AN INVESTIGATION OF THE WEAR OF HUMAN ENAMEL AND DENTAL CERAMICS

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SUMMARY

There has been an increase in the use of ceramic restorative materials in modern dentistry. This is perhaps because of continuous patients' demands for dental restorations that simulate the appearance of their natural teeth. Although ceramic restorations provide good aesthetics, clinicians were always concerned about their abrasiveness against the natural dentition. The objective of this study was to investigate the wear of human enamel and dental ceramics using a wear machine that simulated the chewing cycle. The machine provided an impact action followed by sliding motion of a tooth specimen onto the surface of various restorative materials. Tooth specimens were prepared from the buccal cusp of extracted mandibular premolars. A total of four dental ceramic systems were tested in the study. These were Vitadur Alpha porcelain (aluminous porcelain); Vita Omega porcelain (bonded-to-metal porcelain); Duceram-LFC (hydrothermal low fusing ceramic); and Cerec Vita Mark II (machinable ceramic). Cast gold was also tested for comparison. Overall, throughout the study, a load of 40N was used with a cycle rate of 80 cycles per minute for a total of 25000 cycles. The amount of wear was determined by measuring the cusp height reduction of the tooth using a reflex microscope, and the depth of wear track on the surface of restorative materials using a Dektak 3ST surface profile measuring system. After the wear test, specimens from both tooth and material were subjected to scanning electron microscopy for qualitative evaluation.

At first, tooth specimens were tested against Alpha porcelain specimens that had been treated with three surface finishings namely glazed, unglazed (adjusted porcelain by diamond burs) and polished (adjusted porcelain surface and then polished). The

specimens were tested in distilled water and with/without intermittent exposure to Coca Cola. The results showed no significant differences in enamel wear between glazed and polished groups, but the wear produced by the unglazed porcelain was significantly higher. Exposure to Coca Cola increased significantly the amount of enamel wear produced by all porcelain surfaces. The finishing surface did not influence the wear of the porcelain.

A second study was carried out to investigate the wear of enamel and the four ceramic materials compared with gold. The surface of Alpha porcelain, Omega porcelain and Duceram-LFC were glazed whilst that of the Vita Mark II was polished to simulate clinical conditions. The test was carried out in distilled water only and the results showed that all the ceramics tested were more abrasive and less resistant to wear than gold. Duceram-LFC and Vita Mark II were found to be significantly less abrasive and more resistant to wear than conventional Alpha and Omega porcelains.

The third study investigated the wear of Duceram-LFC and Vita Mark II and their antagonist tooth enamel by testing with intermittent exposure to Coca Cola. The results of Alpha porcelain from the first study were also included. The results showed that compared to those tested in water only, exposure to Coca Cola increased the enamel wear by 19% against Alpha porcelain, 31% against Vita Mark II and 74% against Duceram-LFC, and Alpha porcelain caused the greatest amount of enamel wear. In addition both Duceram-LFC and Vita Mark II were found to become more prone to wear subsequent to exposure to Coca Cola.

The fourth study was carried to find out whether the wear of enamel and ceramic materials would be affected by the presence of food particles, as a three-body wear test. In this study, the ceramics tested were Alpha porcelain, Duceram-LFC and Vita

Mark II. The results showed that incorporation of food slurry in the wear test decreased the wear of both enamel and ceramic for the Alpha porcelain and Vita Mark II groups, whilst there was an increase for the Duceram-LFC group, compared with that observed when the test was carried out in water (as a two-body wear test). The difference between Alpha porcelain and Duceram-LFC tested in the presence of food particles was not significant for both enamel and ceramic wear, however, both were found to be significantly more abrasive and less resistant to wear than Vita Mark II.

Overall, the scanning electron microscopy showed that all ceramics wear by fatigue and abrasive wear mechanisms. The wear of enamel opposed by ceramics was mainly by an abrasive wear mechanism. The wear of gold was a combination of fatigue and adhesive wear mechanisms.

