfactants, and any number of solution modifying agents. Liquid organic contaminates are removed from the metal surface through mechanical action of the washing process and the physiochemical interactions between the organic and surfactant. The surfactant acts on the organic contaminant by adsorbing at the aqueous–organic interfaces.

This self-assembly-like movement of surfactant monomers from solution results in a lowering of the aqueous–organic interfacial tension.[2,3] Changes in the interfacial tension correspond to a variation in a buoyancy force balance, with the result being the eventual detachment of the organic droplet from the surface. The adsorption of surfactant to the aqueous–solid interface is also of concern. Wangerund and Jonsson provide a discussion regarding the formation of surfactant aggregates at solid interfaces and the effects of aqueous surfactant concentration.[4] In the investigation presented in this article, the effects of surface charge will dominate this true self-assembly process, since a large surfactant concentration is maintained. A typical technique for modification of the surface charge of any metal material submerged in a cleaning/degreasing bath is through the addition of caustic materials. It is the modification of surface charge that is of importance when assessing applied potential for enhancing aqueous cleaning.

Modification of surface charge can occur through a number of methods. In this study, surface charge modifications were accomplished through the application of a positive or negative voltage to the metal surface under observation. It is important to remember that surfactant monomers come in a variety of shapes, sizes, and charges. There are four main classifications of surfactants: nonionic, anionic, cationic, and zwitterionic. Nonionic surfactants are assumed to have no inherent charge and as a result modifications of surface potential, should have little or no effect on adsorption. Anionic surfactants have a negative net charge. In the presence of a positive solid surface charge, anionic surfactants adsorb to a greater degree. When a negative surface charge is present, adsorption of anionic surfactants is inhibited or halted entirely. Cationic surfactants have a net positive charge, resulting in increased adsorption to a surface with a negative charge and decreased adsorption to a surface with a positive charge. Zwitterionic surfactants may either exhibit a positive or a negative charge, depending on the pH of the solution. This results in favorable adsorption for either surface charge, with increasing adsorption proportional to increasing magnitude of charge. Another technique for surface charge modification is solution pH, with a higher, more basic pH, causing the surface charge to become more negative.[5] Logically, as pH becomes lower, more acidic, the surface charge becomes more positive. Nassauer and Kessler reported that adsorption of surfactants onto metal surfaces could be greatly affected by the change in surface electrostatic charge as affected by modification in solution pH.[6] Kopal and Keltjens[7] and Pavan and coworkers[8] provide studies on the effect of pH changes on the adsorption of cationic and anionic surfactants, respectively. These groups verify that for surface charges in opposition to the charge of the surfactant, adsorption to the solid surface was increased.

In addition to the effects on adsorption of the surfactant, applied potential is also known to affect the wetting of organic droplets on surfaces. The work of

Ivosevic and Zutic show that for a hexadecane droplet on a charged mercury surface, the droplet will decrease its wetted area as the surface potential of the mercury is made more negative.[9] This would indicate that a hexadecane droplet has an inherent negative surface charge, as opposed to a positive charge. A positive surface charge would cause the droplet to wet the surface to a greater degree as the potential of the surface was made increasing negative. The estimation of the natural surface potential of an organic droplet is an important characteristic value for use in anticipating the effects of surfactant adsorption and applied potential on droplet detachment. Rowe and coworkers have shown that the zeta potential of Mar-Temp 355 droplets, an industrial quench oil, in aqueous surfactant solutions indicate the charge present on the surface of the droplet.[5] The zeta potential was measured for four surfactants: nonionic, Triton X-100; cationic, cetyltrimethyl ammonium bromide (CTAB); anionic, sodium dodecyl sulfate (SDS); and zwitterionic, 3-[(3-chloamidotrophyl)-dimethylammonio]-1 propane-sulfonate (CHAPS). The results from these measurements indicated that the organic droplet had a negative surface charge in all surfactants except CTAB, which was determined to have a positive charge. The adsorption of ionic surfactants affected the surface charge of the organic droplet, imposing the same charge to the surface as the surfactant. The nonionic and zwitterionic surfactants were not seen to change the polarity of the surface; instead, the droplet retained its inherent negative charge. Since surfactant adsorption to the aqueous–organic interface is a function of concentration, the surface charge of the organic droplet must also be a function of the adsorption of surfactant to the interface. Therefore, it is expected that the degree of wetting and, consequently, the detachment time of the droplet from a surface is a function of both aqueous surfactant concentration and applied surface potential. There is a considerable amount of published technical research covering the subject of oil removal from model surfaces by adsorption of surfactants at the aqueous–organic interface.[10–16] If the aqueous surfactant concentration were to be held constant at a value maximizing concentration-dependent surfactant adsorption to the aqueous–organic and aqueous–solid interface, then any changes to the detachment time would be solely dependent on the magnitude and polarity of the applied potential.

