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# **INTERACTIONS BETWEEN TOOTHBRUSH AND TOOTHPASTE PARTICLES DURING SIMULATED ABRASIVE CLEANING**

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## **ABSTRACT**

Most people clean their teeth using toothpaste, consisting of abrasive particles in a carrier fluid, and a filament based toothbrush to remove plaque and stain. In order to optimise cleaning efficiency it is important to understand how toothbrush filaments, abrasive particles and fluid interact in a tooth cleaning contact.

Work has been carried out to visualise, simulate, and model the processes in teeth cleaning. Laboratory cleaning contacts were created between a toothbrush and a transparent surface. Video and short duration flash photography were used to study the processes by which a toothbrush traps abrasive particles, loads them against the counterface, and removes material. Small abrasive particles tend to be trapped at the contact between the filament tip and the counterface, whilst larger particles are trapped by clumps of filaments or at the contact with the side of a bent filament.

Measurements of brush friction force were recorded during cleaning for a range of operating conditions. The presence of abrasive particles in the cleaning mixture increased the coefficient of friction, but the absolute particle concentration showed a lesser effect. It is

surmised that only a few particles carry any load and cause any abrasion; increasing the particle concentration does not directly increase the number of load bearing particles.

Abrasive scratch tests were also carried out, using PMMA as a wearing substrate. The scratches produced during these tests were studied. The microscopy images were used to deduce how the filaments deflect and drag, and how particles are trapped by filaments and scratch the surface. Again, it was observed that few of the brush filaments loaded particles to produce scratches, and that when a filament changes direction of travel the trapped particle is lost.

Results of these studies were used to develop both qualitative and quantitative models of the process by which material is removed in teeth cleaning. The quantitative model contains, by necessity, several empirical factors, but nonetheless predictions compare well with *in vitro* wear results from the literature. The results were also used to draw some broad conclusions on appropriate brushing techniques for optimum tooth cleaning.

**Keywords:** teeth cleaning, abrasive particles, toothbrush, toothpaste

## 1 INTRODUCTION

Teeth are usually cleaned using a toothpaste, consisting of abrasive particles in a carrier fluid, with a filament based toothbrush. Toothbrush 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 operate by mechanically loading and moving a toothbrush head over a test specimen made from dentine, enamel or acrylic. The performance of a new brush design is usually compared with that of a standard brush and

toothpaste. Measurements are made of material removal or the colour change of an applied stain. Toothpastes are tested in a similar manner, by comparison with a standard toothpaste under standardised conditions of load, number and direction of brushing strokes and toothpaste slurry concentration (typical standards include [5] and [6]).

The effects of some key brushing parameters on abrasive cleaning have been studied using both *in vivo* and *in vitro* testing. Loads applied during toothbrushing, measured using instrumented toothbrushes [7, 8], are thought to have a significant effect [7, 9]. Brushing technique also has an influence. Differences have been found in dentine wear as a result of using a vertical uni-directional brushing technique as opposed to a horizontal cross-brushing technique [1, 10]. It has also been noted that filament stiffness as well as filament orientation and tip shape will also play a part, as yet unquantified [11]. There is, however, no clear understanding of why these parameters affect cleaning effectiveness.

In order to understand how the cleaning process occurs and how to make efficiency improvements there is a need to investigate in detail how the abrasive particles in toothpaste actually 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 whilst giving little information about mechanisms occurring in the cleaning contact.

Visualisation studies have been carried out by the present authors [12] that have indicated how abrasive particles interact with the tips of toothbrush filaments. Uni-directional sliding and reciprocating brush motions were investigated. Figure 1 shows a photomicrograph of a clump of filaments sliding against a glass surface with 7  $\mu\text{m}$  silica particles. The particles are trapped at the tip of the toothbrush filament where it contacts the counterface. Particles suspended in fluid approach the filament, as they pass through the contact between the tip

and counterface contact 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, and the particle size.

The particles build-up at the edge of the filament tip contact and enter and circulate in the contact, as shown in Figure 2a. Increasing the load changes the contact geometry and leads to less particles remaining in the tip contact region (see Figure 2b). 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.

Greater particle entrainment into the filament tip contact occurred with a reciprocating action at low filament loads and deflections than with a uni-directional sliding motion. Increasing brushing speed leads to greater particle motion around the filament tips.

The aim of the present study was to extend this work and apply an engineering approach to studying the actual mechanism of material removal in a model tooth cleaning contact. The objectives were to study the effects of particle trapping at a filament tip using both friction and abrasion tests. This was then related to observations made during the visualisation studies and a theoretical analysis of particle indentation and scratching to develop a teeth cleaning model.

## **2 FRICTION TESTING**

In tooth cleaning the friction force arises from; the contact between the filaments and the counterface, capillary forces, and the ploughing force caused by the particles abrading the surface. In these tests the overall friction force was measured as the concentration of particles was varied. The intention was to relate the measured friction force to the abrasive behaviour of the particles.

### **2.1 Test Apparatus and Operating Conditions**

Figure 3 shows the experimental apparatus. Standard toothbrushes (see Figure 4) were deadweight loaded against a PMMA surface and slid at constant velocity (the standard brush has 34 evenly spaced tufts of 36 nylon filaments; the filaments are 11.2mm long and 0.2mm diameter and have rounded tips). The force transducer records the brush tractive force continuously. Mixtures of water, glycerol, and abrasive particles were applied directly to the brush head. The initial position of the brush filaments (i.e. splayed or all orientated in one direction) was seen to cause little difference to the measured steady state friction force. As soon as the counterface starts moving the filaments rapidly re-align so that they point away from the direction of travel. The stiffness of the loading arm is such that it allows some vertical deflection to allow the filaments to re-align in this way.

Tests were performed with 5  $\mu\text{m}$  calcite particles (commonly used toothpaste abrasive), mixed at various concentrations with glycerol or water in equal proportions. The liquid mixture has a similar to the viscosity of toothpaste when diluted with saliva in the mouth during normal brushing.

