The Tribology of Cleaning Processes

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The effect of different chemistries on cleaning of hard surfaces has widely been investigated. However, a fundamental understanding of the physical aspects involved in grime removal is yet to be established. A series of surface experiments are presented in this paper to determine the mechanical properties of cleaning processes. Experimental results showed that tribology is a powerful tool to investigating the mechanical forces associated with cleaning of soiled surfaces. Analysis of protein-based soil removal from stainless steel suggests that friction coefficient decreases by nearly 28 and 75% for dry and wet samples, respectively, with an increase of 8 times in the normal load. The study also indicates a reduction of the coefficient of friction with an increase in frequency due to the reduced adhesion of counterface pin material on the sample and the possible localized softening of the soil surface. Tests performed using wet samples revealed that friction coefficient significantly decreases as a consequence of the water content. The effect of load on wet samples was mainly observed for short soaking periods (5 minutes). Specimens soaked for 45 minutes showed about 84% lower friction coefficient compared to dry samples but no significant dependency on the applied load. The volume of soil removed was higher for experiments presenting lower friction coefficients. Finally, wet cleaning promoted a higher cleaning efficiency requiring less energy to remove more soil. Overall it was established that purely mechanical forces are not sufficient to complete the cleaning process. Future work investigating the relationship of these tribological aspects with the chemistry of cleaning is to be expected.

Keywords: tribology, cleaning, friction, polymerized grease, protein-based grime, surface, thin film

1. Introduction

A large number of domestic and industrial cleaning operations are undertaken daily worldwide, requiring significant amounts of water and energy resources. For example, studies have shown that a standard dishwasher consumes approximately 268 kwh per year and requires between 15 to about 30 liters of water per cycle depending on the machine specifications [1]. According to a study conducted by Stamminger et al., a typical British household uses over 60 liters of water in a full sink dishwashing operation by hand [2]. Considering that there are 26.7 million households in the UK [3], and assuming a single daily washing-up operation, the water consumption with hand dishwashing in Britain is nearly 600 billion liters per year.

Conventionally cleaning is approached from a well-known chemistry perspective. This includes concepts of soil removal based on three main mechanisms: roll-up, in which the system is wetted and there is a decrease of interfacial tensions; emulsification, where thermodynamically unstable suspensions are formed; and direct solubilization, characterized by the spontaneous dissolution of a substance in surfactant solution [4-7]. Although the chemistry behind cleaning mechanisms is relatively well established, the physical aspects of cleaning processes, and the relationship between the two, are yet to be fully explored. An understanding of the mechanical forces required to remove soil combined with known detergency chemistry could help to optimize cleaning operations, reducing energy and water consumption.

A cleaning operation can be reduced to a problem combining surface engineering and the tribology of interacting surfaces. In this case, concepts of friction,
wear, and lubrication are crucial in order to understand the mechanical relationship between the tribo-couple. Friction is the process of energy dissipation between two sliding surfaces [8], which occurs mainly by two mechanisms: adhesion and deformation [9]. These are fundamental concepts for investigating cleaning since typical grimes are usually soft and sticky. There are many factors affecting frictional behavior of a system, e.g., sliding speed, applied load, temperature, presence of water, etc. Wear is a consequence of frictional forces on contacting surfaces interacting in relative motion [10]. This phenomenon involves material loss or deformation due to the interaction between bodies or between a surface and its interfacing environment [11,12]. In light of this, a cleaning process can somewhat be compared to a wear process once both involve material removal. The difference is that instead of wearing off the substrate, a cleaning process would involve the removal of grime layer on the top of a substrate.

In tribo-systems, a material of low shear resistance (lubricant) can be inserted between sliding pairs in order to reduce friction [13,14]. In cleaning operations, water as well as components within the soil could act as a lubricant. For example, food-based grimes may contain oils that lubricate the system and reduce friction; whilst protein particles could promote a third-body effect during cleaning and increase frictional resistance.

Several studies have investigated the tribology of polymer-metal interactions [15,16]. The tribological relationship between these materials is seen as crucial for the type of cleaning described in this paper since stainless steel was used as the substrate and the soils as well as the counterface are polymer materials. It has also been reported that transfer films are formed when polymers slide against metal surfaces [17]. This is of great interest in cleaning operations since grime particles are being removed from the surface. However, less work has been done investigating tribological aspects of soft films. Cleaning operations usually involve the removal of thin layers of polymerized grimes from hard substrates. Thereby, there is a great and novel engineering opportunity in elucidating how thin soft films mechanically behave during soil removal from metal surfaces.

