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INTERACTION BETWEEN TOOTHBRUSHES AND TOOTHPASTE ABRASIVE PARTICLES IN SIMULATED TOOTH CLEANING

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ABSTRACT

There are currently many toothbrush designs on the market incorporating different filament configurations such as filaments at various angles and different lengths and made from several different materials. In order to understand how the tooth cleaning process occurs there is a need to investigate in detail how the abrasive particles in a toothpaste interact with the filaments in a teeth cleaning contact and cause material removal from a plaque or stain layer.

The following describes the development of optical apparatus to enable the visualisation of simulated teeth cleaning contacts. Studies have been carried out using the apparatus to investigate particle entrainment into the contact and how it differs with varying bristle configurations. The effects of filament stiffness and tip shape were also investigated. Various types of electric toothbrushes were also tested.

The studies have shown how particles are trapped at the tips of toothbrush filaments. Particles, suspended in fluid, approach the filament tips, as they pass through they may become trapped. Greater particle entrainment into the filament tip contact occurs with a reciprocating action at low filament loads and deflections than with a sliding motion. Large particles are less likely to enter tip contacts and are trapped between tips or under the filament bend at higher loads.

Whether the particles are likely to be trapped and how long they remain so depends on the filament stiffness and degree of splay on loading and the filament configuration. The direction the filaments point in, the number of filaments in a tuft, the spacing of the tufts and the way the filaments splay when deflected all have an influence on entrainment of particles. Tufts with tightly packed stiff filaments which deflected together on loading were more effective at trapping particles than more flexible filaments that splayed out on loading as they present more of a barrier to particle entry and exit from the tip region.

Keywords: Toothbrush, toothpaste, abrasive particles simulated teeth cleaning.

1 INTRODUCTION

Teeth are usually cleaned using a toothpaste, consisting of abrasive particles in a carrier fluid, with a filament based toothbrush. Toothbrush and toothpaste effectiveness is typically assessed using *in vitro* tests carried out on tooth brushing simulators or by using *in vivo* tests. A number of different simulators have been developed [1, 2, 3, 4]. Most of these simulators work by mechanically loading and moving a toothbrush head over a test specimen, which is typically made from dentine, enamel or acrylic. The performance of a brush design is usually compared with that of a standard brush using a standard toothpaste.

The effects of some key brushing parameters on abrasive cleaning have been studied using both *in vivo* and *in vitro* testing. Brushing load and technique as well as filament stiffness and orientation are thought to have an influence [1, 5, 6, 7, 8]. There is, however, no clear understanding of why these parameters affect cleaning effectiveness.

Brush designs are becoming more complex and may incorporate filaments at various angles and different lengths and use several different materials. In order to understand how the tooth cleaning process occurs there is a need to investigate in detail how the abrasive particles in a toothpaste interact with the filaments in a teeth cleaning contact and cause material removal from a plaque or stain layer. New testing techniques are required to carry out such studies as current test methods, described above, are only able to give the final result without giving information about mechanisms occurring in the contact.

The objectives of this work were to use an engineering approach to devise a means of observing simulated tooth cleaning contacts using optical apparatus and to use this to study particle entrainment into the contact and how it differs with varying toothbrush bristle configurations. The effect of filament stiffness and tip shape were also investigated. Particle entrainment with different electric toothbrushes was also investigated.

2 VISUALISATION APPARATUS

In tooth brushing two techniques are generally used; a short uni-directional stroke and a reciprocating brushing motion. In order to study particle entrainment for various brush designs, two rigs, one to simulate each type of motion, were developed.

2.1 Sliding Apparatus

Simple optical apparatus was used to enable the visualisation of a simulated teeth cleaning contact using uni-directional sliding (shown in Figure 1). A toothbrush head is loaded against a rotating glass disc using a hydraulic actuator. The toothbrush head is located in a clip attached to the hydraulic actuator. Load was varied either by using the actuator or by varying the displacement of the toothbrush head relative to the glass disc (and hence the filament deflection) using spacers. The fluid/abrasive particle mixture is applied either to the brush head prior to loading against the glass disc or fed into the contact as the disc is rotating.

The contact region was observed using a positionable microscope attached to the rig. Image capture was by CCD video camera or short duration flash photography.

2.2 High Frequency Reciprocating (HFR) Rig

A high frequency reciprocating (HFR) rig was set-up as shown in Figure 2 in order to enable visualisation of the cleaning contact. The toothbrush head is clamped in position and the fluid/particle mixture was applied to the top of the filaments. A colourless perspex counterface on the end of an arm attached to an oscillator is then loaded against the toothbrush head. A power amplifier was used to control the frequency and amplitude of the reciprocating motion. The contact region was again viewed through a microscope.

3 EXPERIMENTAL DETAILS

3.1 Specimens

Standard toothbrushes consisting of equi-spaced tufts of filaments of equal length were used in the tests to study particle entrainment and the effect of fluid viscosity, brushing load and speed (as shown in Figure 3).