Loads and brushing speeds used in the tests were based on reported measurements taken during *in vivo* experiments [7, 8]. Loads ranged from 1.8N to 3.7N and brushing speeds from 3cm/s to 15cm/s (although varying the brush speed had negligible effect on the measured friction force).

## 2.2. Results

Table 1 shows the mean friction coefficient varying with load and particle concentration (three tests were performed for each case). The addition of liquid causes a large fall in friction, presumably by lubricating the contact between the filaments and the counterface (all brushes were soaked in water for 20 minutes before use as gradual water uptake into the nylon filaments tended to occur).

The addition of a very low concentration of solid particles (0.2%) causes the friction coefficient to increase by around 25-30% (except for the intermediate load, where the increase was lower). Increasing the level of particle concentration then has only a minor effect on the friction coefficient (as shown in the logarithmic scale graph in Figure 5).

The effect of brush load is that it increases the area of contact between the filaments and the counterface, as the filaments deflect and conform to the surface. This causes the friction coefficient to rise. The effect of particle concentration is surprising, even increasing the concentration by 100 times has a very small effect. There are two possibilities, either the particle abrasive ploughing component of friction is small, or that the majority of the abrasive particles play no part in the frictional interaction.

If we assume an abrasive particle is pressed into the PMMA surface to a depth of, say, 2  $\mu\text{m}$ , then, since the hardness of PMMA is 0.5 GPa, the force required to plough the particle through the surface is approximately 0.002 N (further calculations along these lines are

presented in section 4 of this paper). This represents some 0.5% of the total tractive force. It is conceivable therefore that 50 particles could be ploughing at any one time and causing the observed 25-30% rise in friction coefficient. Each toothbrush has 1360 filaments, so this would indicate that 1 in 27 filaments is causing an abrasive action. However, adding further particles does not cause this to rise further.

The visualisation studies of [12], tended to show that only a few particles in the brush counterface contact carry any load. The other particles are free to move throughout the fluid or remain loosely held between filaments or against the surface. Increasing the concentration does therefore not increase the number of particles carrying and load.

### **3 ABRASION TESTING**

Abrasion tests were carried out in order to deduce further information about the toothbrush cleaning action from the morphology of the scratches formed. The approach enables the study the material removal process and to determine the number of particles trapped at filament tips and causing damage.

#### **3.1 Test Apparatus and Operating Conditions**

Tests were carried out using a high frequency reciprocating (HFR) rig (see Figure 6). A PMMA specimen was clamped into a stationary holder mounted on the base. The toothbrush head is clamped to the end of an electrically driven reciprocating arm. A deadweight is hung on to the toothbrush head, suspended below the PMMA specimen. A function generator and amplifier are used to drive the oscillator at controlled frequencies and amplitudes.

Abrasion tests were carried out with the same standard brush design used for the visualisation and friction studies. Diamond particles (1  $\mu\text{m}$  in size and mixed with glycerol) were used in initial tests as they produced deeper more visible scratches and the intention was to study the behaviour of particles trapped at a filament tip rather than the scale of damage caused.

The fluid/particle mixture was applied to each PMMA specimen using a pipettor to ensure an equal amount was used for each test. The toothbrush head was then loaded against the PMMA specimen. Tests were run for short periods (50 cycles) in order to determine the number of particles scratching at a particular moment as well as longer tests (4500 cycles) to study how particle trapping evolved as brushing was continued. The oscillator was operated at a frequency of 5 Hz, and a peak to peak distance of 5mm was used for all tests. Loads used were 2.5-4.4N.

## **3.2 Results**

### ***3.2.1 Typical Scratch Patterns***

After abrasion tests run with diamond particles for 4500 cycles, the scratch patterns observed were as shown in Figure 7. The picture shows the scratches beneath the passage of one clump of filaments. Each mark visible is made up of a series of scratches formed by particles trapped under one filament. Each filament clump in the toothbrush head used in the tests is made up of 40 filaments (and the brush consists of 34 such clumps). It was clear, by counting the groups of scratches, that not all the filaments were trapping particles (approximately 25% of filaments produced no scratches at any time). This ties in with the observations made when using the reciprocating rig, where it was seen that not all the filaments were contacting the counterface at low loads and particles were able to pass through unhindered. It is also clear that whilst there were 4500 cycles in the test, in an individual scratch cluster formed by a

single filament there are many times fewer scratches. Clearly, a particle is not abrading the surface during each cycle. The particles must stochastically attach themselves to a filament for one or more cycles and then be released.

The peak to peak distance moved by the reciprocating arm was 5mm. In Figure 7 it can be seen that the scratches are not 5mm long. Clearly there is some lag on the filament motion (see Figure 8). This effect has been observed previously [7], although it was not quantified. It is likely, given observations made during the visualisation studies, that on top of the filament lag there is a scratch lag. The filaments will probably move a certain distance before entraining and trapping a particle that then, when loaded by the filament against the counterface, will create a scratch. For a 5mm peak to peak arm movement the average scratch length was 1mm.

When running 50 cycle tests very few scratches were formed (see Figure 9). Most were single scratches rather than the groups seen after the 4500 cycle tests. Clearly at any instant very few particles are cutting and causing scratches. This also indicates that the series of scratches for each filament observed after the 4500 cycle tests were not caused by the same particle remaining trapped. Rather it is more likely that a particle is trapped and a single scratch is formed; on reversing direction the particle is lost; after a certain number of cycles another particle is trapped and a second scratch is formed and the particle is then lost and so on. It was found that at low load, approximately 10% of the filaments in contact produced scratches during the 50 cycle test.

### ***3.2.2 Types of Scratches Observed***

A number of different scratch “types” were observed after the abrasion tests, as shown in Figure 9.

The “single” scratches were observed after the 50 cycle tests. This indicates that particles do not necessarily remain trapped at a filament tip and that the “repeated” scratch patterns observed after the 4500 cycle tests may take many cycles to form. Most of the scratches are continuous grooves in the material surface, however a lesser proportion are discontinuous as shown in Figure 9c. These could be formed by either the particle tumbling through the contact or because the load on the particle is relieved as the filament intermittently transfers its load onto neighbouring filaments. The figure of eight loop or zig-zag repeated scratch formations (Figure 9d and e) occurred less frequently than the repeated single scratches indicating that particles only rarely stay trapped as the direction of brush head motion changes.