The correlation between the wetting and detachment of organic droplets from metal surfaces is shown by the work of both Starkweather and coworkers[16–18] and Rowe and coworkers.[5] Starkweather and coworkers show that the contact angle, an indicator of the extent of wetting, can be used to predict cleaning of surfaces as a function of cleaning system parameters. They demonstrate that the greater the contact angle, the better the cleaning efficiency of the system; therefore, modifications to one or more parameters in the cleaning system that result in a larger contact angle are indicative of better cleaning. The work of Rowe and coworkers furthers this concept by relating the detachment time of a droplet to the cleaning of a stainless steel surface by ultrasonication. It is shown that the time it takes a droplet to detach from the surface is likewise a good indication of the potential for cleaning. Therefore, as an extension of these correlations, the application of an electric potential to the surface, which quickens the detachment time compared to a neutral potential surface, would improve cleaning. Verification of this extension is presented in this article for changes in the charge of a metal surface by application of a potential.

EXPERIMENTAL METHODS

Information on the surfactants used in the drop detachment experiments and in the application of electrical potential to the surface can be found in Table 1. These surfactants were prepared daily to ensure consistency and the concentrations were chosen to ensure maximum interfacial adsorption. The concentrations were equal to or greater than the critical micelle concentration (CMC), above which, maximum surfactant adsorption is achieved. Mar-Temp 355 quenching oil (Houghton International), which consists mainly of mineral oil with a reported density of 7.29 lb/gal at 75°F and molecular weight of 477 g/mole,[19] was used as the oil contaminant in the case studies. A polished 455-stainless steel coupon was chosen as the surface for contamination and cleaning. Experiments were conducted at room temperature and atmospheric pressure.

Single-Drop Detachment

Single-drop detachment experiments were conducted to determine the kinetics of oil droplet removal as a function of applied surface potential. A stainless steel rod was used as the counter electrode. The monitoring apparatus consisted of a high-quality image camera connected to a video

Table 1. Surfactants used.

Surfactant	Type	Exp. concentration (mM)	Supplier	CMC (mM)
Triton X-100	Nonionic	0.3	Fisher Biotech	0.24–0.34
CTAB	Cationic	7.0	Aldrich	1.0
SDS	Anionic	8.0	Fisher Biotech	8.2
CHAPS	Zwitterionic	9.0	Aldrich	8.0

camera recorder and a television monitor. A video processor was used to print a copy of the oil droplet at several stages during the detachment process. This made it capable of monitoring the dynamic evolution of droplet shape and droplet detachment from the 455-stainless steel surface. To maintain a constant pH, HCl, and NaOH (both chemical grade) were used. The experimental set-up is shown in Fig. 1.

The polished 455-stainless steel surface was rinsed and cleaned after each experiment with a solution of 2% Micro detergent and deionized water mixture and water. It was allowed to air dry for 5 minutes, and then a 2-μL droplet of Mar-Temp 355 oil was placed on the surface using a micropipette. The oil droplet was allowed to stabilize on the metal surface before being submerged in a 250-mL square-shaped glass beaker along with 200 mL of the chosen surfactant solution. The experimental parameters held constant include drying time of the 455-stainless steel surface after prewashing, time allowed for the oil droplet to stabilize on the metal surface, room temperature (22°C), drop size, surfactant concentration, and monitoring methods.

Application of Electrical Potential to the Surface

An electrical potential was applied to the 455-stainless steel surface using a low-voltage DC power supply. To obtain a positively charged surface, the positive lead of the power supply was connected directly to the 455-

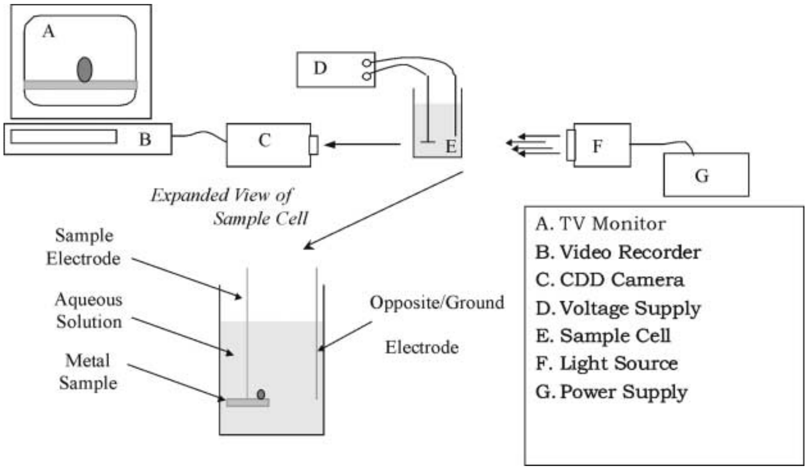

Figure 1. Schematic of experimental setup.

stainless steel surface, while the grounded negative lead was connected to a 455-stainless steel counter electrode placed in the solution. To create a negatively charged surface, the positive lead of the power supply was grounded and connected to the counter electrode. Current was monitored throughout the study and kept less than 5 mA to ensure minimal electrolysis and underscoring the low conductivity of the solutions. The set-up used for the applied electrical potential experiments is also found in Fig. 1.

