AN EXPERIMENTAL STUDY OF THE WEAR CHARACTERISTICS OF HUMAN ENAMEL DURING TOOTH GRINDING

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PREFACE

Many of the difficulties faced by dental clinicians in diagnosing and treating the increasing number of people with tooth wear arise from a lack of detailed understanding of this biological process. Past anthropological studies, though valuable and extensive, have often tended to focus on tooth wear at a population level, attributing observed overall patterns to combinations of diet and cultural practices. Recently, researchers have begun to turn their attention to the specific causes of wear in individuals, including the effects of attrition, abrasion and erosion. These terms fall collectively under the broad umbrella of "tooth wear", "tooth reduction" or "tooth surface loss".

This study examines tooth-to-tooth contact under controlled experimental conditions that simulate bruxism. Though bruxism may affect both enamel and dentine, the investigation focuses on the wear characteristics of enamel. The stimulus for the project is described in the Introduction where it is argued that attrition, resulting from bruxism, can be considered a common physiological entity that contributes significantly to the process of tooth wear.

An *in vitro* investigation of the mechanical properties of human tooth wear may not appear initially to have direct clinical application. However, the results of this type of research provide basic knowledge that is important in explaining why variation in the extent and pattern of tooth wear is observed both within and between populations. By applying knowledge of how the oral environment influences tooth wear, dental clinicians may be able to control aetiological factors and hence the wear process itself.

This thesis provides new information about factors influencing the nature and extent of human enamel wear, and should provide a basis for future experimental and clinical research.

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SUMMARY

The processes of attrition, abrasion, erosion and fracture act on the dentition to produce various degrees and patterns of tooth wear. Attrition results from grinding of teeth without the presence of food, abrasion from solid foreign material being forced over tooth surfaces, erosion from chemical dissolution of dental structure, and fracture from trauma of varying degrees.

The objective of this research was to study enamel attrition using an electro-mechanical machine that was specifically designed and constructed to grind opposing tooth surfaces while controlling for load, speed, duration of contact, direction of movement, number of cycles, and quantity and quality of lubricant. The wear rate of enamel was quantified under various conditions and replicas of experimental wear facets were examined using scanning electron microscopy to assess surface features qualitatively.

The wear rate of human enamel was found to be bi-phasic for any given load. The primary wear phase was relatively rapid but, after reaching a threshold, a secondary wear phase progressed at a reduced rate. The relationship between wear rate and load under non-lubricated and lubricated conditions was assessed by experiments performed during the secondary wear phase. Qualitative assessment of all facets supported the quantitative results.

Enamel wear rates without a liquid lubricant displayed a linear relationship with loads ranging from 0-16.2 kg. Qualitative

assessment of facet surfaces indicated the presence of fine enamel powder resulting from enamel breakdown at the wear interface. This powder acted as a dry lubricant. The addition of water as a liquid lubricant (pH=7) reduced enamel wear. However above about 6kg the wear rate gradually increased until a threshold of 11-13kg was reached, above which the rate of wear increased dramatically. It is postulated that the liquid acted as a lubricant at light loads but was displaced from the facet surfaces at the heavier loads. The effects of this lack of lubrication were exacerbated as the liquid lubricant also washed away any dry enamel powder which would otherwise act as a dry lubricant. The resulting wear rate at loads above this threshold was therefore very high. Qualitative assessment of facet surfaces confirmed the absence of dry enamel powder, while the enamel surface consisted of craters that progressively enlarged due to fracture of enamel fragments from the edges. These fragments were responsible for the parallel striations commonly observed within facet borders.

When a liquid lubricant of pH=3 (acetic acid) was used, the wear rate was further reduced to that of the non-lubricated rate for loads up to 11-13 kg, after which the rate increased substantially. Facet surface appearance was generally smooth due to the build-up of an amorphous material with little evidence of cratering. At high loads, however, the frequency of cratering increased and the smooth amorphous layer disappeared.

At pH=1.2, the wear rate was considerably more than all the other lubricants. At low loads, surface breakdown due to erosion occurred producing an undulating smooth surface. This appearance changed to a flat, rougher surface as the load increased. When saliva (pH=7) was used as a lubricant, the wear rates compared with those of pH=3 below the 11-13kg threshold, and increased dramatically thereafter. Craters of various sizes and parallel striations were produced, similar to those observed with water at pH=7.

This study has not only quantified the behaviour of human enamel under dry and liquid-lubricated conditions, but has also provided qualitative assessments of facet appearance to support the quantitative findings. Clinical reports of a bi-phasic pattern of enamel wear have been confirmed experimentally. It has also been shown that the wear characteristics of enamel are independent of the speed at which opposing teeth are rubbed and their direction of movement, but dependent on load and the quality of lubricant.

Although the model used in this study could only simulate the dynamic biological processes occurring in the human oral cavity, new information has been gained about how dental enamel behaves within a tribochemical environment. Many areas requiring further investigation have been identified and it is planned to extend and refine the tooth wear machine to enable complete dental arches to be worn under controlled conditions in a computer-based system.

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I would like to dedicate this thesis to my wife Voula, and my three children, Xenia, Georgia and Sophia who had to make many sacrifices so that I could have this opportunity to extend my knowledge. Thank you for your continual love and support.

SECTION 1

INTRODUCTION

1.1 INTRODUCTION

Apart from disease or clinical intervention, several processes can change the morphology of teeth during their functional life. These include wear that may be caused by friction of food or other foreign substances forced over tooth surfaces; wear that may be caused by friction from tooth-to-tooth contact without the presence of food or foreign substances; the chemical dissolution of tooth surfaces; and tooth fracture resulting from the functional use of teeth or from trauma.

In clinical dentistry, the belief that unworn teeth provide an ideal functional form and that loss of tooth substance is pathological has persisted for many years (Seward, 1976), often leading to attempts to restore heavily worn dentitions to their original form. For example, tooth wear has been referred to as "lesions of a retrograde nature" (Shafer, Hine and Levy, 1974), reinforcing the notion that the process is not normal and that it must be treated. Furthermore, the adaptive changes in the craniofacial structures that are associated with tooth wear have not been fully appreciated by dental clinicians, adding to the narrow view held by many. In recent years, however, authors have suggested that a certain degree of wear can be considered physiological (e.g., Monasky and Taylor, 1971; Smith and Knight, 1984; Pintado, Anderson, Beyer, Delong and Douglas, 1992). Nevertheless, delineation between "physiological" and "pathological" wear remains subjective and varies between dental clinicians.

Research in dental anthropology has provided a different perspective of tooth wear to that commonly held by clinicians. Evidence from the fossil record (e.g., Wolpoff, 1971), investigations of non-industrialised populations (e.g., Begg, 1954 a,b,c) and studies in comparative anatomy (e.g., Jolly, 1967, 1970; Butler and Bernstein, 1974) have shown that tooth wear is a widespread phenomenon, and that the processes responsible for its progression have acted as selective forces since prehistoric times, shaping the evolution and hence the form and function of the stomatognathic system (Kaidonis, Richards and Townsend, 1992). As a result, most dental anthropologists view tooth wear as a normal physiological process (Barrett, 1969; Molnar, 1972).

If one adopts a biological view of tooth wear, many of the mechanical philosophies promoted in clinical dentistry must be questioned. By recognising progressive change in tooth form as reflecting a physiologically dynamic system, premature and unnecessary clinical interventions can be prevented. Furthermore, when dental treatment is deemed necessary, a more conservative approach may be taken.

The dichotomy of philosophies relating to tooth wear that has existed between the disciplines of dentistry and anthropology is reflected by their different research approaches over the past century. For example, dental anthropologists have concentrated on explaining how diet, culture, and craniofacial geometry contribute to the extent and pattern of tooth wear observed among extinct and extant human populations (e.g., Molnar, 1972; Richards, 1984). Once specific patterns of wear associated with cultural habits have been explained, remaining evidence of tooth wear has been attributed generally to diet (e.g., Campbell, 1925; Mills, 1963; Murphy, 1964a; Barrett, 1977). For example, Barrett (1969) studied the extent of tooth wear among Australian Aborigines, noting that "progressive wear of the teeth invariably resulted from the energetic mastication of tough fibrous foods in which abrasive material was unintentionally incorporated during its collection and preparation for eating."

Vigorous masticatory activity observed in non-industrialised populations has also been thought to be responsible for the development of interproximal wear (Wolpoff, 1971), leading to reductions in dental arch length (Begg, 1954a,b,c), and to helicoidal wear patterns (Murphy, 1964b; Tobias, 1980; Richards and Brown, 1986; Smith, 1986). Little consideration has been given to the possibility that tooth grinding may be a contributing factor to the development of these observed wear patterns. In fact, qualitative and quantitative anthropological research during the past century has often assumed that diet and cultural habits are entirely responsible for tooth surface loss, overlooking the contributions made by the different processes of wear, particularly that caused by tooth grinding.

In contrast to the worn dentitions of non-industrialised groups, "modern" industrialised societies, generally display less wear at a comparable age due to the high level of consumption of soft, processed foods with low abrasive qualities. Dental practitioners may at times observe the same extent of wear in their patients as seen in non-industrialised groups but more often they tend to treat patients whose rate and extent of wear are much less. Some dentists view this as the norm or standard against which all wear should be assessed, without being aware of the commonly occurring extreme wear states often observed in other populations.

Until now, rather than studying the processes of wear, much of the dental research relating to tooth wear has involved testing the wear properties of dental materials in an attempt to develop ideal restorations. Where clinical studies have been conducted, the focus has been on relationships between bruxism and dental occlusion, temporomandibular joint pathology, and myofascial pain dysfunction (e.g., Ramfjord, 1961).

1.2 DENTAL WEAR

1.2.1 DENTAL TERMINOLOGY

There is a lack of consistency in the terminology used in the dental literature to describe different types of tooth wear. This has arisen from gradual changes in understanding of the topic over the past century. For example, Klatsky (1939) summarized the thoughts of Black (1936) and Colyer (1919) by stating that "attrition results from the use of the teeth; abrasion results from tooth abuse". It was implied that attrition was the result of mastication, while tooth abuse was the result of foreign bodies acting on tooth surfaces.

Subtle changes in these definitions have occurred over the years. For example, although wear resulting from mastication continued to be referred to as attrition and wear resulting from the use of teeth as tools was termed abrasion, the wear processes were considered as physiological (Mills, 1955; Murphy, 1964a,b,c; Barrett, 1969) provided no associated dental pathology was evident (e.g., periapical pathology). At times, as noted by Robb, Cruwys and Smith (1991), anthropologists and dental clinicians have used the terms abrasion and attrition synonymously when referring to wear in general.

More recently, Smith (1991) has defined attrition as the "physical wear of one tooth surface against another" and abrasion as the "physical wear resulting from something other than another tooth". Smith goes on to say that attrition occurs from mastication as well as bruxism and that "a degree of attrition is normal", while abrasion occurs when a foreign object like a toothbrush affects the teeth.

Robb et al. (1991) have defined attrition as "wear caused by tooth-to-tooth contact which will always show corresponding wear facets on contacting teeth" and abrasion as "the physical wear caused by objects other than teeth, such as food, clay pipe-stems, nails, pins and oral hygiene procedures." The implication in these definitions is that food does not cause attrition, again highlighting the confusion that can occur in this area. Alternatively, from an engineering perspective, the terms attrition and abrasion refer to specific mechanisms of surface breakdown. These definitions will be described in section 1.2.4.

Recent increased interest in clinical tooth wear has focused attention on the different processes of wear; namely attrition, abrasion and erosion. Because erosion (which is the chemical dissolution of tooth substance) is now being considered more widely, the term "tooth wear" becomes less appropriate as it implies the rubbing together of surfaces. Therefore, it has been suggested that unifying terms such as "tooth reduction" (Kaidonis, Richards and Townsend, 1992) or "tooth surface loss" (Smith, 1991) may be more appropriate to describe all the processes that lead to loss of tooth substance. Because of its common use, the term "tooth wear", though not strictly appropriate, will be used interchangeably with "tooth reduction" in this thesis.

1.2.2 PROCESSES OF WEAR

Tooth reduction, which includes all the processes that may alter the morphology of a tooth from the time of emergence, can be considered under three categories:

(1) Pathological conditions (e.g., caries, root resorption), where change results from the action of micro-organisms or variations in tissue metabolism.

(2) Iatrogenic factors (e.g., dental handpieces used during restorative procedures or occlusal equilibrations), where clinical intervention often results in the removal of sound tooth structure.

(3) General processes of abrasion, attrition, erosion and fracture that occur under conditions which may be considered normal, although any one of these processes, in excess, may lead to pathology. For example, minor fractures of dental tissues (e.g., fine enamel flaking), may be considered to be normal if they result from normal function. In fact, attrition and abrasion occur from fracture at a microscopic level, yet when the fractures are large they may be considered pathological. This example highlights the subjective nature of the decisions clinicians have to make.

The terms attrition, erosion, abrasion and fracture will be used in this thesis to distinguish different causes of tooth loss and their corresponding morphological appearances. Definitions will follow those given by Every (1972), mainly because of their clarity and the fact that they differentiate between wear caused by bruxism and wear caused by diet and cultural behaviours. Although the processes of abrasion, attrition, erosion and fracture will be described as separate entities with distinct effects on teeth, in nature they often act simultaneously (Smith and Knight, 1984), with varying intensity and duration, making it difficult to differentiate between them. An example of the interplay of abrasion and attrition has been observed in a longitudinal study of Australian Aborigines by Kaidonis, Richards and Townsend (1993), where facet definition was found to vary over time due to episodes of tooth grinding superimposed on continually-acting abrasion.

ABRASION

Every (1972) described abrasion as "the wearing of tooth substance that results from friction of exogenous material forced over the surface by incisive, masticatory, and grasping functions." This definition indicates that:

(1) the exogenous material may be any substance foreign to the tooth. This may include sand, grit, etc., that are found in the food of primitive cultures or also relate to the consistency of different foods with different abrasive qualities;

(2) it is during mastication when this type of wear occurs;

(3) if the teeth are used as tools, for instance, the grasping of an object by the teeth so it can be manipulated in some way, then the friction of this exogenous object against the tooth surface may also cause abrasion.

In general, the action of abrasion is not anatomically selective on the tooth surface. The abrasive influence of a bolus of food on a tooth affects the whole crown, including the cusp tips, cusp inclines, pits and fissures, and also, to a lesser degree, the occlusal aspects of the buccal and lingual surfaces.

An exception to this lack of specificity may occur when the teeth are used as tools. For example, in some primitive cultures the repeated grasping of an object (e.g., a spear) with the same two or three teeth to facilitate manipulation by hand, may cause localised severe abrasion. Here the abrasion is "tooth specific". Modern-day examples of this type of abrasion include pipe smokers who abrade specific teeth according to the manner of holding their pipes, or the toothbrush abrasion seen commonly among dental patients (Figs. 1a, b).

An abrasion area (as distinct from a facet) produced by food, is an ill-defined, diffusely circumscribed area. It tends to round off or blunt tooth cusps or cutting edges while the tooth assumes a pitted appearance (Fig. 2). Where dentine is exposed, one sees the scooping out of dentine since it is softer than enamel (Fig. 3).

Microscopically, the morphology of an abraded surface consists of haphazardly orientated scratch marks, numerous pits, and various gouges (Fig. 4). However, abrasive scratches may be almost parallel, resulting when abrasive material is forced in one direction; for example, when food is crushed during the final phase of the terminal power stroke of mastication (approximately 2mm). In these circumstances, one may observe parallel scratch marks oriented towards centric occlusion on various cusp inclines. The length, depth and width of this microdetail varies depending on the abrasiveness of the food and the pressures applied during mastication.

The distribution and extent of abrasive wear over the dental arches is influenced by many variables. Molnar and Molnar (1990) outlined the factors contributing to the various patterns of tooth wear including tooth eruption sequences, enamel thickness, cusp morphology, root angulation, occlusion, arch shape, craniofacial shape, diet abrasiveness and paramasticatory functions such as using the teeth as tools.

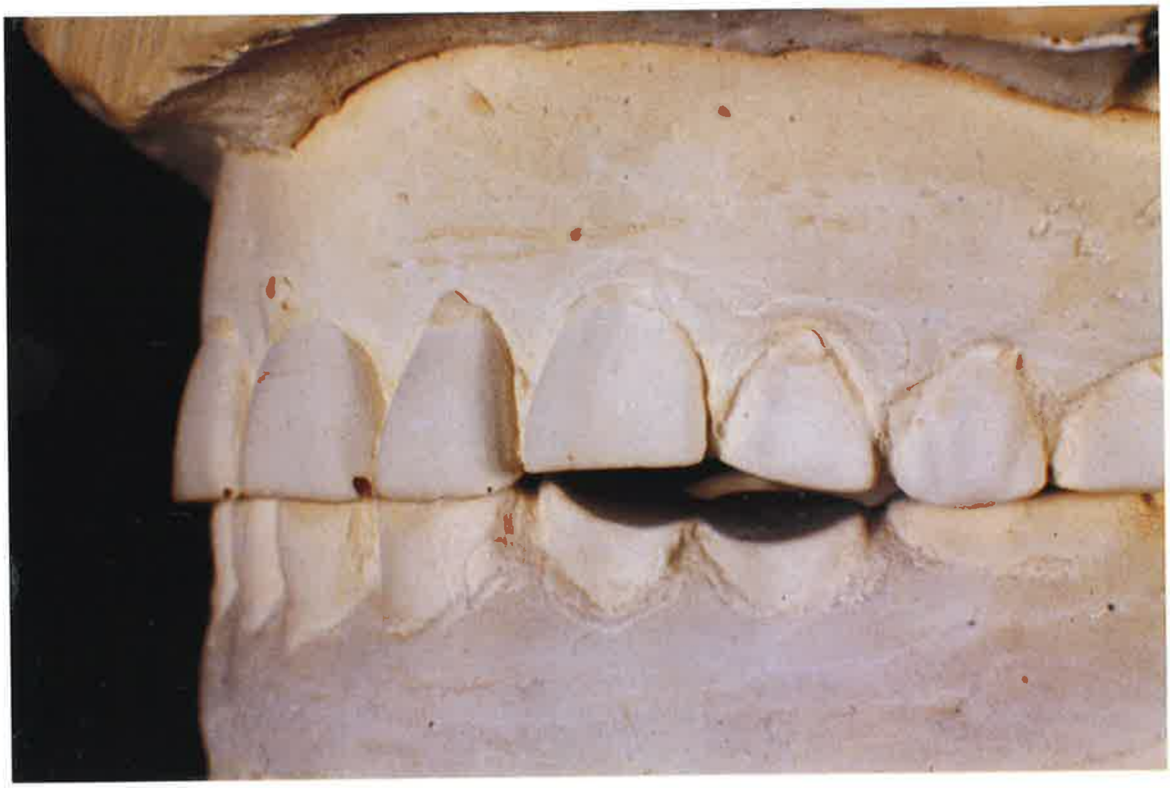

FIGURE 1a: Upper and lower dental casts of a pipe smoker. This "tooth specific" abrasion of the left lateral incisors and canines results from the pipe stem.

FIGURE 1b: Lower arch of a patient with excessive toothbrush abrasion. The cervical areas of the lower teeth are affected, exposing calcified pulp chambers.

FIGURE 2: Lower right first molar of an Australian Aborigine showing dietary abrasion. The tooth shows a pitted appearance over the entire surface.

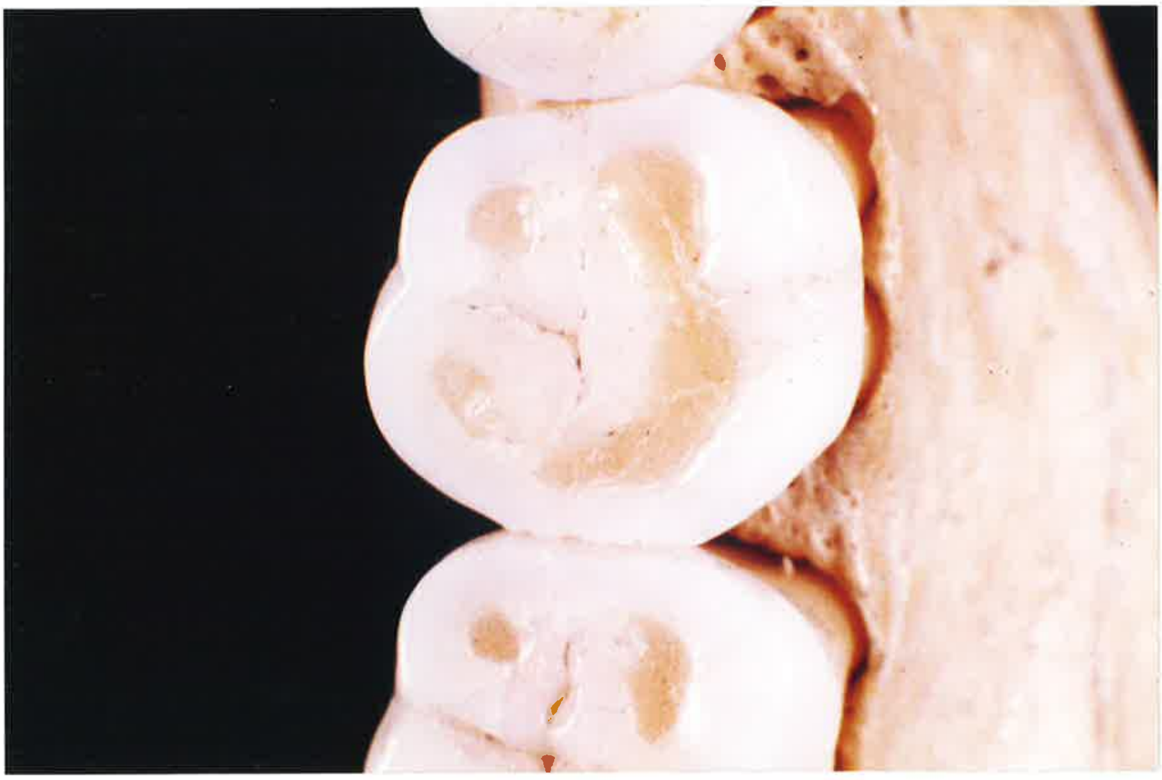

FIGURE 3: Australian Aboriginal molars exposed to abrasion. The cusps have been worn showing exposed, scooped dentine.

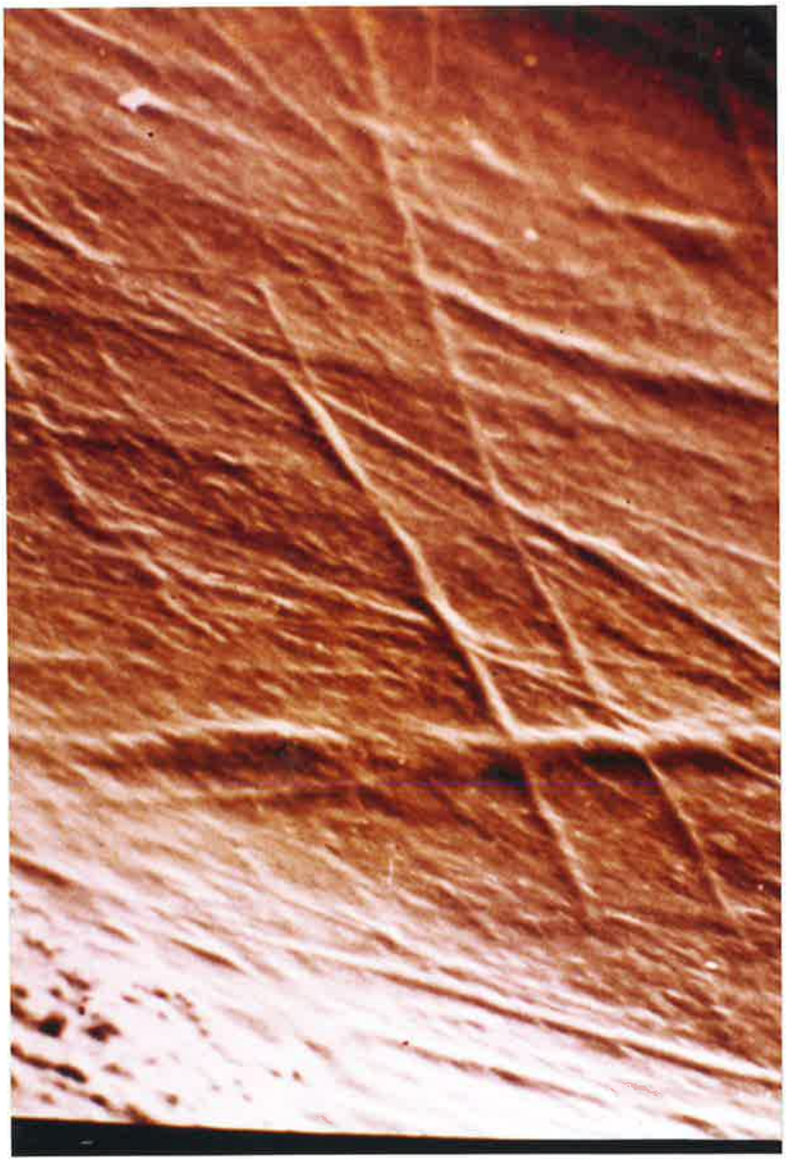

FIGURE 4: Scanning electron micrograph of an abraded surface on an Australian Aboriginal tooth, showing a cross-hatched appearance. (20kv; magnification 100x)

ATTRITION

In this text, attrition will refer to occlusal and incisal tooth wear caused by opposing tooth-to-tooth contact without the presence of food. The term can include interproximal wear caused by tooth-to-tooth contact between adjacent teeth in the same tooth row. Every (1972) appropriately defined this type of occlusal and incisal wear as that caused by "endogenous material: microfine particles of enamel prism caught between two opposing tooth surfaces". The resulting characteristic appearance is the facet, which Every describes as a usually flat area with a very well circumscribed border (Fig. 5a). It is these broken enamel prisms that produce microscopic parallel striations within the well-defined facet borders (Fig. 5b). Details of facet morphology will be discussed in Section 1.2.3.

As with abrasion, the distribution of tooth wear facets is influenced by a number of variables including the combined effect of the individual's dental occlusion and craniofacial geometry. For example, an individual with a deep overbite, (skeletal Class II, Division II malocclusion according to Angle's classification) will usually show characteristic wear on the anterior teeth with very little posterior tooth wear. Furthermore, the extent or degree of wear caused by tooth grinding relates to the episodic activity (Kaidonis, Townsend and Richards, 1993) and the load applied to the teeth during the behaviour. At present, the role of other oral factors that may contribute or alter the degree of wear is unknown.

FIGURE 5a: Flat, well defined wear facets on a third molar.

FIGURE 5b: Scanning electron micrograph of a wear facet surface showing fine parallel striations. (20kv; magnification 200x)

Interproximal wear refers to tooth reduction that commonly occurs on the contacting interstitial surfaces of adjacent teeth. Though not strictly attrition, it nevertheless is partly a product of tooth-to-tooth contact, occurring when teeth move independently during heavy occlusal loading. It has generally been accepted that this independent tooth movement results from two separate forces produced during mastication (Wolpoff, 1971). One force has been described as the mesial force vector: a force component responsible for the continuous mesial migration of teeth maintaining proximal contact. The second force is responsible for the bucco-lingual movement of teeth relative to one another and is believed to be the main force responsible for the resulting wear.

In contrast to this explanation, it has been proposed that the relative movement of adjacent teeth resulting in interproximal wear is principally vertical in direction with simultaneous tooth tipping (Kaidonis et al., 1992a,b). This opinion is based on observations of the micromorphology of worn interproximal areas that show evidence of vertical or near vertical furrowing. In addition, observations of severe bruxers (on relatively soft diets) with excessive occlusal attrition also show advanced interproximal wear, indicating that this type of attrition indeed occurs during occlusal loading and does not necessarily result from the forces of mastication alone.

EROSION

Dental erosion can be defined as the superficial loss of dental hard tissue as a result of chemical processes not involving bacteria (Lovestadt, 1952; Eccles, 1979; Linkosalo and Markkanen, 1985). Most often the chemical agents responsible for erosion are acids resulting from a number of different sources classified as extrinsic or intrinsic (Eccles, 1979). However, foods with alkaline properties may also lead to loss of tooth surfaces over time.

Extrinsic erosion may result from at least two extra-oral sources: industrial, due to the exposure of teeth to atmospheric acids (Ten Brugen Cate, 1968), and dietary, due to demineralizing foods such as citrus fruits and acid beverages (Eccles and Jenkins, 1993). Intrinsic erosion is the result of frequent regurgitation of gastric contents or episodes of vomiting (Hurst, Lacey and Crisp, 1977; Jarvinen and Meurman, 1988; Robb et al., 1991; Aine, Baer and Maki, 1993).