#### **4 THEORETICAL ANALYSIS OF TOOTHBRUSH ABRASION**

The preceding visualisation studies have shown qualitatively how the abrasive process takes place. Abrasive particles are trapped by the toothbrush filaments and pressed against the surface. Only a very few particles become loaded in this way, the majority remain suspended in the fluid or are loosely held around the filament sides. When the brush translates the filaments deflect initially without any slip occurring between the filament tip and the counterface. When the filament starts to slip against the counterface, an abrasive scratch is generated. Most of the time the particle remains stationary with respect to the filament and ploughs a straight scratch (two-body wear mode), but occasionally discontinuous scratches form (three-body wear mode). It is likely that when the brush changes direction, the particle will be lost from the contact.

In this section a simplified semi-empirical model of this abrasion process has been developed on the assumption of trapped particles indenting and scratching (clearly it is desirable that

particles are able to remove stain while not damaging the enamel surface during teeth cleaning). This was achieved by using a theoretical determination of particle indentation to calculate scratch depths and area and the proportion of material removed. Scratch test data was then used to determine the length of the scratch and the number of scratches likely to occur. Finally, the model was validated using experimental test data from the literature.

#### **4.1 Particle Indentation**

The model was developed assuming that a particle trapped at a filament tip acts like a micro-indenter (see Figure 10). Particles were assumed to be sharp cubes indenting on one corner.

Hardness,  $H$  ( $\text{N}/\text{m}^2$ ), is defined as the load,  $W$  (N) divided by the surface (pyramidal) area,  $A$  ( $\text{m}^2$ ) of the indentation. This can therefore be used to derive the depth and width of the indentation caused by a particle from the load exerted by the deflected filament. In scratching only the front part of the indenter (particle) is supporting the load so only this area should be considered (see Figure 11). The load on the particle is determined by dividing the brush load by the number of filaments in contact with the counterface.

#### **4.2 Scratching and Wear**

The volume of material displaced by the loaded particle can be calculated by multiplying the cross-sectional area of the indent formed,  $A_s$  (derived using the indentation depth and the particle geometry), by the length of the brush stroke,  $l$ .

However, this volume of displaced material does not necessarily equal the volume of material removed as wear debris. Firstly, because there will be elastic deflection of the surface during scratching and elastic recovery inside the scratch groove (see Figures 12a and 12b).

Secondly, the displaced material may plastically flow to form raised shoulders either side of the scratch [13, 14] (see Figure 12c).

In order to determine the actual amount of material lost for a given particle profile depth,  $\delta$ , two factors are therefore required; one to determine the remaining proportion of the indenter cross-sectional area,  $A_s$ , after elastic deflection and recovery has occurred ( $g$ ); a second to determine the proportion of displaced material lost as wear debris ( $f$ ). The volume removed from one scratch,  $V_s$ , is then given by:

$$V_s = fgA_s l \quad (1)$$

Values for factors  $g$  and  $f$  were determined from experimental data generated during scratch experiments on a range of materials to study surface elastic deflection, groove elastic recovery and plastic deformation [15]. The data was used to plot  $g$  (reduction in scratch cross-sectional area factor) and  $f$  (material loss factor) against  $E/H$  (see Figure 13).

### 4.3 Statistics of Particle Entrainment

The visualisation work has shown that not all the filaments were in contact with the counterface and of those that were only a certain proportion had particles trapped at their tips causing damage. To model this stochastic behaviour two further empirical factors are introduced; the proportion of filaments in contact with the counterface material ( $b$ ), and the proportion of these with a trapped particle ( $t$ ).

It was also clear from abrasion tests that the length of a brushstroke does not equal the length of a scratch formed by a trapped particle. This is because at the start of the stroke the filament tip does not slide against the counterface whilst its body deflects. A further factor was

required to determine the actual scratch length from the brush stroke length (a brush lag factor) ( $s$ ).

If there are  $N$  filaments on a brush, then the total scratch volume per brushstroke,  $V_b$ , is then given by:

$$V_b = NbtA_s gfls \quad (2)$$

#### 4.4 Comparison Between Model and Experiment

Equation 2 can then be used to estimate the material removal with toothbrush and abrasive slurry. The model has been compared with experimental data on simulated controlled toothbrushing from the literature [16]. This reference reports tests performed to simulate manual and automatic toothbrushing. Manual toothbrushing simulations were carried out using a load of 2.5N, a frequency of 3Hz and a peak to peak brush head displacement of 22mm. Automatic toothbrushing simulations were carried out using mechanical brushes loaded to 1.6N, operated at 30Hz, with a stroke length of approximately 0.4mm. Tests were run on dentin specimens (for 12 hours) and a range of dental materials (for 8 hours). Details of material properties are given in Table 2.

The material specimens used in the experiments were 5mm across so a filament/scratch lag factor,  $s$ , of 1 was used for manual simulations as it was thought that the lag effect would be negligible compared with the large movement of the brush head. The same value was also used for automatic simulations.

Values of  $f$  and  $g$  were estimated for the materials used in the simulated toothbrushing tests using the data presented in Figure 13. The brush area was larger than the specimens so that approximately 25% of the filaments were in contact, giving factor  $b$  a value of 0.25.

Results of the abrasion experiments carried out were used to determine a value for factor  $t$ . The scratches were counted and divided by the number of filament passes over the test area and the number of brush strokes. Approximately 10% of the filaments had particles trapped causing scratches at any one moment, giving  $t$  a value of 0.1.

Details of values of factors  $f$  and  $g$  are given in Table 2. All brushing parameters used in the predictions carried out are given in Table 2. Results for the predictions of Equation 2, using the inputs in Tables 2 and 3, are compared with the experimental data in Figure 14.

As can be seen the model produces reasonable predictions of wear to be expected over a range of materials, but especially for dentin. This is encouraging considering that several empirical factors are used in the model.