Subsequent tests, to study the effect of filament configuration, length, angle and stiffness on particle entrainment, used several different toothbrush head designs (as shown in Figure 4).

Tests were also carried out using a toothbrush with a flexible head design. The brush head consists of stiff and flexible regions intended to allow the filaments to adapt to the contours of the teeth.

Tests were run using a brush with flat filament tips to provide a comparison with the rounded tips used in all the other tests outlined.

Two different types of electric toothbrush were tested. The first, shown in Figure 5, has a rotary action and the other simply vibrates. The head of the rotary action brush is circular and consists of two rings of filaments, the inner ring being slightly shorter than the outer ring. The head rotates 15° either side of the central position. The motion was frozen using a stroboscope. This indicated that the brush operates at 1600 rpm. The vibrating brush has a conventional toothbrush head.

Large (200-300μm) coloured silica particles were used in the initial tests because they were easy to observe during motion. Later tests used ~10μm silica particles which are typical of the abrasives used in many toothpastes. The fluids used were glycerol or water. Particle/fluid mixtures were made up at 1% concentration by mass.

3.2 Operating Conditions

Loads and brushing speeds used in the tests were based on reported measurements taken during *in vivo* experiments [5, 6]. Loads ranged from 250g to 900g and brushing speeds from 3cm/s to 15cm/s.

In the reciprocating motion tests, amplitude and frequency were varied to establish their effect on particle entrainment (amplitudes used were 0-2mm and frequencies 1-2Hz).

In all tests the particle/fluid mixture was applied to the filaments prior to the glass disc/perspex counterface being placed on the apparatus.

4 RESULTS

4.1 Filament Deformation

As shown in Figure 6a, in the sliding motion tests the filaments all deflected in the opposite direction to the brush motion on loading. As the filaments pressed against the glass a contact point at each tip was visible (see Figure 6a). As the load was increased the filaments deflected further and the contact point with the glass moved down the filament, taking on an oval rather than round shape (see Figure 6b). As will be described in subsequent sections, particles passed through the filament tips and accumulated around the contact regions. Some entered these regions and became trapped between the tips and the glass disc.

When using equi-spaced tufts of straight filaments of graduated lengths the filaments splayed in all directions on loading and few clumps of filaments formed (see Figure 7a). Tufts of angled filaments pointing in opposite directions deflected in whichever direction they were angled on the brush head (see Figure 7b).

4.2 Particle Motion and Trapping

With sliding motion using the standard toothbrush design (see Figure 3), when the disc rotation was started and the simulated sliding brush motion began, the fluid and particle mixture moved around the filament tips pressed against the glass. When using 10μm silica particles mixed with water, particles were seen to accumulate evenly at the edge of the filament tip contacts, as shown in Figure 8. During and after the accumulation process particles were seen to pass from the edge of the accumulation into the filament tip contact region and circulate around before passing back into the accumulation of particles (see Figure 8), while others remained in the tip contact. Raising the brushing speed increased the particle motion.

When using a reciprocating motion, particles were trapped at the filament tip contacts as shown in Figure 9. Generally particles remained trapped as the frequency and amplitude were increased and more water was applied, although a few particles were seen to work their way in and out of the tip contact region. This differed from tests run with sliding motion where particles were dragged though the filament tip contacts.

When using higher loads with a sliding motion the filaments deflected further moving the contact region slightly down the filaments. When using 10μm silica particles mixed with water the particles were again seen to gradually accumulate around the edge of the filament tip contact, as shown in Figure 10. The particle formation took on an oval shape due to the different contact geometry and greater numbers built-up behind the tip contacts as if stagnation regions had formed. Less particles were trapped overall than at lower loads.

As the accumulation process was occurring, particles were seen to pass through the filament tip contact as shown in Figure 11. Once the accumulation process had finished, however, no particles were visible in the filament tip contact region.

When using equi-spaced tufts of straight filaments of graduated lengths with a sliding motion the filaments splayed in all directions on loading (see Figure 7a). As a result there were few filament clumps in which particles could become entrained and particles were able to force their way through those that did form as they were so small and loose (see Figure 12).

On loading, tufts of angled filaments were deflected further in whichever direction they were angled on the brush head, but still remained clumped (see Figure 7a). Particles entrained at the ends of these tufts remained so (see Figure 13).

4.3 Effect of Stiffness and Filament Tip Shape

The large tuft of relatively stiff filaments used to investigate whether filament stiffness played a role in particle entrainment deflected little on loading. It was found that particles trapped initially remained lodged in their original positions (see Figure 14). More flexible filaments, under the same applied load, deflected more and splayed out. Particles were therefore able to pass through the filament tips and less particle trapping occurred (see Figure 14).

On loading the toothbrush with a flexible head design particles were observed to move out of the filament tufts initially, especially in the flexible region of the head. More particles were entrained in the tufts of filaments in the stiff region of the head (see Figure 15). Increasing the velocity increased the particle movement. These results are similar to those observed for the stiff and flexible filaments.