The pattern of dental erosion within a dentition tends to reflect the source of the acid. For example, chronic vomiting commonly affects the the palatal surface of the upper teeth that are in the path of the emitted gastric contents, while the lower teeth are usually less affected (if at all) due to the protection by the tongue (White, Hayes and Benjamin, 1978).

The clinical appearance of teeth affected by erosion varies considerably. Where the whole crown is affected, the tooth looses some of its surface definition taking on a glazed appearance with no evidence of sharp enamel ridges (Fig. 6). It has been suggested by Eccles and Jenkins (1993) that this glazed effect is the result of abrasion over an already etched surface, since etched enamel normally has a "white unreflecting surface". In areas where the effect of the acid is extreme, the "typical" erosive lesion is observed with an indented enamel surface. Once softer dentine becomes exposed, the rate of tooth reduction accelerates leading to a scooped appearance often accompaned by sensitivity associated with patent dentinal tubules.

Reports on the incidence of dental erosion have varied considerably between researchers. In the past, the methodologies of most studies were based on scoring the presence or absence of the so-called "typical" erosive lesions found on the labial surfaces of anterior teeth. This tended to give values lower than would be expected if the overall erosive effect of teeth could be estimated. Frequency estimates of 18% derived from a sample of 10,000 extracted teeth have been recorded (Sognnaes, Wolcott and Xhonga, 1972), while in more recent years estimates have ranged between 6% to 42% (Lussi, Schaffner, Hotz and Suter, 1991) depending on the tooth surfaces involved and the age of the subjects. These more recent observations have indicated that the frequency of erosion increases with age and that the occlusal surfaces show a higher incidence of erosion than labial surfaces.

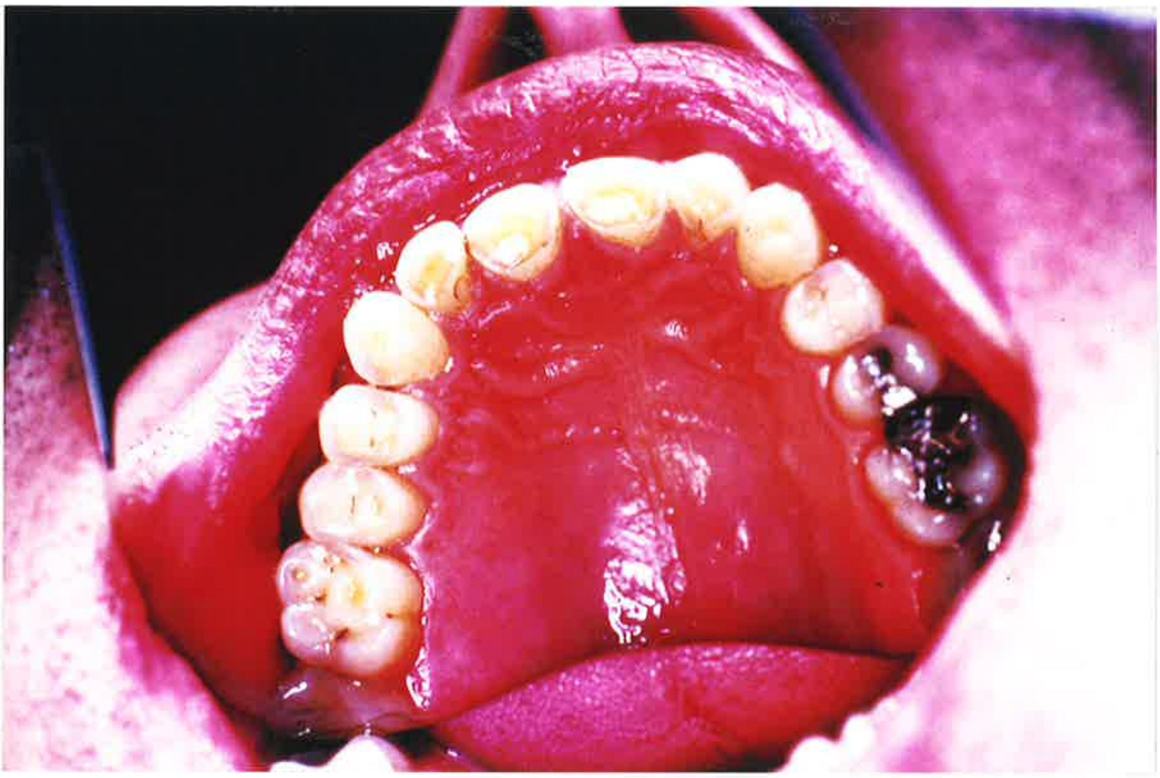

FIGURE 6: Photograph of the incisal and occlusal surfaces of the upper teeth of a patient affected by dietary erosion. The teeth appear glazed (right premolars and right molar), the dentine is exposed and scooped.

FRACTURE

Tooth fracture occurs commonly among dentate species, and though it assumes many forms, it may be categorized into four types:

(1) root fracture

(2) complete crown fracture

(3) cusp fracture

(4) enamel flaking

Root fracture, complete crown fracture, and cusp fracture are commonly observed entities, while enamel flaking, though present in many dentitions, is often overlooked. Enamel flaking is best described as the breaking away of slithers of enamel of various sizes from the incisal edges of anterior teeth and from the edges of posterior teeth where the occlusal table is flat (Fig. 7).

Tooth fracture may result from any kind of physical trauma; from the mastication of food and from tooth grinding where the forces are generally considered to be high. It is during nocturnal grinding and clenching of teeth that most damage from fracture may occur, when the normal physiological protective reflexes of the stomatognathic system are apparently inhibited (Clarke, 1982). Resulting enamel and dentine cracks may eventually propagate through the full width of the cusp or crown (even from minor occlusal forces during mastication) until complete fracture occurs.

FIGURE 7: Photograph of the upper incisor teeth of a patient showing enamel flaking on the upper right central and lateral incisors.

Enamel flaking due to tooth grinding produces characteristic patterns. Often the enamel flaking is observed on the labial incisal edge of the upper anterior teeth and the lingual incisal edge of the lowers, indicating that the forceful grinding movement is from centric occlusion (maximum intercuspation) outwards, opposite to the normal direction of mastication.

1.2.3 MICROWEAR, THE WEAR FACET AND BRUXISM

MICROWEAR AND THE WEAR FACET

One of the controversies that has persisted for many years in the area of tooth wear revolves around the aetiology and description of facets that are universally found on teeth. There are two basic schools of thought on facet formation. One has been described by Butler (1952, 1981), Mills (1963, 1967) and others, who believe that facets are caused by tooth-to-tooth contact during mastication. The other is expressed by Every (1960, 1965, 1970, 1972, 1973, 1975), who states that wear facets are not caused during mastication, but result from the grinding of teeth while the mouth is devoid of food.

Microwear detail observed on teeth has been used as a "blueprint" in attempts to describe the mandibular movements responsible for wear, but interpretations vary. As mentioned earlier, Every has claimed that facets are caused by "endogenous material: microfine bits of enamel prism caught between two opposing tooth surfaces." These enamel prisms break off and become caught as the tooth surfaces are forced over one another producing characteristic parallel striations when viewed microscopically.

Tribologists have described this form of wear as "three-bodied abrasion" and this will be described further in section 1.2.4.

Xhonga (1977), while studying the effects of bruxism on the dentition, also concluded that parallel striations were caused by microscopic particles of enamel prisms. This was contrary to the belief of Rensberger (1973) who stated that "small particles of hardness greater than dental enamel must be interposed between matching facets during jaw movements to striate the wear surfaces". That is, microfine fragments of enamel prism could not scratch enamel because they were of the same hardness.

As described earlier, Every defines the facet as usually flat and very well circumscribed, with fine parallel striations. The facet matches perfectly with an opposing facet that will also have matching parallel striations. He has argued that the mandibular movement responsible for attrition in humans (Every calls this thegotic wear) does not occur during mastication, but results from movement opposite to the normal direction of mastication. In other words, mandibular grinding movements originate from a position of maximum intercuspation (centric occlusion) and move laterally until the mandible is often in an extreme position. Therefore, the mandibular molars on the ipsilateral side tend to move transversely, producing facets with transverse striations. On the contralateral side, the movement is oblique, producing facets with oblique striations. The mandibular incisors move anterolaterally against the maxillary incisors producing facets with anterolateral striations.

Similarly, Every believes that the mandibular movements responsible for the wear amongst other mammals do not occur during mastication (Every and Kuhne, 1971). In some mammals, however, these movements occurs in the same direction as the masticatory stroke while in others they are diametrically opposite. For this reason, concepts depicting specific mandibular movements that have arisen from the explanation of observed microwear in different species (e.g., "orthal retraction" - will be described later) should not be extrapolated to include all species, including humans.

Previous investigations by Kaidonis et al. (1993) involving the longitudinal assessment of Aboriginal dental casts, have indicated that "attrition and its associated tooth grinding behaviour is episodic in nature while abrasion occurs continuously". This interplay between abrasion and attrition strongly suggests that if facets (as they are defined here) are caused by tooth-to-tooth contact during the mastication of food then they should always be present and, if anything, accentuated among non-industrialised populations where the mastication is vigorous. However, this is not observed. Instead, excessive wear typical of abrasion is most often evident. Furthermore, if facets were produced during mastication they should not be transient but remain as constant features because mastication is a daily physiological action. It is likely that variations in diet reflecting nomadic lifestyles or seasonal changes should only alter the degree of wear caused by abrasion. A change to softer foods however, does not decrease the frequency of facetting nor the clarity of facet appearance. Finally, personal observations indicate that patients wearing acrylic night guards that cover the entire occlusal surfaces (ie. all facets) show evidence of a decrease in facet definition over time (caused by abrasion from mastication and, or from superimposed erosion) and an increase in facetting on the acrylic surface, a product of non-masticatory behaviour.

An alternative to Every's thegotic concept is that proposed by Butler (1952, 1981). His observations of living mammals show that during the first cycles of mastication, when the food bolus is large, the chewing strokes are rapid with little lateral movement. The food is "punctured by the cusps and crushed between the teeth" and the teeth do not meet. Only when the food bolus is reduced, do the teeth commence to contact. Therefore, Butler believes that the wear produced by puncture crushing leads to abrasion and that produced by tooth-to-tooth contact during the final chewing motion causes the formation of facets.

Butler describes abrasion as "a general removal of tooth substance", resulting in the rounding of the cusp tips and crests and the smoothing of minor irregularities of the tooth surface. Where dentine becomes exposed by the wearing away of the enamel, a pit develops because dentine is softer than enamel and abrades faster." Butler explains, "In contrast to abrasion, attrition produces flat shiny facets where the tooth surface appears shiny or filed." In considering the microscopic description of the facet, Butler suggests that observed parallel striations are scratch marks produced by small particles of grit in the food.

Mills (1955, 1963, 1967) was one of the first researchers to observe the parallel striations outlined by Every. However, he supported Butler's theory that these striations were the result of wear from mastication and that they "described" the masticatory stroke. So by observing transverse and oblique striations he postulated the existence of a "lingual phase" in mastication. In other words, Mills believed that as soon as the mandible completed its "teardrop cycle" (the buccal phase) and ended in centric occlusion, movement continued laterally towards the non-working side producing an oblique facet of the teeth on the working side.

Similarly, Murphy (1964c) examined the microwear detail of the molar teeth of 97 Australian Aborigines and described the presence of two types of facets. Type A facets had bucco-lingual "scratches" and were said to be caused by food during mastication, and type B facets (on the non-working, contralateral side) resulted from tooth-to-tooth contact, also during mastication.

The quest to define the mandibular stroke of primates also disclosed another type of mandibular movement called "orthal retraction" (Gingerich, 1972, 1973, 1974a, 1974b) where the mandible retruded in an anterior-posterior direction at a certain stage of mastication. In support of this concept, researchers such as Rensberger (1978), Gordon (1982), Teaford and Walker (1984) and Gingerich (1972, 1973, 1974a, b) also concluded that the facets seen on teeth result from tooth contact during mastication.

Though much of the research described so far was based on the observations of striations, it only indicated orientation of the mandible and not the direction of jaw movement. Greaves (1972) suggested that the direction of mandibular movement could be determined by observing the pattern of dentinal wear in relation to adjacent enamel. He claimed that the dentine next to the leading enamel blade is flush with the enamel whereas at the trailing edge it is stepped relative to the enamel. Though this provides supportive evidence of the direction of the masticatory stroke and is indicative of abrasion, it does not indicate the direction of movement that may occur during bruxism.

Other attempts to determine mandibular direction came from *in vitro* tests where rubbing natural teeth on glass with an intermediate abrasive indicated that the wear scratches began with broad pits and extended into continually narrowing striations (Ryan, 1979a, b). Conversly, it can be argued that the opposite effect may occur if abrasive particles are much harder than enamel, resulting in scratches which are initially shallow but progressively deepen and finally stop in a pit caused by the embedded particle.

In summary, it seems that the controversies described in this section are likely to continue until researchers recognise that tooth-to-tooth contact during bruxism produces microwear detail which is morphologically distinct to that produced by food and that the different types of wear are invariably superimposed.

BRUXISM

Tooth grinding behaviour, also called bruxism or parafunction, has been considered for many years by dental clinicians to be a "functional disorder" (Pavone, 1985). It has often been called a pathological habit, associated with symptoms described collectively as myofascial pain dysfunction or temporomandibular joint dysfunction syndromes. Though it has been recognised that stress is associated with bruxism (Schulte, 1982; Rugh, Barghi and Drago, 1984; Kydd and Daly, 1985), it has often been accepted that occlusal factors (eg. interferences or occlusal discrepencies) are the trigger mechanism for this behaviour (Ramfjord, 1961; Arnold, 1981). Although researchers have failed to find an association between occlusion and tooth grinding (Clarke, 1982), Ramfjord's ideas are still accepted by many.

Considerable clinical research has been directed at clarifying the incidence of bruxism. Early estimates ranged from as low as 5% (Reding, Rubright and Zimmerman, 1966) while more recent reviews of reported frequencies gave values of 7%-88% in children and 15%-88% in adults (Cash, 1988). Most studies have been conducted by examining samples of patients and have also included questionnaires to enable the detection of bruxists by self-awareness of the behaviour. It could be argued that questionnaires are likely to lead to erroneous results, because individuals may not be aware whether they are bruxing at night. In addition, children may be over-helpful and report symptoms that do not exist.

Clinical examination would appear to be the best method of identifying the signs of bruxism, but the criteria used to indicate intra-oral signs will determine the reliability of results. For most studies criteria have included either recording the presence of "atypical facets" (Lindqvist, 1974), or the presence of "shiny facets with sharp edges" (Graf, 1969). Atypical facets have been described as flat smooth areas that correspond with similar opposing areas when the mandible has moved at least 3.5mm from centric occlusion to a lateral excursion. Facets showing areas of high polish have also been described by Xhonga (1977), who has stated that the degree of polish of the facet is an indication of the degree of tooth grinding activity. Pavone (1985) has pointed out that the incidence of bruxism varies according to "the definition used, diagnostic criteria applied, type of population sampled, types of questionnaires and the design of the study".

Kaidonis et al., (1993) found the frequency of facetting in an Australian Aboriginal population was very high (over 90% for both anterior teeth and molars). In most instances, there were upper and lower facets that could only be matched in extreme lateral non-masticatory positions, past the canine edge-to-edge relationship. This research, together with similar findings in over 400 Caucasian clinical patients (currently unpublished) indicates that tooth grinding is a very common behaviour among humans and that faceting can be produced without the presence of food. This supports other reports indicating a high prevalence of bruxism, including those of Faulkner (1990), Nadler (1968) who concluded that "......bruxism is practically universal", and Seligman, Pullinger and Solberg (1988) who after studying the prevalence of attrition and its association with factors of age, gender, occlusion and temporomandibular joint symptomatology, stated that "bruxism is a centrally induced phenomenon common to all people and unrelated to local factors".

Current research therefore indicates that most individuals grind their teeth to some degree, consistent with a physiological behaviour and not a pathological habit. It is only when the behaviour becomes excessive and the body is unable to adapt that pathology may eventuate. It is common to see children at times of excitement or times of distress grinding their primary teeth (Cash, 1988) or their gums, even before all primary teeth have erupted (Arnold, 1981). Similarly, angered adults will often clench their teeth. It would seem to be inappropriate to define tooth grinding behaviour as a pathological habit, because habits are learned. The stimulus for bruxism appears to originate within the central nervous system (Clarke, 1982; Seligman et al., 1988), and can be described as innate or instinctive, implying the presence of a dominant genetic code which ensures the presence of the behaviour universally.

1.2.4 TRIBOLOGY: AN ENGINEERING PERSPECTIVE

In addition to dental concepts of tooth wear, there is also a mechanical interpretation of wear that has evolved from the testing of different materials in engineering laboratories. The dental wear processes described so far in this thesis define a relationship between different morphologic wear patterns (e.g., facets) that result from a biological action (e.g., tooth grinding). In contrast, engineering definitions describe the fundamental mechanical processes that occur at the wear interface.

Tribology refers to the study of friction, lubrication and wear, and is derived from the Greek word, "tribo" (tri'vo) meaning "to rub", and "ology" (ologia) meaning "the study of". Wear can be defined as "the progressive loss of substance from the surface of a body brought about by mechanical action" (Mohd and Ramlah, 1990). However, wear can also occur in static situations from chemical degradation, more appropriately called corrosive wear (e.g., rust). Chemical degradation, in combination with movement of surfaces, is called tribochemical wear.

A fundamental concept in engineering is that the study of wear should not focus on one process, but should take account of the overall effects of five separate processes that often act in different combinations to produce "surface loss" (Pugh, 1973). The five fundamental wear processes in tribology that involve relative motion between surfaces are: abrasive wear, adhesive wear, fatigue wear, fretting, and erosive wear (Pugh, 1973). Their progress depends on the structure of the surfaces, the duration of contact of the surfaces, the contact stresses (load), the activity of any lubricating layer and the temperature of the surfaces (Sarkar, 1980a, b). Even electrical stresses (galvanic action) may hasten the process of wear on the affected surfaces (Mohd and Ramlah, 1990).

Abrasive wear results from the cutting away of a surface by abrasive asperities or particles (as no surface is perfectly smooth).

Essentially there are two types: "two-bodied abrasion" where projections on a softer surface may be cut by the opposing harder surface projections, or where the harder abrasive asperities plough into the smoother softer surface, and "three bodied abrasion" where the third body can take the form of a slurry (mixed with a lubricant) which may hollow out opposing softer surfaces.

In this context dental attrition, at the wear interface, is initially an example of two-bodied abrasion. However, as soon as microfine enamel asperities break off and become caught between opposing surfaces, the mechanism causing the wear is three-bodied abrasion. In the case of dental abrasion, particles of food between tooth surfaces act as the third body, therefore producing three-bodied abrasion.

Adhesive wear occurs where friction between opposing surfaces causes local cold welding between asperities. As the relative movement between the surfaces continues, the cold welds fracture, causing material to be transferred from one surface to another. This type of wear is commonly found in metals, however it is also observed in cystalline structures such as dental enamel during tooth-to-tooth contact (Sarkar, 1980b). Furthermore, these broken cold welds may break forming a "three-bodied slurry", typical of abrasion.

Fatigue wear results from moving surfaces placed under dynamic load. Here stress is applied to the asperities of the softer surface causing them to deform in the direction of movement. Plastic deformation energy develops in the subsurface and when this energy is dissipated, radiating cracks develop that spread to the surface. When a section is surrounded by cracks it may become displaced, often by adhesive wear where sections surrounded by cracks are removed.

Finally, fretting wear results when prolonged slow slipping between surfaces occurs under load, whereas erosive wear takes place when fluid particles hit a surface under pressure (e.g., sandblasting or removal of rock under a waterfall). What is termed erosion in dentistry (the chemical dissolution of tooth substance), is referred to as corrosion by engineers.

In addition to the above-mentioned definitions, there are laws in engineering that describe the relationship between friction and the wear of materials. Their relevance is determined by the design of the experimental model. For example, the laws of friction given by Teer and Arnell (1975) state that static frictional force is equal to the force required to initiate sliding between opposing surfaces, while kinetic (or dynamic) frictional force is equal to the force required to maintain the sliding. Furthermore, kinetic friction is usually lower than static friction. These laws are applicable provided that the experimental model involves measuring the force of friction or overcoming friction for a specific set of conditions. However, when the wear characteristics of a material are of interest, other laws govern the wear.

For example, friction is directly proportional to load

$$F=mW$$

where: "m" is the coefficient of friction and is constant only for a given set of specimens under a given set of conditions.

F=friction

W=load

The interaction that takes place between opposing surfaces that are rubbed together is a form of resistance to the relative motion resulting from the asperities (i.e., projections) that produce the roughness of the surfaces (Halling, 1976a, b). The true area of contact between opposing surfaces is the sum total of all contacting, opposing asperities and not the apparent area which is the macroscopic area of the opposing surfaces. Therefore, as the load increases, the opposing surfaces come closer together because of elastic or plastic deformation (depending on the nature of the material), causing an increase in the number of contacting, opposing asperities and therefore increasing the true areas of contact.

Though the laws that govern wear of various materials are extensive and vary depending on a multitude of conditions, some of the principles that describe wear are as follows (Halling, 1976b):

-the volume of worn material is proportional to the distance travelled

-the volume of worn material is proportional to the load

-the volume of worn material is inversely proportional to the hardness of the softer material

Furthermore, the lubrication of surfaces also influences the degree of wear. There are three main types of lubricants which include solids, liquids and gases. All lubricants act by providing a separating medium between opposing surfaces and their properties determine their capacity to function by reducing contact and therefore wear. Solid lubricants have to be soft enough not to cause destructive three-bodied abrasion, yet hard enough not to readily break down and become ineffective under load. Furthermore, their particle shape is also a determining factor, with rounder particles being relatively more effective. One of the best solid lubricants is calcium fluoride, a component of dental tissue, which has excellent properties, even at temperatures as high as 1000 degrees Celsius (Arnell and Teer, 1975). Liquids depend on viscosity and gasses on external pressure (e.g., the air rotor in a high speed drill) to force opposing surfaces apart against loads which tend to force the surfaces together. Finally, anything that may change these properties will have an effect on wear. For example, increases in temperature of a liquid lubricant can decrease its viscosity. This decreases the distance between opposing surfaces which in turn increases the wear.

1.3 ENAMEL WEAR

1.3.1 VARIABLES INFLUENCING ENAMEL WEAR

Based on the theories and laws of tribology developed from studies with mechanical models, the variables that may influence enamel wear are similar to those influencing most solid substances. However, the wear characteristics of homologous solid materials of uniform molecular composition differ from those of composite structures that are made up of different materials, each with separate wear characteristics. It can therefore be postulated that the wear characteristics of enamel, a composite structure of organic and inorganic components, may be different to both the organic and inorganic components on their own. Furthermore, enamel is a brittle substance with a high modulus of elasticity (2.7×10^3 kg/mm^2), implying that a large stress can be applied before any deformation or strain is observed, and when the stress is removed there is a tendency for recovery (Skinner and Phillips, 1967; Sarkar, 1980b). Under load it is an elastic and not a plastic deformation of asperities that causes an increase in real contact area. It is these brittle asperities that break to produce wear when opposing surfaces are rubbed.

The variables that may influence enamel wear include:

- structure of dental enamel
- enamel hardness
- load applied to opposing surfaces
- quality and quantity of lubricant (e.g., saliva)
- pH of the lubricant
- temperature of opposing surfaces
- duration of contact of opposing surfaces

- relative speed of contacting surfaces
- direction of movement of opposing parts

STRUCTURE AND HARDNESS OF DENTAL ENAMEL

There is evidence that the thickness of enamel is greatest on those parts of the tooth exposed to the greatest functional demand (Molnar and Ward, 1977). In addition, it has been suggested that not only the thickness, but also the structure and hardness of dental enamel is an evolutionary adaptation to resist wear during various functions (Janis and Fortellius, 1988).

For example, enamel's desirable property of resisting crack propagation during functional load, is achieved by its structural organisation. Long, rod-like hydroxyapatite crystal bundles (or prisms) are held together by a thin film of protein, thereby increasing the elasticity of the enamel and reducing brittleness.

Furthermore, the path the prisms take, though organised, includes twists and wave forms (decussation) which stop and deflect the propagation of cracks (Rensberger and Von Koenigswald, 1980; Janis and Fortellius, 1988). This resists the cleavage of enamel sections providing resistance to wear, even though this structural form decreases the density and therefore the hardness of the enamel. The presence of gnarled enamel, where enamel prisms are intertwined towards cusp tips may be an indication of this crack reducing property at the expense of enamel hardness. This seems to correlate with clinical observations of xerostomic conditions, in which cusp tips decalcify and decay before other occlusal areas, indicating a reduction of enamel hardness, contrary to suggestions that enamel is hardest at the cusp tips (Osborn, 1981).

To date there is no known evidence confirming that the hardness and therefore the wear resistance of enamel reduces progressively from the cusp tips to the cervical margin. Studies of the susceptibility of various areas of teeth to demineralization have indicated that the cervical area demineralizes most (Macpherson, Damato, MacFarlane, Strang and Stephen, 1991), while there appears to be little if any difference between buccal and occlusal areas. This has led to the belief that different areas of the tooth crown are of similar hardness. Furthermore, these same researchers have shown that the degree of demineralization of the enamel increases when the harder, most fluoridated surface layer is first removed by abrasion.

Janis and Fortellius (1988) have described the variability in hardness of enamel among mammals (including humans) noting that decussated enamel is covered by a thin outer, non-decussated layer, which is harder but more brittle. How the thickness and the degree of hardness of these layers varies within and between individuals and between various populations is unknown. Tests determining the microhardness of enamel using sclerometers have been applied to the outer enamel surface but not at progressive subsurface depths (Remizov, Prujansky and Matveevsky, 1991). These tests were performed to compare the hardness of enamel, dentine, cementum and non-biologic substances, like steel, but sample sizes were too small to give any indication of the variability of hardness that may exist among individuals for each of the dental tissues.

LOAD APPLIED TO OPPOSING SURFACES

Teeth are subjected to a great variety of forces throughout life. Some forces are small and almost continuous, such as those produced by soft tissues including the cheeks, lips and tongue, while others are relatively larger, yet intermittent. Apart from soft tissue pressures that tend to act laterally on teeth, the most substantial forces are applied to occlusal surfaces. Such occlusal loads may occur from three sources:

1. Mastication
2. Bruxism (tooth grinding and clenching without the presence of food)
3. Parafunctional behaviours (e.g., nail biting, thumb sucking, pipe smoking, as well as the use of teeth as tools as observed in many non-industrialised populations).

Researchers have attempted to quantify the occlusal forces acting on teeth, reporting results that vary considerably (Wolpoff, 1971). For example, studies of maximum bite force measurements have provided estimates of 11-125kg between first molars and 14-84kg between incisors (Black, 1908), while Howell and Manly (1948) reported forces as follows: incisors = 24-54kg, canines = 35-73kg, premolars = 48-84kg and molars = 91-192kg. Klatsky and Fischer (1953) noted a difference in the maximum bite force between men (25-91kg) and women (11-25kg) in the molar region. More recently, the maximum bite force in a sample of 20 subjects was found to range between 25-127kg (Gibbs, Mahan, Lundeen, Brehnan, Walsh and Holbrook, 1981). The maximum bite force ever recorded in a human is 443kg (Gibbs, Mahan, Mauderli, Lundeen and Walsh, 1986).

Reports of populations, such as Eskimos living in their natural surroundings, have highlighted how the environment, including culture and lifestyle can influence masticatory muscle strength. Waugh (1937a, b) found that the maximum bite force between first molars in Eskimo males ranged from 91 to 158 kg, while Eskimos living in settlements showed significantly lower values. The high masticatory forces related to their diet and not to their overall body size or strength. This has been substantiated by Brekhus, Armstrong and Simon (1937) who compared a group of dental students with a group of athletes (matched for height and age) and found no difference in bite force between the two groups. A comparison between Minnesota athletes and a group of South American Aborigines living in their natural surroundings showed that the bite force among the Aborigines was substantially greater (Oppenheimer, 1966).

Although it is sometimes assumed that maximum bite forces are a good indication of bruxing force potential, Clarke, Townsend and Carey (1984) have indicated that the forces exerted during nocturnal bruxism range from 28% to 51% of maximum voluntary bite force. In fact, little is known about the variation of forces applied during bruxism within and between individuals.

The forces required for normal mastication are substantially smaller than maximum bite forces and they vary depending on the type of food being consumed. Estimates range from 4-8kg for bread, 14kg for carrot, 7-27kg for meat, and 23-84kg for various nuts if they have been ground to a pulp. The average masticatory force produced has been estimated to range from 0.4-34kg (Wolpoff, 1971).

Studies such as those described are informative, but they only provide an indication of the variability of the maximum human biting potential. They do not indicate what forces are at work during casual, everyday mastication or during grinding and clenching. Maximum effort is not applied necessarily every time one masticates or grinds the teeth.

