Wear, 23 (1973) 141–152

REVIEW PAPER:

WEAR OF DENTAL ENAMEL*

J. M. POWERS and R. G. CRAIG

School of Dentistry, University of Michigan, Ann Arbor, Mich. 48104 (U.S.A.)

K. C. LUDEMA

College of Engineering, University of Michigan, Ann Arbor, Mich. 48104 (U.S.A.)

(Received September 19, 1972)

SUMMARY

Teeth wear for a number of reasons. One of the causes for wear is the use of abrasive tooth pastes. A study is reported in which enamel was damaged by single pass sliding of a diamond indenter. In single crystals of fluorapatite, wear occurs by flaking out of chips of material and severely fractured substrate is left behind. On the other hand teeth are made of small rods of polycrystalline hydroxyapatite of the order of 5 μm in diameter oriented perpendicular to the tooth surface. This rod structure of human teeth prevents large scale flaking out of material. Apparently the subsurface cracks do not extend from one rod to the other so that subsequent passes do not result in severe wear. Small abrasive particles may do considerable damage to rods, but the overall effect is small. Large abrasive particles with high loads cause separation of rods, and cracks appear to propagate but without severe permanent damage.

INTRODUCTION

The wear of dental enamel is of interest in two ways: the health and appearance of the human oral cavity is affected by the condition of the teeth, and the useful life of commercial grazing animals is influenced by the rapidity of destruction of their teeth. In a mature human, teeth are composed of a vital pulp that is surrounded by a relatively thick layer of dentine that is also vital. The dentine in turn is covered by a thin layer of substantially harder, non-living material known as enamel. Once this layer of enamel is worn away, extremely rapid destruction of the underlying dentine and then pulp exposure can occur. Although there is evidence that repair of enamel damaged by light abrasion can occur, major damage is not reversible and subsequent loss of dental function may follow.

---

* Based on a dissertation submitted in partial fulfillment of the requirements for the Doctor of Philosophy in the Horace H. Rackham School of Graduate Studies at the University of Michigan, 1972.

This investigation was supported in part by USPHS Training Grant DE-00181 from the National Institute of Dental Research, National Institutes of Health, Bethesda, Maryland.

WEAR OF ENAMEL AND DENTINE

The destruction of hard dental tissues by a process of wear may be conveniently categorized into three major divisions encompassing the wide variety of factors influencing the wear of enamel and dentine: wear resulting from physiological causes, wear resulting from pathological causes and wear caused by toothbrush and dentifrice use.

Wear resulting from physiological causes

The wear resulting from normal masticatory function is a physiological process termed dental attrition[1]. Attrition in primitive man was and is often severe (pulpal exposure) owing to the abrasive nature of the aboriginal diet (flesh, meat and sandy, fibrous plants) as studies on both skeletal and living representatives of aboriginal populations have attested[2–4]. The attrition of primitive populations is characteristic of that found in ancient and prehistoric man who consumed raw foods[5]. Observations of living, primitive populations have shown that teeth are used for a variety of purposes other than eating, such as chewing of coca leaves[1], chewing of hides as part of the tanning process[3] and for tools in tearing, cutting or holding[6]. As a result of his observations on a number of skeletal dentitions, Dahlberg[7] contends, however, that the abrasives in food are the major cause of attrition, with fine silts and abrasives causing as much or more relative damage than coarser particles.

In the teeth of modern populations, there is little evidence of attrition because of the softness of foods and the lack of function of the masticatory apparatus[5]. Only in exceptional instances among modern people, when the diet consists of hard, bulky, fibrous foods and when a powerful masticatory apparatus is developed, do the teeth exhibit extensive attrition resembling that of primitive populations. In this phase of evolution, caries has replaced attrition as a cause of tooth loss[2].

More fundamental research on the degrees and types of attrition found in the teeth of ancient, primitive and modern populations has dealt mainly with the wear planes produced on molar surfaces[8–10] and with the effects of attrition on facial height[1–14] and on the position of the temporomandibular joint[11,15,16]. Those studies concerned with patterns of wear have shown that not all teeth wear in the same way and that patterns produced are frequently characteristic of certain populations. It appears from those studies dealing with the relationship between attrition and skeletal positions that although there is some loss of facial height due to attrition, continuous tooth eruption and generalized alveolar bone growth are compensatory mechanisms. Other studies have proposed that the edge-to-edge bite, considered characteristic of primitive people, is the result of function and not of some generic mechanism[1,10,17].