When using flat ended filaments at low load with a sliding motion, particles were trapped under the filament tip where it made contact with the glass disc, as shown in Figure 16. Particles were seen to move around under the rest of the filament tip moving in and out of the tip contact region. This was different to the accumulation seen with a rounded filament tip, as shown in Figure 8, where far more particles were trapped.

When using flat ended filaments at an increased load, a small number of particles were seen to accumulate behind the point where the filament was in contact with the glass disc (see Figure 17). It is unlikely these particles were under any load in this position. No particles were trapped in the filament tip contact region. Again this differs largely from the particle trapping for a rounded filament tip at higher load (see Figure 10).

4.4 Electric Toothbrushes

When using the rotary action brush, particle entrainment within the contact was very different from tests run with a conventional brush. Particles were more easily able to move through the filament tips. This was mainly because of the filament tuft arrangement, but also because the filaments were moving relative to the counterface. Trapped particles were agitated within their position (see Figure 18a), which was also not observed with manual brushing simulations. Rotation of the glass disc increased the particle motion. There was a flow of fluid around the edge of the outer ring of filament tufts. This moved particles in and out of the edge of the filament tip region.

When using the vibrating brush “swirls” were visible indicating the path of the filament tips against the glass disc (see Figure 18b). These indicated that the tips followed an orbital path which was approximately twice the length of a filament diameter (~0.4mm). Particle motion was highest in the filaments that were more splayed out and particles were again agitated within their position. Rotation of the glass disc promoted particle movement through the contact. Increasing the load stopped the motion of the filaments.

The light loads used in the tests meant that only slight deflection of the filaments occurred. As with tests run with a reciprocating motion, particles were trapped in the tip contact region rather than just accumulating at the edge of the contact.

DISCUSSION

The particle entrainment process in a model teeth cleaning contact occurs in the following manner; Particles, suspended in fluid, approach the filament tips, as they pass through they may become trapped. Where and how the particles are trapped depends largely on the brushing action, the applied load to the filaments, and hence the degree of filament deflection.

When using a sliding motion small particles build-up at the edge of the filament tip contact and enter and circulate in the contact. Increasing the load changes the contact geometry and leads to less particles remaining in the tip contact region. Larger particles tend to be trapped between the filament tips with only a few entering the tip contact region. At higher loads and hence deflections the particles are trapped under the end of the filaments and none enter the contact regions.

When using a reciprocating motion far more particles are trapped in the tip contact regions than with the sliding motion and they are only dislodged at high amplitudes or frequencies.

Whether the particles are likely to be trapped and how long they remain so depends on the filament stiffness, and hence degree of splay on loading and the filament configuration.

The direction the filaments point in, the number of filaments in a tuft, the spacing of the tufts and the way the filaments splay when deflected all have an influence on entrainment of particles. Tufts with tightly packed stiff filaments which deflected together on loading were more effective at trapping particles than tufts with more flexible filaments that splayed out on loading as they present more of a barrier to particle entry and exit from the tip region.

For all the tests carried out using the optical apparatus the toothbrush head was loaded against the glass disc as shown in Figure 19 (i.e. initial brush configuration perpendicular to the surface). Different brushing techniques, however, may cause the brush head to be used in different orientations, as shown in Figure 20. Clearly this will influence the effect the filament configuration has on entrainment and filament deflection will certainly not be uniform in the cleaning contact.

The tests carried out using the optical apparatus employed a flat counterface. In reality the tooth surface is full of grooves and crevices. This will obviously affect particle entrainment to a similar degree as toothbrush head orientation. It seems likely that filaments that splay more will be more able to enter the grooves and crevices in a real tooth surface.

Rounded filament tips have been recommended in the past as flat ended filaments have been shown to cause soft tissue damage [9]. This was thought to be due to the sharp edges present on the flat ends. This study has shown that flat ended filaments entrain and trap less particles at the filament tip region than filaments with rounded tips which implies that filaments with rounded tips should also give a higher cleaning efficiency.

Electric toothbrushes increase the particle motion and agitate trapped particles. At high loads, however, the filament motion is decreased.

CONCLUSIONS

Optical apparatus has been used to visualise a model teeth cleaning contact. Using the apparatus it is possible to vary parameters such as brushing load and speed.

Visualisation tests run using the apparatus to study particle entrainment into the cleaning contact using various toothbrush designs, have shown that:

- With a sliding motion small particles accumulate around the edge of a filament tip contact with some being entrained into the tip contact.
- With reciprocating motion more particles were trapped in the filament tip contacts than with sliding motion.
- At higher load no particles were trapped in the filament tip contacts.
- With large particles there are two distinct particle trapping mechanisms depending on the brushing load. At low load the particles are trapped in amongst the filament tips with a few entering the tip contact regions, whereas at higher loads most particles are all wedged under the bend in the filaments.
- Some brush designs were more effective at trapping abrasive particles than others, in the apparatus described. Typically where filament tufts deformed and splayed uniformly against the counterface good particle trapping was observed.
- Flat ended filament tips were less effective than rounded filament tips at entraining and trapping particles.
- Electric brushes caused greater particle motion and agitated trapped particles.