It is interesting to note that the scratching distance for the automatic and manual brushing simulations are approximately the same (691.2m for automatic compared with 864m for manual over 8 hours – calculated by multiplying the number of brush strokes by the brush stroke length and by  $s$ , the drag factor).

This indicates that the difference in wear is due to the lower load used. Electric brushes are generally designed so that the oscillating action of the filaments is inhibited as the load on the brush head is increased.

## **5 DISCUSSION**

The scratch and friction tests, alongside the previously visualisation work [10], have demonstrated some of the mechanisms of abrasive cleaning with a filament brush. Particles, suspended in the fluid approach the filament clumps and as they pass around the tips they may become trapped. Where and how the particles are trapped depends on the brush load,

and hence the degree of filament deflection, and the particle size. Lightly loaded brushes trap small particles under the filament tips, whilst heavily loaded brushes trap particles at the shoulder of the deflected filament or in between filament clumps. The particle is then pressed against the counterface by the deflected filament. These loaded particles then act in a predominantly two-body abrasive mode to scratch the surface. However, not all scratches are continuous, some are intermittent consisting of a line of short scratches a few microns in length. This is probably because the particle either tumbles in a three-body mode, or the load on the filament is relieved during the motion, by resting on other neighbouring filaments.

At any instant very few particles actually cause scratches and it is estimated that many filament passes take place before a scratch is created by all the filaments in contact. This is either because it takes a while for the particle to become trapped by a filament or because once trapped only a few particles are loaded in an orientation that actually cause abrasion. Increasing the concentration of particles does not appear to uniquely increase the chances of such an abrasive action taking place.

The above mechanisms are clearly complex, both the particle behaviour and the applicator behaviour are difficult to describe mathematically. Here a simplified semi-empirical approach has been adopted. The model is developed from the scratch test data and indentation calculations. Given the assumptions made regarding particle shape and scratch formation and the nature of the data regarding the number of filaments trapping particles and causing damage, this can only be considered a crude approach. The results of the comparisons between the model and test data, however, appear quite promising.

The input parameters for the model, however, were derived from scratch tests at one particular load. The visualisation studies showed that at different applied loads particle

trapping changed, it is probable therefore that these parameters will vary as load changes. The range of application of the model is therefore currently limited.

It would be interesting to extend the modelling to study the effects of using different brushing techniques. *In vitro* testing of toothbrushes and toothpastes have focused on two different tooth brushing techniques; a horizontal cross-brushing technique (see Figure 15a) and a vertical uni-directional brushing technique (see Figure 15b).

These two techniques correlate to those used in the visualisation studies (cross-brushing - reciprocating and vertical - uni-directional sliding). The visualisation studies carried out using reciprocating and uni-directional sliding can offer an insight to the cleaning power to be expected from using the two different techniques.

*In vivo* force measurements using toothbrushes [7, 19] have shown that a much higher force is exerted when using the vertical brushing technique (7.7N compared with 3.1-4.4N for the cross-brushing technique). It is likely that for the vertical technique the filament will deflect beyond the point where particles are trapped at the filament tip this combined with the observation that more particles are retained in the contact during reciprocating motion may indicate that cleaning power is higher with the horizontal cross-brushing technique. Greater knowledge of how the change in particle entrainment with larger filament deflections affects material removal is required before this can be confirmed.

As filament load is increased it is likely that the load transmitted to the particles trapped at filament tips will increase and higher cleaning power should be expected. There must be, however, given the observations at high filament deflections, a transition load where filaments bend over such that particles no longer trapped at a tip contact and are entrained under the bend of a filament and the load transmitted to particles decreases and subsequently material removal reduces.

An important aspect of tooth cleaning is the removal of a surface stain layer, without damage to the substrate. The enamel tooth surface is very hard, typically around 3-6 GPa [17], whilst dentine is much softer (typically around 0.5 GPa [18]). The experiments performed here are carried out scratching PMMA, which has similar properties to dentine. Clearly the level of damage observed here is closer to that which might be expected on dentine.

## 6 CONCLUSIONS

The presence of a water/glycerol mix causes a reduction in tractive force over a dry brush. This is presumably because the filament is lubricated as it slides against the wetted PMMA surface. When a very low concentration of particles is added (just 0.2%) this friction coefficient increases by 10-20%. The particles become trapped at the filament tips, disrupt lubrication between the filament and counterface and abrade the surface. Increasing the particle concentration does not change the friction greatly. This suggests that relatively few particles are carrying load at any instant.

The scratch tests indicated that few of the filaments in a brush cause any abrasive action. This is because only a proportion are loaded against the counterface initially and relatively few particles are trapped by these filaments. Further, of those that are trapped only a few are carrying load and orientated to create a scratch.

It was estimated that approximately 25% of filaments produce no scratches at any time. The scratching process is intermittent (approximately 10% of the filaments in contact produce scratches at one moment). In general particles do not stay trapped and each scratch is caused by a different particle.

The majority of scratches were continuous and indicated a two-body abrasion process caused by a single particle in one uni-directional pass of the filament. However, occasionally a

particle remained adhered to a filament and scratched on repeated reversals. In addition some scratches were observed to be intermittent indicated that the particle was not continuously loaded as it slides across the counterface.

A simplified model of the removal model was developed. This is based on the indentation and scratching of a single particle when loaded by a brush filament pressed against the counterface. Estimates of the probability of a particle being filament trapped and loaded by a filament were obtained empirically. The model shows a reasonable agreement with published experimental data on abrasion of several dental restorative materials.