Philippas[18] and Philippas and Applebaum[19–21] have conducted extensive research on the influence of age and occlusal wear on the formation of secondary dentine and the size of the pulp chamber. They concluded that, regardless of the degree of occlusal wear, the size of the pulp chamber in the teeth studied decreased with advancing age owing to the continuous formation of dentine. The location of irregular secondary dentine, however, may be influenced by functional pressure[20].

The wear resulting from normal masticatory function in sheep has been investigated for commercial reasons. Barnicoat[22] observed that the incisors of grazing sheep in New Zealand wore more rapidly on improved pasture than on unimproved pasture. It was indicated that chemical weakening of the tooth structure facilitated accelerated wear by attrition. Constituents of actively metabolizing herbage which predisposed the teeth to excessive wear appeared to be enzymes and acids[23]. On the other hand, Healy and Ludwig[24] found a correlation between the amount of soil ingested and the degree of wear found in the incisors of New Zealand sheep. The importance of chemical weakening of tooth structure due to proteolysis was questioned.

That chemical weakening could occur by acid decalcification was demonstrated for human enamel in 1953, when Steel and Browne[25] studied the rate of decalcification as a function of pH for uncleaned, cleaned and mechanically rubbed enamel.

The investigators studying the characteristics of attrition, wear due to normal masticatory function, have relied essentially on deduction through observation of skeletal remains or living representatives of characteristic populations to explain the effects of abrasives in foods, degree of function and age on attrition; furthermore, it would appear that this trend will continue. The work of Brace and Molnar[26] on a machine capable of simulating the actions of the human mandible during chewing to produce a variety of wear patterns suggests a new, though complicated alternative.

Wear resulting from pathological causes

Although the literature describing wear resulting from pathological causes is not extensive, it is apparent that this form of wear can be particularly destructive to individual teeth or the entire dentition. Xerostomia and bruxism are the most frequently reported pathologic causes of wear.

Muller[27] found a high incidence of xerostomia, dryness of the oral cavity, in women during or after the menopause. These patients complained of difficulty in mastication. Their teeth were brittle, and fissures highly susceptible to infection often appeared. Zaus and Teuscher[28] reported rapid destruction of enamel with no respect for contact or tooth form in three cases of congenital dysfunction of the salivary glands. In white rats, ligation of the major salivary gland ducts increased both tooth abrasion and loss of periodontal bone as compared to that of control rats[29]. It was concluded that examination into the causes of abnormal tooth wear must take salivary factors into consideration.

Bruxism is a non-functional mandibular movement that is manifested by occasional or habitual grinding, clenching or clicking of the teeth[30]. In mild bruxism little harm results; however, in severe bruxism the teeth and supporting structures are involved, with the major effects being tooth wear and alveolar bone loss.

Nadler[30] has observed that the abnormal wear caused by bruxism tended to rapidly remove the cusps of teeth. Wear took place mainly on incisal edges of the upper and lower anterior teeth, with these edges becoming highly polished and flattened with time. In the posterior teeth, wear appeared as small, saucer-like excavations. Enamel fissures and wear facets have been reported as clinical signs of bruxism[31,32].

Wear caused by toothbrush and dentifrice use

In modern cultures oral hygiene is necessary for maintaining a healthy oral environment and social acceptance. Therefore, teeth are cleaned, usually with a brush and with a dentifrice that usually contains abrasive species. During the process of cleaning, extraneous debris or deposits are removed from the tooth surface. These deposits given in order of increasing difficulty of removal from the tooth surface are food debris, plaque (a soft, mainly bacterial film), acquired pellicle (a proteinaceous film of salivary origin), and calculus[33]. In general, abrasives such as calcium carbonate, dibasic calcium phosphate dihydrate, anhydrous dibasic calcium pyrophosphate, insoluble sodium metaphosphate or hydrated alumina are the solid dentifrice cleansing materials used[34]. The abrasive should ideally exhibit a maximum cleansing efficiency with minimum tooth abrasion. In addition, a dentifrice should polish the teeth. Not only are highly polished teeth esthetically desirable, but also they may be less receptive to the retention of deposits[35].

The evaluation of the functions (or misfunctions) of dentifrices has been the purpose of numerous investigations. Among the earliest extensive investigations of the wear of tooth structure due to dentifrice abrasion were those reported by Miller[36] in 1907 and van der Merve[37] in 1917. Miller found by the hand brushing of freshly extracted teeth that the commonly used tooth powders were capable of producing marked damage to the teeth. Van der Merve used freshly extracted teeth and a reciprocating motion brushing machine. He found that abrasion at the cemento–enamel junction was often severe enough to expose the pulp chamber of the tooth.