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Figure Captions

Figure 1 Sliding Visualisation Apparatus

Figure 2 Reciprocating Visualisation Set-up

Figure 3 Standard Toothbrush used During Visualisation Studies

Figure 4 Different Filament Configurations used during Visualisation Studies

Figure 5 Rotary Action Electric Toothbrush Head

Figure 6 Deflected Filament and Tip Contact at: (a) Low and (b) High Loads

Figure 7 Deflection of Filaments of Graduated Length (a) and Angled Filaments (b)

Figure 8 Particle Trapping with Sliding Motion

Figure 9 Particles at a Filament Tip with Reciprocating Motion

Figure 10 Particle Trapping with Sliding Motion at Higher Load

Figure 11 Particle Entrained into a Filament Tip Contact

Figure 12 Filaments of Varying Length Under Load with Particles Entrained

Figure 13 Angled Filaments Under Load with Particles Entrained

Figure 14 Particle Entrainment with Stiff and Flexible Filaments

Figure 15 Filaments in Flexible and Stiff Brush Head Regions Under Load with Particles Entrained

Figure 16 Particle Trapping with Flat Filament Tips

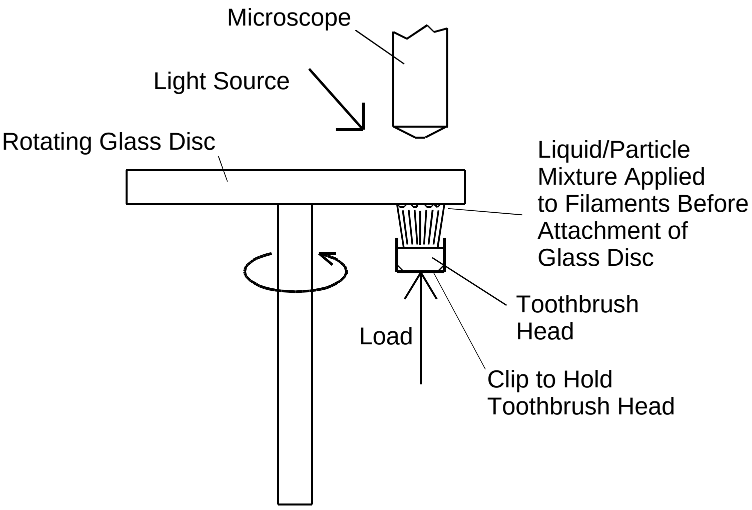
Figure 17 Particle Trapping with Flat Filament Tips at Higher Load

Figure 18 Particle Trapping and Agitation (a) and Filament Tip Motion (b) when using an Electric Toothbrush

Figure 19 Orientation of a Toothbrush Head in the Optical Apparatus

Figure 20 Alternative Toothbrush Orientation

Figure 1



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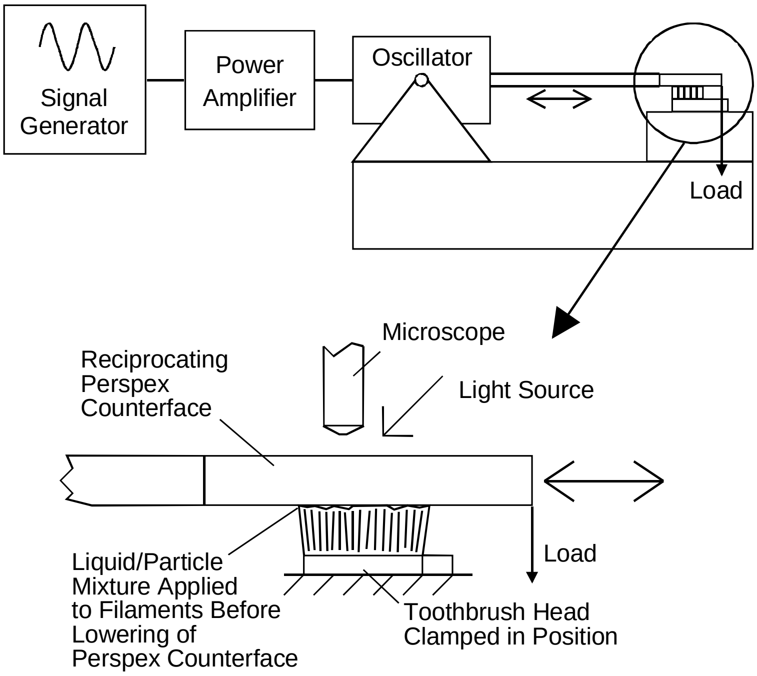