EFFECT OF SALIVA AND pH ON DENTAL ENAMEL

Apart from the daily ingestion of liquids from external sources, under normal circumstances, saliva is the only intrinsic source of moisture in the oral cavity. Although it is not intended to give a detailed description of all aspects of saliva, it must be recognised that the functions of saliva are many, including its capacity to lubricate the oral cavity and upper pharangeal spaces, to buffer external solutions of various pH, especially acids, and to play a role in the surface remineralization of enamel (Kelly and Smith, 1988). The quality and quantity of saliva varies with the time of the day, the gland in which it is produced, the degree of hydration of the body, and especially whether the saliva is stimulated or produced at a resting state.

The buffering capacity of unstimulated saliva is generally very poor because natural buffers such as proteins, phosphate ions and, to a lesser degree, bicarbonate ions are present at very low levels. Salivary pH is essentially dependent on bicarbonate concentration (Edgar and O'Mullane, 1990). At low bicarbonate concentrations salivary pH is maintained at about 5.3, whereas when saliva is stimulated and flow rates increase, the bicarbonate ion concentration increases substantially, changing the pH of the saliva to as high as 7.8. This may be beneficial if the stimulation is mechanical, such as chewing gum. However, the buffering capacity of saliva may not be able to counteract the effect of liquid stimulants such as acetic or citric acid that may have a pH lower than 3.0. The continuous consumption of such liquids will therefore invariably have an erosive effect on the dentition.

The lubricating properties of saliva are dependent on many interrelated factors such as calcium ion concentration and the presence of various proteins and high molecular weight mucinous substances that are predominantly glycoproteins. Generally, a frequent intake of foods and beverages of low pH will substantially decrease the lubricating properties of saliva (Nordbo, Darwish and Bhatnegar, 1984).

It is well known that low pH in the oral environment influences dental enamel by causing dissolution, but the effects on enamel vary depending on acidity levels and the source of the acid. For example, it has been shown that the acids produced by dental plaque cause subsurface dissolution of enamel, while the surface remains intact (Larsen, 1973). In contrast, acids from external sources cause dissolution progressively from the surface (Moreno and Zahradnik, 1974). Research has shown that the difference lies in the concentrations of fluorapatite and hydroxyapatite in the acid solutions adjacent to the enamel surface. If the solution is saturated with fluorapatite and not hydroxyapatite, then the fluorapatite has the ability to become incorporated into the surface layer thereby keeping it intact, while at the same time there is gradual dissolution of the hydroxyapatite in the subsurface layers (Larsen, 1973; Larsen and Fejeskov, 1977). This situation is found in areas where the enamel is covered by plaque. However, if plaque is not present, the acid acting on surface enamel is unsaturated with respect to both fluoroapatite and hydroxyapatite causing progressive enamel dissolution from the surface.

These findings have stimulated further research into the effects of remineralizing solutions on tooth wear *in vivo*. For example, it has been shown that human saliva, calcifying solutions and fluoride mouth rinses have some effect in reducing abrasion and erosion (Kelly and Smith, 1988).

OTHER VARIABLES INFLUENCING ENAMEL WEAR

Tribologic studies have considered other variables that may influence wear during the testing of different materials. These include the temperature of the surfaces being rubbed, the speed and the direction of movement of the opposing surfaces and finally the duration of contact of the surfaces. How these variables affect the wear of a material will depend on the structure of the material itself. For example, uniform structures such as opposing gold surfaces will show identical wear characteristics irrespective of the direction of wear (all other variables being held constant), whereas the direction of wear will have an effect on a material such as wood which has a grain structure.

Every material must be assessed on its merits by considering all possible variables. The effects of temperature, speed, and direction of movement on the wear characteristics of human enamel are currently unknown.

1.3.2 TOOTH WEAR STUDIES

Since Broca's (1879) classification of dental wear (from Heithersay, 1960), there have been many attempts to describe and quantify the wear process. Some researchers have used indices of tooth wear, calculated from ratios of areas of exposed dentine and overall occlusal area, while others have focused on the evaluation of crown height reduction. Unfortunately, scoring methods vary between researchers, making direct comparisons between studies difficult. For example, Lysell (1958) used a four-point scoring method to quantify and qualify tooth wear; Ten Brugen Cate (1968) applied a five-point score while focussing on the effects of erosion; Hansson and Nilner (1975) used a four-point system to quantify vertical tooth loss; Smith and Knight (1984) used a five-point score based on the quantification of area and used this as a predictor of "pathologic" and "physiologic" wear.

In addition to general descriptions of tooth wear based simply on observations (e.g., Taylor, 1971), some researchers have focussed on *in vivo* quantitative investigations, while others have used *in vitro* models, including tooth wear machines, to study surface changes in teeth and make comparisons of the wear of various dental materials.

In Vivo Studies

Clinical studies of tooth wear, though seemingly the most appropriate approach, have disadvantages including the difficulty in directly visualising wear, difficulties with access into the oral cavity, and most importantly, difficulty in controlling the oral environment. Techniques used to assess surface changes on teeth have essentially been two-fold:

(1) Assessment of serial dental models obtained in longitudinal studies may be used, however the length of time over which observations must be made is often quite considerable. From an anthropological perspective, longitudinal research has been invaluable. For example, Molnar, McKee, Molnar and Przybeck (1983) have successfully studied the rate of tooth wear of Australian Aborigines using serial casts collected during a longitudinal growth study.

In an attempt to overcome some of the problems of longitudinal studies, cross-sectional investigations have been undertaken. For example, ratios of exposed dentine to enamel versus age have been used on a population basis to provide standards against which individuals may be compared (e.g., Smith and Knight, 1984).

Replica techniques (e.g., silicone impression materials from which casts using metal, diestone or epoxy resin are constructed) have been used to calculate the rate of vertical tooth loss from aligned negative impressions of replicas obtained in a four-year longitudinal study (Lambrechts, Braem, Vuylsteke-Wauters and Vanherle, 1989)

(2) The surface roughness of tooth replicas has been determined with profilometers that trace the microscopic contour of surfaces (Noordmans, Pluim, Hummel, Arends and Busscher, 1991; Coffey, Goodkind, Delong and Douglas, 1985) using a mechanical stylus, laser or radio-isotope technique (Glentworth, Harrison and Moores, 1984). Even holographic techniques have been used by researchers in the assessment of tooth wear (Atkinson, Groves, Lalor, Cunningham and Williams, 1982).

It is difficult to determine why there have been such marked differences in results obtained using the above-mentioned techniques. One can speculate that the main sources of error lie with inaccuracies of the replicating techniques, from the inherent restrictions of each measuring device, and also from the variation that may exist in teeth within and between populations.

In Vitro Studies

There have been many *in vitro* studies of tooth wear, the majority focussing on the wear characteristics of dental materials. Essentially, tooth wear machines used for these purposes have been variations on a similar theme, with the main differences being in complexity:

(1) The simplest type consists of a mechanism whereby vertical impact stresses of different magnitude can be imparted to prepared specimens (Sarkar, 1980b).

(2) The most common type, consists of a rotating disc against which a specimen is placed, while maintaining control of variables such as load, the number of disc rotations, and the particle size of the abrasive slurry used between the dynamic parts (e.g., Mahalick, Knap and Weiter, 1971).

(3) The most complex machines enable two opposing specimens to be rubbed against one another, again controlling for variables such as those described previously (Harrison and Lewis, 1975). Some of these machines can be immersed in baths containing artificial saliva that acts as a lubricant (eg. Monasky and Taylor, 1971; Douglas, Sakaguchi and Delong, 1985; Delong and Douglas, 1991), while others have been modified to introduce impact stresses to the machine's cycle, supposedly simulating impact wear during mastication. For example, Aziz and Harrison (1988) found that the wear of some restorative materials, including enamel, increased as the impact stress increased.

An extension to this third type has included more complex models where "opposing arches" rather than opposing teeth, can be worn together under a multitude of controlled variables (Molnar, 1968).

With all these systems qualitative and quantitative evaluations are made after specimens have been exposed to the machine environment. These may include calculation of volume loss by weight (Mahalick et al., 1971), the assessment of surface texture by profilometric methods, scanning electron microscopy after using various replica techniques (e.g., Mahalick et al., 1971; Powers, Craig and Ludema, 1973; Delong, Douglas, Sakaguchi and Pintado, 1986), and reflex microscopy (Adams and Wilding, 1988).

So far, correlations between the results of *in vitro* tests and clinical observations have been poor (Harrison, Moores and Glentworth, 1984) because loads, speeds and abrasives have generally been too severe and because of poor reliability due to manipulative errors. Differing experimental machine designs and measuring systems have not allowed investigations to be compared directly. Furthermore, it must be acknowledged that the varying conditions of the oral environment cannot be replicated precisely in an experimental setting. The best we can hope for is a better appreciation of how different variables affect dental wear.

1.4 THE NEED FOR THIS RESEARCH

When research encompasses more than one discipline, as does tooth wear, disagreements often occur. For example, the pattern of the human masticatory cycle has been described extensively yet opinions differ on whether there is a lingual phase in the masticatory stroke or whether there is orthal retraction associated with the movement. Disagreement also exists as to whether wear facets, that are caused by bruxism, can also form from tooth-to-tooth contact during the mastication of food. Microwear detail of worn tooth surfaces has been attributed to diet and used to infer the nature of mandibular movements during mastication. Alternately, microwear detail has been used as evidence to explain mandibular movements during bruxism.

Inferences made about tooth wear from microscopic examination of fossils, skeletal material and even tooth replicas of extant species (i.e., non-controlled observations) are based on a multitude of preconceived ideas, such as the assumption that wear only occurs during mastication. The reality is that diet plays a fundamental role, but the way that dietary-related microwear is "read" also lends itself to questioning. For example, conversations with Molnar (1994) have highlighted the problem of interpretation of microwear, indicating that it is not necessarily a reflection of the general diet of an individual but only evidence of the "last supper". All this indicates that we have much to learn about the causes of the scratches and striations observed on worn tooth surfaces.

Despite some disagreements between researchers, there is general consensus that bruxism occurs in nature, that it produces wear facets on teeth, and that it is a common contributor to the wear process that is difficult to treat. Furthermore, tribologic studies have established that the load between sliding opposing surfaces is closely related to wear rate, leading to the assumption that some bruxists show more tooth wear than others because of the higher occlusal forces applied. Could it be that differences in wear rate may also result from the influence of other previously overlooked oral factors (e.g., pH of the oral fluids)?

This study examines tooth wear under controlled experimental conditions simulating the behaviour of bruxism. Though the resultant tooth wear may involve both enamel and dentine, the project focusses only on the wear characteristics of enamel, leaving investigations of dentine for the future. By learning more about the wear behaviour of dental tissues under different conditions, certain aspects of the oral environment may serve as predictors of potential problems which may be intercepted.

SECTION 2

EXPERIMENTATION

2.1 INTRODUCTION

To assess the variables that influence enamel wear under controlled conditions, the following experimental approach was adopted:

(1) The design and construction of an electromechanical tooth wear machine where opposing tooth specimens could be subjected to wear while controlling for variables such as load, uni-directional or bi-directional movements, duration of contact, number of cycles, speed of each cycle, as well as the quantity and quality of selected lubricants.

(2) A series of preliminary experiments to establish the appropriate operating conditions for the machine, to establish which variables affected enamel wear, and to quantify the sources of error.

(3) A series of quantitative studies to establish the relationships between the experimental variables (e.g., load and lubricant pH) and the rate of enamel wear. The lubricants selected were water (pH=7) simulating a serous oral environment, acetic acid (pH=3) resembling an acidic diet, hydrochloric acid (pH=1.2) resembling the effects of regurgitated acid, and natural saliva (pH=7). Also included were studies of enamel wear under non-lubricated conditions where tooth specimens were worn dry to resemble an extreme xerostomic oral environment.

(4) Qualitative studies of the microscopic appearance of wear facets produced under different conditions.

(5) The systematic evaluation of the relationships between the quantitative and qualitative variations of tooth wear.

2.2 QUANTITATIVE ASSESSMENT OF WEAR

2.2.1 MATERIALS AND METHODS

MACHINE DESCRIPTION

The tooth wear machine used for evaluating dental wear was specifically designed and purpose built for this project. Close consultation with the Department of Mechanical Engineering at The University of Adelaide resulted in a design that allowed control of the variables influencing wear. Figures 8a-d show the machine design together with the component parts.

The apparatus consists of a stainless steel base and frame onto which all parts are secured. The machine is driven by a 75 watt D.C. electric motor configured to operate at variable speed. The motor powers a 10:1 reduction gearbox that moves a series of interchangable cams controlling the movement of one of two specimen holders. Depending on the selected cam, movement can be controlled in either or both of two dimensions (horizontal and vertical). A simple adjustment screw on the cam follower accurately establishes the degree of movement in the horizontal plane, allowing control of the duration of contact of the enamel surfaces of specimen teeth. A magnetic counter attached to the resultant drive of the gearbox, records the number of cycles of the machine.

FIGURE 8a: Electromechanical tooth wear machine showing: (1) the machine with its cover, (2) the controls, (3) the counterbalance overhead pully system used to reduce the load below that of the movable section of the machine, and (4) the hypodermic needle directed towards the specimens.

FIGURE 8b: Lateral view of the tooth wear machine with the cover removed showing motor, pully, gearbox and the framework housing the upper movable section controlled by the cam.

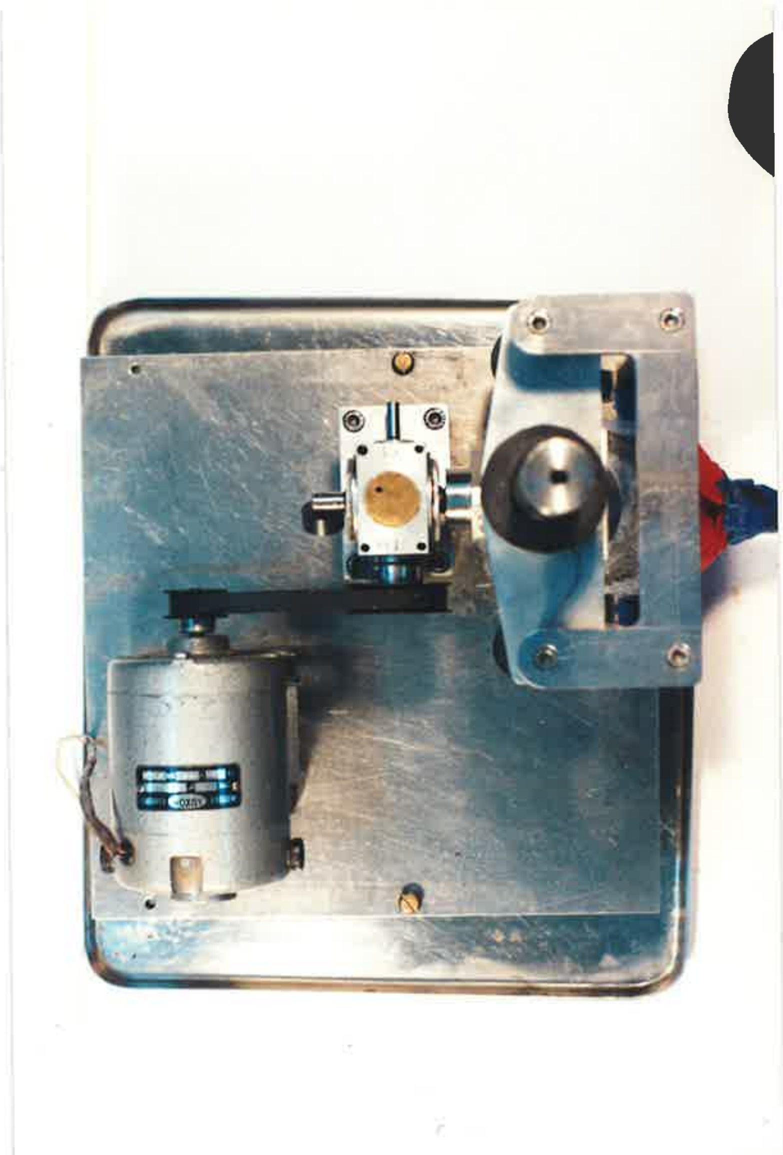

FIGURE 8c: Top view of the tooth wear machine with the cover removed showing motor, pully, gearbox and the framework housing the upper movable section controlled by the cam.

FIGURE 8d: Gravity-fed lubricating system showing (1) lubricant reservoir, (2) flow control, and (3) plastic tubing leading to a hypodermic needle mounted on an adjustable stand.

Unless otherwise stated, all experiments described in this study were based on uni-directional movements where a moving upper specimen was rubbed against a fixed lower specimen in one direction for a specified duration, after which the cam lifted the upper specimen and repositioned it at the beginning of the stroke. This action comprised one cycle.

Specimens were mounted in the machine using specifically designed holders. The lower holder consisted of a stainless steel cylinder, arranged vertically on a flat base that could be secured to the stationary base frame of the machine. The internal diameter of the specimen holder was designed to accept the specimen cylinder which was then secured and indented by a laterally-directed screw. This ensured accurate repositioning of the specimen at all times. The upper specimen holder, which also had a similar internal diameter and a laterally-directed screw to secure the specimen, was an integral component of the movable part of the machine that was controlled by the cam.

The upper mobile section of the machine was designed to support weights for applying loads to the specimens, giving an operating range of 0.25kg to 16.2kg. Though the machine could accept heavier loads, preliminary tests indicated that the incidence of tooth fracture was very high above this operating range. Without the addition of load, the inherent weight of the upper movable component of the machine was measured at 3.2kg. Therefore, to achieve loads below 3.2kg, the upper movable component of the machine was attached to a counterbalanced overhead pully system.

SPECIMEN PREPARATION

Freshly extracted human teeth were obtained from routine dental treatment in the Department of Dentistry at The University of Adelaide. These teeth were premolars extracted for orthodontic reasons or impacted third molars, all of which were non-carious with very little or no wear. The teeth were sectioned longitudinally by splitting in a mesio-distal direction so that each specimen consisted of a buccal or lingual half-crown with a root portion. The pulpal tissue was then removed for other experimental purposes and the two halves placed in water. Before each experiment, the teeth were cleaned in water using finger pressure (while wearing latex gloves) until any attached soft tissue was removed. They were then allowed to dry for at least ten days.

Each half tooth was attached to a scanning electron microscope (SEM) stud with the tooth crown centrally positioned. The stud was then attached to a plastic cylinder 18mm in length (Fig. 9). The diameter of each cylinder was such that it fitted exactly into the upper and lower specimen holders of the tooth wear machine. The adhesive used to attach all specimens was Araldite epoxy resin (24 hour setting time to achieve maximum strength), manufactured by Ciba Geigy. For all specimens, 24 hours was allowed for complete curing of the adhesive.

FIGURE 9: Examples of tooth specimens fixed to SEM studs (24mm diam.) which in turn were fixed to plastic cylinders. Specimens and all adhesive were covered with nail polish (in red) to reduce the effects of the ingress and egress of water.

Preliminary tests (Section 2.2.3) verified that moisture uptake occurred while specimens were in contact with water, and that both moisture uptake and loss occurred with dry specimens, depending on atmospheric conditions. The extent of fluctuation in water uptake and loss was assessed in teeth, plastic cylinders, and adhesive separately, representing all components of the experimental set-up. All materials contributed to the observed fluctuations, with the dental tissues showing the greatest change, followed by the adhesive. As fluctuations could affect the experimental results, attempts were made to reduce the effect of moisture, especially during stages where lubricants were used. This included covering the tooth surface (excluding the facet), the adhesive, and the SEM stud with non-soluble nail vanish so that only the facet remained exposed to the lubricant.

For all experiments, control specimens were prepared and exposed to identical environmental conditions of lubrication and temperature as the specimens used in each of the experiments (except for the wear process itself). Where necessary, facets were first prepared on the controls using the machine, to ensure that the enamel exposed to the lubricant in the control specimens corresponded as closely as possible to the specimens being tested.

METHOD OF LUBRICATION

The lubrication of facets during dynamic wear was achieved by the use of a gravity-fed drip system consisting of a plastic reservoir on an adjustable stand from which plastic tubing led to a hypodermic needle. A volume control which accurately adjusted the flow rate was attached to the tubing (Fig. 8d).

The hypodermic end of the tubing was clamped to an adjustable stand so that the lubricant could be directed precisely onto the facet without impinging upon the movement of the opposed tooth surfaces. The lubricant run-off from the specimens was directed from the base of the machine into a container.

QUANTIFICATION OF ENAMEL WEAR

The method used for quantifying wear was based on measuring the weight of tooth structure removed during grinding. Specimens were weighed to an accuracy of 0.1mg using an A & D, ER-182A Electronic Analytical Balance which was calibrated according to specifications and tested using precisely-manufactured known weights. To ensure accuracy, the balance was kept on a free-standing table at all times, away from vibrations, and the specimens were weighed in a closed chamber to avoid the effect of air currents.

In every case, each specimen and its control were weighed five times and the average of these weights recorded. Corrections were made for moisture uptake or loss within each experimental specimen according to the moisture fluctuations observed within the control. Even in experiments where no lubricants were used, the controls were used to adjust for water uptake and loss induced by environmental fluctuations in humidity.

Where the specimens were subjected to wear under dry conditions, any change in weight of the controls caused by water absorption from the atmosphere was noted and appropriate adjustments made to the recording weight of the specimen. Where experiments involved use of a liquid lubricant, the controls were also kept in an identical lubricant until the end of each experiment. After specimens were dried of surface moisture using paper towelling, they were allowed to stand for two hours to dehydrate to a stable state (this was confirmed by observing no decrease in weight over five consecutive weighs) and then weighed. Weights were then corrected by comparing with identically treated controls.

2.2.2 STATISTICAL METHODS

For each experiment, data were summarised in tabular form with loads, sample sizes, mean wear rates and their corresponding standard errors, standard deviations, ranges of values, and coefficients of variation presented. The coefficient of variation (CV) was calculated as:

$$CV = 100 \text{ (standard deviation / mean)}$$

Mean wear rates and their standard errors were also plotted against load to display relationships graphically.

Raw data were plotted and regression lines or curves fitted using a computer package (Cricket Graph III - version 1.0). Regression lines or curves were fitted to the data to represent trends only and to facilitate interpretation.

The statistical package SPSSX (SPSS Inc. Chicago) was applied to calculate estimates of skewness and kurtosis for the tooth wear data and normal probability plots were generated. These approaches confirmed that the data were normally distributed ($P>0.20$). Mean values of wear rates for selected pairs of samples in the preliminary analyses were compaired using Student's t-test for independent samples. Where appropriate, analysis of variance (ANOVA) was performed between selected experimental groups using SPSSX to determine whether there were statistically significant differences between mean wear rates under various conditions. Post hoc comparisons of mean values were made using Tukey's method. Statistical significance was set at the 0.05 probability level.

2.2.3 PRELIMINARY EXPERIMENTS

MEASURING ENAMEL WEAR

When quantifying enamel wear by weight, it was established that the ingress and egress of water contributed most towards the unreliability of the data. This occurred when experiments were conducted on dry specimens, and especially on those where various lubricants were used. Therefore, a number of preliminary tests were conducted to determine the rate, extent and pattern of water fluctuations within specimens and their effect on quantifying tooth wear. This information allowed the establishment of an experimental procedure that reduced the degree of error produced by moisture.

Specimens were tested for the degree of water uptake or loss by observing the fluctuations in weight that occurred with time.

(1) Six dry specimens were weighed over a period of almost 60 hours, during which there was no functioning air conditioning (and therefore air exchange from outside the building) for the first 15 hours. Tables 1a, b below show the weight of the specimens at various times and the degree of

change from their original weights respectively, while Figure 10 provides a graphic representation of the results.

TABLE 1a: Weights (mg) of six dry specimens recorded over a 59 hour period.

	SPECIMENS					
Period (hours)	1	2	3	4	5	6
0	9255.9	9441.0	9398.3	9286.4	9797.1	9323.3
17	9255.7	9440.6	9397.8	8285.9	8796.7	9323.1
19	9255.7	9440.5	9397.9	9285.9	9796.7	9323.1
36	9255.9	9441.0	9398.2	9286.3	9796.9	9323.1
59	9256.2	9441.2	9398.2	9286.4	9797.0	9323.4

TABLE 1b: Change in weight (mg) of the six specimens during indicated periods.

	SPECIMENS						
Period (hours)	1	2	3	4	5	6	Mean
0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.00
0-17	-0.2	-0.4	-0.5	-0.5	-0.4	-0.2	-0.37
17-19	0.0	-0.1	0.1	0.0	0.0	0.0	0.00
19-36	0.2	0.5	0.3	0.4	0.2	0.0	0.27
36-59	0.3	0.2	0.0	0.1	0.1	0.3	0.17

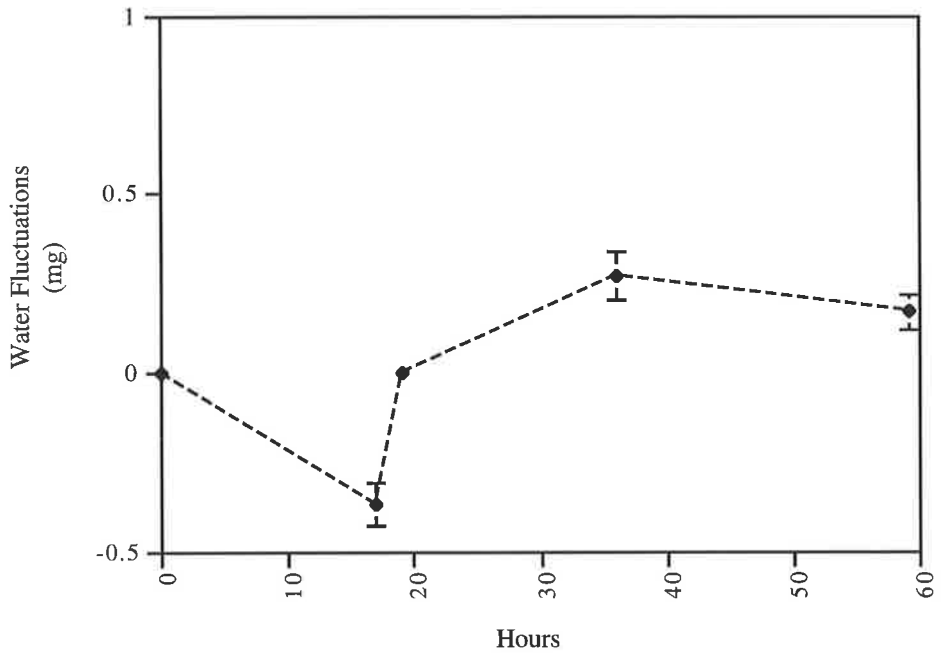

FIGURE 10: Mean fluctuations in weight (with standard error bars) caused by the ingress and egress of water in six specimens over a 59 hour period.

The resulting fluctuations reflected changes in atmospheric conditions and had a maximum range of about 1mg over a 60 hour period. The fastest change occurred around 18 - 20 hours when the air-conditioning was turned on, allowing fresh air to enter the building. Without such a dramatic change in environmental conditions, fluctuations in weight were smaller and about 0.3mg, which was approximately 0.003% of the average weight of specimens which was of the order of 10g.

Though this percentage variation is very low compared to the average weight of the specimens, it was significant at light loads because the weight of tooth surface loss was of similar magnitude. Accurate calculation of the ingress and egress of moisture and consequent adjustment of the specimen weights was therefore essential.

Interpolation between points on Figure 10 provided an indication of the degree and rate of water fluctuation that could occur over time provided that the functioning of the air conditioning in the building remained constant. This was substantiated by numerous other observations of controls during the experimental procedures.

(2) Attempts to find other ways of overcoming the moisture problem were not successful. For example, drying specimens to a consistent "moisture free" state before each weight assessment was attempted. Specimens dried for a number of days in a closed environment using silica sachets and then removed from their dry environment for about two hours (simulating the time specimens were used on the machine), absorbed water very rapidly and subsequent attempts to dehydrate these specimens to their original level were difficult and time consuming. Similar unreliable results were obtained when specimens were dried in an oven. Furthermore, it was not known whether, and to what degree, the structural properties and hence wear characteristics were affected by extreme dehydration.

(3) Attempts to weigh specimens in a saturated state were also unsuccessful. Specimens were removed from a water bath, excess surface moisture removed with the use of water

absorbent paper, and weighed. Immediate water evaporation was rapid and extensive, producing progressive weight loss of more than 20mg over a period of five consecutive recordings. The rate of continuous weight loss reduced to a stable level over a period of about two hours, after which only changes in atmospheric moisture affected the weight.

It was therefore decided that when using various lubricants, controls should be exposed to the same lubricants for the same amount of time as the experimental specimens. After a period of grinding, specimens and controls were dried with water absorbent paper, allowed to dry further for two hours, then weighed. In this way, adjustment for the ingress of water ensured that the measured change in weight represented an accurate measure of tooth surface loss.