A great number of investigations have been carried out to determine the effect of dentifrice and brushing conditions on the rate of tooth wear. For example, Souder and Schoonover[38] concluded that the injury to enamel by dentifrices containing harsh abrasives was evident after 25 min of hand brushing. Wright and Stevenson[39] found that wear resistance was closely proportional to the tissue hardness when a very hard abrasive compound was used. Stookey and Muhler[40] evaluated the abrasion produced by current dentifrices on enamel and dentine. Abrasion was produced by a mechanical brushing machine. It was concluded that some products produced abrasion too high or too low to warrant commercial distribution. The authors noted that increasing the load on the brush over a range of 75 to 300 g resulted in an increase in the enamel and dentine abrasion scores (calcium pyrophosphate standard). In a rather complicated, but similar experiment, Manly[41] confirmed that the force on the brush was very significant. Tainter and Epstein[42] evaluated the abrasion of enamel due to synthetic and natural bristles in toothbrushes using dentifrice. They found that toothbrushes with bristles made of plastics caused less wear of enamel than those made with natural fibers. However, Manly[43] showed that the brush itself had little abrasive power when compared to that of the common dentifrices.

One other very important variable was found by Mannerberg[44] who studied the differences in the wear of tooth surfaces of extracted teeth *versus in vivo* brushing. The effects of abrasion were evaluated by shadowed collodion replicas viewed in transmitted light. In the machine brushing experiments using extracted teeth, evidence of the crystalline prism ends of enamel could be observed in the scratches; whereas in the *in vivo* experiments, the prismatic pattern often disappeared in those regions where a scratch had been produced. It was suggested that the scratches were gradually filled by the precipitation of an inorganic substance from the saliva.

As should be apparent from the studies reviewed in the preceding sections, research on the wear of enamel and dentine caused by toothbrush and dentifrice use has been characterized to date by attempts to duplicate as closely as possible the oral situation. These attempts have involved the use of human dental tissue, commercial dentifrice preparations and various machines that imitate brushing motion. The variables affecting such studies have been shown to include: (i) dentifrice properties such as hardness, particle size and particle distribution of the abrasive and composition and concentration of the remaining components; (ii) toothbrush properties such as geometry, hardness, stiffness, and a number of bristles; (iii) substrate properties such as orientation, hardness and surface preparation; and (iv) testing conditions such as brush load, stroke length, stroke rate, number of strokes, and the presence of saliva.

Because of the great biological variability involved in the use of human dentine and enamel and because of the difficulty in preparation of these specimens, many investigators were led to substitute other materials, which could be conveniently standardized with respect to physical properties, in their studies of toothbrush and dentifrice abrasion. For example, Ray and Chaden[45] used several toothpastes on a paraffin covered disc (to simulate a brush) which rubbed against cast antimony (to represent dentine) or hardened steel (to represent enamel). On the antimony specimens, it was found that the most abrasive toothpaste was 25 times as abrasive as the least abrasive toothpaste. No appreciable abrasive action occurred on the hardened steel specimens. Beyeler and Mooser[46] studied the effect of hard and soft bristles with a variety of common toothpastes on the abrasion of methyl methacrylate specimens using a motor-drive brushing machine. Pfrengle and Pietruck[47] studied the effect of dentifrice thickening agents on the abrasion of antimony, copper and silver plates. Usually investigators have not been able to correlate the wear behavior of metals or plastics with that of hard dental tissue.

Most of the above mentioned works were studies of gross wear behavior of materials. Various combinations were rubbed together and the loss of material was measured by various techniques. A less common approach is to study the detailed mechanism(s) controlling the surface failure of enamel under an applied stress resulting primarily from sliding. The present paper reports the results of such a study whereby enamel is simulated by single crystals of fluorapatite* and the abrasives in a dentifrice (or food) are simulated by a small, hemispherical diamond slider. Subsequently, extracted human teeth are studied, and the results are compared with the results obtained with fluorapatite.