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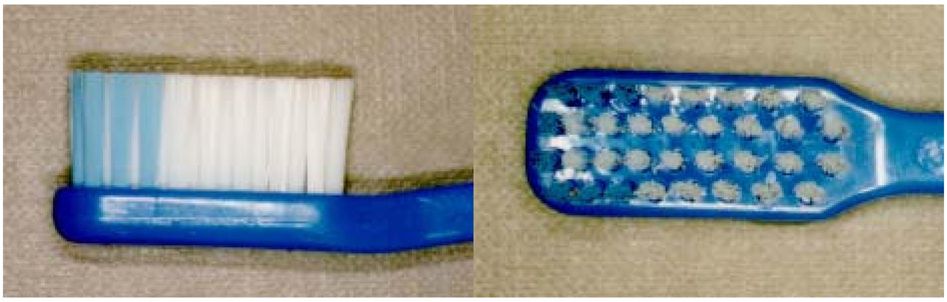

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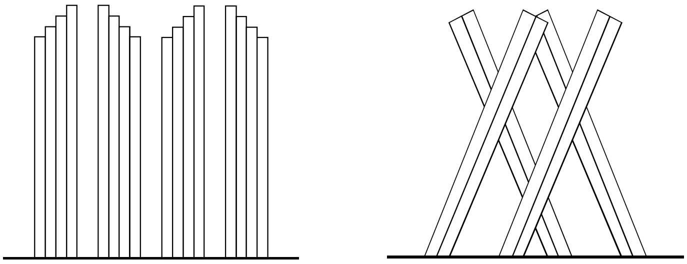

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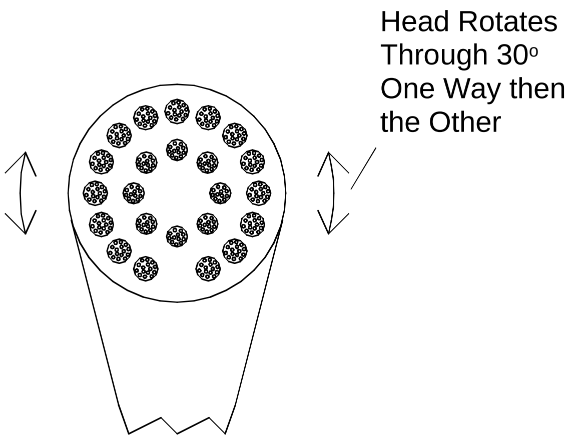

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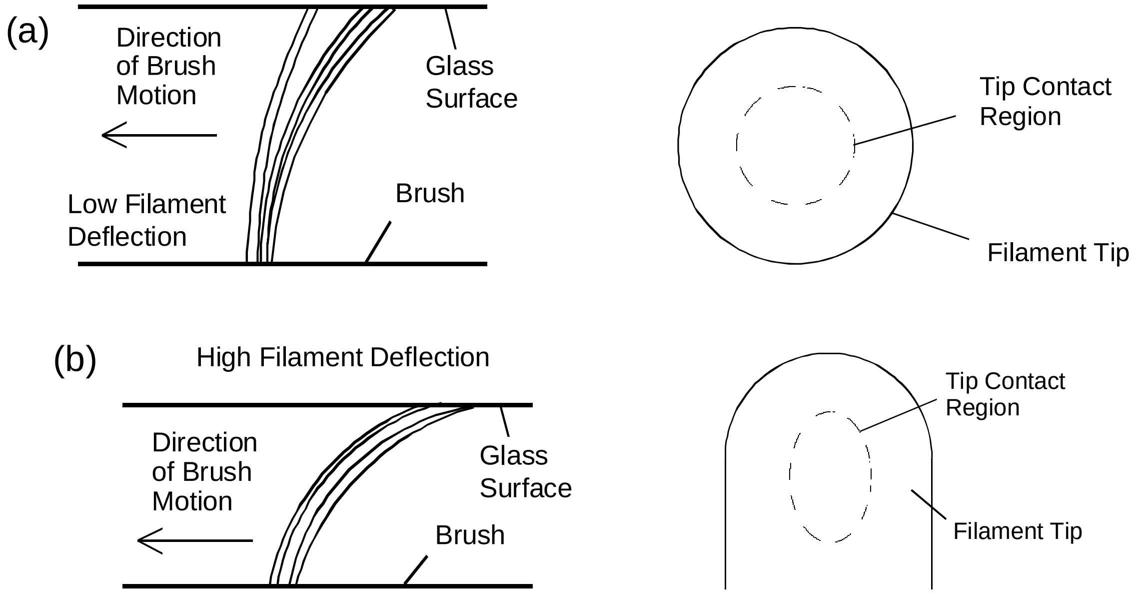

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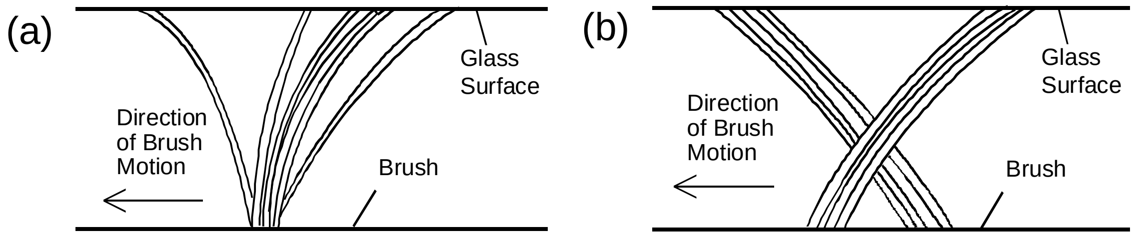