EFFECT OF TEMPERATURE ON ENAMEL WEAR

During initial tests, specimens were monitored using an electronic thermocouple to measure the temperature produced at the facet surface. Fine electrodes were placed within about 2mm of the dry facet borders while under dynamic load and the working temperature was monitored at regular intervals. The accuracy of the thermocouple was tested and standardised against a conventional mercury (bulb) thermometer in a water environment.

Recorded temperatures ranged from room temperature at the beginning of the experiment to a stable working temperature range of about 32-35 degrees Celsius while the machine was functioning. This working temperature was not only the result of friction between opposing teeth, but also due to heat produced by the electric motor that operated the system. This temperature range was considered acceptable as it was consistent and close to body temperature. There was no intention within this experimental model to determine how the wear characteristics of enamel changed over an extreme range of temperatures.

EFFECT OF CYCLE RATE ON ENAMEL WEAR

To test whether the relative speed at which the specimens were rubbed influenced the wear rate, two samples (each of four pairs) of specimens were prepared, and worn with a load of 3.2 kg. The first four pairs were run at a rate of 50% of the machine speed (80 cycles/min) while the second four pairs were run at 100% (160 cycles/min).

TABLE 2: Comparison of average loss of enamel (mg) at 80cycles/sec and 160 cycles/sec of machine speed.

	80 cycles / min. n=8			160 cycles / min. n=8				
Cycles	Wt	S.D.	S.E.	Wt	S.D.	S.E.	t-value	P
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.000
10000	1.00	0.59	0.21	1.60	0.31	0.11	2.55	0.022
20000	1.55	0.42	0.15	3.30	0.70	0.25	6.06	0.001
30000	2.58	0.56	0.20	3.80	0.61	0.22	4.17	0.001
40000	3.23	0.69	0.24	4.60	0.50	0.12	4.55	0.001
50000	3.74	0.72	0.25	5.20	0.39	0.14	5.04	0.001
70700	4.98	1.12	0.36	6.20	0.99	0.35	2.31	0.035
89000	5.80	1.64	0.58	7.30	1.39	0.49	1.97	0.066

For each sample, the specimens were evaluated over a period of 89×10^3 cycles and the mean of the accumulative enamel loss (mg) at different time intervals were recorded (Table 2). The mean enamel loss and associated standard errors of the two samples are described in Figure 11.

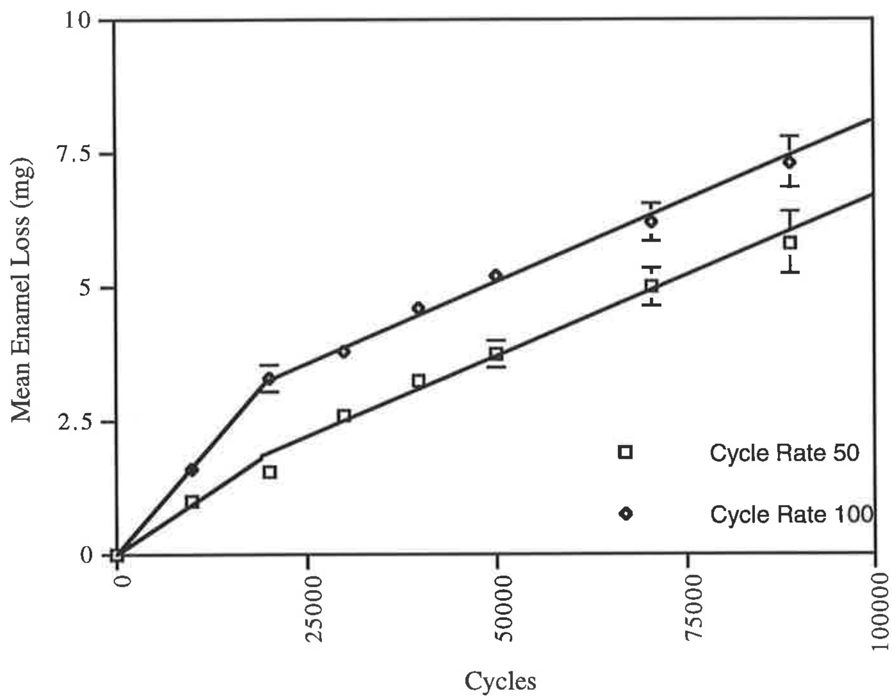

FIGURE 11: Mean enamel loss (mg) at 80cycles/min and 160cycles/min of machine speed.

The results of t-tests comparing mean enamel loss at two different cycle rates (ie. 80 cycles/min compared with 160 cycles/min) indicated significant differences in enamel loss ($p<0.05$) when the machine was run for up to 70.7×10^3 cycles. Although the mean enamel loss at 160 cycles/min exceeded that of 80 cycles/min when the machine was run for 89000 cycles, the difference was not statistically significant reflecting the relatively large standard errors associated with the mean values.

A two-way ANOVA (two-way analysis of variance) of enamel weight loss by machine speed (cycles/min) and number of cycles confirmed a significant increase in weight loss according to machine speed ($p<0.05$) and significant weight loss with increasing number of cycles ($p<0.05$). Furthermore, the interaction term between machine speed and number of cycles was not significant ($p=0.69$), indicating that the rates of wear at 80 cycles/min and 160 cycles/min followed similar patterns with increasing total number of cycles. It is evident from Figure 11 that the observed differences in enamel loss arose during the first $20x10^3$ cycles.

An explanation for the difference in weight loss of enamel at the two different machine speeds relates to an inherent property of the machine. As the rubbing imparted to teeth was uni-directional, the cam responsible for this movement was lifted before returning and being lowered again to the start of the cycle. As the speed of the machine was increased the lowering of the load was controlled less by the cam and more by gravity. Tribologists refer to this type machine action (the free-falling of a load) and its resultant effect on specimens as impact stress.

The results during the first $20\text{-}25x10^3$ cycles illustrated in Figure 11 are confirmed by Aziz and Harrison (1988) who has shown that impact stress in conjunction with a cyclical rubbing motion tends to increase the wear rate. Around $20\text{-}25x10^3$ cycles, the facet area reaches a threshold above which the impact stress is reduced until it has an insignificant effect (this will be explained later in this section) resulting in similar wear rates at different machine cycle speeds.

It was decided to run all experiments at 80 cycles/min to maintain consistency and to eliminate the effect of impact stress. In fact, impact stress is unlikely to be an important factor during bruxism or mastication as studies have shown that the mandible undergoes a marked deceleration prior to tooth contact (Bates, Stafford and Harrison, 1975).

EFFECT OF BI-DIRECTIONAL MOVEMENTS

It is not known whether bruxism involves uni-directional or bi-directional mandibular movement. Though this can only be resolved by a clinical study, it was felt that it was necessary to test for any differences in enamel wear rate between uni-directional and bi-directional machine movements.

With the machine adjusted to provide bi-directional movements and the duration of contact and number of cycles kept constant, two samples, each of three pairs of teeth were worn at 3.2kg and 9.95kg respectively and the average weight of enamel loss for each load was recorded (controls were used to adjust for moisture fluctuations). These results were compared with those for uni-directional movements.

It was found that the difference in average wear rates between the two movements was not statistically significant (P>0.05). Figure 12 demonstrates the relationship as load increases.

TABLE 3: Comparison of mean rate of tooth wear for uni-directional and bi-directional movements for various loads (kg).

	Uni-directional			Bi-directional			
Load	n	Mean	SE	n	Mean	SE	t-value
3.2	28	0.06	0.01	6	0.04	0.01	1.55
9.95	18	0.13	0.02	6	0.15	0.03	0.44
16.2	20	0.20	0.05				

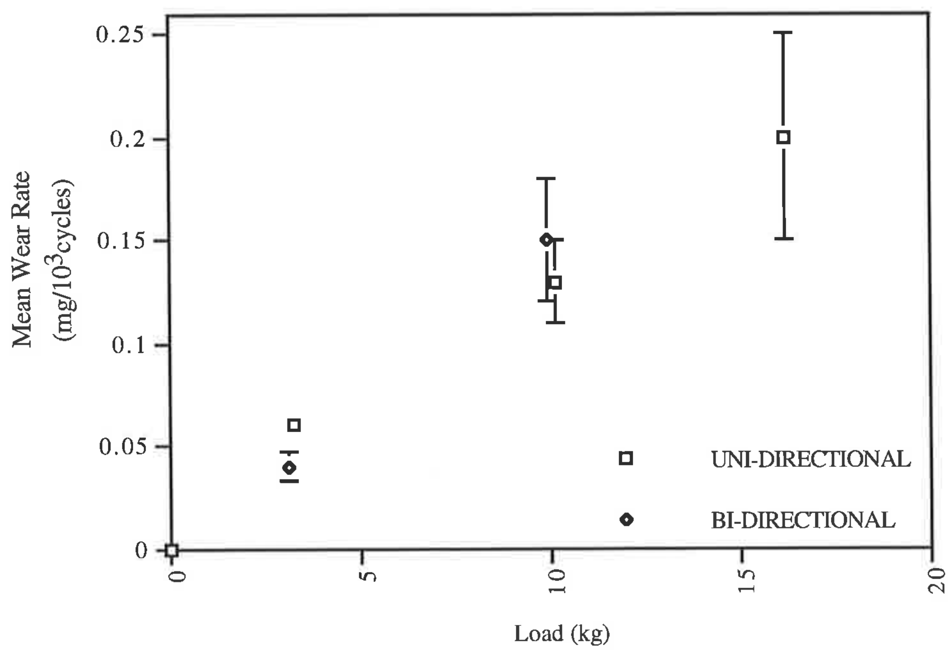

FIGURE 12: Comparison of mean enamel wear rate (with standard error bars) between uni-directional and bi-directional movements.

EFFECT OF pH ON ENAMEL

Because experiments were conducted using lubricants with varying acidity (pH=1.2 to pH=7), it was necessary to determine whether the amount of enamel dissolution from acid alone was substantial enough to bias the measure of tooth loss under dynamic load. Therefore, the weight of enamel loss was determined using specimens where facets were exposed to acids over predetermined periods.

Specimens, each completely sealed with varnish (except for the exposed facets produced under dynamic load), were subjected to the effects of acetic acid (pH=3), hydrochloric acid (pH=1.2) and water (pH=7) respectively. All three specimens were dried (as described previously) and weighed after one hour, and then again one hour later. The weights of the specimens exposed to acid were then corrected for water uptake by comparing them with controls exposed to water. Any loss in weight after correction was attributed to the effect of the acid.

With acetic acid at pH=3, no measurable loss of enamel could be detected due to the effect of acid over a two hour period. Even after eight hours, acetic acid could not be distinguished from weight changes in specimens exposed to the changes observed in controls. However, with hydrochloric acid at pH=1.2, the effects of enamel dissolution became measurable at about two hours. It was therefore decided that for all experiments involving lubricants, the time of exposure to the lubricant should be limited to approximately one hour to ensure that the direct effects of acid were minimised. This ensured that any measurable tooth surface loss could be attributed to the grinding effects of the machine.

PROGRESS OF ENAMEL WEAR

Comparison of Upper and Lower Specimens:

To determine the progress of enamel wear, eight pairs of teeth were worn at 3.2kg for a total of 89×10^3 cycles at a machine speed of 80 cycles/min and data were collected and averaged at 10×10^3, 20×10^3, 30×10^3, 40×10^3, 50×10^3, 70.7×10^3 and 89×10^3 cycles. This was equivalent to 23 hours of total wear for every pair of specimens, taking a total of about 180 hours to complete all eight pairs. It became apparent that the pattern of enamel wear rate showed two phases. The first (1^o) phase was of shorter duration and faster rate than the second (2^o) phase. For both phases the relationship between number of cycles and enamel wear was linear (Fig. 13).

Unpaired t-tests showed no significant differences ($P>0.05$) in mean enamel loss between upper and lower specimens regardless of the total number of cycles considered. ANOVA confirmed that enamel loss increased significantly with number of cycles ($p< 0.05$). No significant interaction was found between specimens (upper or lower) and number of cycles ($p=0.99$) indicating a similar pattern of enamel wear in both upper and lower specimens with increasing number of cycles (Fig. 13).

TABLE 4: Cumulative loss of enamel (mg) for both upper (n=8) and lower (n=8) specimens over a total of $89x10^3$cycles.

	Upper		Lower		
Cycles	Mean	SE	Mean	SE	t-value
10000	2.75	0.22	2.53	0.18	0.760
20000	4.98	0.40	4.73	0.38	0.450
30000	6.63	0.31	6.03	0.29	1.420
40000	8.08	0.35	7.48	0.30	1.310
50000	9.10	0.33	8.68	0.34	0.890
70700	11.58	0.40	10.80	0.47	1.270
89000	13.55	0.56	12.60	0.64	1.120

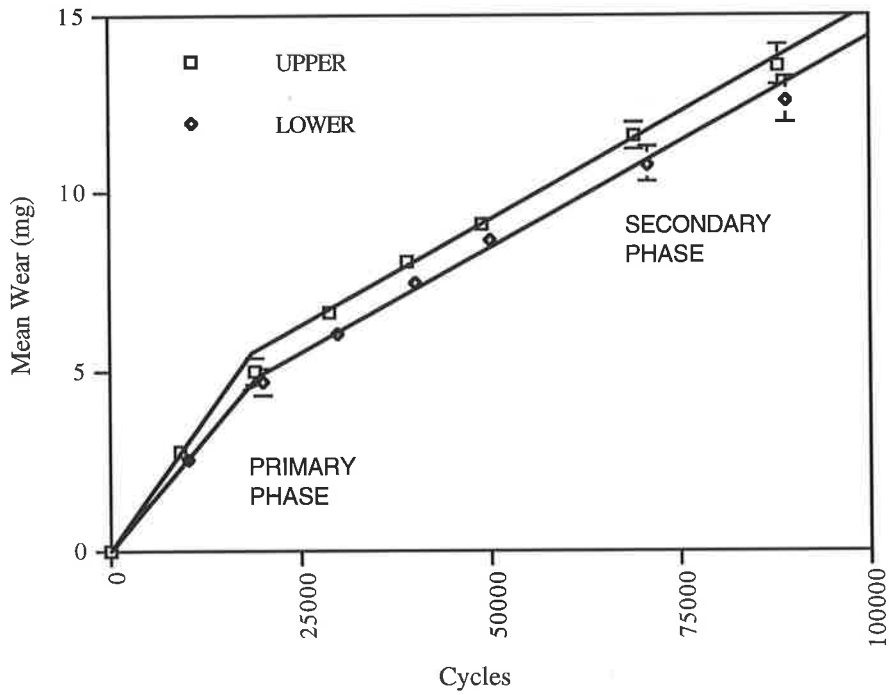

FIGURE 13: The two phases of enamel wear (with standard error bars) for upper and lower specimens at a fixed load of 3.2kg.

Though it is not customary to draw lines of best fit between mean values, the lines were purposely added to highlight the primary and secondary phases of wear

Progress of Enamel Wear at Different Loads:

Data were collected from 55 pairs of teeth worn during the primary wear phase and 33 pairs of teeth worn under dry conditions during secondary wear phase at loads of 3.2kg, 9.95kg and 16.2kg. Table 5 gives average wear rates for each phase, indicating significant differences in rate between 3.2kg, 9.95kg and 16.2kg. (Data for the primary phases of wear at 6.7kg and 13.2kg were included in the table for comparison)

TABLE 5: Wear rates during both phases of wear at different loads.

Load (kg)	Primary Phase ($mg/10^3$ cycles)	Secondary Phase ($mg/10^3$ cycles)	t-values
3.2	0.13	0.06	3.890
6.7	0.39		
9.95	0.49	0.13	4.820
13.2	0.77		
16.2	0.51	0.20	3.020

A two-way ANOVA of wear rate by phase and load confirmed that the two phases of wear were significantly different ($p<0.05$); that the wear rate by load was significant ($p<0.05$) and that the two-way interaction between the phases of wear and load was also significant ($p<0.05$), indicating different trends in wear rate between primary and secondary phases under increasing loads.

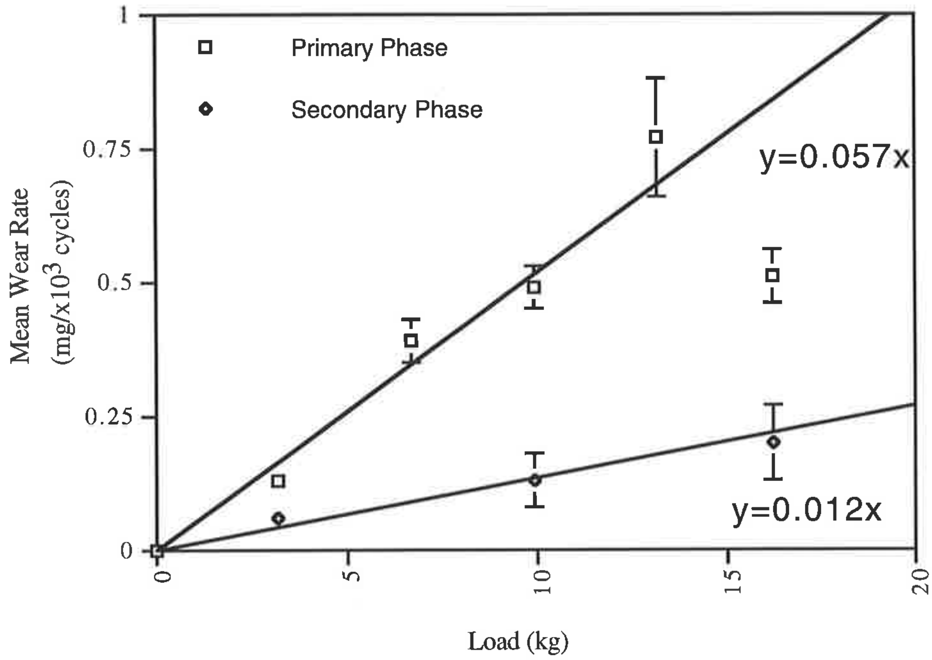

FIGURE 14: Mean wear rates (with standard error bars) of the primary and secondary phases at different loads.

Figure 14 provides a graphical representation of trends in average wear rate for both primary and secondary phases. Wear rates estimated from lines of best fit were $0.057 mg/10^3 cycles/kg$ for the primary phase and $0.012 mg/10^3 cycles/kg$ for the secondary phase. That is, the rate of enamel loss per kg of increased load in the primary phase was approximately five times that of the secondary phase.

FACET AREA

Measuring the loss of tooth structure by weight (mg) or by volume (mm^2) fails to disclose the changes that occur in the area and vertical height of wear facets. It is possible that two equal amounts of tooth structure can be removed, one representing a small surface area but a large loss in vertical dimension, the other the opposite. Though this relationship will vary depending on the shape or camber of the original tooth surface, it is also acknowledged that facet development is complex and very difficult to model for a number of reasons. For instance, the areas of opposing contacts change throughout a complete uni-directional movement, where the area of contact is relatively small at the start of the cycle, increases during the slide, and finally reduces as the opposing areas move past one another. It is therefore reasonable to expect that for any fixed load, the stress, which is dependent on area, would be higher when the contact areas are small (at the beginning and end of each stroke) and lower when the contact areas are larger.

Given the complexity of the interactions occurring at the wear interface, individual facets have been shown to increase in size linearly for many different materials, including enamel, after a preliminary phase (Ratledge, Smith and Wilson, 1994; Wassell, McCabe and Walls, 1994). It was therefore decided as part of the preliminary tests to describe the pattern of change in facet area during the wear process.

To assess facet area, all specimens were mounted on a dental survey table that was modified to accommodate the plastic mounting cylinder of each specimen. This allowed each facet to be positioned on a horizontal plane while being viewed under a stereo-microscope. Due to the very shallow depth of field offered by higher magnifications, the facet surface could be accurately positioned in the horizontal plane.

A millimetre ruler was placed at the level of the facet so that standardized photographs could be obtained. The facet photographs were traced, outlines digitized and the areas computed using a purpose-written program and a Hewlett Packard 98748 computer.

To assess the changes in facet size over time, four specimens were worn under controlled conditions until the secondary phase of wear was reached. An initial area was calculated by making positive resin replicas from silicone impressions of the facets. The teeth were worn between $5x10^3$ to $10x10^3$ cycles, after which the areas were again calculated. Initial and subsequent areas were calculated for two consecutive periods during the secondary phase of each specimen in an attempt to determine whether the increase in area was linear or not. Facet areas of all worn experimental specimens were calculated, and the relationship between stress and facet area was examined.

The patterns of increase of facet areas during the secondary wear phase are shown in Figure 15, while the results are summarized in Table 6. It shows facet area (mm^2) and corresponding total number of cycles at the end of two consecutive periods (i.e., period 1. and period 2.) of four specimens. The gradients of the regression lines provide an indication of rate of increase in area.

TABLE 6: Accumulative facet area (mm^2) and the corresponding total number of cycles of four specimens for two consecutive periods during the secondary wear phase.

	SPECIMENS							
Period	1		2		3		4	
	Cycles	Area	Cycles	Area	Cycles	Area	Cycles	Area
1	8031	2.18	7198	5.66	7525	0.71	7992	0.29
2	16083	3.63	15922	9.18	15217	0.74	15850	0.82

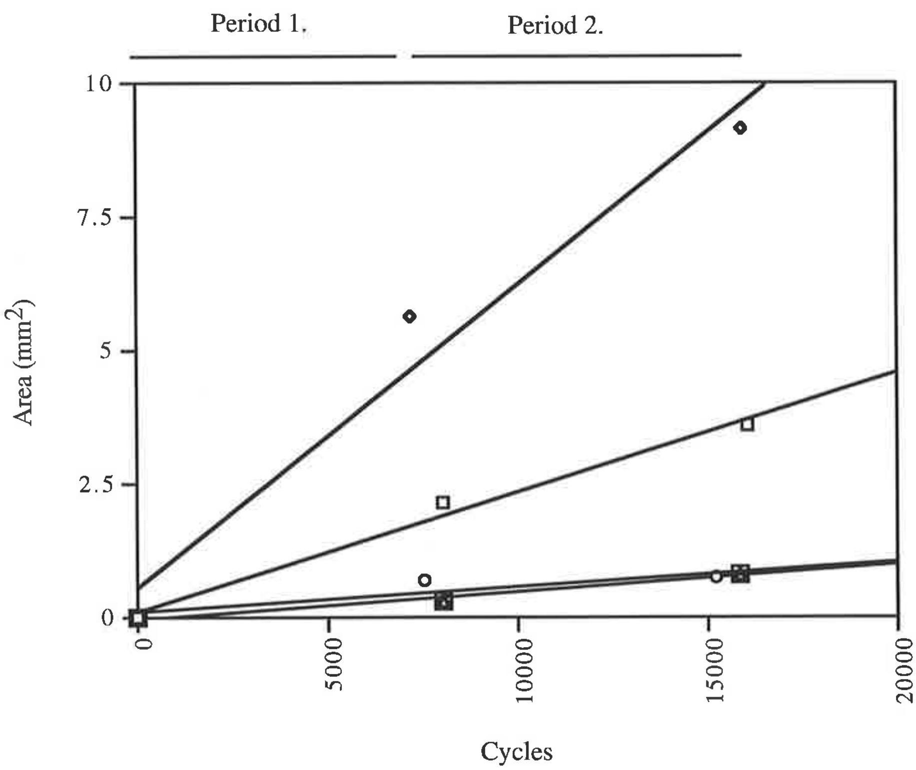

FIGURE 15: Trends of increasing facet area over two consecutive periods for each of four specimens

Though results relating to rate of increase of facet area were based on only four specimens, they nevertheless supported findings of other researchers who have described the increase in facet areas of enamel and other dental materials as being linear with time, after a preliminary phase (Ratledge et al., 1994).

Because of the constantly changing geometry of the area of contact during each wear cycle, and the progressive change in facet area with increasing wear, the problem of quantifying and describing the precise area of contact at each stage during the wear cycle is complex. Therefore, it is inappropriate to describe the applied stress (kg/mm^2) and instead loads were reported. However this represents an interesting theoretical problem which could be studied later.

OTHER CONSIDERATIONS

In addition to the preliminary tests, other considerations were addressed to ensure consistency between experiments. To control for the effect of differences in enamel hardness, opposing tooth segments used in experiments were obtained from the same tooth and care was taken to ensure that the enamel surfaces showed no evidence of developmental or congenital disturbances. Furthermore, all assessments of wear rates were made after the initial or primary phase of wear had removed the surface layer which tends to vary in hardness between individuals (Macpherson et al., 1991).

To minimise the possible effects of enamel rod orientation on variation in hardness between enamel surfaces, the buccal and lingual surfaces of the prepared teeth were opposed in the machine with enamel rods orientated as close as possible to perpendicular to the enamel surface.

Finally, the use of lubricants with different viscosities would impose an additional variable into the system. Therefore, the viscosities of all lubricants used (except saliva) were determined by conducting viscosity tests on samples at the Institute of Medical and Veterinary Science in South Australia. These tests confirmed that the viscosities of all the lubricants were similar, ranging from 0.93 to 1.04 centipoises @ 60 revs/min.

2.2.4 EXPERIMENTS CONDUCTED

The preliminary trials indicated which variables affected the wear of enamel and also gave an insight into the progress of enamel wear at varying loads. This information helped in designing the main experiments in this study.

Observations of the wear rate of enamel were made at varying loads and under the following conditions:

(1) the teeth were worn dry without lubrication (experiment 1)

(2) with lubricant at pH = 7 (experiment 2)

(3) with lubricant at pH = 3 (experiment 3)

(4) with lubricant at pH = 1.2 (experiment 4)

(5) with fresh saliva as a lubricant at pH = 7 (experiment 5)

During the experiments, variables were controlled as follows:

(1) The duration of contact between specimens was kept constant. This was achieved by setting the lateral

displacement of the upper, movable part of the machine at 3mm and ensuing that both upper and lower specimens remained in contact throughout the movement. This was important because frictional wear occurs when solids move relative to one another while in contact, therefore (with all other variables constant), two opposing objects in contact for a longer period while in motion will produce more wear.

(2) The movement between the teeth was uni-directional. It was shown during the preliminary tests that there was no significant difference in wear between uni-directional and bi-directional movements.

(3) The temperature remained constant. Preliminary tests indicated that the temperature of the specimens remained stable during experimental procedures.

(4) The machine was run at 80 cycles per minute. From the preliminary tests, it was observed that the cycle speed at which specimens were worn did not affect wear rate, although at 160 cycles per minute the amount of wear was slightly greater due to the impact stress imparted into the grinding cycle. It was therefore decided to run the machine 80 cycles per minute because this minimised the effects of impact stress and fell within the reported range of rates of human mandibular movements (Bates et al., 1975).

(5) All assessments of wear were made during the secondary wear phase after "wearing-in" specimens past the primary phase.

(6) The buccal aspect of each tooth was rubbed against the lingual aspect of its opposing specimen. This overcame to some extent the variability in enamel hardness that may exist

between teeth from different individuals and also the effects of enamel rod orientation within the same individual.

(7) All lubricants (except saliva) had similar viscosity, ensuring that the effects of pH were not being confounded by differences in viscosity.

(8) Where an acidic lubricant was used, the operating time of the machine was kept to less than 90 minutes so that any possible loss of enamel by chemical action was minimized. Therefore, measured tooth loss was attributed to the effects of tooth grinding.

(9) Short operating times ensured that water uptake by the specimens under lubricated conditions was kept to a minimum.

EXPERIMENT 1 (dry conditions)

Rates of enamel wear under dry conditions during the secondary phase of wear were determined at loads of 1.7kg (n=6), 3.2kg (n=28), 9.95kg (n=18), and 16.2kg (n=20). This was achieved by first wearing the specimens until the primary phase was complete. At each load, specimens were weighed at the commencement of the experiment (early in the secondary phase) and at the end of the experiment when the final weight was assessed and adjustments made for any atmospheric moisture fluctuations. The difference in weight was divided by the number of cycles to determine the rate of wear in mg of tooth loss per 1000 cycles (mg/10^3cycles). Finally, mean rates of wear and their standard errors were calculated at each load.

EXPERIMENT 2 (lubricated conditions : Water at pH=7)

Rates of wear were assessed at loads of 3.2kg (n=8), 6.7kg (n=18), 9.95kg (n=22), 13.2kg (n=12), 16.2kg (n=16) during the secondary phase of wear using the same methods of assessment as described for experiment 1. Specimens were first worn during the primary phase under dry conditions (to eliminate unnecessary exposure to water), then they were lubricated and the wear quantified during the secondary phase.

Control specimens for this experiment had also been worn past the primary wear phase under dry conditions, producing a secondary phase facet similar to that of the test specimens. Controls were exposed to the lubricant for exactly the same period of time and their weights assessed before and after exposure to moisture. The increase in weight due to moisture uptake was taken into account when weighing the specimens under study.

EXPERIMENT 3 (Lubricated conditions: acetic acid at pH=3)

The loads to which specimens were subjected were, 3.2kg (n=2), 9.95kg (n=12), 14.2kg (n=11), and 16.2kg (n=14). The methodology was identical to experiment 2.