Bench-Top Ultrasonic Bath Cleaning Experiment

Oil removal experiments were also done using a bench-top ultrasonic cleaning bath (Crest Ultrasonic Bath, supplied by Ultrasonics Corportation) to investigate the correlation between single-drop detachment and ultrasonic cleaning. The same surfactants were used in this investigation. The 455-stainless steel surface was cleaned using Micro detergent and rinsed with deionized water. The metal surface was then dried in an oven for 5 minutes at 120°C. It was then cooled to room temperature, and the mass weighed and recorded. The metal surface was next submerged in Mar-Temp 355 oil for 5 minutes and was then hoisted for 3 hours on a wire to drain the excess oil. The contaminated metal surface was then weighed and recorded. It was then submerged in a 2000-mL glass beaker containing the surfactant. The beaker was placed in the Crest Ultrasonic bath, which was tuned to 108 W of output. The ultrasonic energy at the location where the metal surface was suspended was measured at 11 W/in^2 by an ultrasonic meter (Ultrasonic Energy Meter II, supplied by PPB, Inc.). After 3 minutes in the Crest Ultrasonic bath, compressed air was blown along the cleaned metal surface for 1 minute to remove excess solution. The cleaned metal surface was then weighed and recorded. The percent removal of oil by the Crest Ultrasonic bath was calculated by the equation:

$$\text{Percent oil removal} = \frac{(X - Y)}{(X - W)} \times 100 \tag{1}$$

where W is the mass of the clean metal surface prior to the contamination, X is the mass of the contaminated metal surface, and Y is the mass of the cleaned metal surface.

RESULTS

The application of the electrical potential to the 455-stainless steel surface affects the effectiveness and kinetics of oil removal in the presence of the surfactant solutions. The data quantitatively represent the time needed for the first droplet to detach from the metal surface submerged in the desired surfactant solution while modifying the surface potential. Drop-detachment time refers to the time needed for the first observable portion of the droplet to detach from the sessile oil drop on the surface. The data are shown in Figs. 2 through 5. In the experiments involving CHAPS, which is zwitterionic, a pH modification was made.

For Triton X-100, Fig. 2, oil droplets on the metal surface exhibit a monotonic decrease in detachment time as the applied potential is increased from negative to positive. The application of a negative potential to the metal surface results in an increase in detachment time as positive potential results in a decrease when compared to no potential adjustments. Application of

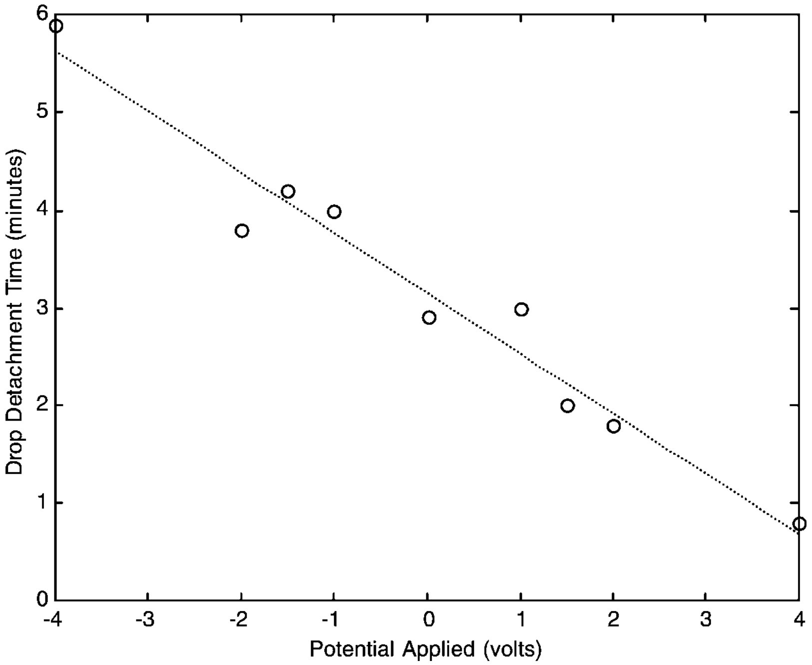

Figure 2. Drop detachment in Triton X-100 solution for varied potentials.

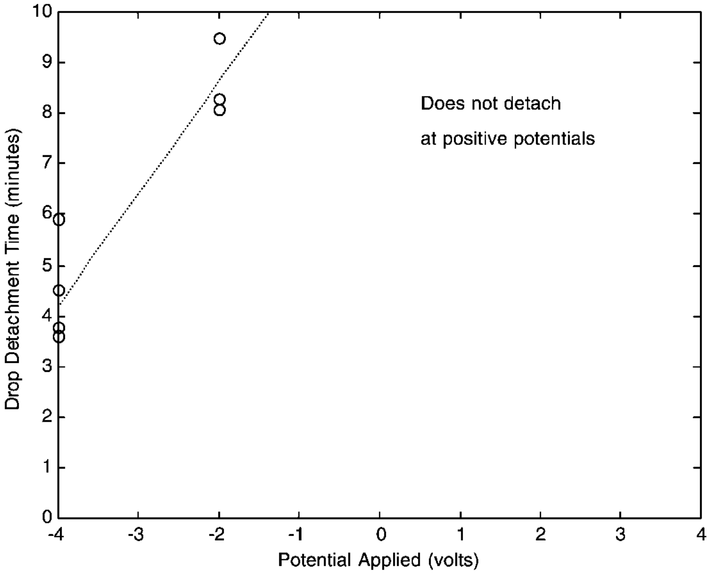

Figure 3. Drop detachment in CTAB solution for varied potentials.