WEAR OF FLUORAPATITE SINGLE CRYSTALS

Methods and materials

Details of the experiment are contained in other papers[48–50]. Briefly, the apparatus used in this investigation for scratching the surface of a specimen and measuring the friction consisted of mechanisms which can be conveniently categorized as follows: surface grinder, loading jig, friction transducer, diamond slider and sample holder. Diamond sliders (100–150 μm in diameter) were slid in a single pass across

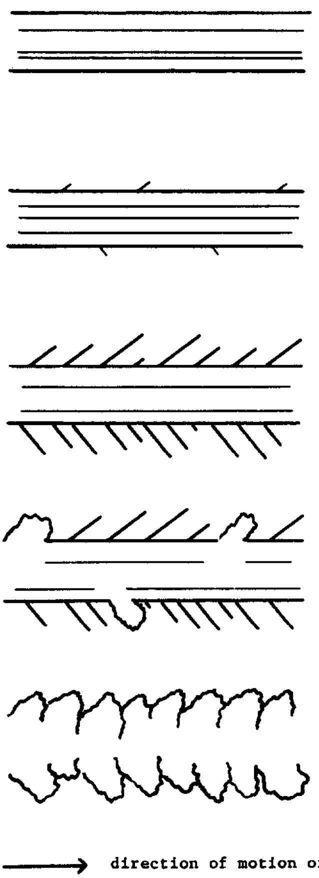
* In human enamel the mineral phase is composed of crystallites of hydroxyapatite. Pure hydroxyapatite has a formula written as $Ca_{10}(PO_4)_6(OH)_2$. The formula for fluorapatite is $Ca_{10}(PO_4)_6F_2$.

the basal surfaces of natural fluorapatite single crystals in distilled water. Crystals were given a polishing and surface treatment prior to scratching.

Results

A summary of the more interesting results taken from more detailed papers[48–51], is presented here. The first observation was that fluorapatite fractures in a manner similar to other brittle substances. The severity of surface failure varied according to the load, speed, and crystallographic direction of sliding.

The wear scars, as observed from metallographic and scanning electron microscope (s.e.m.) photomicrographs, were classified on a one to five ordinal scale, which is illustrated in Fig. 1. This scale was developed in an attempt to discriminate among three major types of failure modes: a ductile mode characterized by smooth grooves (class 1); a cleavage mode characterized by tensile cracks (class 3); and a chipping mode characterized by extensive chevron formation (class 5). Classes 2 and 4 represented modes of failure somewhere in between the modes described. This scale was meant to characterize surface failure only and did not attempt to account for



1. Behavior entirely ductile with no tensile cracks.
2. Behavior mostly ductile, but with some tensile cracks.
3. Behavior essentially characterized by tensile cracks.
4. Behavior mostly characterized by tensile cracks, but with some chevrons appearing.
5. Behavior characterized by numerous chevrons - brittle.

→ direction of motion of slider

Fig. 1. Failure classification scale.

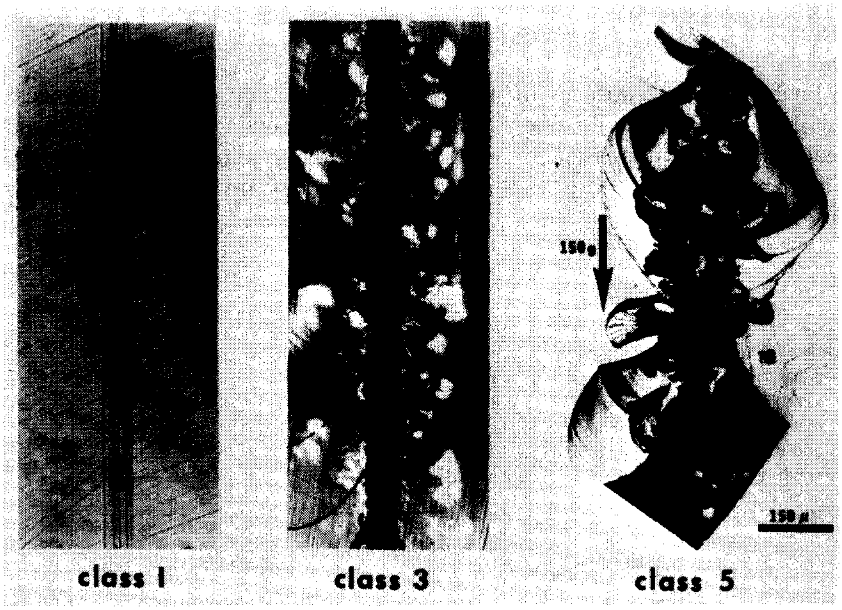


Fig. 2. Optical photomicrographs of wear scars exemplifying the failure classification scale.

visible subsurface deformation or fracture. Photomicrographs exemplifying the failure classification scale are shown in Fig. 2[50]. As can be seen in the photomicrographs, the class 1 surface failure appeared to be a track formed by plastic flow. The class 3 surface failure retained a center scar apparently formed by plastic deformation, but cracks were formed along this scar. The cracks were formed by tensile failure of the fluorapatite owing to the combined effects of a Hertzian stress caused by the normally loaded hemispherical indenter and a stress state caused by the frictional forces of sliding[51]. The chipping mode of failure (class 5) was characterized by extensive chevron formation with the center of the wear scar no longer showing much evidence of ductility. Sliding at a speed of 0.025 cm/sec caused more damage than a speed of 0.076 cm/sec[48].