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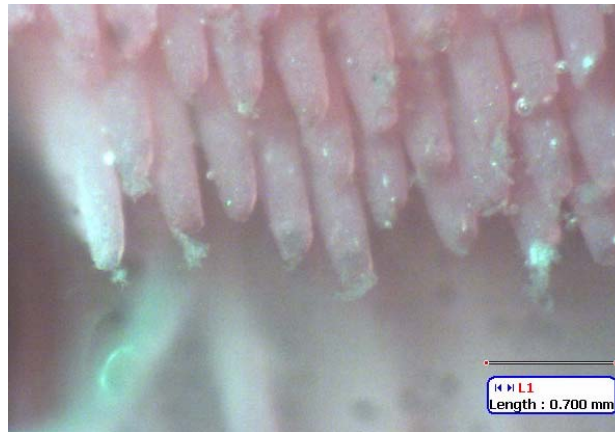
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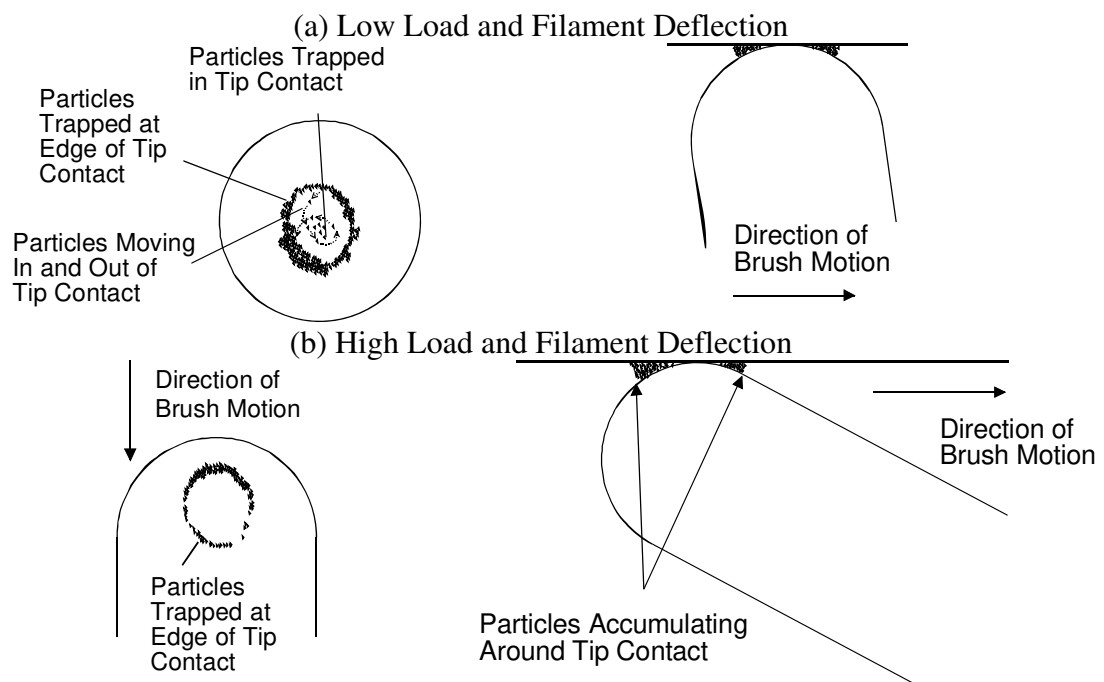
## Figure Captions

- Figure 1 Photomicrograph of a Clump of Filaments Sliding against a Glass Surface with 7  $\mu\text{m}$  Silica Particles
- Figure 2 Particle Entrainment at a Toothbrush Filament Tip at (a) Low Load and (b) High Load
- Figure 3 Friction Testing Apparatus
- Figure 4 Standard Toothbrush used During Friction Testing
- Figure 5 Friction Coefficient Variation with Particle Concentration and Brush Load
- Figure 6 High Frequency Reciprocating Scratch Test Set-up
- Figure 7 Scratches Formed by One Clump of Filaments (4500 cycle test)
- Figure 8 Single Filament in Contact with a Counterface Showing Filament Lag
- Figure 9 Different Types of Scratch Observed
- Figure 10 Particle Trapped at a Filament Tip
- Figure 11 Particle and Scratch Geometry
- Figure 12 (a) Illustration of Elastic Deflection of the Material Surface,  $d_e$ , with Total Penetration Depth,  $\delta$ ; (b) Remaining Scratch Profile Superimposed with Two Particle Positions to Illustrate Elastic Deflection of the Surface,  $d_e$ , Elastic Recovery in the Scratch Groove,  $d_r$  and Recovered Scratch Depth,  $d$  (c) Formation of Shoulders During Scratching
- Figure 13  $f$  and  $g$  against  $E/H$  (plotted using data from published scratch tests [15])
- Figure 14 Model Wear Predictions for Dentin and Dental Materials Compared with Experimental Data [16] (M - manual brushing simulation, A - automatic brushing simulation, error bars represent maximum and minimum experimental data)
- Figure 15 Brushing Techniques (a) Horizontal Cross-Brushing; (b) Vertical Uni-directional Brushing Technique