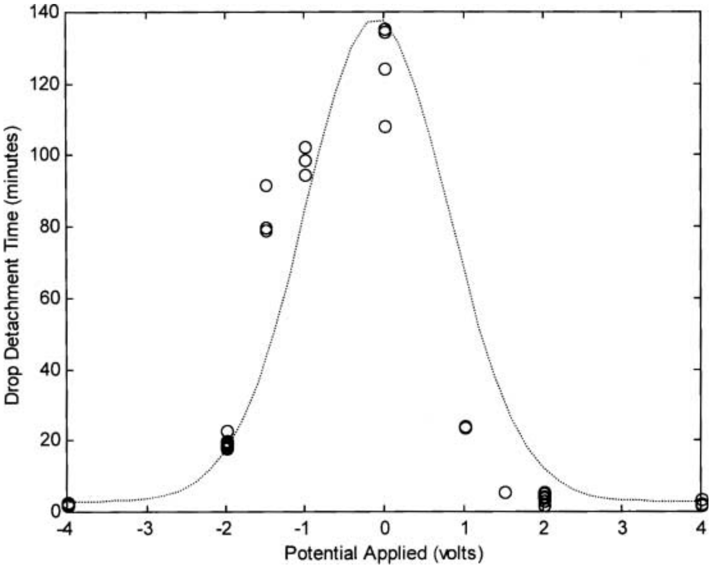

Figure 4. Drop detachment in SDS solution for varied potentials.

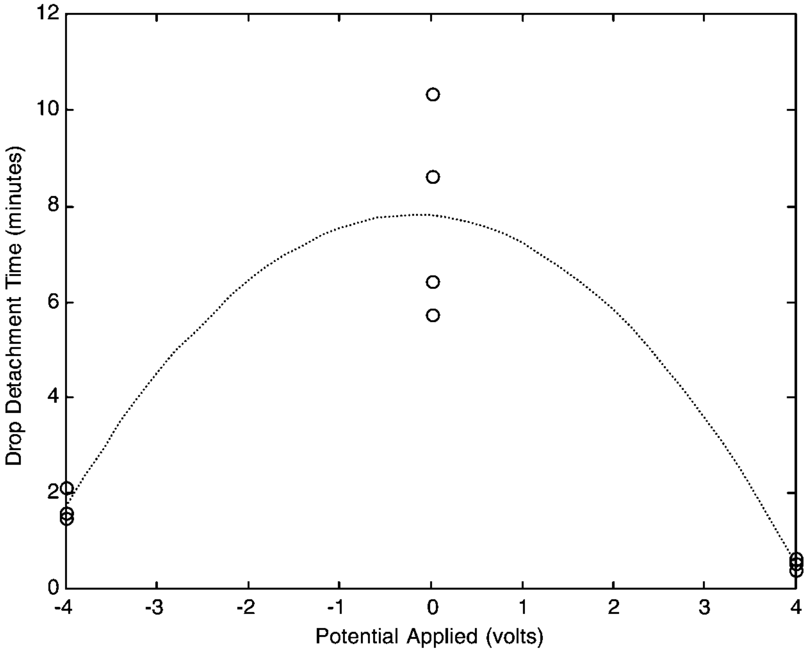

Figure 5. Drop detachment in CHAP solution (pH = 12.15) for varied potentials.

+ 4 volts results in a threefold decrease in oil detachment time, while − 4 volts results in an increase of twofold oil detachment time.

For CTAB, when no potential adjustment is made, oil droplets show no tendency to detach or decrease the extent of wetting over a 2-hour period. A positive potential results in no change of this behavior, while a negative potential, − 4 volts, exhibits a reduction in oil-droplet-detachment time the metal surface (see Fig. 3).

Results for SDS (see Fig. 4) show that the oil-droplet-detachment time decreased when the applied potential delivered to the surface was either increased or decreased. Compared to no surface potential modification, the drop detachment time of the oil decreased by a factor greater than 50 with the application of ± 4 volts.

To compare results from CHAPS to the rest of the surfactants, the pH was adjusted to make it act like a nonionic, anionic, and cationic surfactant. Oil-drop-detachment data was taken at three values of pH shown in Figs. 5 and 6. At pH 2.75, oil-drop detachment only occurred when negative potential was applied. No detachment was observed over a 2-hour period when no voltage