EXPERIMENT 4 (Lubricated conditions : HCl at pH=1.2)

The loads to which specimens were subjected were 3.2kg (n=10) and 6.7kg (n=10). The methodology was identical to experiment 2.

EXPERIMENT 5 (Lubricated conditions : Human Saliva at pH=7)

The loads to which specimens were subjected were 9.95kg (n=9), 14.2kg (n=6), and 16.2kg (n=4). Fresh human saliva at pH=7 was continuously added to the experimental and control specimens using a spoon. Saliva denatures very rapidly outside the oral environment and therefore it could not be collected and stored. The methodology for this experiment was as described above.

2.2.5 CONCLUDING COMMENTS

The procedures for conducting the preliminary and final wear rate experiments were time-consuming. For example, preliminary tests to determine the progress of enamel wear took over two days for preparation followed by 23 hours of machine time for each pair of specimens. This was equivalent to 180 hours of tooth grinding (7.5 days continuously) for eight pairs of specimens, not including the weighing procedure. When lubricants were used, an additional two hours were allowed for the drying of each pair of specimens so that a stable state was reached before weighing.

It was intended initially to achieve sample sizes of about 15 to 20 experimental specimens with each group. However, specimen failures (e.g., fracture) and time constraints limited numbers in some groups. Data from some of the preliminary tests (e.g., phases of enamel wear, progress of enamel wear etc.) were included in the wear rate experiments under dry conditions to maximize sample sizes.

Loads were selected by using combinations of available weights that were added to, or counterbalanced against, the 3.2kg upper movable part of the machine.

2.3 QUALITATIVE ASSESSMENT OF FACETS

Qualitative assessment of facets was made using a stereo-microscope for low magnification and a scanning electron microscope where higher magnification was necessary.

For the light microscopy, a Wild Heerbrugg stereo-microscope with the ability to magnify up to 50 times was used. To this was attached a uni-directional external light source that could be adjusted to provide reflection for observation of all facet microdetail. In addition, an SLR camera mounted to the microscope allowed facet detail to be photographed. The photographs were used to compare the wear patterns produced under different environmental conditions.

Detailed qualitative assessment of wear facets was made possible with the use of a Philips XL20 scanning electron microscope housed in the Centre for Electron Microscopy and Microstructure Analysis at The University of Adelaide. Specimens consisting of composite resin impressions of facet surfaces were splatter-coated with gold/palladium and examined. The method used for making composite resin impressions was similar to that of Scally (1980), consisting of wetting the facet surface with unfilled light cured resin (e.g., Scotchbond (by 3M)), then curing, before applying filled resin in bulk (e.g., Z100 (by 3M)). The resin was then cured for a second time and "flicked off" by an appropriate dental instrument. The examination of a negative model proved to be as accurate and easier to prepare than positive replicas obtained from polyvinylsiloxane impressions. This approach also eliminated the need to pour impressions and the potential problem of producing air bubbles and other compounding inaccuracies (e.g., curing shrinkage).

Teeth selected for qualitative assessment displayed facet morphologies typical of the experimental sample from which they were obtained. The characteristic features observed on facet surfaces included:

(1) General smoothness of the surface. A smooth surface was one that showed few surface features and appeared polished.

(2) Parallel striations across the facet surface produced by fragments removed from the surface because of the dynamic action of the load.

(3) Evidence of compaction of third-body enamel fragments producing an impregnated layer upon the facet surface. The enamel fragments arose from microfine fracture of the underlying enamel surface.

(4) Voids within the impregnated enamel powder. These voids often undermined the surface of the impregnated layer, similar to a "cavernous" system, continuously being formed and broken down by the action of the dynamic load.

(5) Craters caused by removal of fragments of enamel from the surface while under dynamic load. These were not undermined.

These characteristics are illustrated in Appendix I (Atlas of Facet Morphology).

SECTION 3

RESULTS

3.1 INTRODUCTION

The quantitative and qualitative results of experiments are described in the order outlined in Section 2. The results are compared and interpretted in Section 4.

3.2 QUANTITATIVE ASSESSMENT

3.2.1 EXPERIMENT 1: DRY CONDITIONS

Wear rates under dry conditions were determined at loads of 1.7kg (n=6), 3.2kg (n=24), 9.95kg (n=14), and 16.2kg (n=11). Descriptive statistics for wear rates are shown in Table 7. Figure 16a shows mean wear rates with the corresponding standard error bars at each load, while Figure 16b shows a regression line fitted to the raw data.

TABLE 7: Mean wear rates (mg/10^3cycles) of dry specimens at different loads (kg), including descriptive statistical measures of standard deviation (SD), coefficient of variation (CV) and the standard error of the mean (SE).

Load	n	Mean	SE	SD	Range	CV
1.70	6	0.04	0.02	0.04	0.01-0.09	100
3.20	24	0.06	0.01	0.03	0.01-0.11	50
9.95	14	0.13	0.03	0.10	0.05-0.35	77
16.20	11	0.20	0.06	0.21	0.01-0.50	105

Table 7 shows that standard deviations quantifying the dispersion of wear rates about their respective means increased as the load increased. When values of coefficient of variation were compared, it was found that relative variability in wear rate was greater at the lighter and heavier loads but lower at intermediate loads.

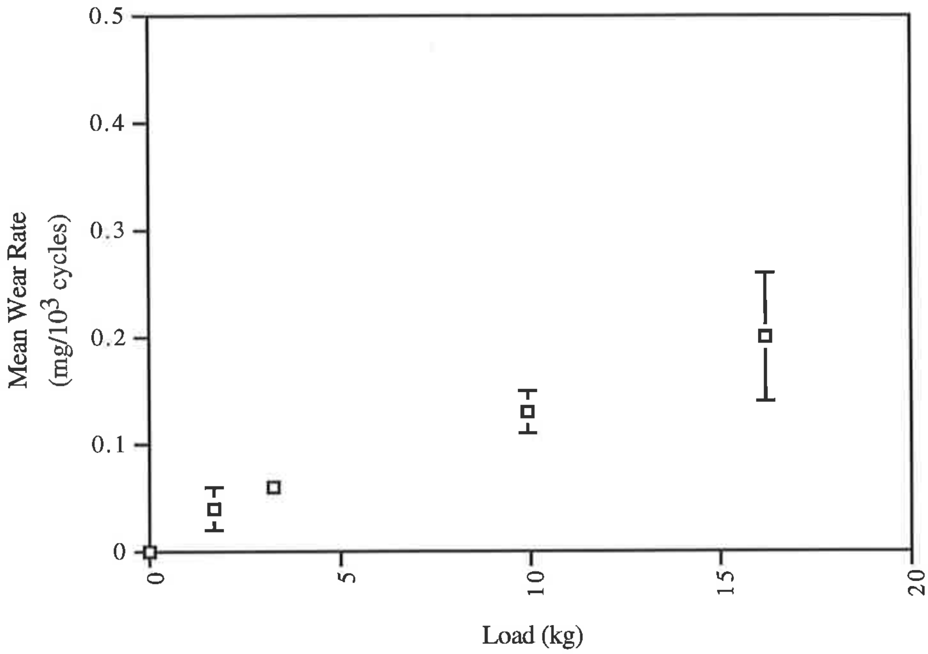

FIGURE 16a: Relationship of mean wear rate (with standard error bars) versus load under dry conditions.

Figure 16a shows that under dry conditions, enamel wear rate was higher with heavier loads, over the range of 1.7-16.2kg. The standard error of the mean wear rate was generally low but increased at the heavier load of 16.2kg. Figure 16b shows a regression line fitted to the individual data points. This line is presented only to provide an indication of the trend for heavier loads to be associated with greater rates of enamel wear.

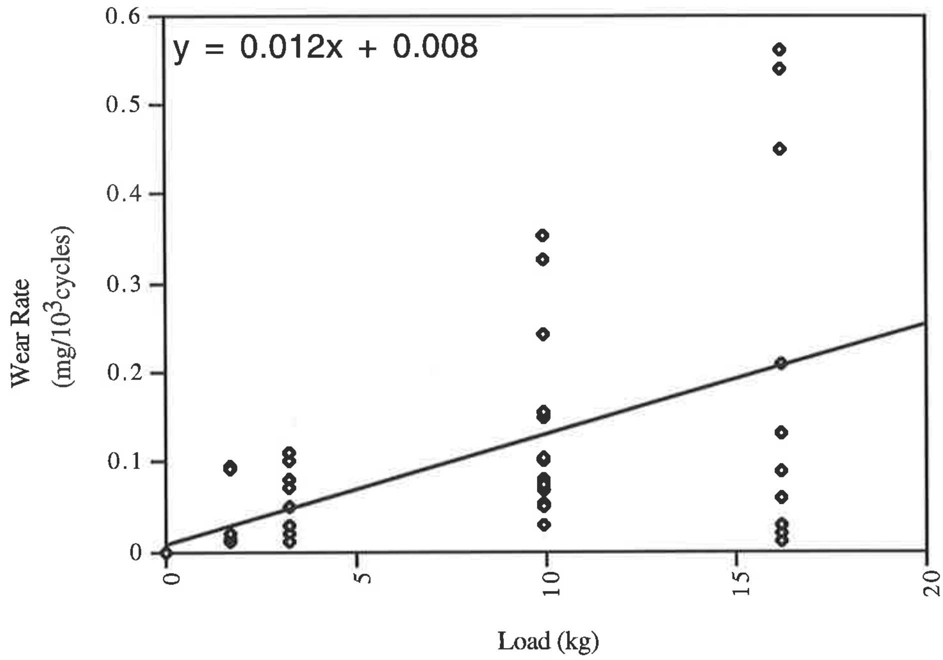

FIGURE 16b: Regression line showing the trend between wear rate and load under dry conditions.

A one-way analysis of variance (ANOVA) of wear rate by load followed by Tukey's post-hoc test, indicated a significant difference with the rate of wear between 3.2kg and 16.2kg at the 0.05 probability level.

3.2.2 EXPERIMENT 2: LUBRICANT, pH=7

Table 8 shows the results when specimens were worn in the presence of a liquid lubricant at pH=7. The rate of wear was assessed at loads of 3.2kg (n=8), 6.7kg (n=16), 9.95kg (n=20), 13.2kg (n=9), 16.2kg (n=13). Details of the mean wear rates with corresponding descriptive statistics are shown in Table 8. Figure 17a shows mean wear rates and corresponding standard errors versus load, while Figure 17b displays a regression curve fitted to the raw data.

TABLE 8: Mean wear rate (mg/10^3cycles) of lubricated (pH=7) specimens at different loads (kg), including descriptive statistical measures of standard deviation (SD), coeficient of variation (CV) and the standard error of the mean (SE).

Load	n	Mean	SE	SD	Range	CV
3.20	8	0.01	0.01	0.04	-0.04 - 0.06	400
6.70	16	0.09	0.03	0.11	-0.14 - 0.23	122
9.95	20	0.22	0.05	0.22	-0.22 - 0.49	100
13.20	9	0.85	0.11	0.34	0.32 - 1.40	40
16.20	13	0.89	0.17	0.61	0.19 - 1.96	69

Table 8 shows that the standard deviations of wear rate data were greater for heavier loads, whereas coefficient of variation were greater at lighter loads that produced little wear. The negative values shown at the lower ranges of some of the data indicate the effect of water uptake by some of the experimental specimens, even after adjustments were made with the controls.

Figure 17a shows that under lubricated conditions at pH=7, enamel wear rate was higher with heavier loads, over the range of 3.2-16.2kg.

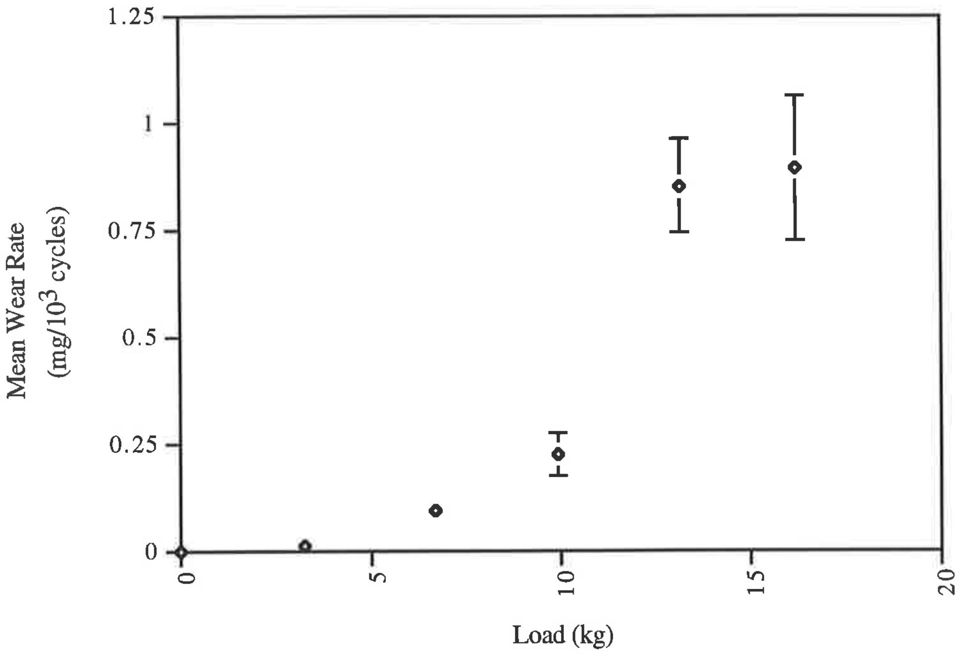

FIGURE 17a: Relationship of mean wear rate (with standard error bars) versus load under lubricated conditions (pH=7).

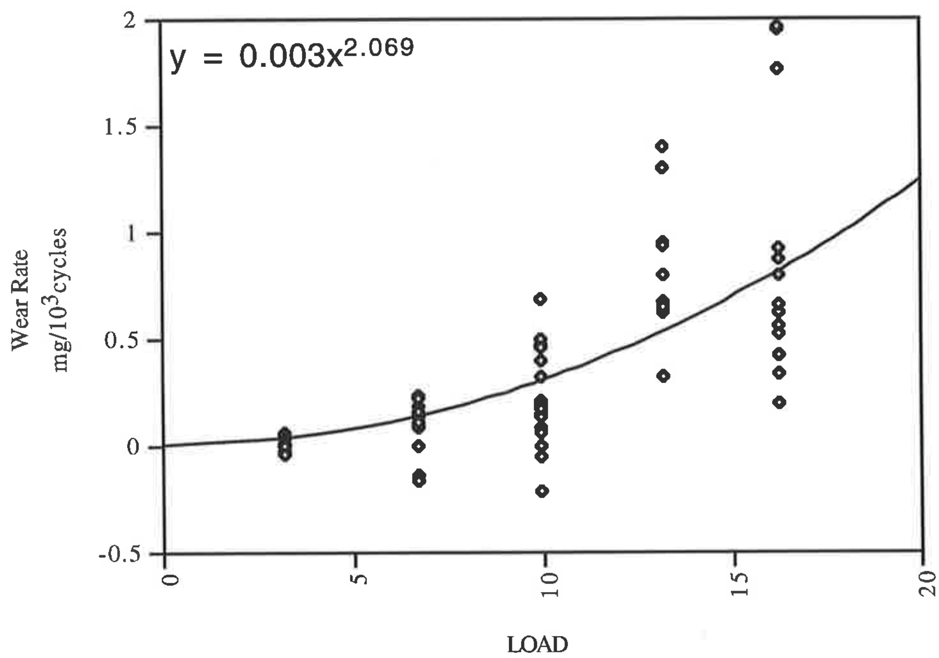

FIGURE 17b: Positive power curve showing the trend between wear rate and load under lubricated conditions (pH=7).

Figure 17b shows a regression curve fitted to the individual data points, indicating the tendency for more rapid wear rates to be associated with heavier loads. A one-way ANOVA, followed by Tukey's post-hoc test, disclosed a significant difference ($p<0.05$) in wear rate between the following loads: 3.2kg and 13.2kg, 3.2kg and 16.2kg, 9.95kg and 13.2kg as well as between 9.95kg and 16.2kg. Therefore, there was evidence of significantly more rapid rates of wear at loads above about 10kg, confirming the trend in Figure 17b.

3.2.3 EXPERIMENT 3: LUBRICANT, pH=3

Table 9 shows the results when specimens were worn in the presence of a liquid lubricant at pH=3. The rate of wear was assessed at loads of of 3.2kg (n=2), 9.95kg (n=12), 14.2kg (n=11), and 16.2kg (n=13). Details of the mean wear rates with corresponding descriptive statistics are shown in Table 9. Figure 18a shows the mean wear rates and corresponding standard error bars at each load, while Figure 17b shows a regression curve fitted to the raw data.

Table 9 shows that higher mean enamel wear rates were obtained at heavier loads. Standard deviations followed the same trend and were greater at heavier loads, however the standard errors remained fairly constant. Except for the load of 3.2kg, coefficients of variation were high, especially at 9.95kg. The very high value of coefficient of variation at 9.95kg reflects the extremely low mean wear rate at that load. Negative values at the lower end of each range resulted from moisture fluctuations either from experimental or control specimens.

TABLE 9: Mean wear rate ($mg/10^3$cycles) of lubricated (pH=3) specimens at different loads (kg), including descriptive statistical measures of standard deviation (SD), coeficient of variation (CV) and the standard error of the mean (SE).

Load	n	Mean	SE	SD	Range	CV
3.2	2	-0.060	0.01	0.01	-0.07 to-0.05	17
9.95	12	0.003	0.06	0.20	-0.46 to 0.38	6666
14.20	11	0.090	0.06	0.20	-0.30 to 0.50	222
16.20	13	0.350	0.06	0.75	-0.23 to 2.17	214

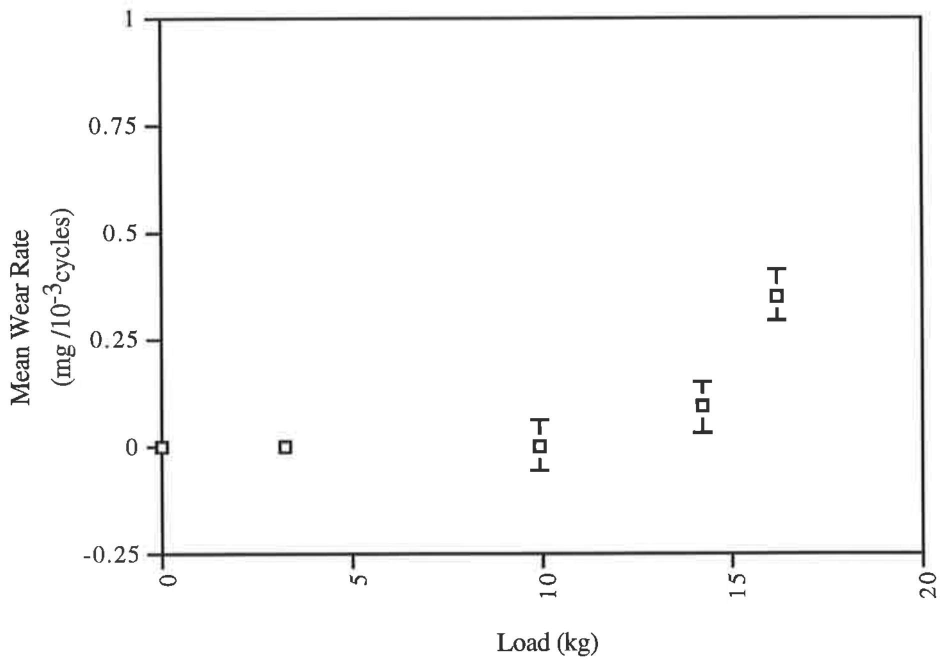

FIGURE 18a: Relationship of mean wear rate (with standard error bars) versus load under lubricated conditions (pH=3).

Figure 18a shows that mean wear rates were low at light loads and higher at loads above about 11-13kg. When a regression curve was fitted through individual data points (Figure 18b), it showed little tendency for greater wear at the heavier loads.

A one-way ANOVA confirmed the trend evident in Figure 18b, as there was no significant difference in wear rate evident between any of the loads ($P>0.05$).

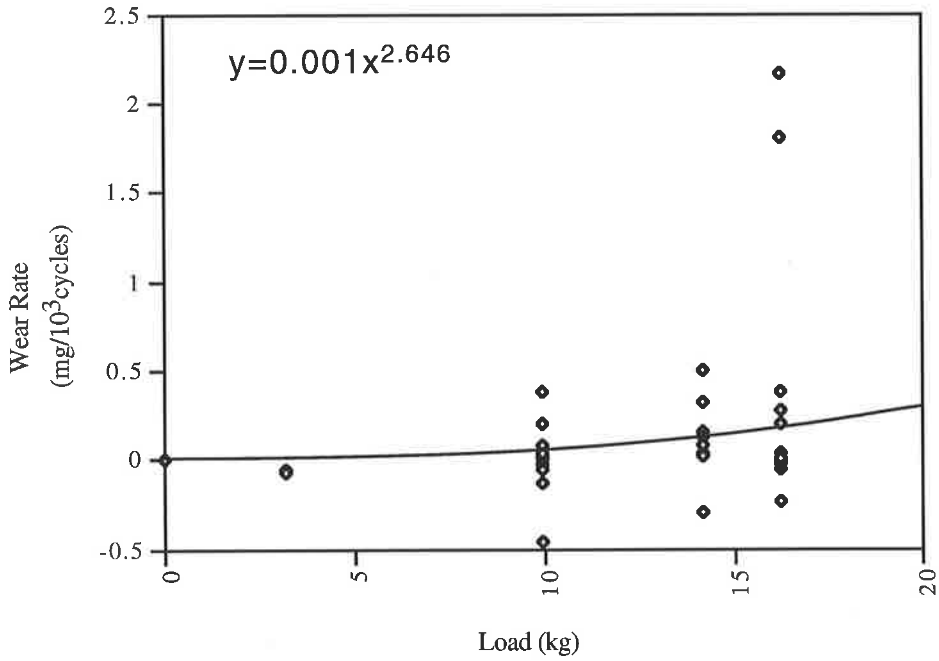

FIGURE 18b: Regression curve showing the trend between wear rate and load.

3.2.4. EXPERIMENT 4: LUBRICANT, pH=1.2

Specimens were subjected to loads of 3.2kg (n=9) and 6.7kg (n=9) with the liquid lubricant at pH =1.2. Details of the mean wear rates with corresponding descriptive statistics are shown in Table 10. Figure 19a shows mean wear rates with the corresponding standard error bars at each load, while Figure 19b shows a regression line fitted to the raw data.

TABLE 10: Mean wear rate (mg/10^3cycles) of lubricated (pH=1.2) specimens at different loads (kg), including descriptive statistical measures of standard deviation (SD), coeficient of variation (CV) and the standard error of the mean (SE).

L	n	Mean	SE	SD	Range	CV
3.20	9	0.42	0.12	0.37	-0.40 - 0.81	88
9.95	9	0.94	0.14	0.41	0.36 - 1.55	44

Table 10 shows that with a pH=1.2, the mean wear rate was substantially greater at the heavier load. Coefficients of variation for both weights were similar in magnitude. Standard errors of the mean wear rates were of a similar order of magnitude.

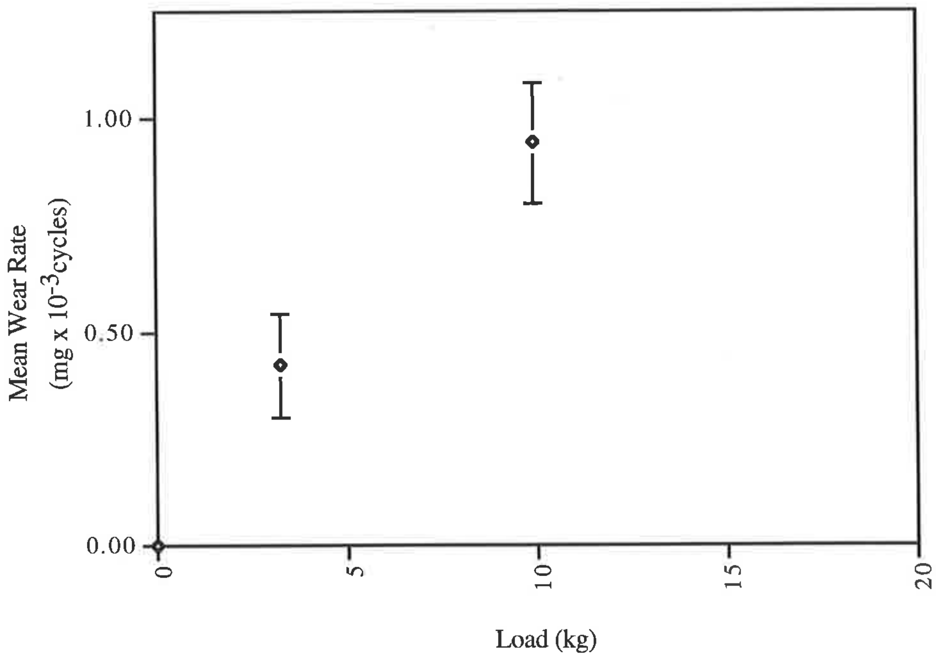

FIGURE 19a: Relationship of mean wear rate (with standard error bars) versus load under lubricated conditions (pH=1.2).

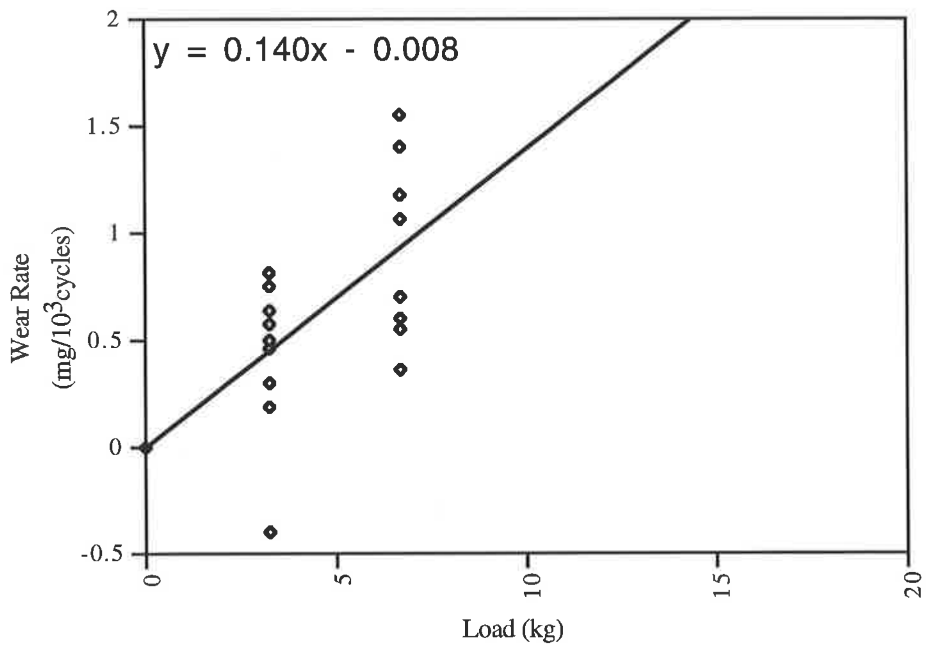

FIGURE 19b: Regression line showing the trend between wear rate and load under lubricated conditions (pH=1.2).

Figure 19b shows a regression line fitted to the individual data points, showing a trend for greater wear at heavier loads. A one-way ANOVA of wear rate by load followed, by Tukey's post-hoc test, showed a significant difference in wear rate ($p<0.05$) between the loads.

3.2.5. EXPERIMENT 5: LUBRICANT, SALIVA pH=7

Specimens were subjected to loads of 9.95kg (n=9), 14.2kg (n=6) and 16.2kg (n=4) while using fresh saliva of pH=7 as the lubricant. Details of the mean wear rates with corresponding statistical measures are shown in Table 11. The mean wear rate was greater at heavier loads. The coefficient of variation was very high at 9.95kg associated with a very low mean rate of enamel wear.

TABLE 11: Mean wear rate (mg/10^3cycles) of lubricated (saliva, pH=7) specimens at different loads (kg), including descriptive statistical measures of standard deviation (SD), coeficient of variation (CV) and the standard error of the mean (SE).

L	n	Mean	SE	SD	Range	CV
9.95	9	0.01	0.03	0.09	-0.12 - 0.19	900
14.20	6	0.49	0.08	0.21	0.16 - 0.75	43
16.20	4	0.55	0.21	0.41	0.13 - 1.00	75

Figure 20a shows the mean wear rates, with corresponding standard error bars, versus load. Figure 20b shows a regression line fitted to the raw data, indicating a very low rate of wear up to about 10-12 kg, after which the rate increased significantly.