The mode of chipping appeared to be similar to that found in amorphous materials such as glass. On the other hand, evidence was found that the direction of cracks formed under milder sliding conditions was sensitive to crystallographic planes[51]. It was found that cracks, such as observed in class 3 failure, were oriented at an angle larger than 45° from the wear track for sliding in a $[2\bar{1}\bar{1}0]$ direction*. When sliding in a direction 90° from the $[2\bar{1}\bar{1}0]$ direction, the cracks were oriented 30° from the wear track. In both cases the cracks were pointed towards the origin of sliding. The coefficient of friction and the normal load required to produce cracking on the surface were higher in the $[2\bar{1}\bar{1}0]$ direction.

---

* Fluorapatite is a crystal of hexagonal symmetry. The $[2\bar{1}\bar{1}0]$ direction is parallel to a prism plane on the basal plane.

THE WEAR OF HUMAN ENAMEL

Methods and materials

The buccal-occlusal surfaces of human, mandibular left third molars were scratched with a diamond hemisphere (360 μm in diameter) in a mesial-distal sliding direction as shown in Fig. 3[51]. The normal loads were varied from 100 to 1000 g in increments of 100 g and in 1 kg increments up to 5 kg. All tests were run in distilled water.

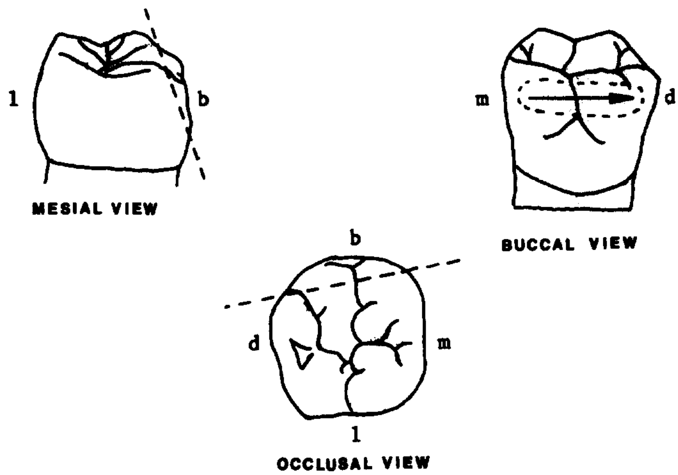


Fig. 3. Schematic diagram of the experimental procedure.

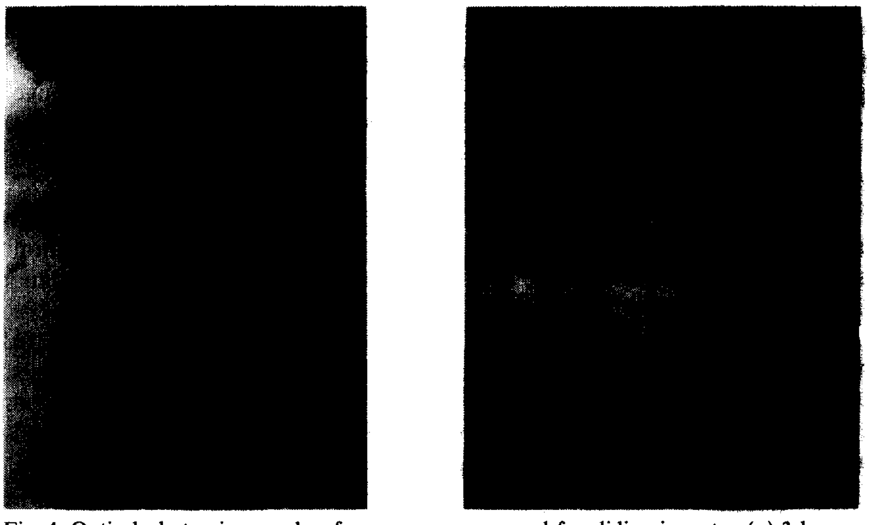


Fig. 4. Optical photomicrographs of wear scars on enamel for sliding in water. (a) 3 kg normal load; (b) 4 kg normal load.