Finally, the results suggest that a simple two-body wear test is not sufficient to determine the wear properties of dental ceramics and their abrasivity on tooth structure. Among all the ceramic systems tested, Vita Mark II was demonstrated to be the most acceptable in regard to its abrasivity on tooth enamel and its resistance to wear. The hydrothermal ceramic Duceram-LFC was found to be the most susceptible to the effects of the environmental media.

Declaration

This thesis is the original work of the author.

Ahmad Al-Hiyasat

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In Loving Memory of my Father

CONTENTS

INTRODUCTION
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INTRODUCTION AND AIM

It is generally accepted that gradual wear of opposing teeth in the human dentition is a normal phenomenon, although the wear rate may vary among individuals depending on different factors such as the abrasive content of foods and oral habits (Monasky and Taylor, 1971; Jacobi *et al.*, 1991). However, this natural process may be disturbed by the introduction of restorations with wear properties which differ from those of the replaced tooth structure (Monasky and Taylor, 1971; Jagger and Harrison, 1995a). Therefore, in restorative dentistry the goal should be to reconstruct occluding surfaces that not only resist wear but do not wear opposing surfaces excessively (Wiley, 1989). More and more people are keeping their natural teeth for longer, perhaps, because of increasing dental awareness, and this coupled with an increasing demand for the restoration of teeth as opposed to extraction, has resulted in clinicians treating more patients with worn dentitions (Jagger and Harrison, 1995a). Short clinical crowns are an obvious clinical problem in restorative dentistry (Johansson and Omar, 1994). When managing these problems, the dentist is required not only to treat tooth wear but also to prevent it (Jagger and Harrison, 1995a). If the tooth surface is opposed by abrasive restorative materials, the former can be rapidly abraded and could produce sensitivity of the teeth and occlusal imbalance, especially if the contact is with ceramic surfaces (Jacobi *et al.*, 1991). Therefore, when designing the individual restoration the wear of the masticatory surface must be considered (Mahalick *et al.*, 1971).

Wear is a fact of restorative dentistry and whether dentists maintain a physiological or introduce a pathological pattern of wear during treatment is under their control

(Wiley, 1989). The clinical management of wear problems and the prevention measures for it must involve an understanding by which the wear of restorative materials occur and the subsequent effect on dental structures (Mair *et al.*, 1996). The mechanism of wear is complex, including variables such as the properties of the two contacting material structures and the surrounding and interfacial media (Dahl *et al.*, 1993). Guidance in understanding clinical wear can be deduced from studies of industrial wear, which have led to the definition of several conditions and mechanisms considered to control the wear process (Moon and Draughn, 1982). Although it has been customary to regard tooth wear and material wear as separate fields of research, the same fundamental processes are active on all types of structures. In addition, in order to investigate the wear it is necessary to understand how it can be measured and evaluated, both clinically and in the laboratory (Mair *et al.*, 1996). Clinical studies are advantageous in determining differential rates of wear. However, they present many variables that are difficult to control, they require time, and do not allow investigation of the factors contributing to wear. Conversely, laboratory wear tests are needed to evaluate the relative wear rates of restorative materials (Smalley and Nicholls, 1986) as well as their abrasive effect on the opposing natural teeth (Ratledge *et al.*, 1994 and Suzuki *et al.*, 1996). Several different wear machines have been developed in an attempt to simulate the masticatory cycle and accelerate its effect, in order to investigate the wear of both restorative materials and opposing natural teeth under controlled conditions (Monasky and Taylor, 1971; Harrison and Lewis, 1975; DeLong and Douglas, 1983; De Gee *et al.*, 1986; Leinfelder *et al.*, 1989; Jacobi *et al.*, 1991; Ratledge *et al.*, 1994).