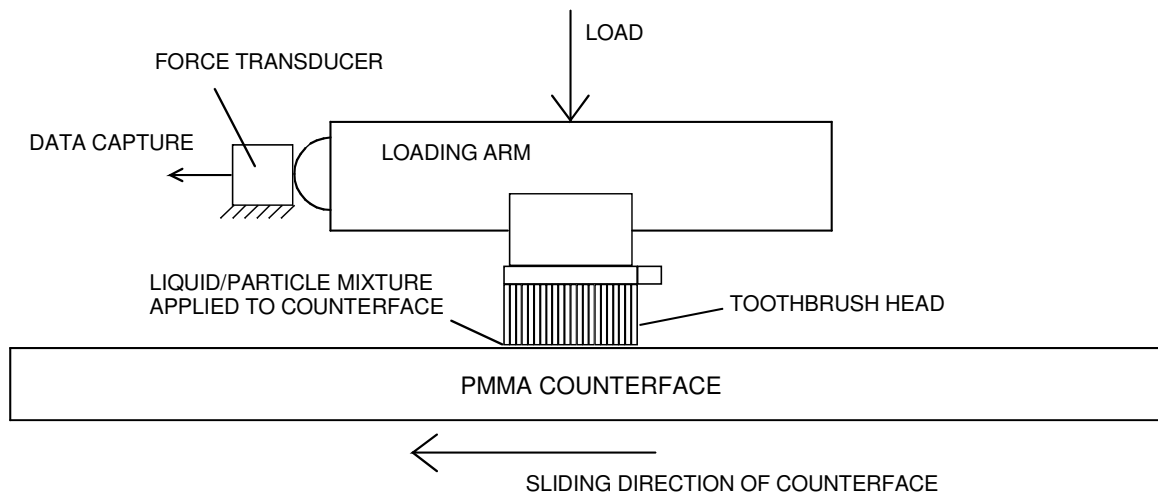
**Figure 1**



**Figure 2**



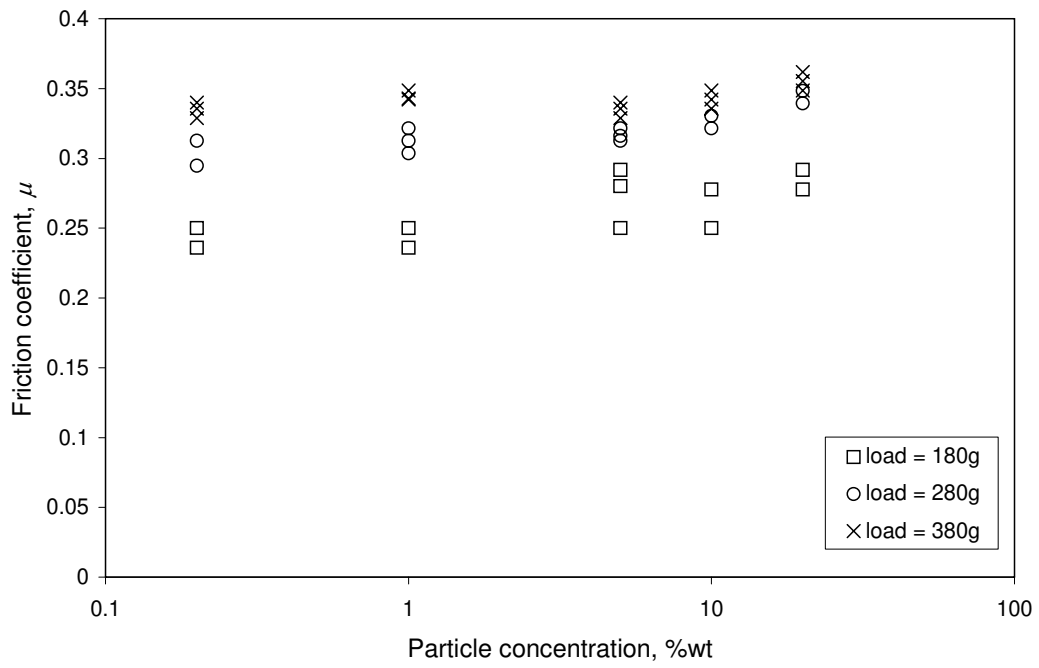
**Figure 3**



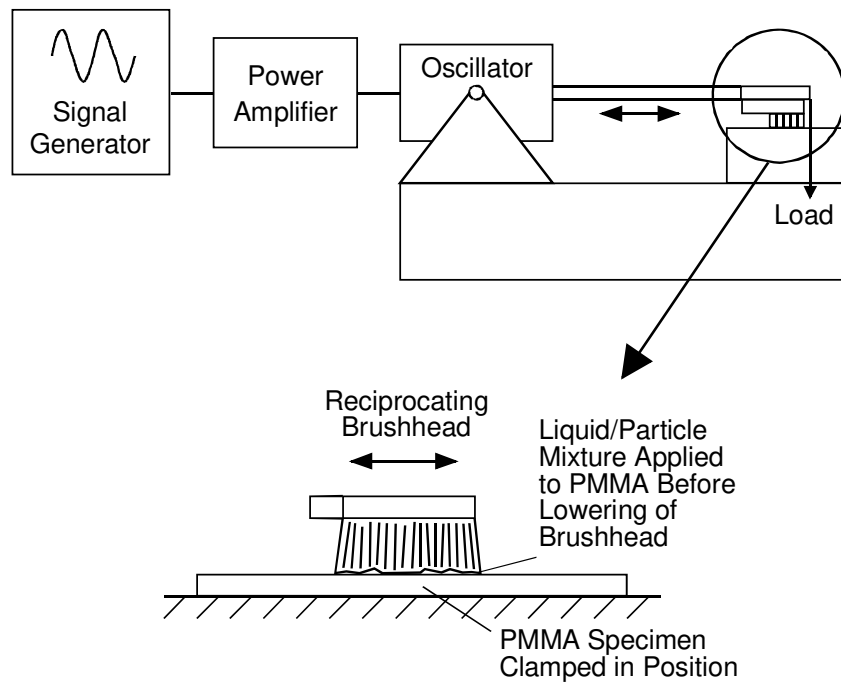
**Figure 4**



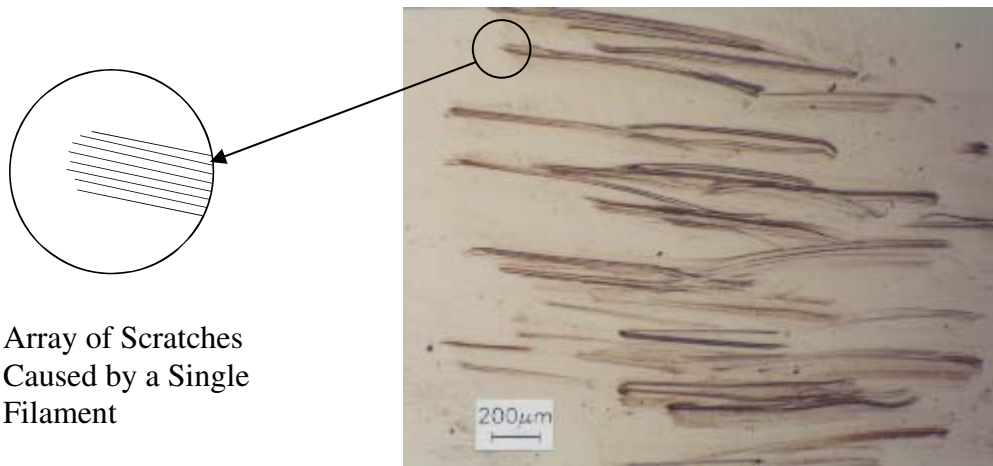
**Figure 5**



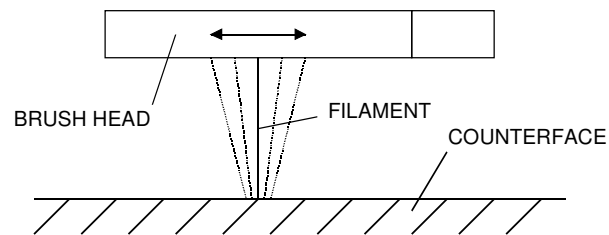
**Figure 6**



**Figure 7**

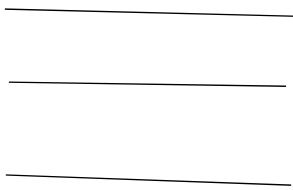


**Figure 8**

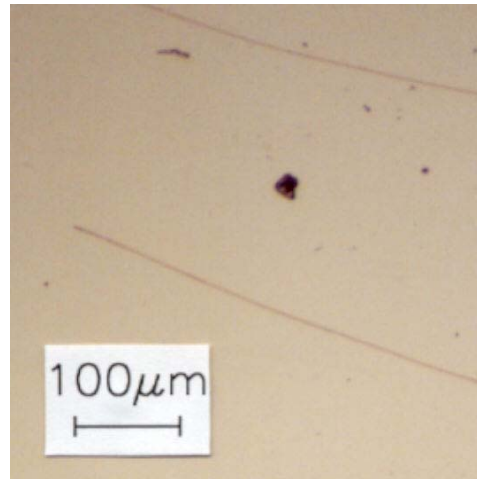


**Figure 9**

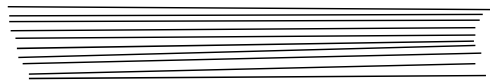