Results

In general, classes of failure of human teeth were seen to correspond to the surface failure of fluorapatite. However, the unique structure of enamel produced some differences. The outer surface of human teeth is made up of enamel rods about 5 μm in diameter, oriented perpendicular to the surface of the tooth. Figure 4 shows these rods in the vicinity of wear scars. Loads up to 3 kg apparently caused some separation between rods, whereas at a load of 4 kg additional tensile cracks are seen to extend farther into the surrounding area without causing separation of rods at some distance from the scar. Another view of the enamel rods (Fig. 5) was taken slightly out of focus on a metallograph to enhance the contrast of the specimen in order to show the Hunter–Schrager bands*. Cracks were observed to follow the contour of these bands.

A magnified view of the enamel rods that were observed near the wear scar shown in Fig. 5 is given in Fig. 6. These rods were observed to a lesser extent near the wear tracks formed in the load range of 100 to 1000 g.

Discussion

At low loads human enamel and fluorapatite appear to wear in the same way. On the other hand, at high loads the single crystal of fluorapatite wears catastrophically whereas enamel does not. It is apparent that the enamel rods hinder the propagation of large cracks in teeth. Thus, it might appear that a single crystal material such as fluorapatite is not a good model for predicting surface failure of tooth enamel.

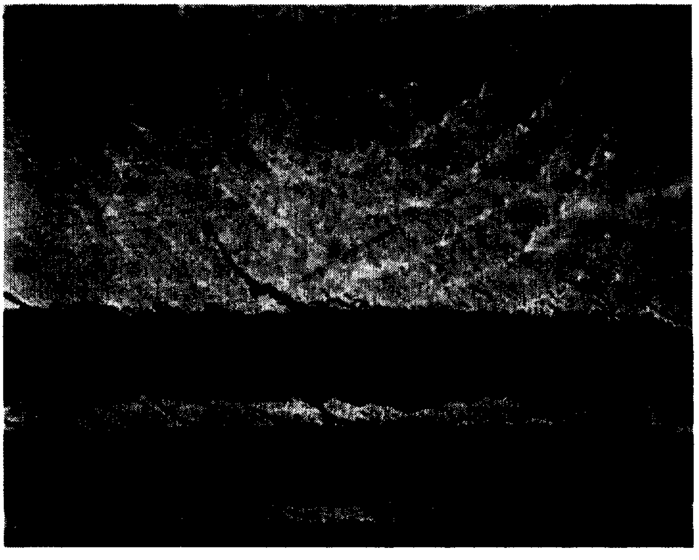


Fig. 5. Optical photomicrograph of wear scar on enamel.

* Hunter–Schrager bands are an optical effect that result from a change in direction of the enamel rods during formation.

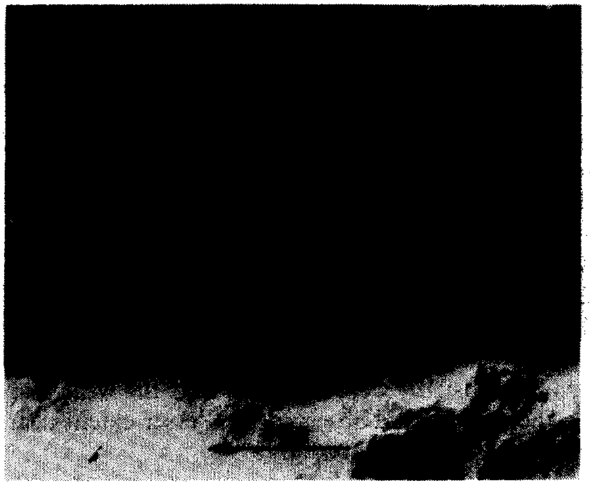


Fig. 6. Scanning electron photomicrograph of enamel rods in vicinity of wear scar.

The problem of interpretation, however, lies in the scale of events. A slider such as that used in the present study produces a large contact area and distributes its load among a number of rods.

A smaller diameter slider with a radius less than 5 μm, however, might be expected to concentrate stress at a given time on only one rod. Under this condition surface failure could be quite different, *i.e.*, similar to that observed in single crystals. Abrasive particles as used in grinding with dental burs and stones probably produce these conditions. Frazier[52,53] has observed, for example, that enamel samples, collected either by grinding with high- or low-speed diamond stones or by carbide burs, contained large amounts of finely divided enamel, a relatively large number of scattered individual crystals and relatively few particles (usually < 5 μm in size). Prolonged ball grinding produced a significant amount of finely-divided material (< 0.025 μm), the amount increasing with increased grinding.

CONCLUSIONS

Fluorapatite is apparently a satisfactory model for predicting surface failure of human teeth in the presence of abrasive substances, provided the abrasive particles are smaller than the diameter of the rods in the enamel. Larger abrasive particles, *i.e.*, larger than 5 μm, do relatively less damage than small particles. The enamel rod structure of human teeth prevents large scale flaking out of material. Large abrasive particles do cause separation of rods in the vicinity of highest contact pressure and cracks appear to propagate along natural flaws in the enamel.