Cleaning could potentially be correlated to wear since it involves material removal from a certain area. The mechanical behavior of the soft soil layer changes with wear of the surface since the particles being ploughed create a third body effect [15]. This means that particles are likely to be entrained between the substrate and the counterface during the grime removal process. In light of this, frictional forces will be directly affected by the amount of material transfer during the cleaning process. An understanding of the relationship between the friction coefficient and the amount of soil removed at different operational settings can indicate the best conditions for optimized and efficient cleaning processes.

This paper describes a series of experiments to determine the tribological properties of idealized cleaning processes using tribological experiments and surface characterization techniques. The aim is to establish a clear understanding of tribo-engineering of the cleaning process. This is done through a correlation between friction coefficient and experimental parameters such as load and frequency to cleaning efficiency. The cleaning behaviors of dry and wet samples were investigated and the influences of external factors on the process were analyzed.

2. Experimental methods

2.1. Sample preparation

The grime for this study was polymerized grease consisted of protein and vegetable oil baked on stainless steel plates. Test samples were prepared by mixing 25 mass% protein powder and 75 mass% vegetable cooking oils in a beaker. A controlled amount of the mixture was then taken with a pipette and applied onto the stainless steel substrate. The fluid stain was then spread across the surface with a roller. The samples were baked in a fan oven at 135°C for 3 hours. As vegetable oils consist mainly of triglycerides, i.e. esters of glycerol presenting three long-chain fatty acids, they act as precursors for monomer chains that yield the polymerization process [18]. As a result, a polymerized grease layer baked-on stainless steel tiles was formed. This layer was the grime that should be cleaned from the hard substrate.

2.2. Soil characterization

3D optical microscopy was used to measure surface roughness and thickness of the polymerized soil on the stainless steel substrates. 3D images were collected from the dry soil on stainless steel using an Alicona 3D optical microscope (Infinite Focus model) and processed using the Alicona IF-Laboratory software. Results of height distribution of dry samples were gauged using an ADE Phase Shift interferometer to verify the micron range of soil topography. The same instrument was used to investigate the particle size across the surface before and after soaking. 2D images were obtained for dry samples as well as for specimens soaked in water for 5 and 45 min.

Validation of chemical composition of different topographic areas was acquired through infrared microscopy. Experimental tests were performed using a Bruker IR microscope, Lumos model. Optical micrographs were obtained using the Lumos Wizard software which allowed pointing select sample areas of interest in order to obtain infrared spectra of these regions. IR spectra were acquired for top and bottom regions (peaks and valleys) of the soil and an analysis involving band assignment was performed.

2.3. Tribological tests

Tribological experiments were performed using a Plint TE77 reciprocating tribometer. Preliminary tests were conducted using a 12mm stroke length at 2 and 4...
Hz, and 5, 10, 20 and 40 N loads under dry conditions. Further tests were performed also using wet samples soaked in water for 5 and 45 min. Wet samples were tested using a 12 mm stroke length at 2 Hz, and 5 and 40 N loads. The cleaning implement (upper reciprocating specimen) was a 3-D printed 8 mm diameter pin made using a compliant formulated thermoplastic elastomer (TPE). The filament used to print the cleaning implement consisted of a polyurethane-based polymer with hardness of approximately 85 A according to the Shore durometer test defined in ASTM D2240.

2.4. Cleaning characterization

A volumetric analysis to quantify the amount of removed material was performed in order to correlate mechanical forces to cleaning. 3D images acquired before and after the tribological experiments were used to calculate the grime volume in a specified cleaning area. Similarly to the soil characterization section, an Alicona 3D optical microscope was used to collect the images and the volume of the soil samples were calculated using Alicona IF-Laboratory software.

The cleaning area considered for volume lost calculation was defined as the area delimited by the 12 mm stroke length and the 8 mm diameter of the counterface pin material. The volume lost was obtained by subtracting the remaining soil volume on the specified area from the initial average grime volume for a respective area on the same sample. The results were then compared to frictional behavior generating a correlation between cleaning efficiency and mechanical forces for different experimental conditions.

The energy input from the equipment during the 1-minute tribological experiment called ‘total process energy’ was also estimated. The total energy in each test was correlated to the applied load as well as the environmental condition (dry/wet). It is worth mentioning that the total process energy is not the minimum energy required to remove materials from the surfaces, but the energy involved in the time-defined processes. This was calculated by the total associated forces for different experimental conditions.