(a) Single scratches



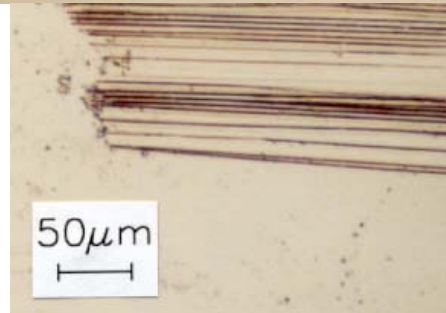
(50 cycle tests)



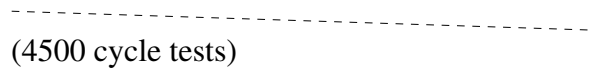
(b) Repeated individual scratches



(4500 cycle tests)



(c) Discontinuous scratches



(4500 cycle tests)

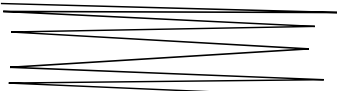


(d) Repeated looped scratches



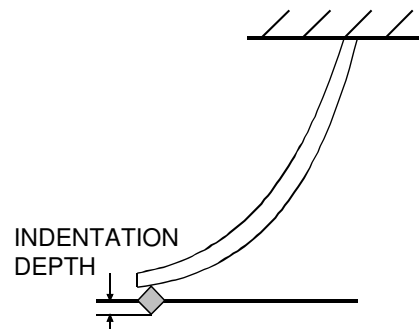
(4500 cycle tests)

(e) Repeated connected scratches

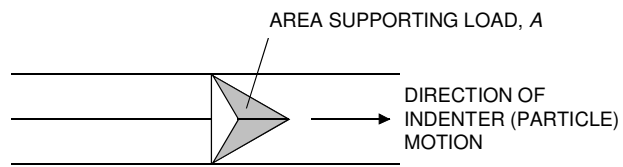


(4500 cycle tests)