REFERENCES

1 R. W. Leigh, *Dental Pathology of Aboriginal California*, University of California Press, Berkeley, 1928, p. 408.
2 J. E. Anderson, Human skeletons of Tehuacan, *Science*, 148 (1965) 496–497.

3 P. O. Pederson, Investigations into dental conditions of about 3000 ancient and modern Greenlanders, *Dent. Rec.*, 58 (1938) 191–198.
4 C. E. Snow, Indian Knoll skeletons of site Oh 2, Ohio County, Kentucky, *Univ. Kentucky Rep. Anthrop.*, 4 (1948) 382–554.
5 Meyer Klatsky, Dental attrition, *Am. Assoc. J.*, 26 (1939) 73–84.
6 H. E. Noble, The teeth of the Richmond River Blacks, *Aust. J. Dent.*, 30 (1926) 4–12.
7 A. A. Dahlberg, Dental evolution and culture, *Hum. Biol.*, 35 (1963) 237–249.
8 L. H. D. Buxton, The teeth and jaws of savage man, *Trans. Br. Soc. Study Orthod., 1916–1920* (1920) 79–88.
9 M. S. Goldstein, Dentition of Indian crania from Texas, *Am. J. Phys. Anthrop.*, 6 (1948) 63–84.
10 F. St. J. Steadman, Malocclusion in the Tasmanian Aborigines, *Dent. Rec.*, 57 (1937) 213–249.
11 L. Lysell and R. Filipsson, A profile roentgenologic study of a series of medieval skulls from northern Sweden, *Dent. Abstr.*, 3 (1958) 663.
12 T. Murphy, Compensatory mechanisms in facial height adjustment to functional tooth attrition, *Aust. Dent. J.*, 4 (1959) 312–323.
13 G. G. Philippas, Effects of function on healthy teeth: evidence of ancient Athenian remains, *Am. Dent. Assoc. J.*, 45 (1952) 443–453.
14 A. E. Webster, The effect of time and wear on the human teeth, *Dent. Rec.*, 38 (1919) 331–335.
15 E. Korber, Development of symmetrical types of attrition in the animal and human dentition, *Deut. Zahnarztl. Z.*, 12 (1958) 840–844.
16 T. Murphy, Mandibular adjustment to functional tooth attrition, *Aust. Dent. J.*, 3 (1958) 171–178.
17 R. D. Emslie, The ideal occlusion for periodontal health, *Dent. Rec.*, 72 (1952) 179–188.
18 G. G. Philippas, Influence of occlusal wear and age on formation of dentin and size of pulp chamber, *J. Dent. Res.*, 40 (1961) 1186–1198.
19 G. G. Philippas and E. Applebaum, Age factor in secondary dentin formation, *J. Dent. Res.*, 45 (1966) 778–789.
20 G. G. Philippas and E. Applebaum, Age changes in the permanent upper lateral incisor, *J. Dent. Res.*, 46 (1967) 1002–1009.
21 G. G. Philippas and E. Applebaum, Age change in the permanent upper canine teeth, *J. Dent. Res.*, 47 (1968) 411–417.
22 C. R. Barnicoat, Attrition of incisors of grazing sheep, *Nature*, 185 (1960) 179.
23 C. R. Barnicoat, Attrition of the Hypsodont sheep's tooth, in *Mechanisms of Hard Tissue Destruction* (R. F. Sognnaes, Ed.), American Association for the Advancement of Science, Washington, D.C., 1963, 764 pp.
24 W. B. Healy and T. G. Ludwig, Ingestion of soil by sheep in New Zealand in relation to wear of teeth, *Nature*, 208 (1965) 806–807.
25 J. Steel and R. C. Browne, Effect of abrasion upon the acid decalcification of the teeth, *Br. Dent. J.*, 94 (1953) 285–288.
26 C. L. Brace and S. Molnar, Experimental studies in human tooth wear. I, *Am. J. Phys. Anthrop.*, 27 (1967) 213–222.
27 W. Muller, Xerostomia, *Deut. Zahnarztebl. Z.*, 12 (1958) 378–380.
28 E. Zaus and G. W. Teuscher, Report on three cases of congenital dysfunction of the major salivary glands, *J. Dent. Res.*, 19 (1940) 326.
29 G. E. Carlsson, A. Hugoson and G. Persson, Dental abrasion and alveolar bone loss in the white rat. I, *Odont. Rev.*, 16 (1965) 308–316.
30 S. C. Nadler, The effects of Bruxism, *J. Periodont.*, 37 (1966) 311–319.
31 B. O. Barletta, Bruxism: frequency of its main diagnostic characteristics, *Oral Res. Abstr.*, 4 (1969) 237.
32 J. Eschler, Bruxism and function of the masticatory muscles, *Parodontol., Zurich*, 15 (1961) 109–116.
33 C. Dawes, G. N. Jenkins and C. H. Tonge, The nomenclature of the integuments of the enamel surface of teeth, *Br. Dent. J.*, 115 (1963) 65–68.
34 S. D. Gershon, H. H. Pokras and T. H. Rider, Dentifrices, in *Cosmetics, Science and Technology*, (E. Saragin, Ed.) Interscience, New York, 1957, pp. 296–353.
35 R. W. Phillips and G. Van Huysen, Dentifrices and the tooth surface, *Am. Perf.*, 50 (1948) 33–41.
36 W. D. Miller, Experiments and observations on the wasting of tooth tissue variously designated as erosions, abrasion, chemical abrasion, denudation, etc., *Dent. Cosmos*, 49 (1907) 1–23, 109–124, 225–247.
37 S. W. van der Merve, Some aspects of modern dentifrices, *J. Dent. Res.*, 7 (1927) 327–336.