Dental ceramics are known for their natural appearance and their durable chemical and optical properties (Kelly *et al.*, 1996). Porcelain-fused-to-metal restorations were introduced to dentistry in the early 1960's, and since then they have almost replaced the metal crowns which dominated pre-1960 dentistry (Christensen, 1986). Further developments in restorative dental materials occurred in 1965 when the aluminous porcelain crown was introduced by McLean and Hughes (1965). A high strength core porcelain was constructed onto which a matched expansion veneer porcelain was baked (McLean, 1988). Although ceramic restorations have satisfied patient demand in respect of their aesthetics, they may be, abrasive and potentially destructive to the opposing natural teeth. This has been observed clinically (Wiley, 1989) and demonstrated in laboratory studies (Jacobi *et al.*, 1991; DeLong *et al.*, 1992; Ratledge, 1994; Jagger and Harrison, 1995a). Therefore, some clinicians feel that occlusal contact areas should be of metal rather than porcelain (Wiley, 1989).

Nevertheless, in a survey in 1986 Christensen found that 75% of the dentists questioned used porcelain on the occlusal surface of posterior teeth most or all of the time, whereas 73% of the same group of dentists would place a metal occlusal surface on their own teeth. Moreover, occlusal adjustment of porcelain restorations at the chairside or intraorally is sometimes needed. This adjustment will break the glazed surface of the porcelain and may produce a surface that is highly abrasive and more destructive to the opposing teeth (Monasky and Taylor, 1971; Wiley, 1989).

Ceramics were first used in dentistry in the 18th century and since then developments have continued leading to the different types of ceramic materials and systems that are

in use today (McLean, 1991). The hydrothermal ceramic is one of the new categories that has been introduced in the market since 1989 (Mattmüller *et al.*, 1996). In this type of ceramic material the hydroxyl group has been introduced into the glass network of the ceramic, thus reducing the fusing temperature of the material (e.g. Duceram-LFC, Ducera, Dental GmbH, Rosbach, Germany). Because of this structure the manufacturers claim that the hydrothermal ceramics have a self-healing process by forming a silicon-hydroxyl layer on the ceramic surface when introduced in the mouth or in contact with water, thus protecting the ceramic surface from damage and sealing micro flaws continuously (Komma, 1993).

The evolution of a CAD-CAM system for production of machined restorations has added a new option to restorative dentistry. One of the best-known is the Cerec system (Siemens, Benheim, Germany) (Denry, 1996). With this system computer technology is used in combination with a milling machine to produce a ceramic restoration cut from a manufacturer-made ceramic block at the chairside (Smith and Cardwell, 1989; Mörmann and Krejci, 1992; Heymann *et al.*, 1996; Mörmann and Schug, 1997). Cerec Vita Mark II (Vita, Zahnfabrik, Bad Säckingen, Germany) are ceramic blocks made from feldspathic porcelain with fine particle size (Vita product information) which can be used with the Cerec system to produce ceramic restorations using the CAD-CAM technology.

With these changes and new developments in ceramic structure, the aim of the present study was to investigate the wear of human enamel and the opposing ceramic materials in a wear machine that was developed to simulate the chewing cycle under

various conditions. At first the tribology (science of interacting surfaces in relative motion) was reviewed to understand the mechanism of different types of wear. This was followed by a general review of wear in dentistry, the ceramic systems used in dentistry and the wear of dental ceramics and opposing tooth structure. The experimental part of the study investigated the effect of different variables namely, the porcelain finishing surface, ceramic types (microstructure), acidic media exposure, and a simulated food slurry media (three-body wear) on wear of tooth enamel and ceramic restorative materials.

CHAPTER 1

REVIEW OF THE LITERATURE

1.1. DEFINITION OF WEAR

Wear can be defined as the time-dependent removal of material from surfaces that are in motion relative to each other (Moon and Draughn, 1982). Other definitions have been published in the literature. Burwell (1957) defined wear as the unwanted removal of solid material from rubbing surfaces. Jahanmir (1978) defined it as the removal of material from solid surfaces as a result of relative sliding motion at the surface. The Institution of Mechanical Engineers of the United Kingdom defined wear as "the progressive loss of substance from the surface of a body brought about by mechanical action". These mechanical actions may be rubbing, impact, scraping, and erosion which could cause wear of the material resulting in the progressive removal of a substance from the surface of the material (Sulong and Aziz, 1990). Wear manifests itself whenever load and motion are present (Mahalick *et al.*, 1971). Thus, it is inevitable when two surfaces undergo slip-sliding under load (Sarkar, 1980).