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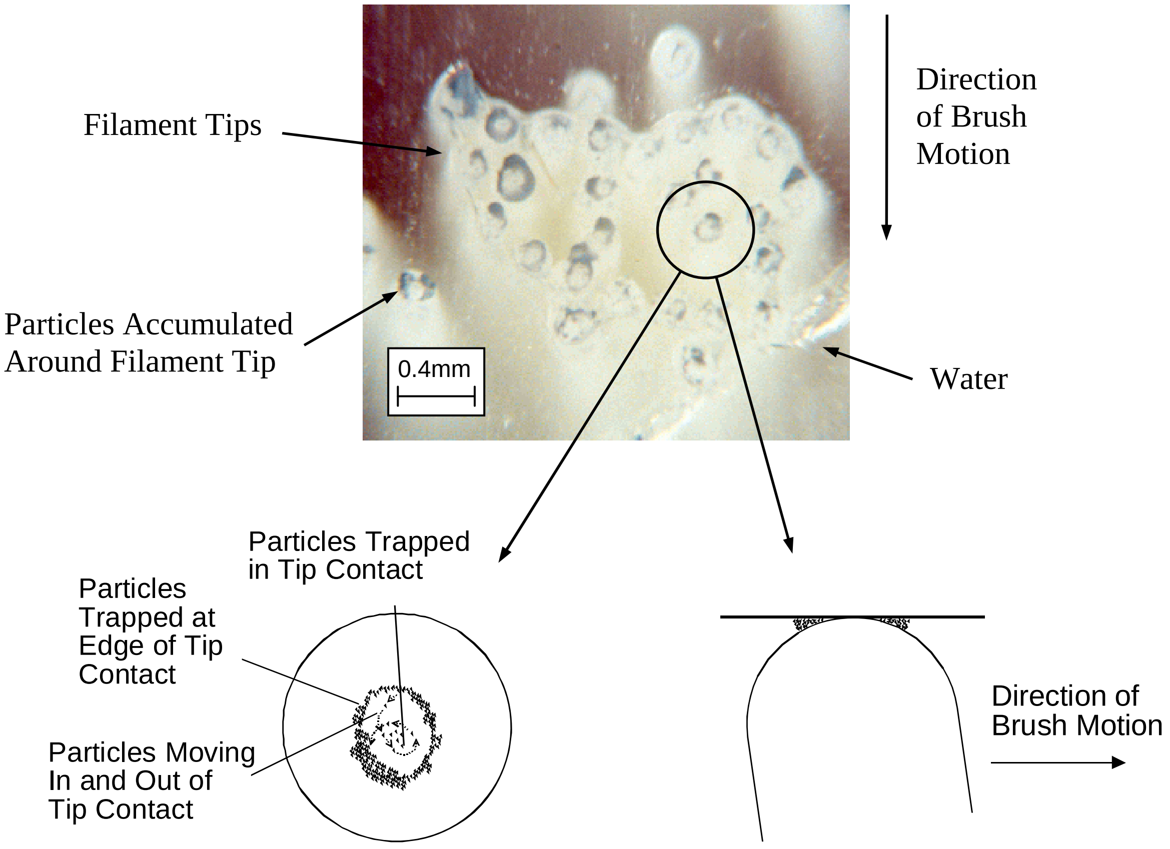