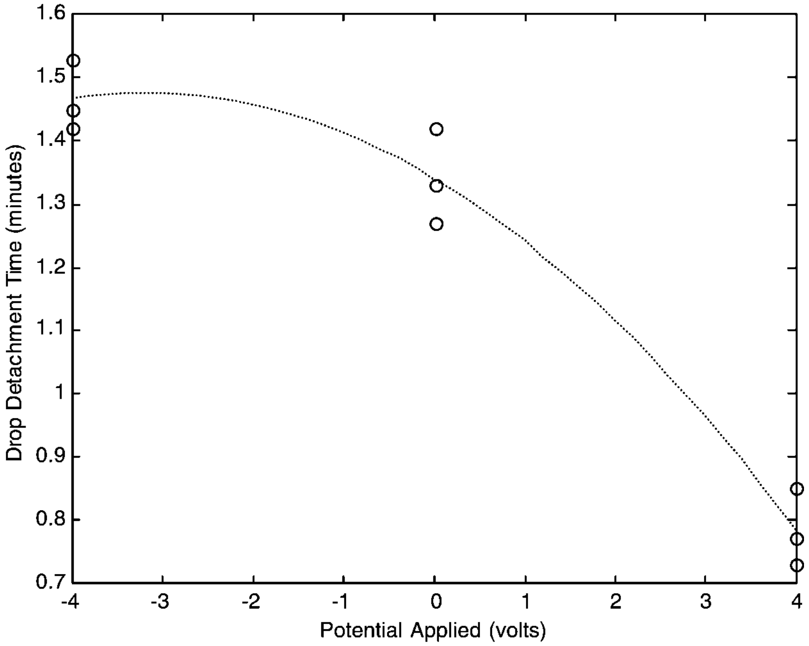

Figure 6. Drop detachment in CHAP solution (pH = 5.95) for varied potentials.

was applied or the potential was positive. This is the same trend observed for CTAB, which leads to the belief that at low pH, CHAPS acts as a cationic surfactant. When the pH is increased to 12.15, a trend similar to SDS is observed where a decrease in oil-droplet-detachment time is shown for both a positive and negative applied potential. The application of ± 4 volts resulted in a sevenfold decrease in oil-droplet-detachment time. At a pH of 5.95, +4 volts resulted in a twofold decrease in oil-drop-detachment time, while −4 volts resulted in a slight increase in the detachment time, resembling the trend seen for Triton X-100 the nonionic surfactant.

Cleaning Effectiveness Experiment

The effects of applied potential on the cleaning effectiveness in the Crest Ultrasonic bath are shown in Figs. 7 through 9. The applied potential effect on the cleaning effectiveness of Triton X-100 is shown in Fig. 7. There is an increase in cleaning effectiveness as the applied potential is increased from

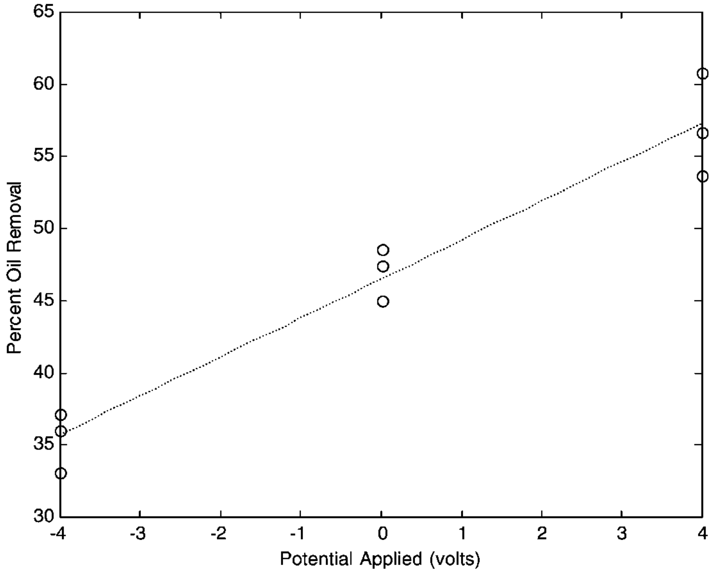

Figure 7. Ultrasonic cleaning in Triton X-100 solution for varied potentials.

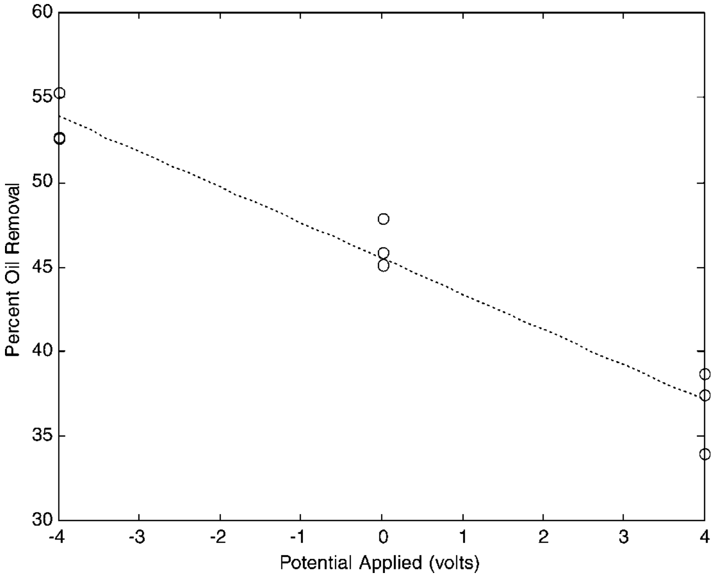

Figure 8. Ultrasonic cleaning in CTAB solution for varied potentials.