1.2. TYPES AND MECHANISMS OF WEAR

Wear is considered to be a natural process which occurs whenever two or more surfaces move in contact with one another (Zum Gahr, 1987; Mair, 1992). The mechanism of wear is complex, including variables such as the properties of the contacting substances and the surrounding and interfacial media (Dahl *et al.*, 1993). There are different mechanisms through which wear can occur. These mechanisms can operate either singly or in combination. The situation becomes more complicated if more than one mechanism is operating at the same time (Burwell, 1957). Indeed to understand the mechanisms of wear it will be helpful to discuss the distinct types of wear, and the mechanism of each.

1.2.1. Adhesive Wear

Adhesive wear occurs as a result of the formation and rupture of interfacial adhesive bonds (cold-welded junctions) between the moving surfaces (Dahl *et al.*, 1993). According to Burwell (1957) when two flat surfaces (no matter how smooth and fine) are brought into solid contact, they will only touch at a relatively few isolated points. It is these small contact areas that carry all the load between the two surfaces. The true contact area has been defined as the sum of these small local areas which are actually in contact as opposed to the remainder which is called the apparent contact area. It follows that, because of the generally very small size of the true contact area even under relatively low loads, the local pressures are extremely high and usually exceed the yield point of the softer of the two materials in contact. As a result of these high local pressures, combined with a sliding motion, minute welds are formed at each of the local contact areas and, with continued sliding, these welds are sheared. These conjunctions are continuously formed and broken as solids slide over one another (Moon and Draughn, 1982). The amount of wear depends upon where the conjunction is sheared (Arnell *et al.*, 1991). If the force required to break through the interface of the materials is larger than the force required to break through some continuous surface inside one of the materials, the break will occur along the surface of that material and wear particles will be produced (Rabinowicz, 1965). If the conjunction shear takes place at the original interface, no wear particles will be produced. However, if shear takes place away from the original interface, particles of the material are transferred from one surface to the other (Arnell *et al.*, 1991). These particles may be also transferred back to the original surface, or become loose wear

particles (Powell *et al.*, 1975; Moon and Draughn, 1982). Normally this transfer of materials is observed from the softer material to the harder, but occasionally from the harder to the softer (Rabinowicz, 1965; Moon and Draughn, 1982; Arnell *et al.*, 1991). As a result of this transfer, plates of material may build up on one surface which may subsequently break away and contribute to the three-body abrasive wear (Mair, 1992).

1.2.2. Abrasive Wear

Abrasive wear is the removal of materials by micro-cutting (ploughing) (Dahl *et al.*, 1993). It occurs when a hard rough surface slides over a softer material, where the asperities on the harder surface cut into the softer material causing substance removal from the softer material (Moon and Draughn, 1982). As the harder rough surface slides against the softer surface, it digs into it and ploughs a series of grooves, the material originally in the grooves is normally removed in the form of loose particles (Rabinowicz, 1965). This process can be minimised if the harder material surface is smooth (Moon and Draughn, 1982). However, abrasive wear can also arise if hard particles are found between sliding surfaces. The source of these particles could be from the surrounding media or may be formed by other wear processes acting in the system (adhesive wear) (Moon and Draughn, 1982). The mechanism of this form of abrasive wear seems to be that the abrasive particles adhere temporarily to one of the sliding surfaces, or else are embedded in it, and plough out a groove in the other surface (Rabinowicz, 1965).

Therefore, abrasive wear can be divided into two forms (Mair, 1992), namely:

two-body abrasive wear: when the cutting asperities are fixed to one or both surfaces; and three-body abrasive wear: when there is a slurry of loose abrasive particles between the sliding surfaces. With two-body abrasive wear the shape of the harder and rough surface is imposed into the softer surface, whereas with the three-body abrasive wear the slurry or particles may 'hollow out' the softer area producing a heterogeneous surface (Mair, 1992).