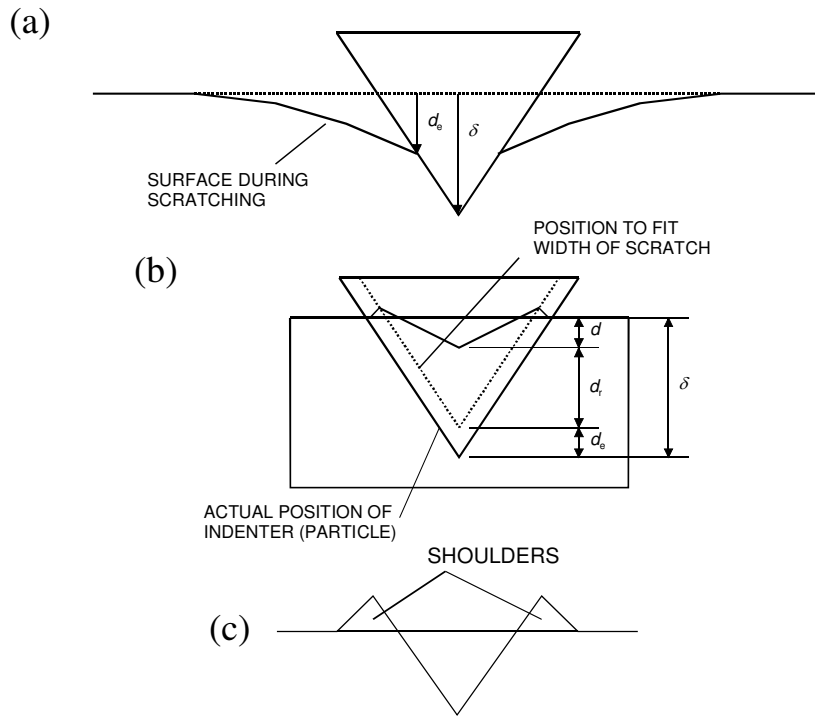
**Figure 10**



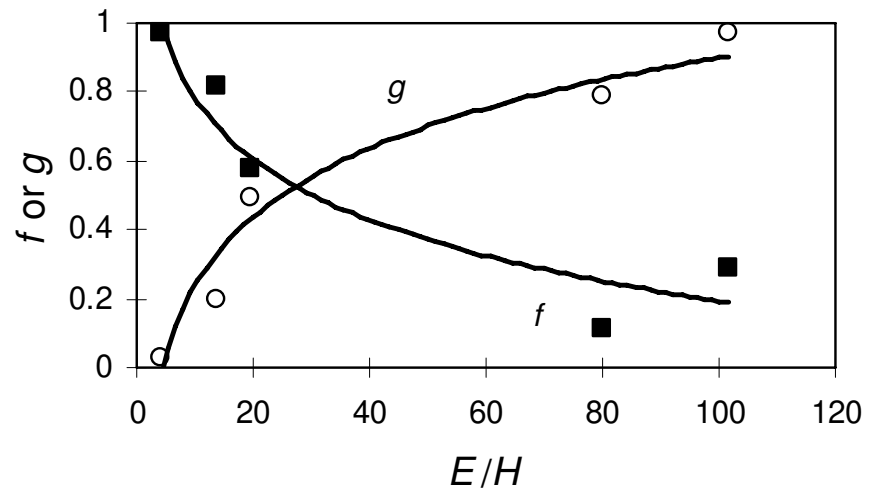
**Figure 11**



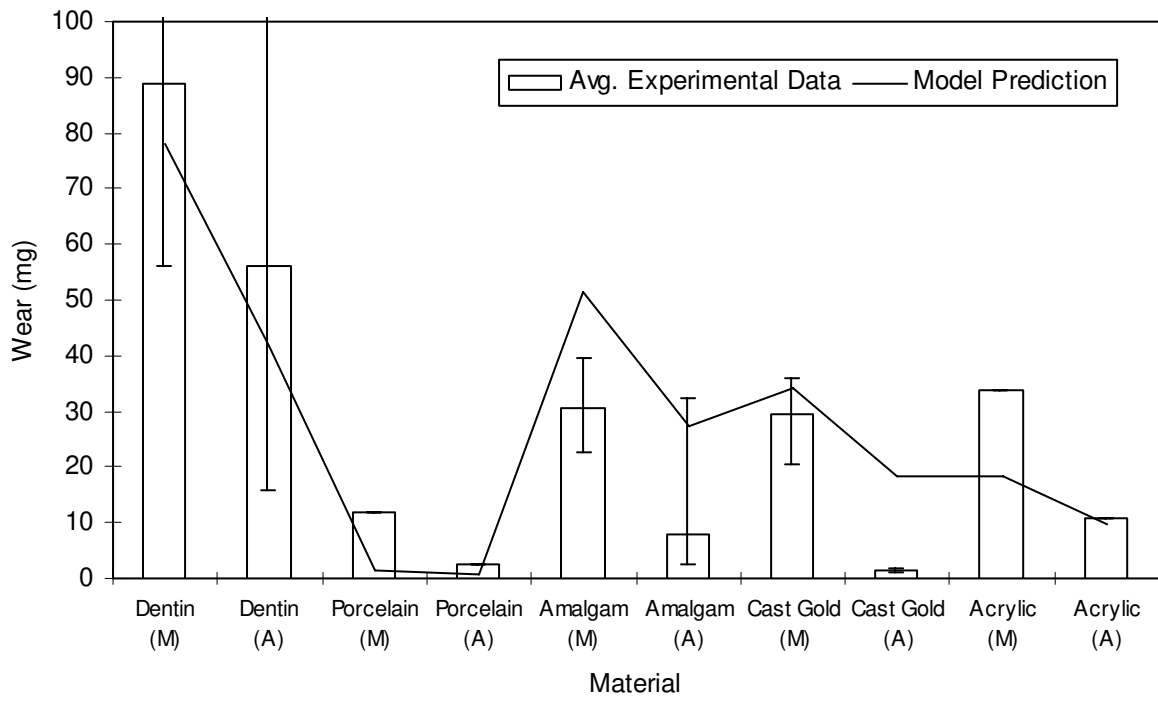
**Figure 12**



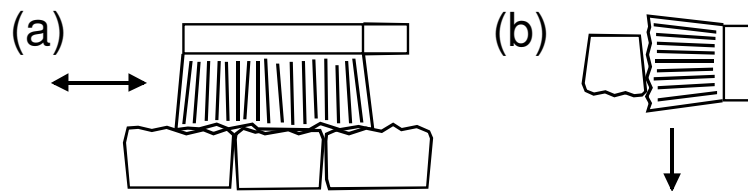
**Figure 13**



**Figure 14**



**Figure 15**



## **Table Captions**

Table 1	Friction Coefficient Variation with Particle Concentration and Brush Load
Table 2	Material Properties
Table 3	Brushing Parameter Inputs for Model Predictions

**Table 1**

Particle concentration	Friction coefficient		
	180g	280g	380g
dry	0.42	0.41	0.38
0%	0.17	0.28	0.26
0.2%	0.24	0.30	0.33
1%	0.24	0.31	0.34
5%	0.28	0.32	0.33
10%	0.26	0.33	0.34
20%	0.28	0.34	0.36

**Table 2**

Material	Dentin	Dental Porcelain	Amalgam	Cast Gold	Acrylic
Hardness (GPa)	0.5	4	1.18	0.34	0.22
Elastic Modulus (GPa)	14.7	10	52.4	75	3.4
Density (kg/m <sup>3</sup> )	2150	2400	10000	19000	1160
$E/H$	29.4	2.5	44.4	221	15.5
$g$	0.6	0.1	0.7	1	0.2
$f$	0.8	1	0.4	0.05	0.8

**Table 3**

Brushing Type	Manual	Automatic
Load (g)	250	167
Brushstroke length, $l$	5	0.4
Number of filaments	1360	1360
Number of strokes	172800 (dentine) 259200 (dental materials)	1728000 (dentine) 2592000 (dental materials)
$b$	0.25	0.25
$t$	0.1	0.1
$s$	1	1
Total scratch length (m)	864 (dentine)	691.2 (dentine)