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The total energy applied during the tribo/cleaning test can then be defined as the sum of the works of the two characteristic steps of the process and can be seen in Equation 3.

\[ W_{total} = W_1 + W_2 \]  \hspace{1cm} (3)

The obtained results for total process energy were then compared to the volume of grime removed for each experimental condition. A relationship between energy and cleaning efficiency was established.

3. Results and discussion

3.1. Soil characterization

Figure 1 shows a 3D image collected from the dry soil on stainless steel using the 3D Alicona optical microscope. The surface roughness of the surface as well as the soil particles distribution was observed.

Figure 1 shows peak regions representing protein agglomerates with heights varying from 30 to 80 μm, while the valleys consist of a thin layer of lipids baked onto the surface with approximate thickness of 15-30 μm. These results are in complete agreement with additional verification done using interferometry analysis which presented comparable height distribution profile. The height distribution profile offers an indication of the average soil thickness and can be used to determine the initial bearing surface.

2D optical micrographs comparing dry and soaked samples are displayed in Figure 2.

It can be seen in Figure 2(a) that most protein particles are smaller than 80 μm and a few agglomerates of small particles are observed. After 5 minutes soaking in water protein particles start to swell and their size expand forming larger agglomerates as highlighted in the top and bottom areas of Figure 2(b). Samples soaked for 45 minutes (Figure 2(c)) showed that swelling of proteins significantly increases their size resulting in large agglomerates of over 300 μm. This not only enlarges the initial bearing area but also softens the thin soil layer and potentially facilitates the grime removal process. Structural changes in the surface are thereby highly
dependent on the soaking time, and this determines the final bearing surface prior to any mechanical action.

An optical micrograph and infrared spectra of the soil peak and valley are shown in Figure 3. The blue spectrum represents the peak regions (proteins) whilst the red one denotes the valley areas (fatty films).

Characteristic infrared bands were identified and assigned to specific vibration modes according to the literature. A summary of the main allocated bands in each spectrum are displayed in Table 1.

Infrared microscopy results shown in Table 1 confirmed that the agglomerates found in the 3D image analysis consist of mainly protein particles whilst the valleys represent a thin fatty film.

Blue spectrum (Figure 3) corresponds to the peak regions of the soil and showed typical characteristics IR bands for albumin protein. The broad band near 3300 cm⁻¹ was assigned to N-H stretching vibration of peptide groups [19]. The IR spectral range within 1644-1638 cm⁻¹ is characteristic of amide I due to peptide C=O stretching vibrations [20]. Correspondingly, the amide II band is represented by the peak around 1524 cm⁻¹ (β sheet components) [21] whilst the amide III band is identified by the peak at 1238 cm⁻¹ [20], both of them resulting from N-H bending vibrations and C-N stretching vibrations. The band at around 1449 cm⁻¹ arises from CH₂ bending vibrations [22]. Side-chain COO⁻ is thought to be the origin of the peak near 1390 cm⁻¹ [19]. Thus, agglomerates in the polymerized soil are formed mainly of albumin protein since the main absorptions bands obtained in the IR spectrum are comparable to the representative structure of protein.

The analysis of the red spectrum in Figure 3, which represents the valley area of the grime, revealed characteristic IR bands which suggest the predominant presence of vegetable cooking oils in that region. Bands at 2924 and 2854 cm⁻¹ represent C-H stretching vibrations of saturated carbon-carbon bonds [23]. The peak at about 1737 cm⁻¹ was assigned to C=O stretching of the carbonyl groups, while the band at 1457 cm⁻¹ originated from CH₂ bending vibrations [24]. The band around 1163 cm⁻¹ is thought to be due ester C-O-C stretching [23]. Another distinct band was found near 722 cm⁻¹ which is indicative of C-H out-of-plane stretching of saturated carbon-carbon bonds. It was noted that all intense absorptions bands detected in the infrared analysis were in accordance with the typical structure of a triacylglycerol bearing unsaturated fatty acids [23]. In light of this, it can be inferred that the valleys regions of the polymerized soil baked-on stainless steel consisted primarily of vegetable oils.
3.2. Tribological tests

3.2.1 Effect of load on friction during soil removal

The effect of load on friction coefficient during dry soil removal can be seen in Figure 4 showing the frictional behavior of the samples over time for a series of different loads.

It is seen that there is a machine lag of about 2 seconds in the measurements and then friction increases until the polymer-polymer systems stabilizes. The time interval needed to achieving the steady-state is called ‘running-in’. This period is characterized by changes in the geometries and physicochemical properties of the sliding pairs while conforming against each other [25]. This phenomenon is highly dependent on the soil being removed since its structural components are rearranged or displaced by the applied load.