1.2.3. Fatigue Wear

Fatigue wear occurs as a result of the formation and propagation of subsurface microcracks when two surfaces move under dynamic load (Mair, 1992). The rolling and /or sliding or impacting contact of solids can result in cyclic surface stressing (Zum Gahr, 1987). Cyclic stresses, generated because of loading and unloading when two surfaces move over each other, cause a lowering of the mechanical properties of the materials (Moon and Draughn, 1982). Fatigue failure is defined as failure caused by repeated application of stresses which are insufficiently high to cause failure in a single application (Arnell *et al.*, 1991). The fatigue of materials proceeds in the sequence of elastic and plastic deformation of materials and cracks are formed in the plastic deformation zone below the surface (Zum Gahr, 1987). The general principle is the cumulative application of stress cycles, where each stress individually is well within the elastic limit, which can cause a material to fail by fracture (Rabinowicz, 1965). In any event, each cycle of plastic deformation will correspond to one fatigue cycle, and the accumulation of such cycles will eventually cause a fatigue fracture and the generation of wear particles (Arnell *et al.*, 1991).

According to the Delamination Theory which has been described by Suh (1973, 1977) when two sliding surfaces are in contact, the asperities of the softer surface are easily deformed and some are fractured by the repeated loading action. Either when these asperities are deformed or removed, a relatively smooth surface is generated. Thus, the contact becomes an asperity - plane contact. As the asperities of the harder surface plough the softer surface, each point along the softer surface experiences cyclic loading. The surface traction exerted by the harder asperities on the softer surface induces plastic shear deformation in the subsurface which accumulates with repeated loading. As the deformation continues, cracks are nucleated in the subsurface. Further loading and deformation causes cracks to extend and to propagate, joining neighbouring ones. The material becomes weakened because of these cracks and at certain weak points these cracks finally shear to the surface. Eventually, a small area of the surface material becomes surrounded by a network of linked cracks and the fragment is subsequently displaced (Mair, 1992). The fragment can be plucked out from a surface by adhesion or abrasion mechanisms (producing loose particles), and the surface becomes susceptible to further damage. Those particles produced may cut into adjoining structures and cause abrasive wear (Moon and Draughn, 1982). This clarifies the interaction between fatigue, adhesive, and abrasive wear mechanisms.

However, the surface of the harder material can also be worn by a softer material since the latter can cause subsequent plastic deformation in the harder, as long as its hardness in the fully work-hardened condition is more than about half the initial

hardness of the former surface (Arnell *et al.*, 1991). According to Arnell *et al.* (1991) fatigue is always the basis of wear particle formation.

1.2.4. Brittle Fracture Wear

Brittle fracture wear has been described by Rabinowicz (1965) as a variation in the fatigue process wear (fracture wear), which occurs in brittle materials (e.g. sintered ceramic, glass) whose tensile strength is less than one third of their compressive strength. When one surface slides across another surface the position of the maximum tensile stress is behind the contact area. If the tensile stress is less than one third of the compressive stress which is under the contact area, tensile failure will take place behind the contact area at the maximum tensile stress position. During sliding, a characteristic series of cracks is observed in the wear track. Subsequently, large wear particles tend to be produced as a result of the surface break-up. This is the type of wear that has been described by Powers and Craig (1972a,b,c) for fluorapatite crystals (Powell *et al.*, 1975). In their study Powers and Craig (1972c) observed that in all instances the tensile cracks or chevrons formed pointed toward the origin of their formation which is opposite to the direction of the relative motion of the slider. Such mechanism of wear is confined to brittle materials, in which crack growth is accompanied by only low plastic deformation (Zum Gahr, 1987).