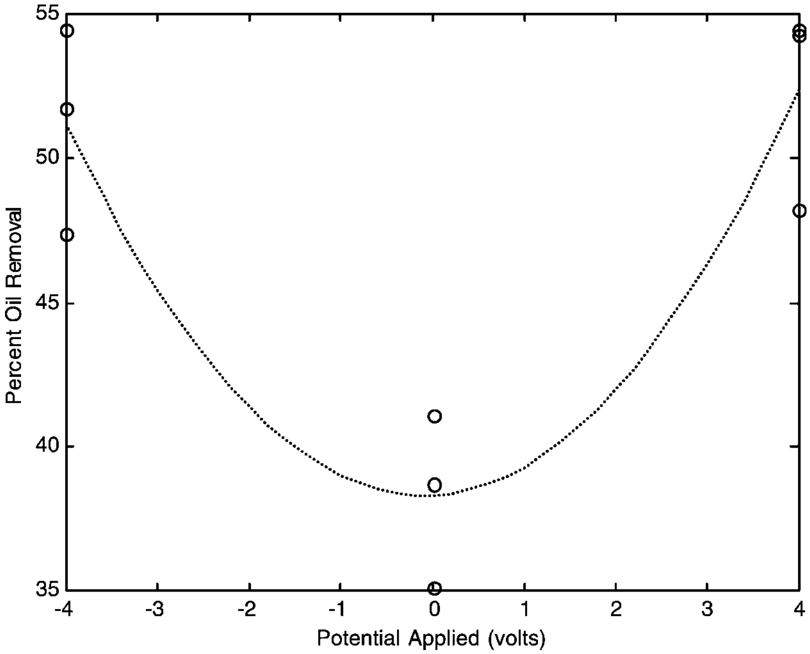

Figure 9. Ultrasonic cleaning in SDS solution for varied potentials.

negative to positive. The application of +4 volts to the metal surface results in a 10% improvement in cleaning effectiveness compared to no potential adjustment. The application of a negative potential reduces the cleaning effectiveness. This can also be related to the oil-drop-detachment time trend for Triton X-100, as shown in Fig. 2.

The effect of the applied potential on the cleaning effectiveness in the CTAB solutions is shown in Fig. 8. It is observed that there is an increase in the cleaning effectiveness as the applied potential is decreased from positive to negative. The application of −4 volts results in nearly a 7% improvement in cleaning effectiveness over no potential adjustment. The cleaning effectiveness, if reduced as a positive potential, is applied. As observed before with SDS and Triton X-100, this is consistent with the oil-drop-detachment time trend shown for CTAB in Fig. 3. It is assumed from the ultrasonic bath data that a decrease in oil-drop-detachment time is likely to occur as applied potential is decreased from positive to negative.

In the SDS solutions (Fig. 9), a negative or positive potential applied to the metal surface in the ultrasonic bath resulted in an increased cleaning efficiency. An application of ±4 volts resulted in an increase in cleaning efficiency of nearly 15%. This is consistent with the oil-drop-detachment time trend shown for SDS in Fig. 4, showing the correlation between cleaning effectiveness and oil-drop-detachment time. It is proposed that since cleaning effectiveness increased as oil-drop-detachment time decreased, oil-drop-detachment time can be used to predict ultrasonic cleaning bath results.

A correlation between droplet-detachment times and extent of oil removal is shown in Fig. 10. It is evident from this figure that as the detachment time decreases, the percentage oil removal increases. The values for this plot were estimated using values from a curve fit corresponding to the dashed lines, which were supplied for visual assistance in Figs. 2 through 9. This correlation indicates that a remarkable similarity in the percentage removal of oil as a function of detachment time exists for three of the examined surfactants: Triton X-100, SDS, and CTAB. Ultrasonication tests were not performed for correlation with the applied potential experiments for CHAPS.

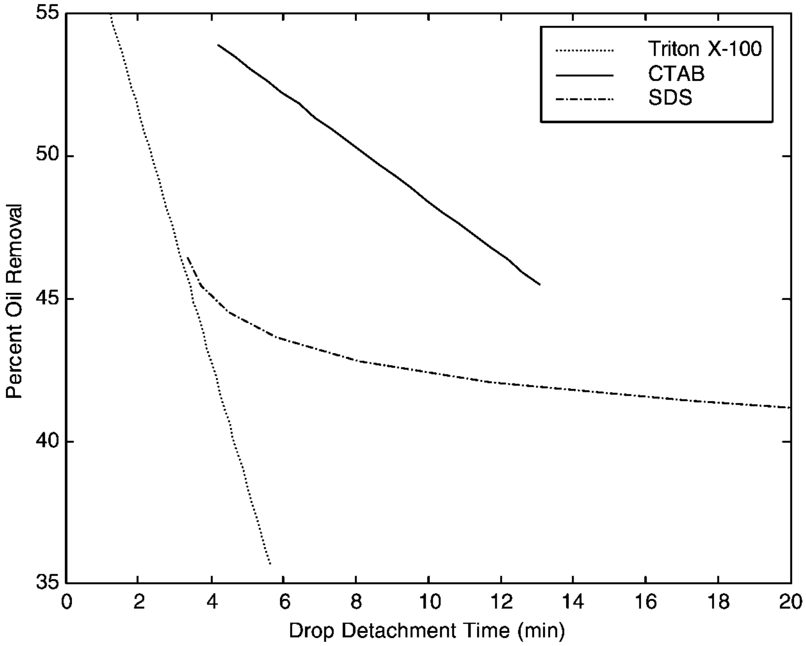

Figure 10. Correlation of percent oil removal to drop-detachment time.