A one-way ANOVA followed by Tukey's post-hoc test indicated that there was a significant difference in wear rate ($p<0.05$) between loads 9.95kg and 14.2kg, as well as 9.95kg and 16.2kg. This confirmed the trend of an increased rate of wear above a load of about 10kg.

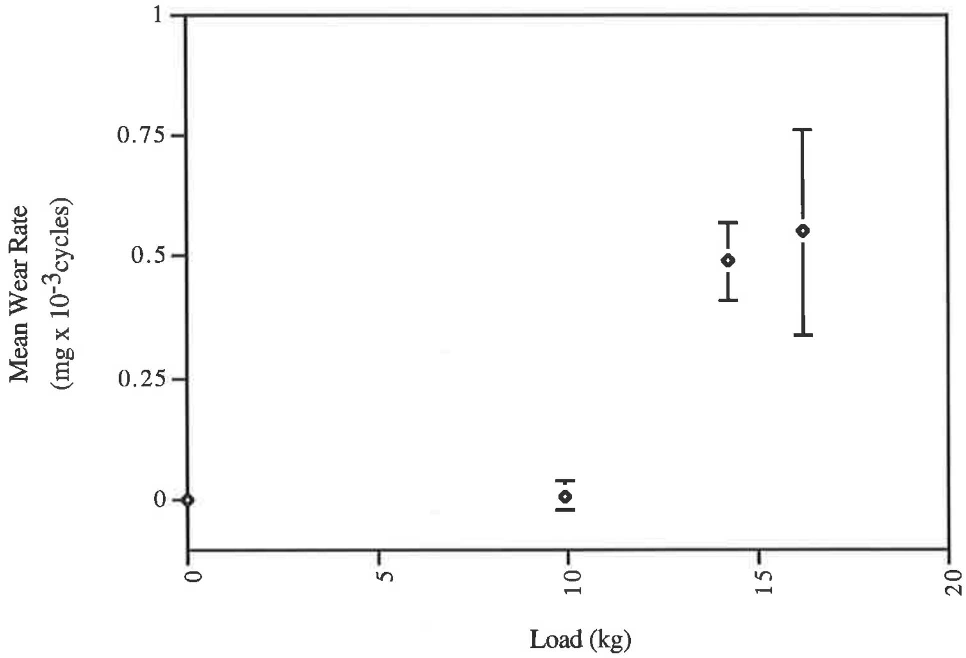

FIGURE 20a: Relationship of mean wear rate (with standard error bars) versus load under lubricated conditions (saliva, pH=7).

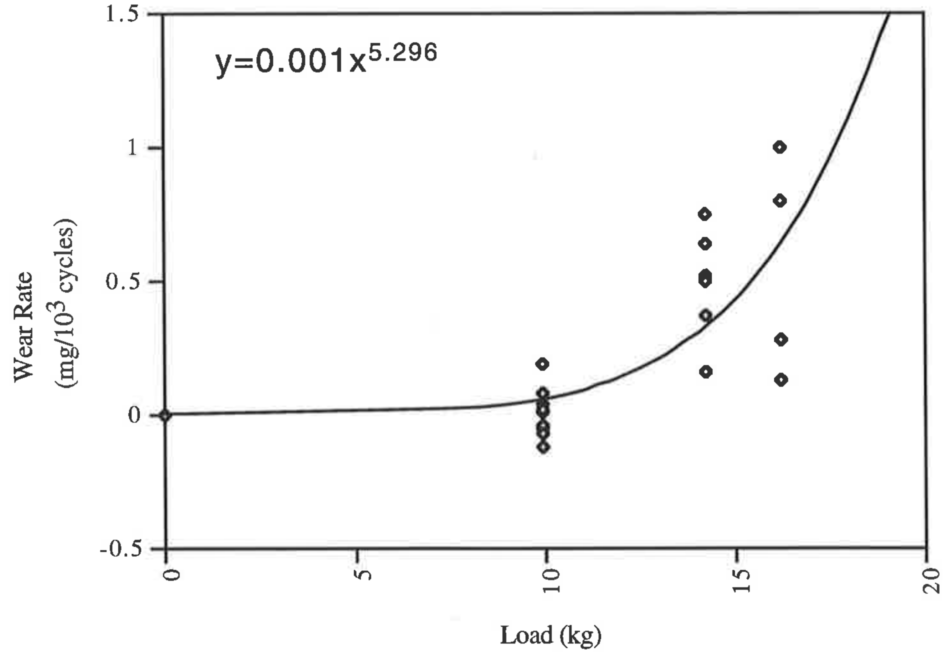

FIGURE 20b: Regression line showing the trend between wear rate and load under lubricated conditions (saliva, pH=7).

3.2.6 SUMMARY OF RESULTS

A comparison of regression curves showing the trends of wear rates at various loads (maximum of 16.2kg) for all five experiments is provided in Figure 21. A similar summary of mean wear rates, sample sizes and standard deviations is given in Table 12a.

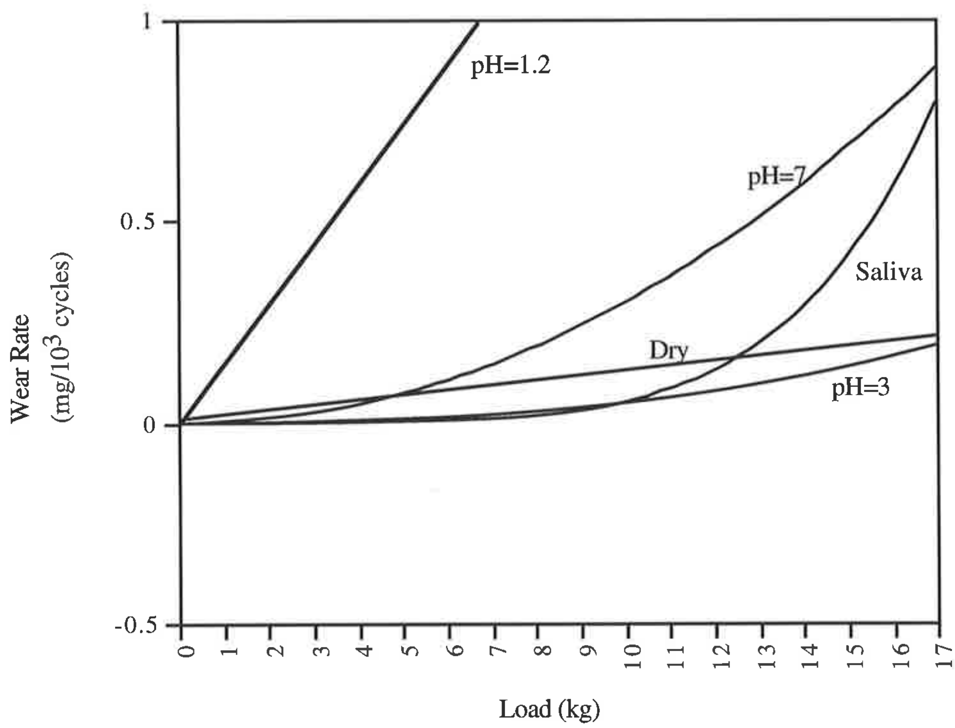

FIGURE 21: Regression lines and curves comparing the trends of enamel wear rates at different loads in all five experiments.

A one-way ANOVA, followed by Tukey's post-hoc test was applied to compare wear rates with various lubricants at loads of 3.2kg, 9.95kg and 16.2kg. There was a significant difference in wear rate ($p<0.05$) between the lubricant with pH=1.2 compared with other lubricants at loads of 3.2kg and 9.95kg. At 16.2kg, the wear rate of lubricant with pH=7 was significantly different (p<0.05) to that of the dry specimens. Table. 12b summarize these results.

TABLE 12a: Summary of all five experiments including the sample sizes (n), mean wear rates ($\bar{x}$) and the standard deviations (SD).

LOAD (kg)	DRY n / $\bar{x}$ / SD	pH=7 n / $\bar{x}$ / SD	pH=3 n / $\bar{x}$ / SD	pH=1.2 n / $\bar{x}$ / SD	Saliva n / $\bar{x}$ / SD
1.7	6/.04/.04				
3.2	24/.06/.03	8/.01/.04	2/-.06/.01	9/.42/.37	
6.7		16/.09/.11			
9.95	14/.13/.10	20/.22/.22	12/.003/.20	9/.94/.41	9/.01/.09
13.2		9/.85/.34			
14.2			11/.09/20		6/.49/.21
16.2	11/.20/.21	13/.89/.61	13/.35/.75		4/.55/.41

TABLE 12b: One-way ANOVA (followed by Tukey's post-hoc test) comparing the wear rates of the various lubricants at different loads.

Load (kg)	Significant differences
3.20	pH=1.2: Sig. Diff. to dry, pH=7 and pH=3
9.95	pH=1.2: Sig. Diff. to dry, pH=7, pH=3 and Saliva
16.2	pH=7: Sig. Diff. to dry.

Although post-hoc tests failed to demonstrate differences in wear rates between various lubricants at loads of 3.2kg, 9.95kg and 16.2kg, the ANOVA model lacks power when the variances of the different experimental groups differ considerably. In these circumstances, pair-wise comparisons of selected groups using t-tests can provide additional information. Results of comparing selected pairs of wear rates using t-tests were as follows:

(1) At 3.2kg, the wear rates between dry and pH=7 were significant (p=0.001).

(2) At 9.95kg, the wear rates between dry and saliva were significant (p=0.006); between dry and pH=3 were borderline significant (p=0.053), and between dry and pH=7 were not significant.

(3) At 16.2kg, the wear rates between dry and pH=7 were significant (p=0.002); dry and saliva were significant (p=0.044), and dry and pH=3 were not significant.

The regression lines and curves in Figure 21 indicate that under dry conditions the wear rate of enamel tended to be linear. When water (pH=7) was used as a lubricant the wear rate fell below that of the dry conditions but increased when the load exceeded approximately 5-6kg, and continued to increase substantially. Similarly, the use of saliva as a lubricant reduced the wear rate even further and this lower rate was maintained up to a load of 11-13kg above which it increased substantially. At pH=3, the wear rate was similar to that using saliva, but above the 11-13kg threshold, the rate increased only slowly with load. The wear rate at lubricated conditions of pH=1.2 was the highest recorded in all experiments, the effect being apparent even at very light loads.

A two-way ANOVA of wear rate by load and lubricant indicated significant differences in wear rates between lubricants ($p<0.05$) and also disclosed a significant two-way interaction term ($p<0.05$) confirming that the trends in wear rate with heavier loads were not uniform with different lubricants.

3.3 QUALITATIVE ASSESSMENT

Qualitative assessment of the specimens was based on scanning electron micrographs of wear facets. Surface morphology of specimens exposed to the experimental conditions (dry, pH=7, pH=3, pH=1.2 and saliva) described above were compared. Specimens were selected to represent typical morphologies of each sample group based on previously defined features.

Table 13 and Figures 22(a-e), indicate the loads at which representative samples were obtained and assessed qualitatively, while the electron micrographs in Appendix 2 (Fig. A2.1 - Fig. A2.18) show the qualitative results.

TABLE 13: Conditions under which eleven samples (numbered from 1-11) were selected for scanning electron micrographic evaluation.

LUBRICANTS	LOADS		
	3.2 kg	9.95 kg	16.2 kg
Dry	(1)	(2)	
pH=7	(3)	(4)	(5)
pH=3		(6)	(7)
pH=1.2	(8)	(9)	
Saliva		(10)	(11)

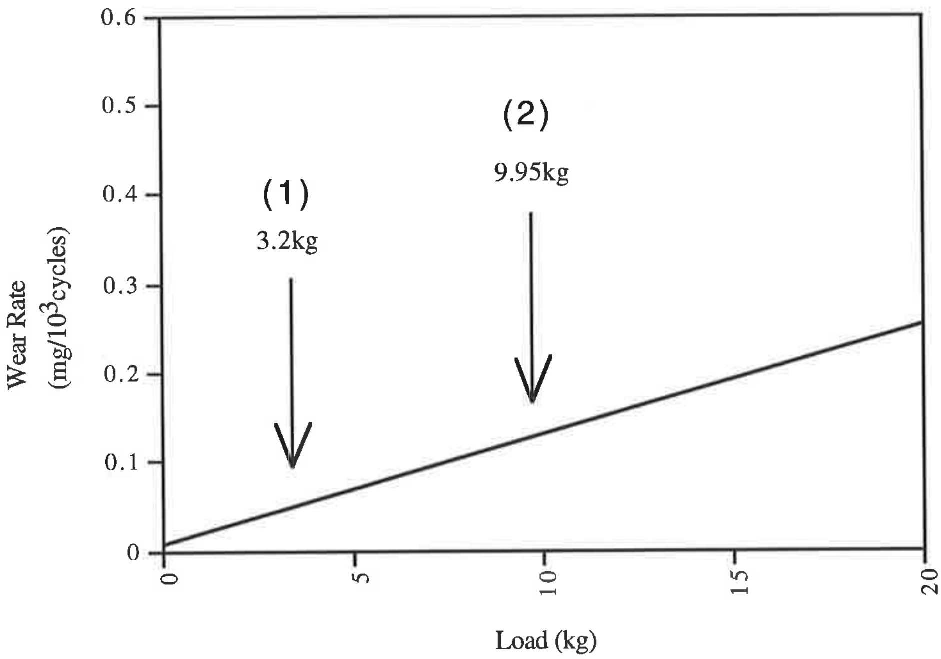

FIGURE 22(a): Loads at which specimens were obtained for electron-micrographic assessment of wear under dry conditions.

(1) <u>3.2kg Dry</u>

Under dry conditions, the facet showed a layering of enamel powder compacted under pressure upon the surface. The micro-morphology shown by the electron micrographs at this load therefore describes surface characteristics of the fused enamel layer. There were definite striations (approximately 50μm in width) running parallel to each other, interspersed with voids of various sizes (Fig. A2.1). Many voids showed evidence of undermining (Fig. A2.2).

(2) <u>9.95kg Dry</u>

At 9.95 kg the pattern of surface breakdown was essentially the same as at 3.2 kg in that a layering effect was also evident. However, there was no evidence of striations, voids were greatly reduced in number, and the layering of the facet surface was more pronounced. However, at the low magnification of 25x, smooth areas were also observed (Fig. A2.3).

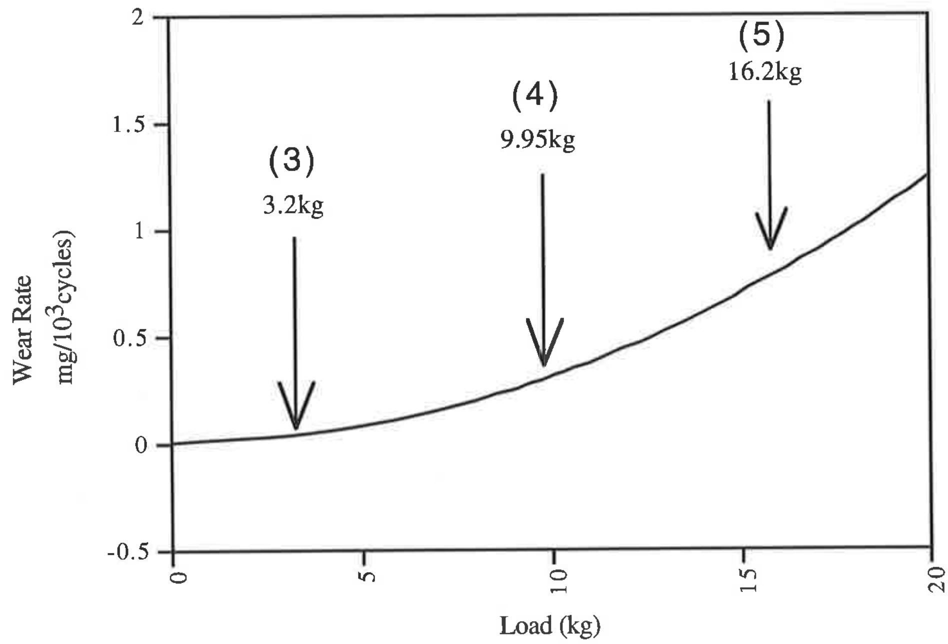

FIGURE 22(b): Loads at which specimens were obtained for electron micrographic assessment of wear under lubricated (pH=7) conditions.

(3) <u>3.2kg pH=7</u>

Smoother, textured surfaces (Fig. A2.4) with faint parallel striations were observed when the lubricant with pH=7 was used compared with dry conditions. Surface breakdown was still evident but without evidence of layers of fused enamel powder on the surface.

(4) 9.95kg pH=7

At 9.95kg, there was further surface breakdown (Fig. A2.5) with parallel striations that were more defined. Between areas of facet surface breakdown, the facet surface was smooth. The cratering was more pronounced at this load compared to 3.2kg (Fig. A2.6).

(5) 16.2kg pH=7

At 16.2kg there was even more surface breakdown including large craters (Fig. A2.7), with the rest of the surface being smooth. The width of the striations did not increase proportionally, indicating that enamel fracture was of smaller particle size, probably removed from the periphery of the craters.

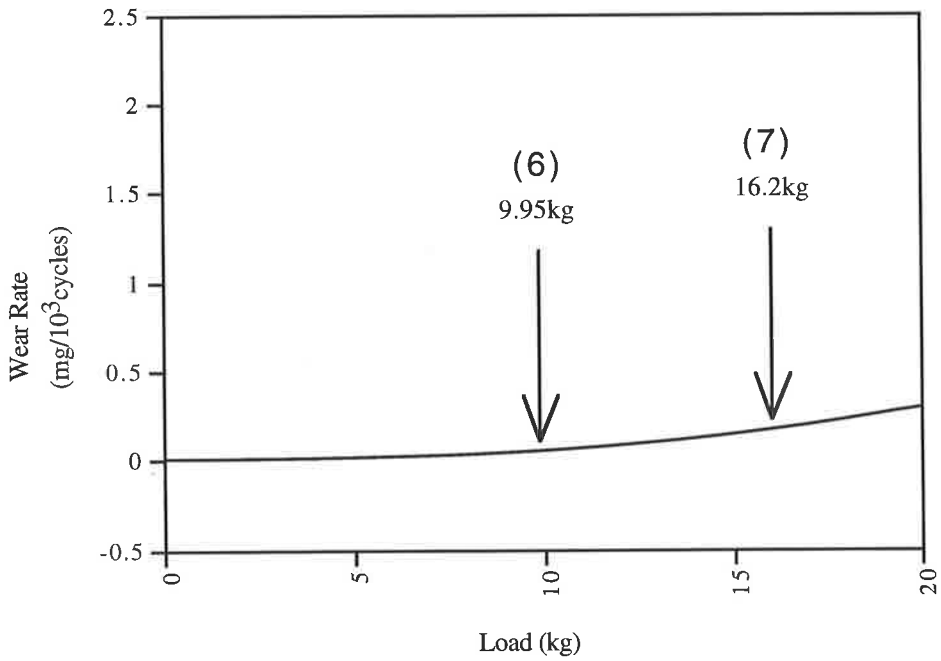

FIGURE 22(c): Loads at which specimens were obtained for electron micrographic assessment of wear under lubricated (pH=3) conditions.

(6) 9.95kg pH=3

With the presence of acid at pH=3, the surface of the facet was extremely smooth. Only occasionally were craters with co-existing parallel striations evident (Fig. A2.8).

(7) 16.2kg pH=3

With an increase in load to 16.2kg, there was a considerable change in the appearance of the facet. The surface texture of some parts of the facet became considerably rougher, covered with many fine parallel striations while, in other regions, the surface seemed smooth (Fig. A2.10). Craters were not evident on the surface but it was rough with no evidence of the amorphous layer seen at lighter loads (Fig. A2.11).

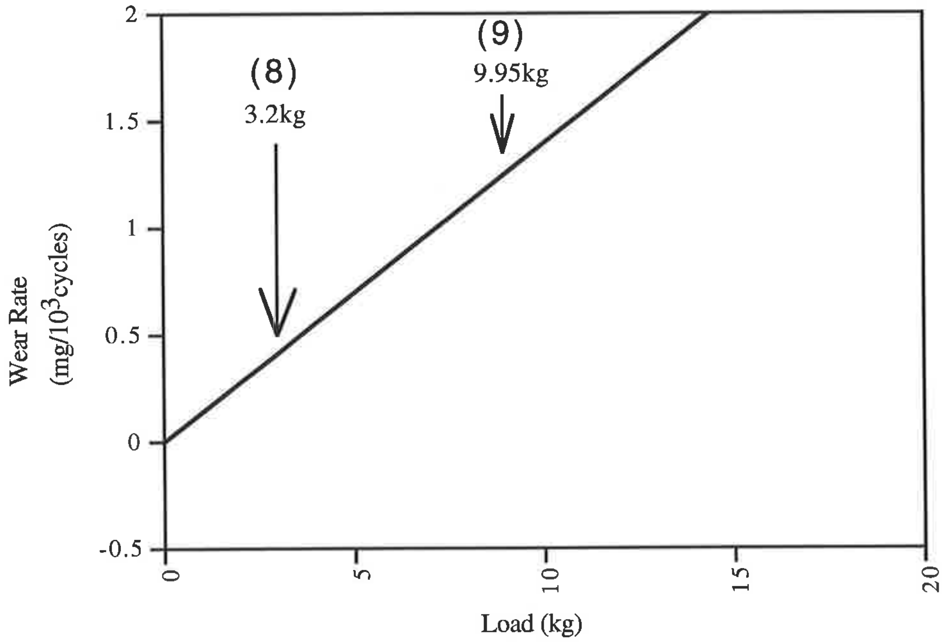

FIGURE 22(d): Loads at which specimens were obtained for electron micrographic assessment of wear under lubricated (pH=1.2) conditions.

(8) 3.2kg pH=1.2

Under these conditions the facet surface was very smooth yet undulating Fig. A2.12) indicating faster enamel dissolution than enamel loss from wear. Craters were sparse and there were no striations except for some very minor ones (approximately 2μm in width) evident at higher magnification (at 1600x). At these higher magnifications, enamel prisms were evident with considerable etching of the surface (Fig. A2.13).

(9) 9.95 pH=1.2

At higher load, the character of the previously described surface changed considerably. The surface of the facet was flatter (Fig. A2.14) and smoother than at 3.2kg with a large number of craters and with evidence of striations.

(10) 9.95 Saliva, pH=7

With saliva as the lubricant, the facet surface was flat but the amount of surface breakdown leading to crater formation was high (Fig. A2.15). Where the craters merged, very wide areas of surface breakdown resulted (Fig. A2.16). Fine parallel striations on smooth surfaces could be seen but only under higher power (800x) (Fig. A2.17).

(11) <u>16.2 Saliva, pH=7</u>

The surface appearance of the facet was similar to that at a load of 9.95kg, the only difference being that surface breakdown was far more substantial (Fig. A2.18) and the number of craters were more widespread. No furrowing was evident and fine parallel striations could be seen at high power.

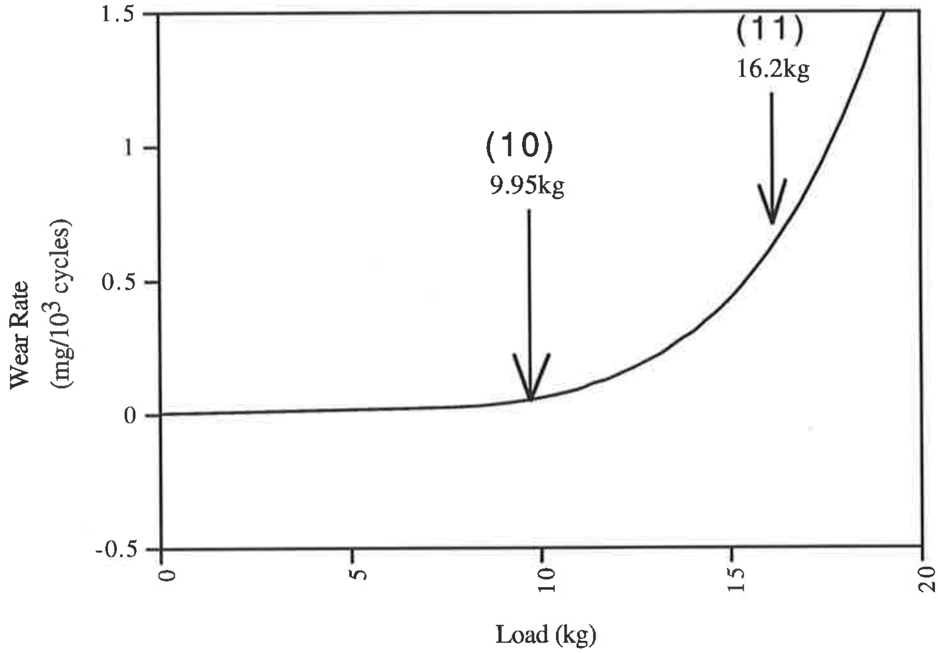

FIGURE 22(e): Loads at which specimens were obtained for electron micrographic assessment of wear under lubricated (saliva pH=7) conditions.

SECTION 4

DISCUSSION

The behaviour of enamel during diurnal and nocturnal tooth grinding is complex. It is affected by oral conditions that change constantly, differing between and within individuals throughout any twenty-four hour period. Because of the complexity of the situation, the characteristics of enamel wear cannot be tested under all possible conditions, and furthermore, *in vitro* studies cannot duplicate the dynamic oral environment. All we can hope for is to gain a "feel" for the wear characteristics of enamel under test circumstances that we know occur naturally.

Several oral conditions were simulated in this study, including: xerostomia; a lubricated, serous environment of pH=7; a lubricated environment of pH=3 resembling the effects of an acidic diet, and an oral environment of pH=1.2 resembling the effects of regurgitated gastric acid. Experiments with natural saliva at pH=7 were also conducted and the results compared with those obtained using artificial lubricants.

The results of preliminary experiments identified factors which could influence enamel wear and were therefore valuable in finalising the design of the experimental model. For example, it was found that the speed at which two enamel surfaces passed over one another did not influence the amount of wear, provided that impact stress was eliminated from the movement. Also, during the mechanical process, temperatures remained near 37^0 Celsius, similar to that found in the oral environment. Qualitative observations confirmed no differences in the appearance of facets at different speeds. The machine speed selected for all experiments was 80 cycles per minute which is well within the limits of masticatory speed (Bates, Stafford and Harrison, 1975), although the speeds that are generated during grinding are currently unknown.

Preliminary tests also showed that there was no significant difference in the rate of enamel wear between uni-directional and bi-directional movements. Although the experimental model was based on uni-directional movements, it is still unknown whether bruxism is uni- or bi-directional, even though there are suggestions from some researchers that the movement is uni-directional (Every, 1972). Further research is required in this area.

Two phases of enamel were observed at all loads (Fig. 13). This finding is consistent with clinical studies where quantification of wear rates among patients in longitudinal trials has demonstrated the presence of primary and secondary phases, described as "running-in" wear followed by "steady state wear". The initial phase appears to persist for a period of about two years after which a slower secondary phase has been observed (Lambrechts et al., 1989). This pattern was also observed by Monasky and Taylor (1971) during *in vitro* experimentation with enamel and other dental materials, as well as by Sakaguchi, Douglas, Delong and Pintado (1986) and by Winkler, Greener and Lautenschlager (1991) with posterior composite restoratives.

The surfaces of newly-erupted teeth are curved, with each surface (whether buccal or lingual) or cusp, differing in the degree of camber. The area of contact between unworn opposing tooth surfaces is therefore very small. At a fixed load, the pressure or stress produced over such small areas is high. For example, a load of 16kg over an area of 0.5 mm^2, effectively produces a pressure of about 3,200kg/cm^2 (31,360N/cm^2). For this reason, during the early stages of wear of each specimen in this study, high stresses produced fast wear rates that resulted in the primary wear phase. However, as the wear facets increased in area, the pressures produced were progressively reduced until a theshold was reached, after which the wear rate decreased to a slower secondary phase. Though Figure 13 shows the primary wear phase of enamel as linear, it is postulated that the phase maybe curvi-linear. Tribologic research relating to the empirical laws of adhesive wear (Burwell and Strang, 1952), has confirmed also that when conical specimens of various materials are worn during *in vitro* investigations, the pattern of the primary phase is curvi-linear. Alternatively, wear studies of dental materials with non-conical specimens (e.g., cylindrical specimens, the ends of which have been worn against rotating discs) have resulted in a linear relationship with the number of cycles at fixed loads (McCabe and Smith, 1981). More data from the first 20×10^3 cycles are needed to confirm whether the primary phase is linear or primarily curvi-linear. The wear rates in this investigation were based on the secondary phase .

Figure 14 showed that the wear rates for the primary phase at higher loads were more variable than rates for the secondary phase. It is postulated that at very high stresses, enamel breakdown tends to change from a characteristic and controlled rate to a more haphazard "destructive" progression. This information might have relevance in the clinical assessment of young patients especially during the mixed dentition stage when teeth are newly emerged. A faster than normal rate of wear for the newly erupted teeth in these individuals should be of no concern provided they are monitored to ensure that a slower secondary wear phase is attained.