Results in Figure 4 indicate that the friction coefficient reduces with increasing normal load as reported by Santner and Czichos for other polymer materials [26]. Fluctuations in friction coefficients were observed for experiments using 5 and 10 N which can be attributed to stick-slip behavior. This is due to the adhesive nature of the ‘sticky’ soil surface. It is worth noting that high load experiments resulted in almost constant friction coefficients after achieving a steady state at approximately 6-10 seconds. Thereby, the stick-slip behavior decreases with an increase of the applied load. This can be explained by the deformation of the soil peaks and the further ploughing of the remaining layer being squashed out of the cleaning area producing a smoother surface. Furthermore, visual observations suggest that the employment of high loads quickly removes the bulk part of the soil leaving mainly oil in the remaining layer. This residual oil perceived through a fingerprint test may act as a lubricant and thus contribute to the reduction of friction.

The trends obtained during the tribological experiments are shown in Figure 5. One can see that

<table>
<thead>
<tr>
<th>Peak (Blue)</th>
<th>Valley (Red)</th>
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<tbody>
<tr>
<td>Band (cm⁻¹)</td>
<td>Assignment</td>
</tr>
<tr>
<td>≥ 3300</td>
<td>N-H stretching vibration</td>
</tr>
<tr>
<td>1644-1638</td>
<td>C=O stretching vibrations</td>
</tr>
<tr>
<td>1524</td>
<td>N-H bending vibration/C-N stretching vibration</td>
</tr>
<tr>
<td>1449</td>
<td>CH₂ bending mode</td>
</tr>
<tr>
<td>1390</td>
<td>COO⁻ protein side-chain</td>
</tr>
<tr>
<td>1238</td>
<td>C-N stretching vibration/N-H bending vibration</td>
</tr>
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with an increasing load the friction coefficient decreases almost linearly while there is a significant reduction of the standard deviation.

It can be seen in Figure 5 that the standard deviations of friction coefficients are greater for experiments performed under low loads. This is due to the fluctuations in friction force measured at 5 and 10 N (Figure 4) since the upper specimen repeatedly alternated between moments of brief rests, when adhesive interactions dominated; and instants of shearing, when the sliding pairs were in relative motion.

3.2.2 Effect of speed on friction during soil removal

The effect of speed on friction coefficient during soil removal can be seen in Figure 6 for tests performed at 2 Hz and 4 Hz.

The friction coefficient reduced as the reciprocating frequency increased. The decrease of friction coefficient with sliding speed may be explained by the reduced adhesion of the counterface pin material on the sample and possible localized melting of the soil. Factors such as frictional thrust, frictional heat, and shear forces were increased with sliding speed and may have accelerated surface smoothening and wear rates [27]. Furthermore, high speed experiments typically cause a primarily elastic behavior in the contact points of sliding pairs generating an inversely proportional friction-speed dependency [28]. The short contact time between surfaces due to high velocities is also another factor influencing the decrease of friction with increasing frequency mainly because adhesive interactions have less time to occur [16].

Results also show that influence of load on friction is less pronounced for high frequency experiments since the friction coefficients range was smaller for experiments done at 4 Hz than for those performed at 2 Hz. This could be due to the fast smoothening of the surface roughness and thinning of the soil layer. The thinner is the remaining grime layer; the greater is the effect of the stainless steel substrate on the interaction of sliding pairs. This is explained by the low concentration of protein left on the surface and the presence of a remaining thin oily film. As the substrate is the same for all experimental conditions, very thin soil films will be subjected to an inferior influence of the applied load and thus will induce a smaller frictional range.

3.2.3 Effect of water on friction coefficient

Figure 7 shows the tribological results found for samples soaked in water for 5 and 45 min and tested under applied loads of 5 and 40 N at 2 Hz.

The effect of the applied load on wet samples can be seen in Figure 7. Similarly to the dry samples friction coefficients decreased as the applied load increased. The stick-slip behavior virtually disappeared for water soaked specimens. This may be due the presence of water which weakens adhesive interactions between sliding pairs. Water absorption by the polymerized soil leads to a swelling effect in the material and a reduction of surface strength. Such factors influence the final mechanical properties of the layer as studied by Yamamoto and Takashima for other polymer layers [29].