Proposed Mechanistic Model

For interpretation of surfactant effects on oil-droplet detachment from a metal surface, the electrostatic surfactant adsorption model proposed by Rowe and coworkers has to be modified.[5] The model as originally proposed deals with electrostatic surface potential while recent work involves electrical potential. Electrostatic surface potential focuses on the short-range intermolecular charge related repulsive/attractive forces that can be varied by changing solutions conditions such as pH, ionic strength, and so forth, whereas electrical potential focuses on long-range coulombic forces. The particular applied electrical potential used for each individual test was kept constant, and the effects of the longer-range repulsion/attraction can be observed independent of solution conditions.

It is widely known that at low-surface electrostatic-charge densities, a monolayer of surfactants adsorbs at the solid surface.[4] Adsorption occurs due to electrostatic attraction, and the monolayer is able to neutralize the charge imposed on the solid surface. In the case of applied electrical potential on a metal surface, a monolayer of surfactants adsorbing to the surface is no longer able to neutralize the surface charge. The electric field near the metal surface can continue to attract unlike-charged surfactant molecules or repulse the like-charged molecules. This results in an accumulation or depletion of surfactant molecules near the metal surface. The adsorption process is known to be a function of surfactant concentration, surface charge density, and the nature of the electrostatic potential. Since the surfactant concentration was kept constant in this study, the magnitude and polarity of electrical potential applied to the metal surface are the only variables.

As the electrical potential across the metal surface increases, the long-range attractive/repulsive electrical forces between the surface and individual surfactant ions increases. At extreme pH conditions of cleaning solutions, Nassauer and Kessler[6] measured the surface electrostatic charge to be 1000 mV, which is insufficient for surfactant aggregate formation, so a monolayer is thought to adsorb to the surface.[4] At high-surface potentials, a strong repulsive force is thought to exist when surfactant ions and the metal surface are like charged. This depletes the surrounding solution of surfactant ions. The strength of this repulsive force is dependent on the charge of the surfactant head group. Coulomb's law states that if a highly charged anionic surfactant contacts a highly negative charged surface, the repulsion is expected to be greater than the one between the same highly charged surface and a weaker charged anionic surfactant. So, when the surfactant head groups and the charge on the metal surface are similar, it is believed that the long-range electrical-repulsive force between the droplet surface and the metal surface is high enough in magnitude to repel a portion of the oil droplet even though surfactants may be depleted near the aqueous–solid interface. This is the foundation for the mechanistic model based on the accumulation/depletion phenomena and long-range electrostatic repulsion between metal surface and the oil surface. This model can be used for various surfactants and applied electrical potentials and is illustrated in Fig. 11.

This new model for applied electric potential can be correlated to the original model involving electrostatic surfactant adsorption proposed by Rowe and coworkers.[5] The original model proposed was based on the work of Boulange-Petermann and coworkers,[20] studying zeta potentials on stainless steel. It was discovered that at high pH, the surface is negatively charged, while at low pH, the surface acquired a positive charge. Therefore, anionic surfactant molecules at low pH are attracted to the surface resulting in a monolayer of surfactants adsorbed onto the surface, while cationic surfactant at high pH conditions are attracted to negatively charged surfaces. In cases involving oppositely charged solid surface and surfactant molecules, a hydrophobic surface develops for enhanced attachment of oil to the surface. Rowe and coworkers[5] believed that when an anionic surfactant comes in contact with a similar charged surface, the hydrophilicity of the charged surface and the electrostatic repulsive forces between the negatively charged surface and the anionic surfactant molecules result in favorable oil-droplet detachment. This correlates with the results seen and postulated by the revised model proposed this study for applied electrical potential.

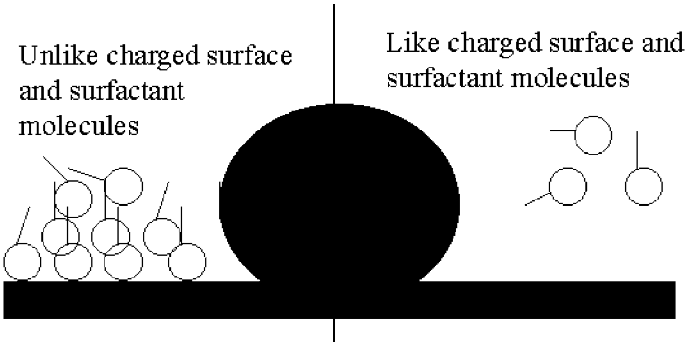

Figure 11. Proposed mechanistic model depicting the effect of applied potential on attraction *(Left)*/repulsion *(Right)* of surfactant molecules to the metal surface.