Enamel wear rates under dry conditions increased with an increase in load at a rate of about 0.012 mg/10^3cycles/kg. Though this is only an approximate value obtained from a regression line fitted to raw data (Figure 16b), it is consistent nevertheless with tribological studies of other materials (McCabe and Smith, 1981).

Qualitative observations of facets produced under dry conditions showed evidence of enamel powder compacted on the surface. The results suggested that as the load increased, the degree of compaction of the powder increased leading to a reduction in the number and size of the voids described previously. Parallel striations observed on the surfaces of compacted layers resulted from adhesive wear, where particles were removed from the compacted surfaces and dragged along. At times the fragments re-fused onto the surface under load. At high loads, the lack of striations was indicative of the re-fusing of particles immediately after the adhesive process had dislodged them.

The compacted layers seemed to have two functions: they acted as a separating medium between opposing facets thereby reducing the wear in a manner similar to a dry lubricant, and they also acted as the third-body in three-bodied abrasion. The source of this dry lubricant is the facet surface itself which must also break down under load. Further research is required to describe the nature of the interactions at such interfaces.

When water (pH=7) was used as a lubricant, the relationship of wear rate against load was best described by a power curve (Fig. 17b). Qualitative assessment of facet surfaces at 3.2kg, 9.95kg and 16.2kg showed no evidence of fused enamel powder but a progressive increase in general surface breakdown: crater size increased with load and parallel striations progressively became more evident with a tendency to increase in width, but only to a certain extent. At the highest load of 16.2kg, the width of the striations was similar to that at 9.95kg, indicating that there is probably a limit to the size of the microfine enamel fractures that may occur during surface wear.

At light loads, the lubricating ability of water was sufficient to reduce the wear rate of enamel substantially. However, as the load increased, a threshold was reached when the water was displaced, loosing its lubricating capabilities. The water was also responsible for washing away enamel particles before they built up into a compacted surface layer. Therefore, above this threshold the wear rate increased substantially, more than that observed with the dry lubricant in experiment 1, reflecting the absence of both wet and dry lubricants. These observations seemed to confirm that enamel powder found on enamel facets under dry conditions behaved as a dry lubricant.

The pattern of wear changed when an acid of pH=3 was used as a lubricant. Figure 18b shows that wear rate also fell below that of dry conditions at light loads, but progressively increased until it was comparable to that of the dry conditions at 16.2kg. There was no statistically significant difference in wear rate between loads of 3.2kg and 16.2kg, confirming that the wear rate was relatively stable. Furthermore, at and below 9.95kg, wear rates with this lubricant were significantly less than those obtained under dry conditions. These results are contrary to the expectation that mechanical action in combination with acid would cause an increase in the rate of wear.

Qualitatively, the main distinguishing feature observed with this lubricant (pH=3) was at loads below 11kg-13kg with the facet surface displaying a smooth and amorphous appearance. This appearance was not evident at heavier loads, but other facet characteristics (e.g., striations, craters) were present. Overall, the amount of surface breakdown was much less than that seen with the lubricant pH=7.

Further research is required to explain the mechanisms of wear at pH=3, as the wear interface is affected by complex tribochemical interactions. At present it is known that chemical reactions occur continuously in the oral cavity between the enamel surface and inorganic ions immediately adjacent to the tooth surface (Macpherson et al., 1991). These ions include $Ca_5(PO_4)_3F$ (fluorapatite), $Ca_5(PO_4)_3OH$ (hydroxyapatite), $CaHPO_4$, CaF_2 and $Ca_4H(PO_4)_3$.

In vitro studies have shown that in the presence of an unsaturated solution of hydroxyapatite and fluorapatite adjacent to the tooth surface, dissolution of the enamel produces a surface similar to a typical erosive lesion (Larsen, 1973). If the solution is saturated with respect to fluorapatite but unsaturated with respect to hydroxyapatite, then fluorapatite is deposited on the enamel surface, keeping it intact even though the subsurface enamel is demineralised (this is observed in enamel caries where fluoride in plaque contributes to the saturation of the fluorapatite).

It is postulated that during tribochemical wear with a lubricant at pH=3, the environment adjacent the facet surface may differ at times to that described above. If the solution adjacent to the enamel surface is saturated or supersaturated with respect to both fluorapatite and hydroxyapatite, precipitation of solid particles such as calcium phosphate and calcium fluoride may occur. It is postulated that these particles act as a third body between the affected surfaces in the form of an amorphous slurry. In combination with this, the etching of the enamel surface produces undermined enamel asparities (projections) that break off under load producing a continuous supply of particles between the opposing surfaces. The breakdown of these enamel particles under load helps maintain the saturated levels of hydroxyapatite adjacent to the tooth surface and also probably maintains a remineralization process as well. Furthermore, the lubricating properties of calcium fluoride (CaF_2), a compound recognised by tribologists as one of the best dry lubricants known (Arnell and Teer, 1975), cannot be discounted.

Experiments using hydrochloric acid at pH=1.2 resulted in a significantly higher wear rate than for other lubricants and at 0.14mg/10^3cycles/kg was about ten times higher than that of wear under dry conditions. The appearance of the facet surface at loads of 3.2kg indicated a considerable amount of surface destruction and evidence of enamel etching. The facet surface was very smooth yet undulating (Appendix II, Fig. A2.12) indicating faster enamel dissolution than enamel loss from mechanical action. Craters were sparse with little evidence of striations. As the load increased (9.95kg), the facets became flatter and smoother (Appendix II, Fig. A2.14), indicating that enamel loss from mechanical action was greater and hence over-riding the effects of enamel dissolution. This finding is consistent with personal clinical observations of the interplay between the processes of wear discussed in the Introduction. For example, a patient may be bruxing but show no evidence of facetting because of superimposed erosion.

Under lubricated conditions of pH=1.2, the dissolution of enamel was faster and extended deeper interprismatically than at pH=3. This produced a weaker enamel surface (severely undermined enamel projections) resulting in excessive surface loss when load was applied. It is postulated that because the chemical reaction favoured enamel dissolution, saturation levels at the wear interface would not occur. Further research is required, not only at various pH levels, but also to investigate differences between the reactions of different acids.

Even though the quality and quantity of saliva varies considerably between and within individuals, it was compared with the other lubricants to determine whether the observed wear rates fell within the ranges obtained using the *in vitro* model. Had the wear rates obtained using fresh human saliva been considerably different to those obtained in the other experiments, it could be argued that the in-vitro model (with its selection of lubricants) was not representative of the oral environment.

The results, however, indicated that the enamel wear rate in the presence of saliva was low when the load was below a threshold of about 11kg-13kg, while above this threshold the rate increased considerably. The qualitative assessment of facets produced with saliva as a lubricant indicated an increase in facet surface breakdown with increased load. There was evidence of an increase in crater size as the load increased, with merged craters producing wide areas of destruction. Also the microwear detail of these facets was very similar to that produced with a lubricant at pH=7.

A comparison of the regression lines and curves summarising the trends of wear rates at various loads (maximum of 16.2kg) for all five lubricants has been provided in Figure 21. A graphical summary of the results of the statistical tests comparing wear rates under differing conditions is shown in Figure 23. Lubricants associated with wear rates that were not significantly different have been grouped together, while wear rates that were significantly different are shown separately. Except for the lubricant at pH=1.2, all the other lubricants seemed to have a common threshold between 11kg to 13kg above which the wear rate increased considerably. Although this holds true for the lubricant at pH=7, a slight increase in wear rate seemed to occur at a lower load (5kg to 7kg).

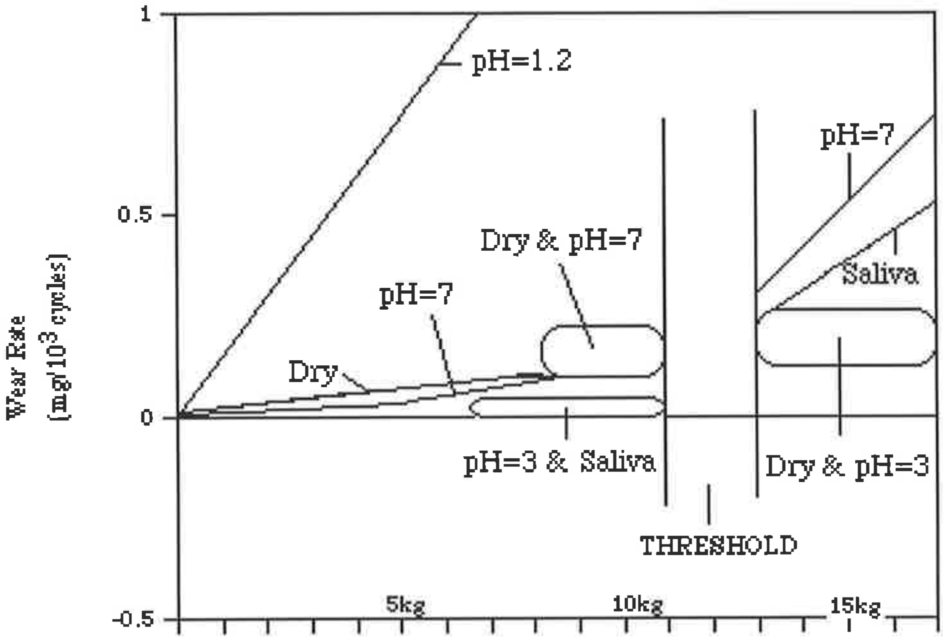

FIGURE 23: Summary of the trends of wear rates for all lubricants at various loads.

Every measure used to quantify tooth wear has its limitations, whether it be area, vertical height or volume. Area gives no indication of the amount of loss in vertical dimension of tooth structure, and vice versa. However, from a dental perspective, it can be argued that a measure in vertical dimension may be important and may cause adaptation in other craniofacial structures and in extreme cases, pathology. For example, excessive loss of occlusal vertical dimension may have effects ranging from angular cheilitis to temporomandibular joint problems. Alternately, assessments of volume, while providing an overall measure of wear, give no idea of the relationship between area and vertical dimension.

As outlined previously (Section 2.2.3), the complex problem of describing the continually changing area of contact during each wear cycle, and hence the constantly changing applied stress (kg/mm^2) was not addressed in this study. Rather the applied load in kg was used for all analyses with the knowledge that facet areas were increasing progressively over the course of each experiment.

As a matter of interest, almost 200 facet areas from the five main experiments were measured after the termination of each experiment; individual stresses were calculated and volumes in mm^3 determined (vol in mm^3 = weight of material (mg) / density of enamel (2.59 mg/mm^3). An interesting relationship was noted when all the facet areas for all five experiments were plotted against stress (Fig.24a).

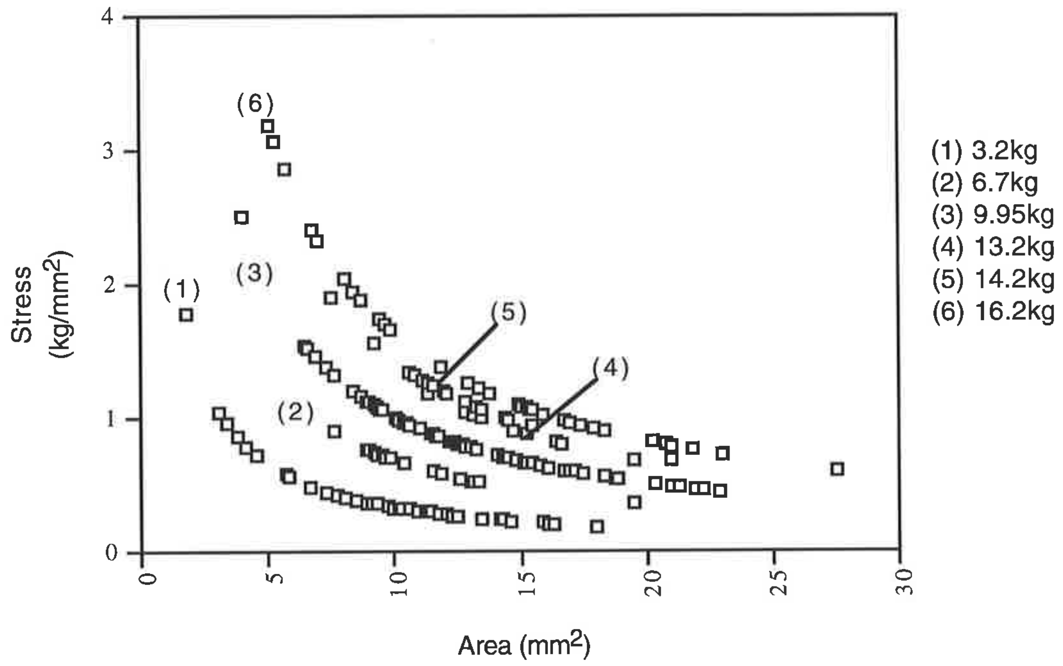

FIGURE 24: Relationship between the stress applied and facet area at different loads.

Figure 24 shows that there was an inverse relationship between stress and area with any fixed load. As facet area increased, stress progressively decreased with values for all loads tending to converge. This may imply that teeth with large facet areas (especially those that have lost all cusps and have a relatively flat occlusal areas) may have low stresses imposed upon them no matter what the load, and in turn displaying lower wear rates. This is also consistent with the observation of higher wear rates on newly erupted teeth (i.e., mixed dentition stage) where the facet areas are very small. An "area specific" research project is necessary to support or refute this suggestion.

Another relationship is described in Figure 25, where the loss in vertical dimension is shown to increase linearly with increase in volume of enamel removed. The volume of enamel worn was determined:

= enamel worn (mg) / enamel density (2.59)

and the vertical dimension was then calculated:

= 3 x volume (mm^3) / facet area (mm^2)

Though this relationship is to be expected as there is a mathematical association between volume, vertical height and area, (and also assumes the enamel surface is conical), it nevertheless confirms the accuracy of the experimental model. It also confirms that research quantifying vertical tooth height loss as a measure of wear can provide valuable information from a clinical perspective.

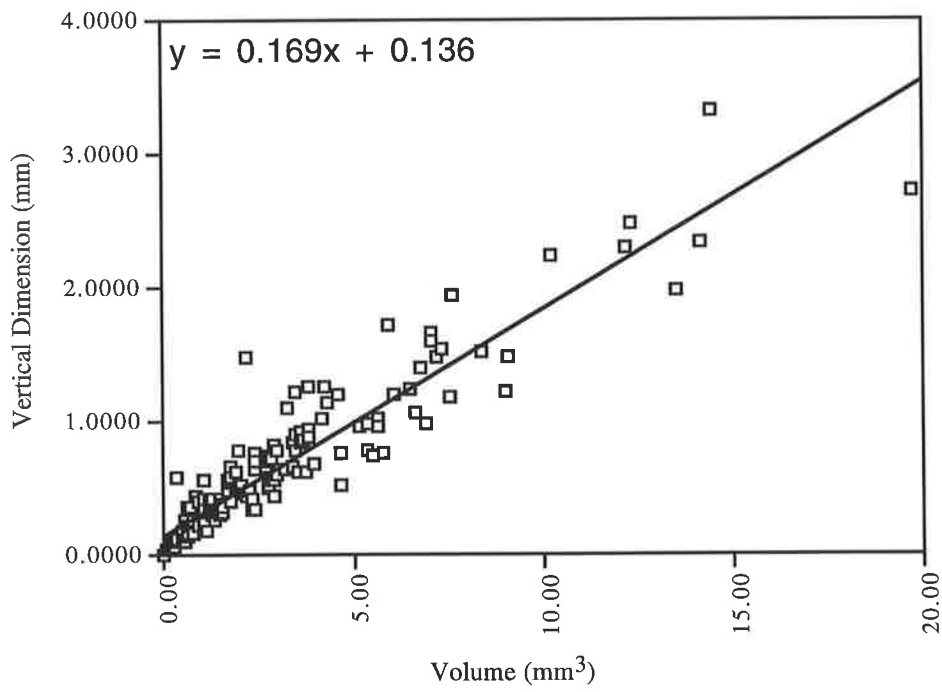

FIGURE 25: Linear relationship between vertical dimension loss (mm) and volume (mm^3) of Facets.

Based on on comparisons of qualitative and quantitative *in vitro* information obtained from this study and from qualitative *in vivo* comparisons, it is postulated that the majority of wear facets observed in patients develop at loads below 11-13kg. This does not preclude the possibility that some individuals achieve higher grinding loads at times of extreme stress. However, the evidence suggests that wear rates observed above this load threshold are generally fast and may be considered catastrophic, compromising the potential lifespan of the tooth. Averaging of the gradients of all the trends in Figure 21 at about 16.2kg provides an estimated wear rate of approximately 0.14mg/10^3cycles/kg which is very high indeed. Though such catastrophic wear rates sometimes observed clinically, it seems that wear rates are generally much lower, occuring at loads below 11kg to 13kg. This postulate is different from the assumption, based on voluntary bite force experiments, that bruxists attain forces between 100-400kg.

Though this project has focused on characteristics of dental enamel wear *in vitro*, preliminary qualitative comparisons between wear facets produced *in vitro* and those observed clinically provide support for the model's validity. Using the qualitative *in vitro* information as a reference, it is possible by direct comparison to provide an insight into the possible oral conditions of individuals with worn dentitions. This raises the possibility of using an "atlas" of tooth wear to gain an insight into the clinical environment. For this to occur, the *in vitro* model of enamel wear needs to be extended to include a greater range of pH levels, including saliva at different viscosities etc.

SECTION 5

CONCLUSION

This research project was specifically designed to determine the wear characteristics of human dental enamel using an *in vitro* mechanical model. It is acknowledged that any *in vitro* model can only simulate a dynamic biological process and therefore has limitations. However, the information gained has provided a better understanding of how dental tissues behave within a tribochemical environment. Many questions have arisen that require further investigation and there is a need to extend and refine the model to include a full dental arch with computerised control of all possible variables influencing dental wear. Such continual refinements will bring the model a step closer to simulating the oral environment.

The results from this research have not only quantified the wear behaviour of dental enamel under dry and liquid-lubricated conditions of varying pH, but have also shown that qualitative comparisons of facets with those from patients may help to provide insights into the effects of acidic oral environments on tooth wear. In particular, the quantitative research has highlighted the existence of two phases of wear as reported in other clinical studies. The qualitative evidence suggests that physiologic levels of wear generally occur below certain load thresholds. Above these thresholds, faster possibly pathological rates of wear are observed. These load thresholds seem to lie around 11kg-13kg, indicating that the loads associated with bruxism are likely to be much lower than those suggested by researchers in the past (Gibbs et al., 1981). It has also been shown that acetic acid at pH=3 tends to decrease wear and maintain low wear rates at higher loads than observed with other lubricants.

Qualitatively, there is evidence that the wear process at the facet interface involves removal of surface enamel particles due to a combination of tribologic abrasion, adhesion, fatigue and chemical dissolution. These particles are at times dragged across the facet surface producing parallel striations and leaving craters that progressively increase in size until they merge. There seems to be a limit to the size of striation width irrespective of load, implying a maximum size of enamel particle that can be removed from the facet surface. There is also evidence that under xerostomic conditions, broken enamel prisms may act as a dry lubricant capable of preventing high wear rates at loads above a theshold of 11kg-13kg.

In addition, this study has clarified the effect of other factors on the wear of human enamel during tooth grinding. For example, it has been shown that:

(1) The wear characteristics of dental enamel are independent of the speed at which opposing teeth are worn.

(2) The volume of enamel loss is independent of the direction in which teeth are worn.

(3) Though upper and lower contacting teeth may have different facet areas, the weight and therefore volume of enamel loss remains constant, highlighting the importance of quantifying volume (or weight) during tooth wear studies.

Several areas need to be addressed further as a result of this *in vitro* investigation including:

(1) Determining the exact nature of the tribochemical interaction that occurs at the wear interface under various pH conditions.

(2) Determining the wear characteristics of dentine.

(3) Including the full complement of teeth in a computerised model that simulates all muscles of mastication and controls other variables contributing to tooth wear.

SECTION 6

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SECTION 7

APPENDIX

APPENDIX I

An Atlas of Facet Morphology: showing the characteristic features observed on facet surfaces.

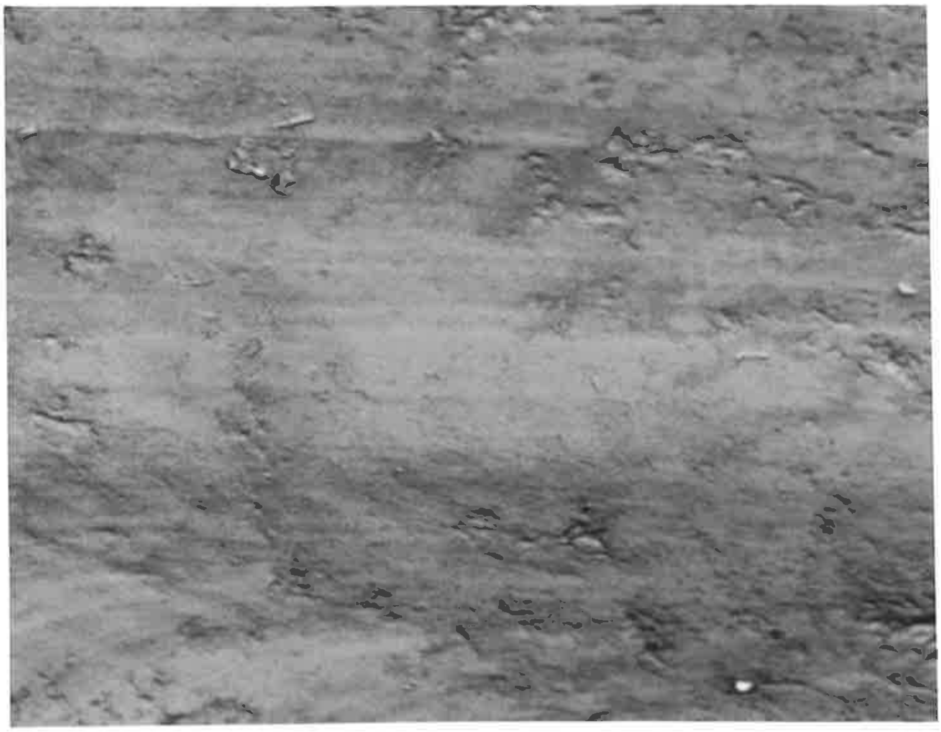
(1) General smoothness of the surface

(2) Striations across the facet surface

(3) Evidence of impregnated third body enamel fragments within the surface

(4) Voids within the impregnated enamel powder.

(5) Craters caused by removal of fragments of enamel from the surface

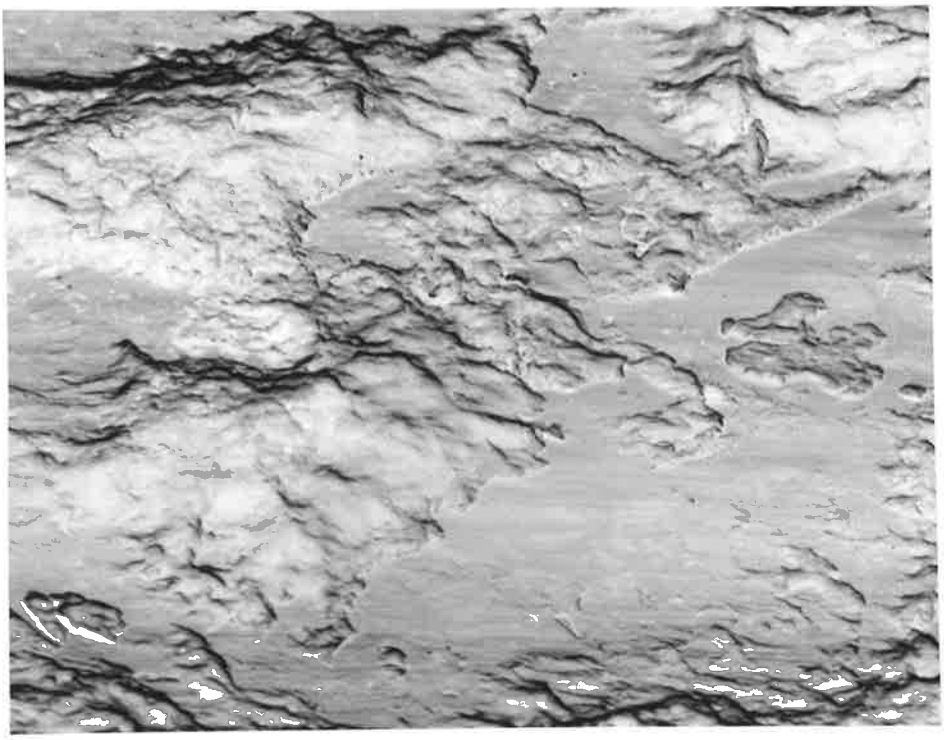


(1) Scanning electron micrograph, sections of which show a fairly smooth surface. (20kv; magnification 50x)

(2) Evidence of very faint striations on a facet surface, seen on the same electron micrograph as in (1).

(3) Electron micrograph showing impregnated third body enamel fragments within the surface. (20kv; magnification 50x)

(4) Electron micrograph showing evidence of a void within the impregnated third body enamel fragments on the facet surface (20kv; magnification 800x).



(5) Electron micrograph showing evidence of severe cratering within a smooth facet surface. (20kv; magnification 200x).

APPENDIX II

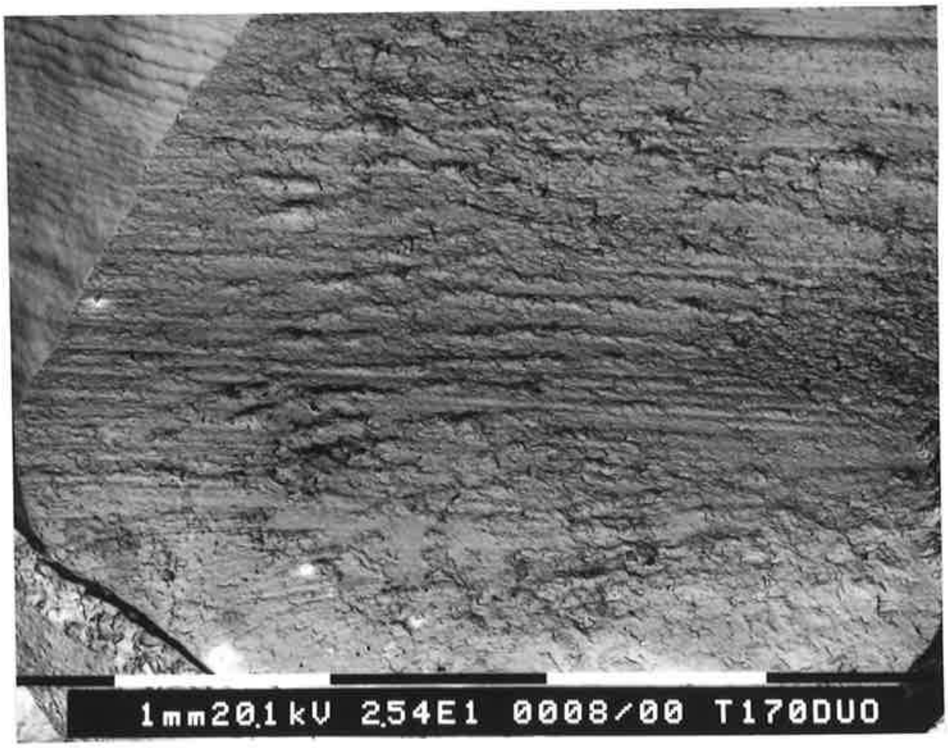


Fig. A2.1: Dry at 3.2kg.

(Electron micrograph: 20kv; magnification 25x)

Compacted enamel powder forming a layer over the facet surface. There was evidence of continuous breakdown of this layer, the fragments of which were removed and dragged across the surface producing parallel striations.