38 W. Souder and I. C. Schoonover, Abrasion and solution of teeth—a sensitive, visual method for detecting these injuries, *Am. Dent. Assoc. J.*, 30 (1943) 1725–1734.
39 K. H. R. Wright and J. I. Stevenson, The measurement and interpretation of dentifrice abrasiveness, *J. Soc. Cos. Chem.*, 18 (1967) 387–407.
40 G. K. Stookey and J. C. Muhler, Laboratory studies concerning the enamel and dentin abrasion properties of common dentifrice polishing agents, *J. Dent. Res.*, 47 (1968) 524–532.
41 R. S. Manly and D. H. Foster, Importance of factorial design in testing abrasion by dentifrices, *J. Dent. Res.*, 46 (1967) 442–445.
42 M. L. Tainter and S. Epstein, A standard procedure for determining abrasion by dentifrices, *Am. Col. Dent. J.*, 9 (1942) 353–379.
43 R. S. Manly, Factors influencing tests on the abrasion of dentin by brushing with dentifrices, *J. Dent. Res.*, 23 (1944) 59–72.
44 F. Mannerberg, Appearance of tooth surface as observed in shadowed replicas in various age groups, in long term studies, after toothbrushing, in cases of erosion, and after exposure to citrus fruit juices, *Odont. Rev. (Malmo)*, 11 (Suppl. 6) (1960) 1–116.
45 K. W. Ray and H. C. Chaden, The abrasive power of modern dentifrices, *Dent. Cosmos*, 75 (1933) 1070–1077.
46 K. Beyeler and M. Mooser, Recherches à propos du nettoyage des dents des brasses à brin naturels et en matières synthétiques. Pouvoir abrasif du brossage avec et sans pates dentifrices, *Schweiz. Mschr. Zahnhk.*, 70 (1960) 123–152.
47 O. Pfrengle and C. Pietruck, Beeinflussung der Abrasivitat von Zahnpastenputzkorpern durch Quell- und Verdickungsstoffe, *Fette, Seifen, Anstrickmit.*, 64 (1962) 847–851.
48 J. M. Powers and R. G. Craig, Wear of fluorapatite single crystals. I. A method for quantitative evaluation of wear, *J. Dent. Res.*, 51(1) (1972) 168–176.
49 J. M. Powers and R. G. Craig, Wear of fluorapatite single crystals. II. Frictional behavior. *J. Dent. Res.*, 51(2) (1972) 605–610.
50 J. M. Powers and R. G. Craig, Wear of fluorapatite single crystals. III. Classification of surface failure, *J. Dent. Res.*, 51(2) (1972) 611–618.
51 J. M. Powers, The influence of crystallographic direction and environment of the ductile to brittle transition of fluorapatite single crystals under sliding, *Dissertation*, University of Michigan, Ann Arbor, 1972, 201 pp.
52 P. D. Frazier, Adult human enamel. II. An electron microscope study of the effect of grinding, *Calcium Tissue Res.*, 5 (1970) 277–287.
53 P. D. Frazier and C. V. Coltvet, Adult human enamel. I. Influence of grinding upon X-ray diffraction profile breadth, *Calcium Tissue Res.*, 3 (1969) 308–317.