As a consequence of swelling of the thin layer, there is an increase in the contact area and a decrease of interfacial shear strength [30]. These elements stimulate plasticization of the thin polymerized soil which gets softer propelling the reduction in friction and facilitating the grime removal process.
A comparison between dry and wet specimens is shown in Figure 8.

One can see that friction coefficients of the hydrated samples were much lower in comparison to values obtained for dry samples. This trend is in accordance with the work reported by Mens and de Gee who observed that water lubrication generated a reduction of friction coefficient for several polymers [31]. As can be visualized from Figure 8 experiments performed under 5 N load the coefficients of friction reduced nearly 54% for samples soaked during 5 minutes; while specimens soaked for 45 minutes presented a decrease in friction of approximately 70%. As for experiments applying 40 N load, the reduction was even more pronounced since all samples showed a reduction of about 84% independently of the soaking time.

Hydration is an important factor in cleaning operations involving protein/oil-based soils since it softens the grime through a water adsorption process and vastly reduces friction coefficients. Water lubrication of the surface facilitates a mass transfer process which allows the grime to be removed from a determined cleaning area. The hydration time affects mainly grime removal operations involving low mechanical forces from external actions. Although the application of high load values also decreases frictional forces, it is barely influenced by the soaking time.

3.3. Cleaning characterization

Figure 9 shows an example of a typical cleaned sample after a wet test using 40 N load.

It can be seen that most of soil has been removed from the cleaning area delimited by the diameter of the upper specimen and the stroke length as exemplified in Figure 9. Exactly the same area was selected for all tests once the stroke length and diameter of the upper specimen were constant parameters. However, a fine remaining oily layer is also seen which indicates that in this case tribological forces are not fully ‘cleaning’ the surface. This suggests a need for chemical action in order to obtain a completely ‘clean’ surface. The removal of most protein grains and the permanency of oil on the surface also corroborates for the low friction coefficients found for wet experiments. This is due to the lubricant properties of the oil left on the stainless steel substrate and the lack of protein to promote the third body effect during the cleaning process as described for dry tests.

Figure 10 shows a correlation between the volumes of soil removed from the substrate and friction coefficient obtained through different experimental conditions.

One can see that the amount of soil removed is related to the average friction measured during the cleaning process. Lower averages of friction coefficients were observed for experiments resulting in higher volumes of grime being removed from the cleaning area. This trend is soil-dependable and related to the two-phase nature of the samples (proteins and lipids). As the majority of the soil agglomerates are removed with mechanical action, a residual oily layer is likely to be left in cleaning processes under these experimental conditions without chemical agents. Thus a smoother remaining layer is left on the substrate in comparison to the initial bearing surface of the soil. In light of the above, lower frictional values for this particular type of soil being cleaned in absence of chemicals indicate an optimized cleaning operation because less grime is left on the surface. It should be noted that none of the surfaces were found completely clean since a remaining grime deposit was always observed. The soil adhered on the stainless steel substrate is very rough (Figure 1) and the fluctuations in friction shown in Figure 4 reveal that the surface is also sticky. In light of this, the relationship shown in Figure 10 between cleaning and friction is to be expected since the bulk soil removal reveals a smoother contact surface consisting of a fine remaining oily layer which may act as a lubricant and promote a further reduction of frictional resistance.
The analysis of cleanliness of surfaces cleaned under dry conditions (Figure 10(a)) revealed a highly significant effect of the load on the amount of soil removed. Dry samples cleaned under 40 N load exhibited approximately 52% higher grime removal than samples investigated under 5 N. The high load applied on the soft soil topography generates a prompt flattening of the surface and a pronounced ploughing effect which is visually eminent. Therefore, more grime is squashed out of cleaning area and a reduction in friction coefficient is observed. Moreover, the elevated applied load is responsible for mechanically overcoming the adhesion between the soil and upper specimen (counterface pin material). Considering that adhesive interactions are weakened by the load, frictional resistance also decreases.

The effect of load in wet conditions, however, is less prominent as shown in Figure 10(b). Experiments performed with samples soaked in water and tested under 40 N removed around 6% more soil than the tests with 5 N load. Although the trend is the same as found for dry samples, the proportionality between friction and volume removed is smaller than for experiments using different loads. This might be due to the increased soil volume and decreased mechanical strength [30] as a result of the swelling process during sample hydration. Therefore, the magnitude of mechanical forces needed to clean the surface is lower and less subjected to the applied load effect.