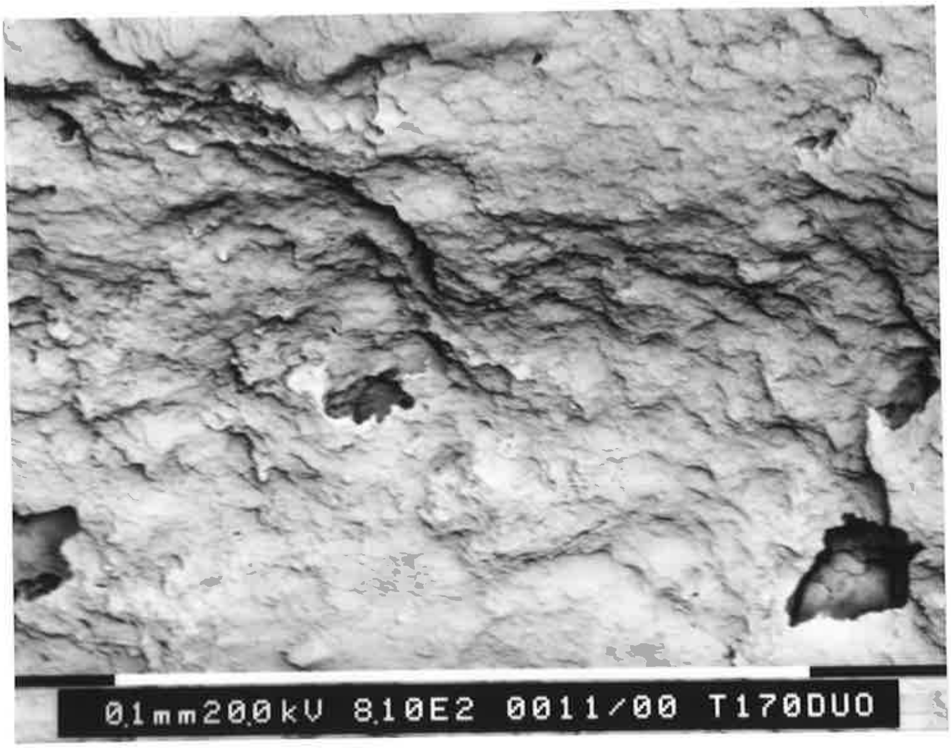


Fig. A2.2: Dry at 3.2kg.

(Electron micrograph: 20kv; magnification 800x)

At higher power the compacted enamel layer showed evidence of being made up of multiple layers. Within the compacted layer there were voids which became exposed as the surface breakdown occurred. The voids appeared undermined, the degree depending on their level of exposure.

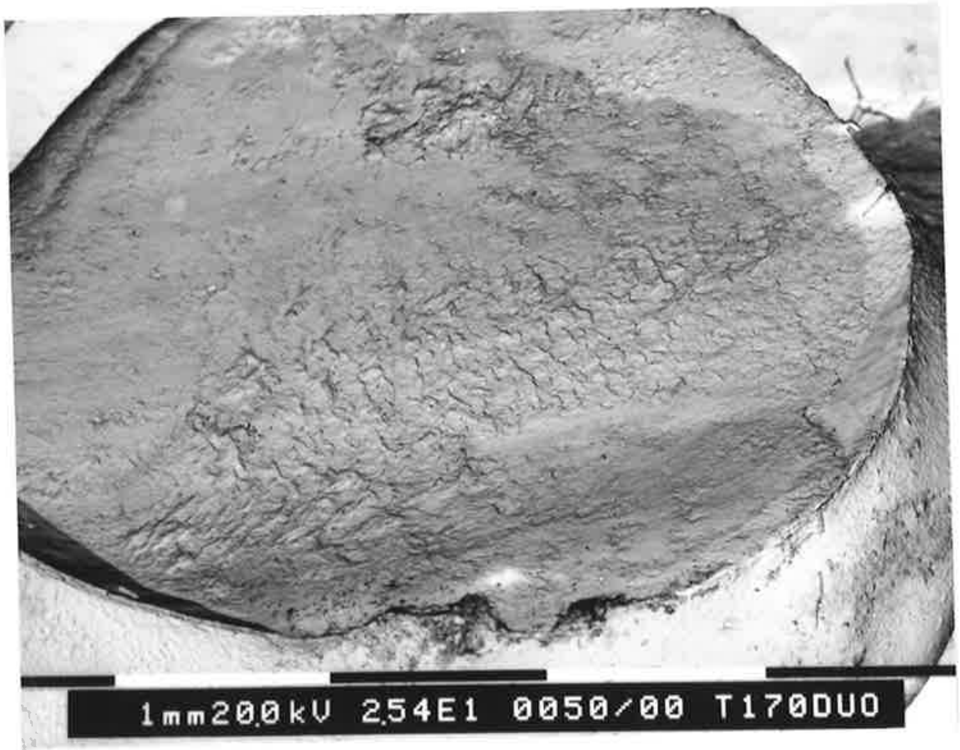


Fig. A2.3: Dry at 9.95kg.

(Electron micrograph: 20kv; magnification 25x)

Due to the higher load, the enamel powder layer was further compacted producing areas of smooth surface. The striations were not evident and the number of voids were reduced. It is postulated that any fragments removed by the wear action immediately re-compact by the higher load.

Fig. A2.4: Lubricant pH=7 at 3.2 kg.

(Electron micrograph: 20kv; magnification 25x)

With the use of a lubricant, most of the fractured enamel produced during the wear process was washed away leaving the bear enamel surface. Enamel fragments produced from the surface breakdown were dragged along the facet surface resulting in obvious parallel striations.

Fig. A2.5: Lubricant pH=7 at 9.95kg.

(Electron micrograph: 20kv; magnification 25x)

With an increase in load there was an increase in surface breakdown. The striations became more pronounced.

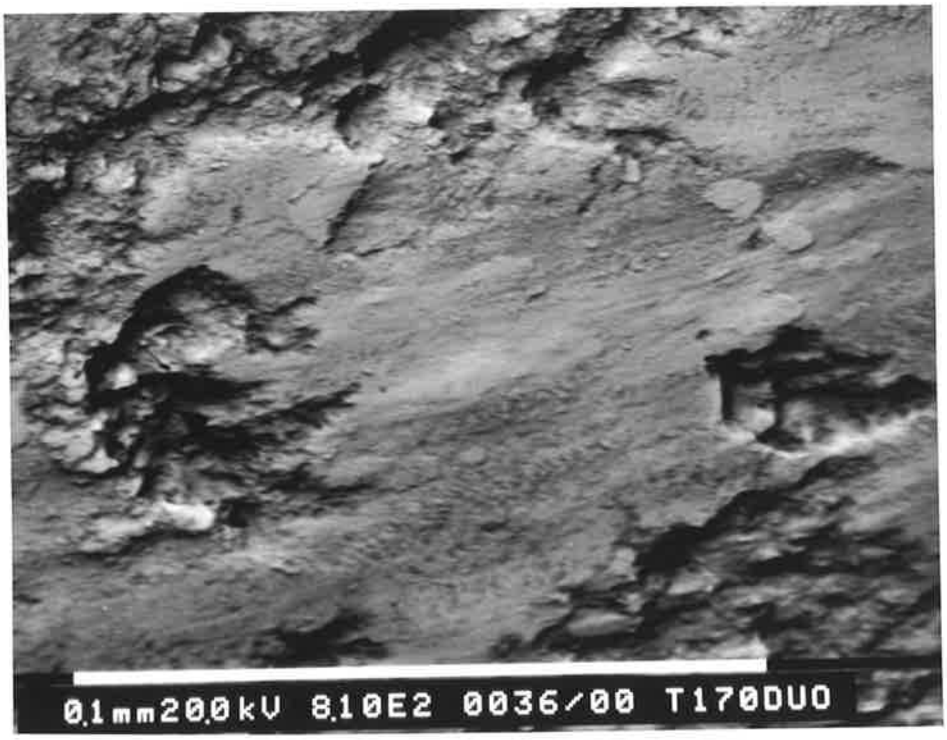


Fig. A2. 6: Lubricant pH=7 at 9.95kg.

(Electron micrograph: 20kv; magnification 800x)

Higher magnification of the surface breakdown showed evidence of deep cratering.

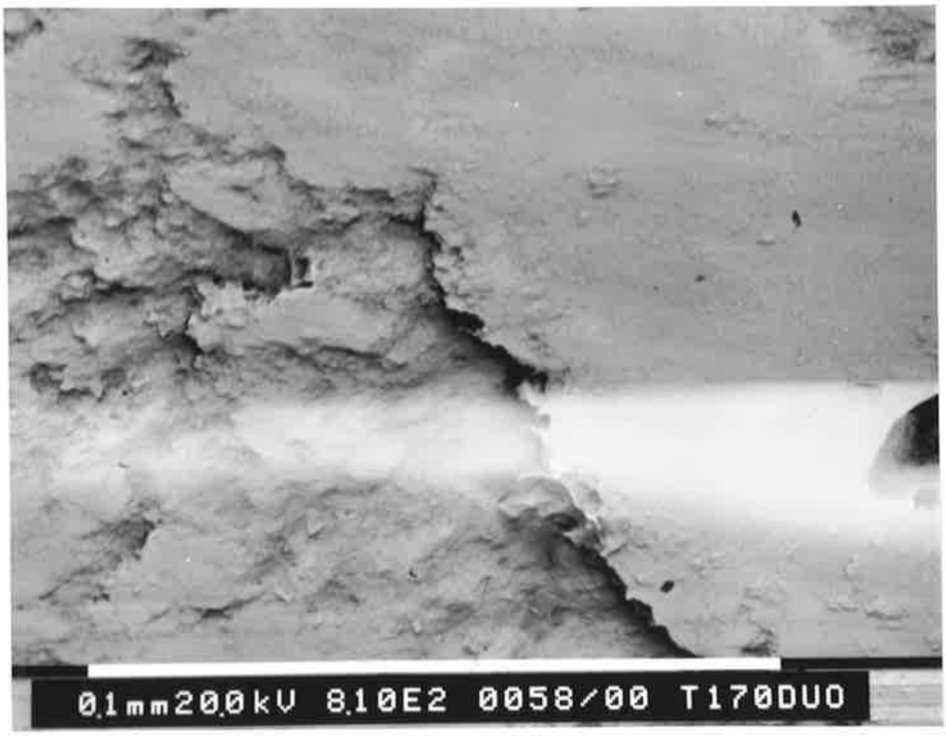


Fig. A2.7: Lubricant pH=7 at 16.2kg.

(Electron micrograph: 20kv; magnification 800x)

With a load at 16.2kg, the degree of surface breakdown increased further, producing very large craters. This photograph shows part of a large crater.

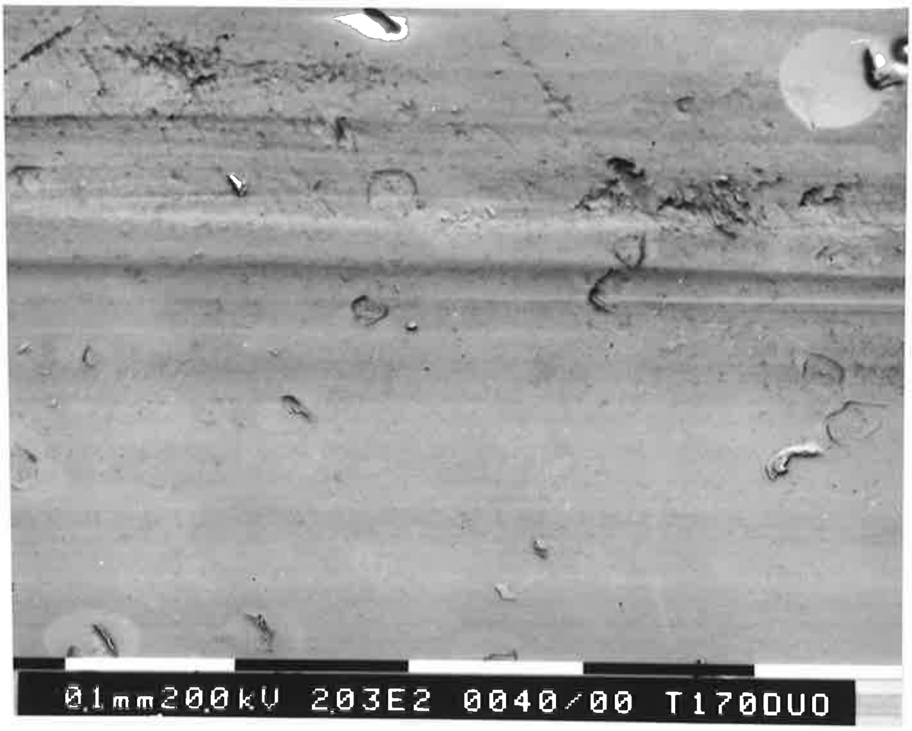


Fig. A2.8: Lubricant pH=3 at 9.95kg.

(Electron micrograph: 20kv; magnification 200x)

Smooth amorphous surface with occasional striations and cratering.

Fig. A2.9: Lubricant pH=3 at 9.95kg.

(Electron micrograph: 20kv; magnification 1600x)

At much higher magnification of the smooth amorphous layer confirmed no characteristic surface detail.

Fig. A2.10: Lubricant pH=3 at 16.2kg

(Electron micrograph: 20kv; magnification 25x)

The increase in load produced more wear and a rougher appearing surface with evidence of striations among areas that appeared completely smooth.

Fig. A2.11: Lubricant at pH=3 at 16.2kg.

(Electron micrograph: 20kv; magnification of 800x)

Higher magnification of the smooth areas did not show the amorphous layer seen at lighter loads, instead a rougher surface was evident with signs of striations.

Fig. A2.12: Lubricant at pH=1.2 at 3.2kg.

(Electron micrograph: 20kv; magnification 25x)

Under very acidic conditions the facet surface was very smooth yet undulating indicating that enamel dissolution was faster than the wear from the dynamic load. Craters were sparse with no evidence of striations at this magnification.

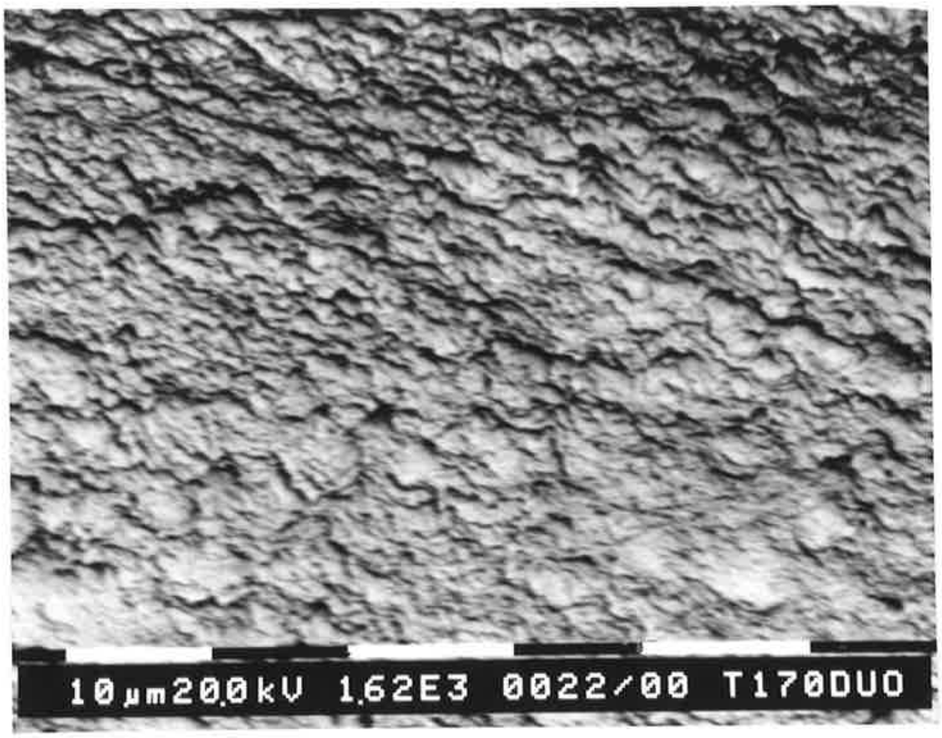


Fig. A2.13: Lubricant at pH=1.2 at 3.2kg.

(Electron micrograph: 20kv; magnification 1600x)

Striations at this magnification were very rare. The few present were approximately 2µm in width. At these higher magnifications, enamel prisms were evident with considerable etching of the surface (No 13).

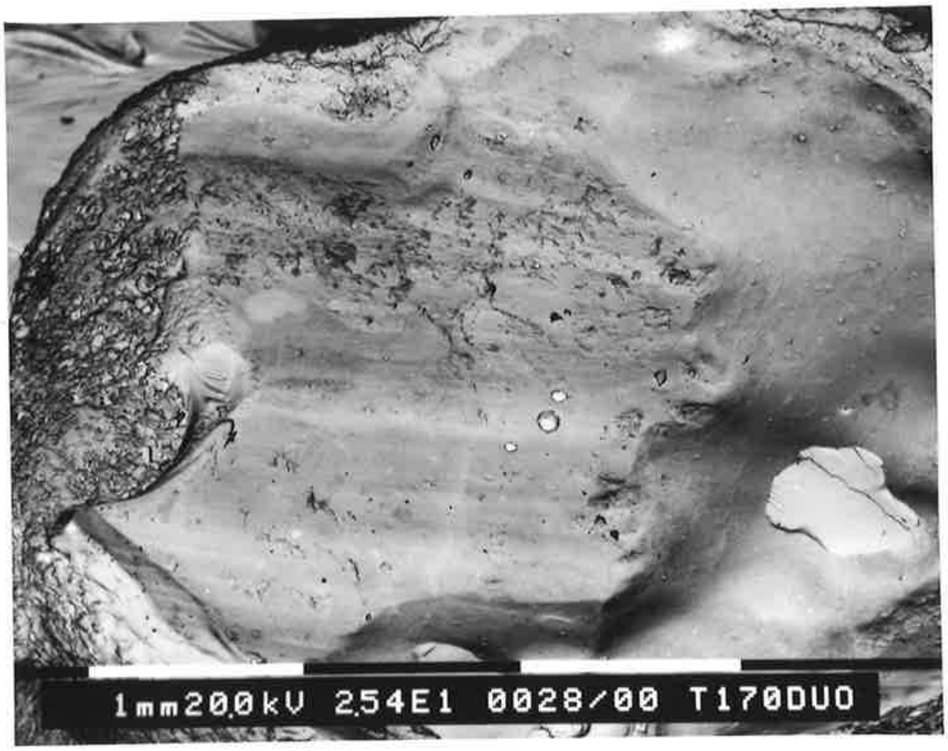


Fig. A2.14: Lubricant at pH=1.2 at 9.95kg.

(Electron micrograph: 20kv; magnification 25x)

At he higher load the surface was flatter and rougher with evidence of cratering and some striations. Fast enamel dissolution was still evident.

Fig. A2.15: Lubricant saliva pH=7 at 9.95kg.

(Electron micrograph: 20kv; magnification 25x)

Facet surface was flat but the amount of surface breakdown leading to crater formation was high.

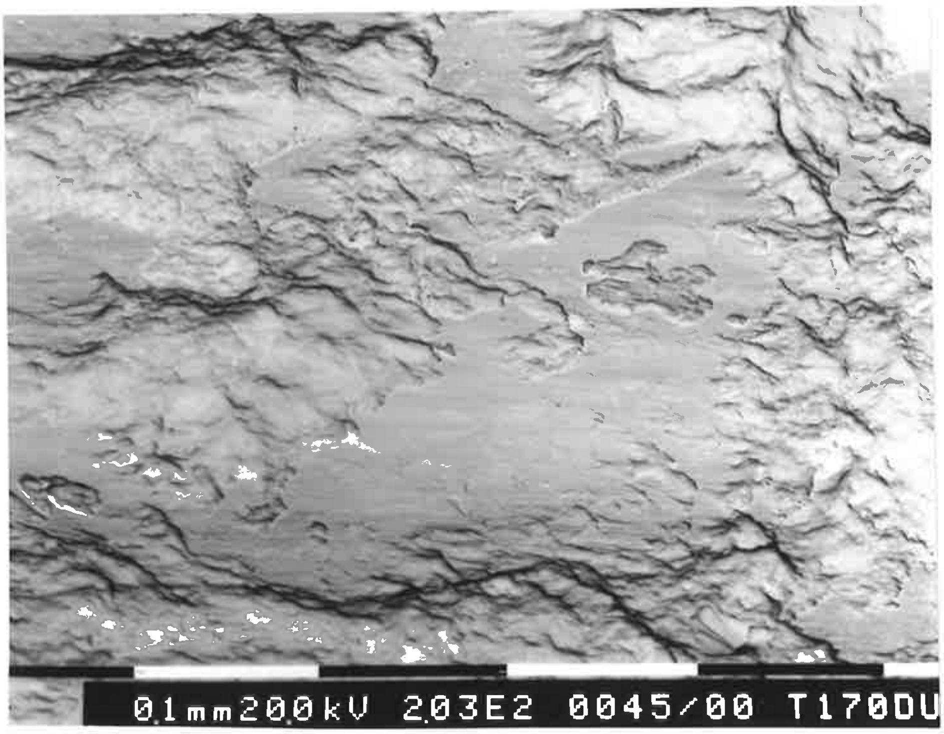


Fig. A2.16: Lubricant saliva pH=7 at 9.95kg.

(Electron micrograph: 20kv; magnification 200x)

At higher power, the craters merged, producing large areas of surface breakdown.

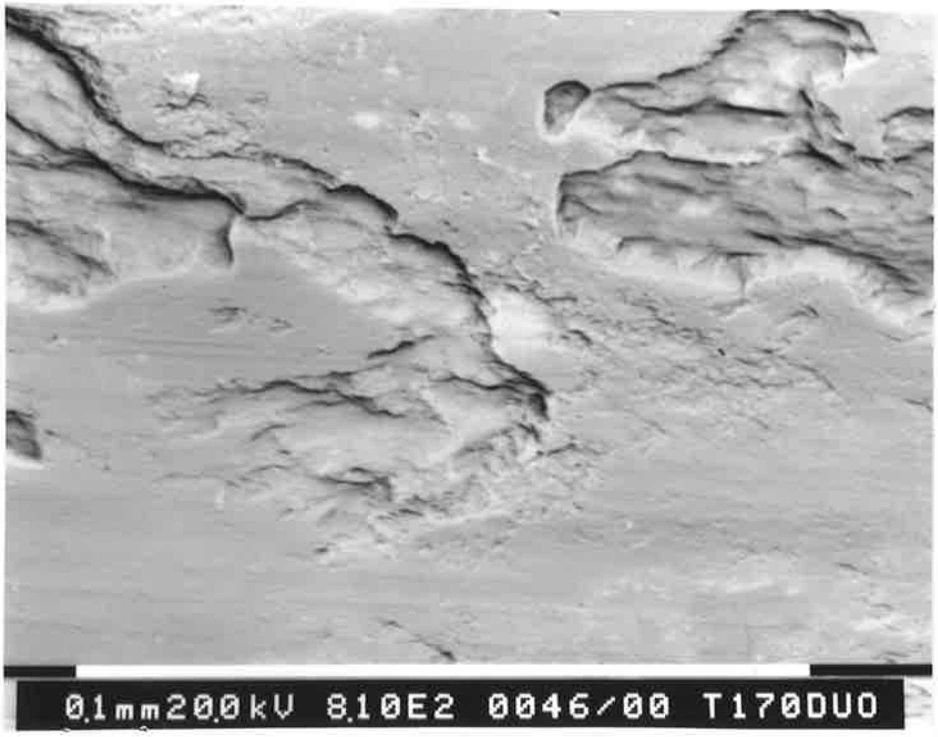


Fig. A2.17: Lubricant saliva pH=7 at 9.95kg.

(Electron micrograph: 20kv; magnification 800x)

Between large areas of cratering, fine parallel striations on smooth surfaces could be seen.

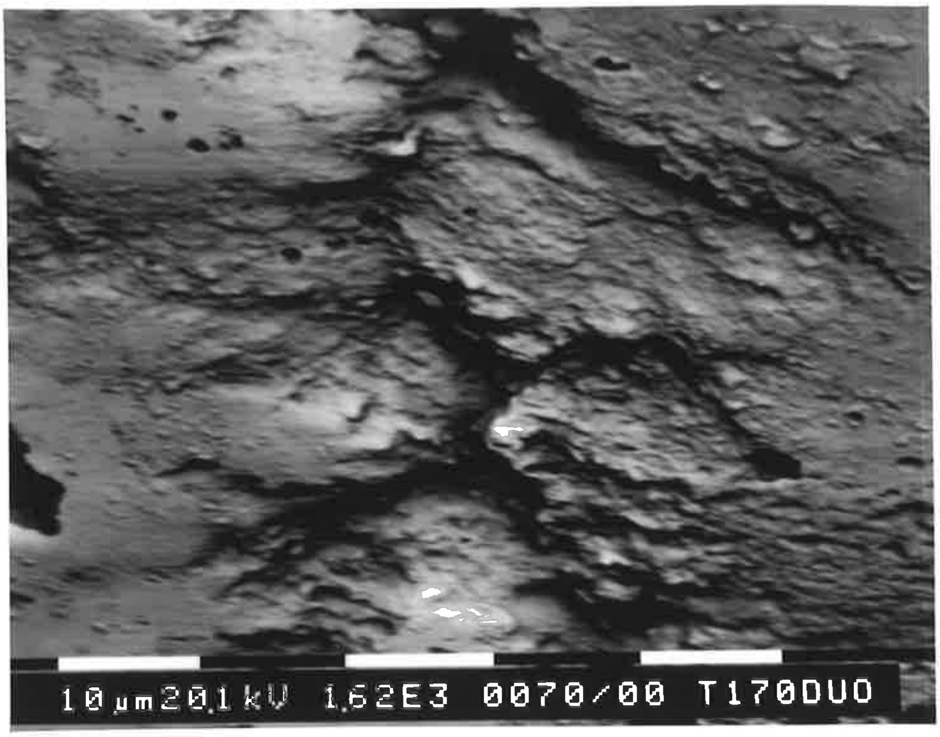


Fig. A2.18: Lubricant saliva pH=7 at 16.2kg.

(Electron micrograph: 20kv; magnification 1600x)

The surface appearance of the facet was similar to the 9.95kg load, however the only difference being that surface breakdown was far more substantial and the number of voids were more widespread.

APPENDIX III

PERSONAL PUBLICATIONS

(1) Kaidonis JA, Townsend GC and Richards LC (1992) Abrasion: an evolutionary and clinical view. Aust. Prosthodont. J. 6: 9-16.

(2) Kaidonis JA, Townsend GC and Richards LC (1992) Brief communication: Interproximal tooth wear - a new observation. Am. J. Phys. Anthropol. 88: 105-107.

(3) Kaidonis JA, Townsend GC and Richards LC (1992) The morphologic features and aetiology of interproximal tooth wear. In T. Brown and S. Molnar (eds.): Craniofacial Variation in Pacific Populations. Adelaide: The University of Adelaide. pp. 121-127.

(4) Kaidonis JA, Townsend GC and Richards LC (1993) Nature and frequency of dental wear facets in an Australian Aboriginal population. J. Oral Rehabil. 20: 333-340.

(5) Kaidonis JA, Richards LC, Townsend GC and Tansley GD (1992) Qualitative and quantitative *in vitro* studies of human enamel Wear. J. Dent. Res. 72: 591.

(6) Kaidonis JA, Townsend GC, Richards LC (1990) Nature of wear facets in dentitions of Australian Aboriginals. J. Dent. Res. 69:942.

(7) Kaidonis JA, Townsend GC, Richards LC (1993) Wear characteristics of enamel during bruxism. J. Dent. Res. 73: 739.

(8) Kaidonis JA, Townsend GC, Richards LC (1994) Non-carious changes to tooth crowns. In GJ Mount and WR Hume (eds.): Preservation and Restoration of Tooth Structure. Sydney: McGraw Hill, (In press).

(9) Townsend GC, Dempsey P, Brown T, Kaidonis JA, and Richards LC (1994) Teeth, Genes, and the Environment. Pers. Human Biol. 4: 35-46.

(10) Kaidonis JA, Townsend GC, Richards LC Tansley GD (1994) Qualitative assessment of dental wear facets. J. Dent. Res. (In press)

Kaidonis, J.A., Townsend, G.C. and Richards, L.C. (1992) Abrasion: an evolutionary and clinical view.
Australian Prosthodontic Journal, v. 6, pp. 9-16, 1992

Kaidonis, J.A., Townsend, G.C. and Richards, L.C. (1992) Brief Communication: Interproximal tooth wear - a new observation.
American Journal of Physical Anthropology, v. 88 (1), pp. 105–107, May 1992

NOTE: This publication is included in the print copy of the thesis held in the University of Adelaide Library.

It is also available online to authorised users at:

http://dx.doi.org/10.1002/ajpa.1330880109

Kaidonis, J.A., Townsend, G.C. and Richards, L.C. (1994) Morphologic Features and Aetiology of Interproximal Tooth Wear.
Human Biology, v. 66 (2), pp. 357-359, April 1994

NOTE: This publication is included in the print copy of the thesis held in the University of Adelaide Library.

Kaidonis, J.A., Richards, L.C. and Townsend, G.C. (1993) Nature and frequency of dental wear facets in an Australian Aboriginal population.
Journal of Oral Rehabilitation, v. 20 (3), pp. 333–340, May 1993

NOTE: This publication is included in the print copy of the thesis held in the University of Adelaide Library.

It is also available online to authorised users at:

http://dx.doi.org/10.1111/j.1365-2842.1993.tb01615.x

Townsend, G.C., Dempsey P., Brown, T., Kaidonis, J.A. and Richards, L.C. (1994)
Teeth, Genes and the Environment.
Perspectives in Human Biology, v. 4, pp. 35-46, 1994

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