1.2.5. Impact Wear

Impact or percussive wear is defined as the form of wear arising from repetitive impact of two solid surfaces (Jahanmir, 1978). The most common mechanism of impact wear is by formation and propagation of subsurface cracks in ductile materials,

and by formation and propagation of surface cracks in brittle materials (Engel, 1976). In dentistry, considering the repetitious nature of the mandibular teeth closing onto the maxillary teeth, impact wear probably occurs during mastication, swallowing, and clenching. The inherent action in mandibular and maxillary tooth closure is probably a combination of impact and slip action (Sulong and Aziz, 1990).

1.2.6. Erosive Wear

Erosive wear is the form of wear that occurs when liquid or solid particles impinge on a solid surface (Arnell *et al.*, 1991). The essential feature of erosive wear is that the wear medium (e.g. sand or water) forms the second surface. This distinguishes erosive wear from three-body abrasive wear, where the particles are compressed between two separate surfaces (Mair, 1992). However, it differs from impact wear in the sense that erosive wear occurs by impact of small solid particles on the surface, whereas impact wear occurs from repetitive impact of two solid surfaces (Sulong and Aziz, 1990). Sarkar (1980) described two types of erosion in dentistry, idiopathic and chemicomechanical. Idiopathic erosion has the effect of giving localised surface of teeth a polished appearance. Chemicomechanical erosion occurs because of mechanical action, such as impact, sliding, or both occurring on teeth, restorations, or prostheses in the presence of acid or other solutions of varying pH values in the mouth.

1.2.7. Corrosive Wear (Tribochemical wear)

Corrosive wear is a chemical wear which results from the interaction of the environment with sliding surfaces, followed by the rubbing off of the products of the

reaction (Pugh, 1973). In other words, corrosive wear results from the interaction of chemical degradation and movement of the surfaces. At first the surface is weakened by chemical degradation and then removed by rubbing against an opposing surface (Mair, 1992). Initially, the chemical attack will be rapid and the rate of reaction will tend to slow down, or it may even cease completely after a cohesive film has been formed on the surface which in the absence of sliding, protects the material from further corrosion. However, in the presence of a sliding action between the surfaces the film is removed so the original surface is again exposed, and the chemical attack continues (Moon and Draughn, 1982; Sulong and Aziz, 1990).

1.2.8. Fretting Wear

Fretting wear occurs whenever low-amplitude vibratory sliding takes place between two surfaces (Arnell *et al.*, 1991). This type of wear occurs by interaction of several wear mechanisms, the oscillatory sliding causes fatigue wear, which may be enhanced by adhesion. Corrosion has a strong influence on fretting wear, producing hard corrosion products of wear particles which can also lead to abrasion (Jahanmir, 1978; Arnell *et al.*, 1991). However, Mair (1992) has reported that the conditions of fretting wear do not occur in the mouth and therefore he suggested that this process does not feature in dental wear.

Basically, most types of wear are similar in nature since they occur as a result of an interaction between two surfaces. Wear is controlled by the type of interacting materials, the environment, the loading condition, and the type of sliding interaction (Jahanmir, 1978). The oral cavity environment is complex, consisting of fluids with

changing composition and pH, cyclic thermal conditions, and cyclic mechanical forces exerted during mastication, bruxing, and tooth brushing. In such an environment, it is probable that all the wear mechanisms are active with the predominant mechanism changing as the conditions of the environment and material combinations change (Moon and Draughn, 1982).

1.3. WEAR IN DENTISTRY

Wear is a common phenomenon in dentistry which occurs when two surfaces undergo slipping or sliding movement as a load is applied (Sulong and Aziz, 1990). Thus, wear of natural hard tissues is considered a natural process and can be expected to some degree in all dentitions (DeLong *et al.*, 1989).