Dry samples showed much greater standard deviation in comparison to wet specimens. This could be explained by the stick-slip behavior that promotes a fluctuation in the results. Furthermore, the sticky effect in dry samples makes it more difficult to plough the soil away from the cleaning area. The larger amount of remaining grime on the substrate makes it more challenging to control the process at a low STDV. In a wet environment, the fast diffusion of water molecules into the system lessens polymer strength and hardness [30,32]. Moreover, the presence of water results in a reduction of the attractive forces between polymer chains and facilitates the soil removal process similarly to findings of Wang et al. for other polymer systems [32]. This is substantiated by the higher volume of grime removed in wet conditions when compared to dry tests.

An analysis of the energy involved in the process was also performed and revealed that the cleaning process energy is correlated to the volume of grime removed for tests with the same environmental conditions. The results are shown in Figure 11.

The total process energy reported was derived from the work per unit area for the entire 60 seconds established as the total experimental time for the cleaning processes. The volume removed from the cleaning area was taken after this period though the majority of the soil removal is believed to occur during the initial ‘running-in' time which corresponds approximately to 3-5% (Eq. 1) of the energy involved in the complete process. The remaining period corresponding to the steady state was used to ensure a more effective surface cleaning for different external conditions (dry and wet). Thereby the steady state time also contributed to the final energy calculation, although the extent of its actual influence on the process is yet to be fully defined.

The effect of load is more prominently observed for dry samples since a large energy difference of approximately 6 times greater has been obtained for tests at 40 N as compared to 5 N. This effect is less pronounced for wet samples where the energy for the 5 N tests is nearly half of the energy for 40 N experiments.

Soil hydration is highly a significant factor in cleaning operations. This is shown by the larger volume of grime removed in wet environments when compared to non-hydrated conditions. The presence of moisture in the system reduces the strength of the polymerized grease [30] and therefore less energy is required for the cleaning process to take place. This trend supports the analysis of friction coefficients where the cleaning behavior was more effectively affected by load for dry samples. In a real life cleaning situation, this means that consumers with different cleaning habits would achieve similar cleaning quality.

Figure 11 reveals that wet experiments promoted the
removal of over 90% of soil whilst dry processes resulted in the removal of nearly 28 and 80% for experiments performed at 5 and 40 N, respectively. Not only was the volume cleaned higher for wet samples, but the energy input required to achieve such removal was lower, especially for the 40 N experiments as presented in Figure 11. This observation is a great aspect to be used in cleaning optimization since it allows removing more grime using a lower amount of energy.

It is worth mentioning that the energies employed in these experimental conditions are much higher than the typical apparent adhesive forces reported for protein-based deposits on stainless steel which are in the order of magnitude of $10^4$ J.mm$^{-2}$ [33]. For dry samples, even after applying more energy than the typical adhesion range, only a partial cleaning is perceived. This is a clear indication that cleaning of baked-on soil depends not merely on mechanical forces but also on chemical action to weaken the adhesive interactions. The results provide an opportunity for future work correlating the tribological behavior described in this paper with the chemical role of surfactants and detergent systems.

4. Conclusions

Results from the experiments described above show that tribology is a powerful tool to investigate the behavior of soiled surfaces. It has been observed that friction coefficient decreased by about 28% for dry samples and 75% for wet specimens, as a consequence of increasing the normal load from 5 to 40 N. Friction coefficient also decreased with increasing sliding speed. Similarly, wet samples also showed a reduction of friction as the applied load rose. However, the magnitude of this effect was less pronounced.

The effect of water was also shown and revealed that the hydration of protein-based soil dramatically reduces the energy required to remove grimes from the stainless steel substrates leading to a greater volume of soil removed in wet conditions than in a dry environment.

Cleaning was correlated to the average friction coefficient obtained during the process. Results revealed that a surface gets cleaner more efficiently when the average coefficient of friction reduces significantly. This trend was noted in this particular case due to the structural nature of the two-phase soil. Empirical observations suggested that the majority of the bulk soil (proteins) is removed with the mechanical action, lessening the third-body effect between the sliding pairs and leaving a fine oily layer on the substrate. This smoother ‘clean’ surface that is generated during the cleaning operation corroborates the obtained decreasing trend of friction coefficient.

The presence of water facilitates the cleaning process and promotes efficient results even for different loads being applied to the sample. This parameter could be the key to understanding the operation. Future work will involve an in-depth investigation of this effect by varying hydration times and performing more complex experiments adding chemical elements such as surfactants and cleaning solutions in order to elucidate how they correlate to the described physics of grime removal. Combining these factors is a promising path towards more efficient and environmentally-friendly cleaning processes.

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