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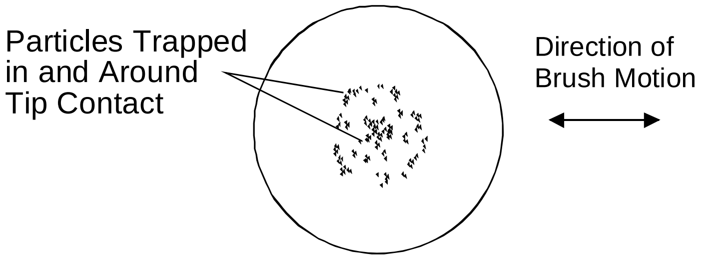
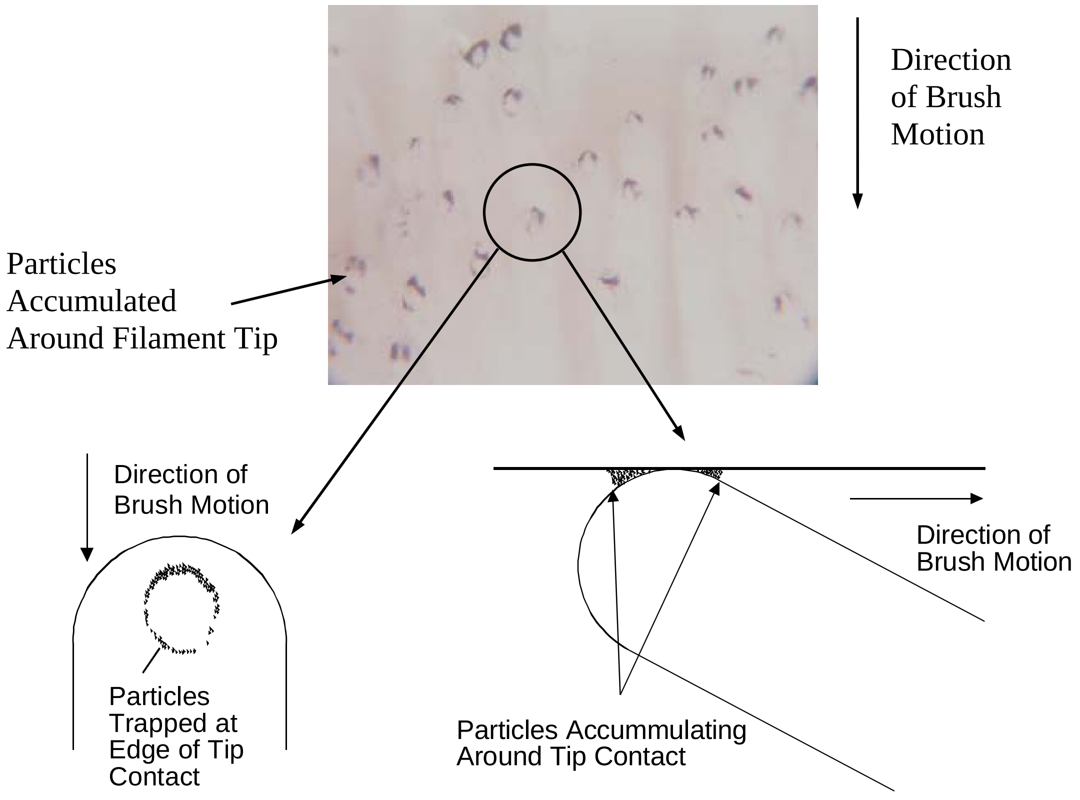


Figure 10



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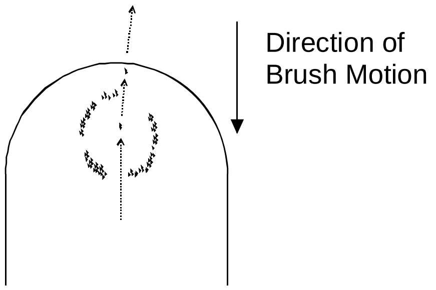

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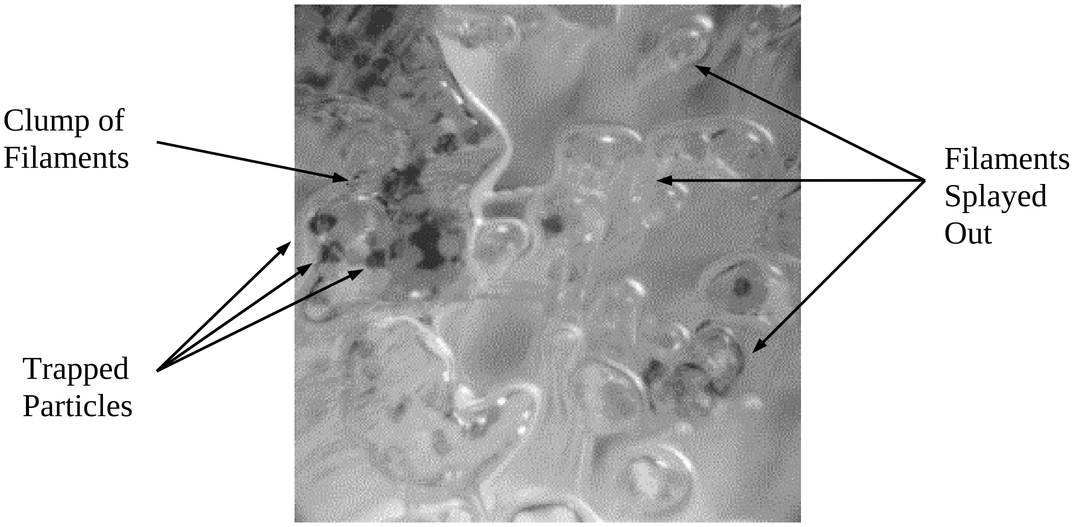

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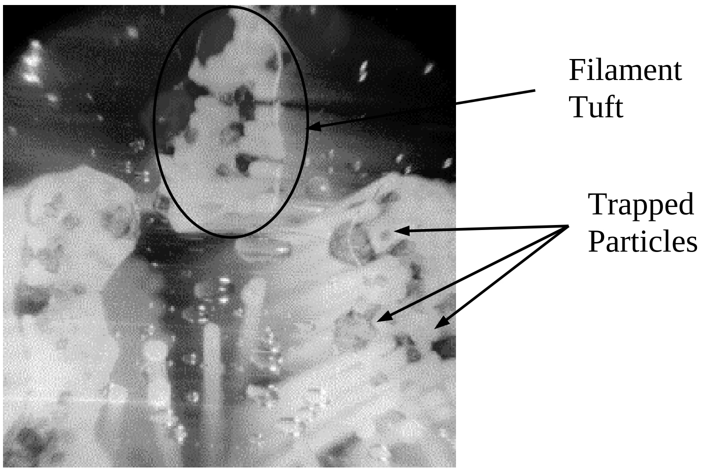