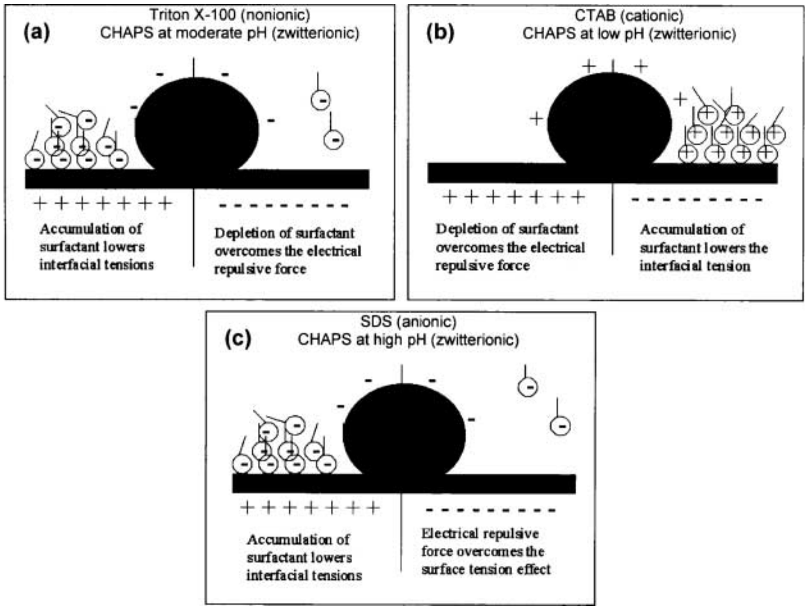

Figure 12. Illustration detailing effect of applied potential on the adsorption of surfactant molecules to the metal surface.

DISCUSSION

The application of the proposed mechanistic model for removal of oil droplets by the nonionic surfactant Triton X-100 is shown in Fig. 12a. As shown in Fig. 4, an increase in the electrical potential from negative to positive results in an increase in droplet-detachment time. Over the range of −4 to +4 volts, a sixfold increase in drop-detachment time was seen. It was believed that the hydrophilic group of Triton X-100 was neutral, but zeta potential measurements revealed a slightly negative charge.[5] This should result in a weak repulsive force between the oil droplet and the metal surface, which correlates to the results shown in Fig. 2, that Triton X-100 behaves like a negatively charged surfactant. This effect is observed when a negative potential is applied to the metal surface. When positive potential is applied, Triton X-100 molecules accumulate on the surface neutralizing the positive charge. As more surfactant molecules accumulate onto the surface, the surfactant preferentially wets the metal surface with respect to the oil droplet therefore displacing it.

In Fig. 12b, the removal of the oil droplets by cationic surfactant CTAB using the proposed mechanistic model is shown. In Fig. 3, it is shown that the oil-droplet detachment only occurs when negative potential is applied. A positive potential results in repulsion between the surfactant head groups adsorbed at the oil–aqueous interface and the positively charged metal surface. Earlier zeta potential measurements reveal a small positive charge associated with the surfactant absorbed to the oil–aqueous interface; this results in a repulsive force depleting the surrounding solution of surfactant molecules.[5] This explains the reasoning that positive applied voltage did not remove the oil droplet. With the application of the negative potential, CTAB molecules accumulate at the surface in effect neutralizing the negative charge resulting in preferential wetting of the surface with respect to the oil droplet, thus displacing it.

The removal of oil by anionic surfactant SDS using the proposed mechanical mechanism is shown in Fig. 12c. It is shown in Fig. 4 that an increase in the magnitude of applied potential results in a significant increase in cleaning effectiveness. Drop-detachment kinetics increase by a factor of 54 as the applied potential ranges from 0 to ±4 volts. Earlier zeta potential measurements revealed SDS to be a highly negative surfactant; therefore, long-range repulsive force would result and rapid detachment of the oil drop from the surface due to the induced surface charge from the adsorbed surfactant.[5] When applied potential initially increases from positive to negative, a local depletion of surfactant molecules at the surface–aqueous interface occurs. As the applied potential grows more negative, long-range repulsive forces overcome the local depletion of surfactants resulting in quick removal of the oil droplet from the metal surface. With the application of positive potential, SDS molecules accumulate on the metal surface, in effect, neutralizing the positive charge. This accumulation of surfactant molecules preferentially wets the surface with respect to the oil droplet, thus removing it from the surface.

The use of the proposed mechanistic model for oil-droplet removal is also shown for CHAPS in Fig. 12a through c, with the correlating pH variations. The increase in the CHAPS solution pH should cause it to behave like an anionic surfactant, while a decrease in pH should shift it to cationic. The results shown in Figs. 5 and 6 confirm this. As with SDS solutions, at high pH the application of positive potential results in a decrease in droplet-detachment time. As with CTAB, at low pH, the application of negative potential results is the only case of droplet detachment. At intermediate pH values, CHAPS is expected to act like a nonionic surfactant, which is confirmed in the comparison with the Triton X-100 data.

CONCLUSION

The effect of applied electrical potential on oil removal was studied in the presence of four types of surfactant solutions. A mechanistic model of oil-droplet removal from a metal surface based on the magnitude and polarity of electrical potential and the four types of surfactants was proposed. The electrical potential applied to the metal surface is believed to cause a similar effect on surfactant adsorption to the solid–aqueous interface as modification of solution pH. Trends of oil-drop detachment as a function of surfactant type and applied potential were observed and correlated well with cleaning effectiveness in an ultrasonic bath. When oil droplets detach more rapidly, this results in a higher cleaning effectiveness than when oil droplets detach more slowly. Nonionic-surfactant solutions provided more rapid oil-droplet detachment as the magnitude of voltage applied to the metal surface increased in the positive direction. Anionic-surfactant solutions provided a quicker droplet detachment as the applied potential to the metal surface increased either negatively or positively. Cationic-surfactant solutions yielded more rapid droplet detachment as the applied potential increased in the negative direction. Zwitterionic-surfactant solutions compared well with the trends for nonionic-, anionic-, and cationic-surfactant solutions when the solution pH was modified.

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