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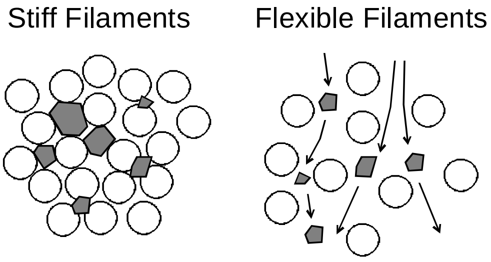
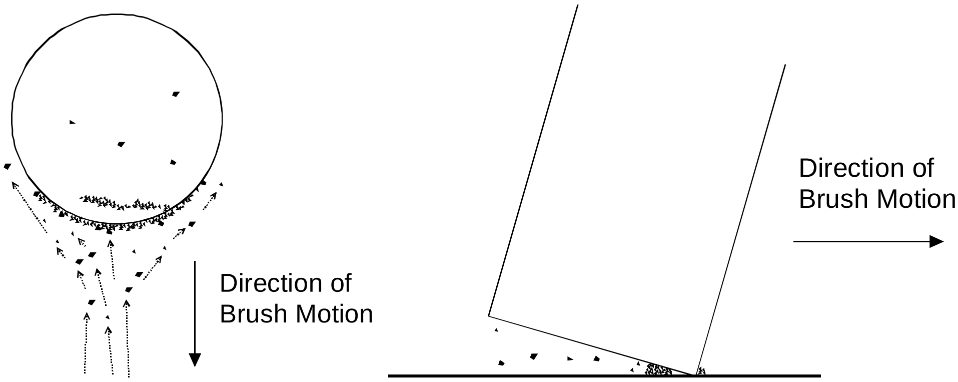


Figure 15

Figure 16



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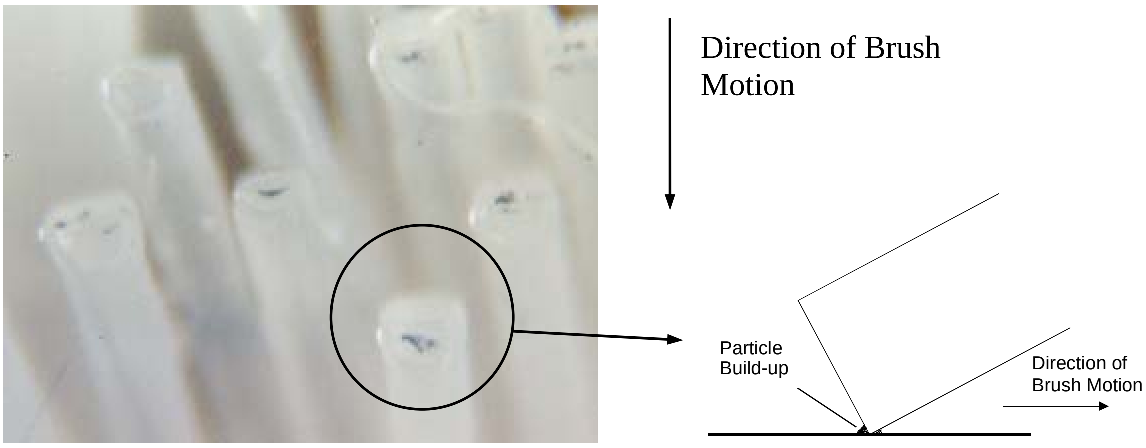

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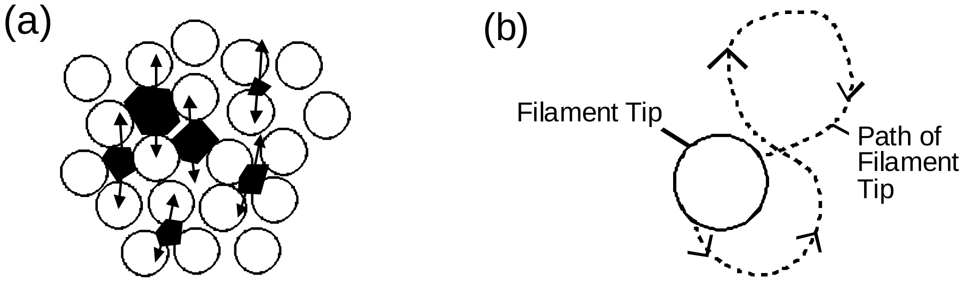

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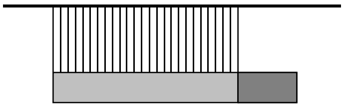

Figure 21