Anthropological studies show that tooth wear has been seen on the dentitions of populations of earlier cultures. Marked occlusal tooth wear has been found in skulls of Egyptian mummies from 5,000 to 3,000 B.C. (Pindborg, 1970). Tooth wear also has been seen in 3,000- to 5,000- year old skulls from the Shell Mound Indians of Alabama, the cusps were worn down and dentine was exposed in the majority of teeth (Mehta, 1969). Skulls of a Romano-British population, found in a cemetery and dating from 200 and 400 A.D., also showed teeth with occlusal tooth wear (Whittaker *et al.*, 1982). Jaws from the sixth century that were collected from a Jute cemetery near Lyminge, Kent, UK, showed occlusal tooth wear which affected the anterior teeth mainly at right angles to the long axis, and the posterior teeth showed progressive loss of buccal cusps in the mandibular arch and palatal cusp, in the maxillary arch (Picton, 1957). A positive correlation between tooth wear and cultural

factors was found in a comparative study of tooth wear among skeletal remains of North American Indians from three areas: California 2000 - 3000 years B.C.; the Valley of Mexico 1100 - 100 B.C.; and the Southwest 1275 -1550 A.D. Dietary specialisation and division of labour appear to be responsible for the degree and type of wear found in this study (Molnar, 1971). Indeed, often the degree and kind of tooth wear varies from population to population and this variability is possibly related to certain material aspects of cultures such as diet, food preparation techniques and tool usage (Molnar, 1971).

The tooth wear process could be disturbed by dental restorations introduced into the oral cavity because the wear properties of these materials differ from those of the replaced tooth structure (Monasky and Taylor, 1971). As the teeth, together with any restorations, move in contact with one another, wear is inevitable (Mair, 1992) and this can be potentially detrimental if the tooth is opposed by abrasive restorations, such as ceramics (Jacobi *et al.*, 1991).

Many studies have been directed towards the investigation of the clinical aspects of tooth wear and its aetiology. However, before discussing these, it would be helpful to review the factors that affect tooth wear. Recognition of the latter would enable not only a better understanding of the aetiological factors of tooth wear, but also in the selection of the appropriate dental materials to restore the patient's dentition.

1.3.1. Factors Affecting Wear

According to Moon and Draughn (1982) the factors that could affect wear are:

1. Force

The greater the force exerted during chewing and tooth contact, the greater is the resulting wear.

2. Slide Distance

An increase in the sliding contact distance between teeth will increase tooth wear. This could explain the appreciable wear that may be observed on the palatal surfaces of maxillary or incisal edges of mandibular anterior teeth, whilst they act as guide planes in jaw closure. Clinically, this wear is observed most frequently when porcelain anterior crowns come into contact with natural teeth (Moon and Draughn, 1982; Wiley, 1989; Rosenblum and Schulman, 1997).

3. Contact Area

A decrease in the contact area results in an increase in the stress of the opposing surface which in turn increases the tooth wear. When the force of mastication is acting over a small area, the stress is greater than when the same force is exerted over a larger area. A sharp tooth cusp with a small contact area , would therefore, promote a greater degree of wear and a more rapid change in occlusal dimension than a blunt tooth cusp with a larger contact area.

4. Surface Roughness

When two rough surfaces are brought into contact over one another, the contact will be only at the high spots producing high localised stresses, thereby increasing wear.

5. Frequency of Contact

Wear is increased with more frequent occlusal contact of mandibular teeth with their antagonist maxillary teeth. This could be observed in patients exhibiting bruxism, and is also shown by the increased wear with age (elderly patients), as a result of accumulated number of occlusal contacts (Moon and Draughn, 1982).

6. Environmental Factors

The mechanical and chemical environment in the mouth can affect the wear process. Factors such as low salivary pH, a coarse diet, exposure to an abrasive atmosphere, lack of salivary flow and excessive tooth brushing may affect the wear of dental hard tissue and materials.

1.3.2. Dental Terminology

Tooth wear may be defined as the surface loss of dental hard tissues other than by caries or trauma (Kidd and Smith, 1990). It is an all-embracing term for attrition, abrasion and erosion (Milosevic, 1993). These terms have been used to describe the wear of both tissue and dental materials used to restore the tooth hard tissue (Mair, 1992).

Attrition, abrasion and erosion are three separate and distinct processes, each of which result in the loss of tooth substance (Shafer *et al.*, 1974). However, tooth substance loss may result from a combination of two or more of these processes and it is difficult to determine the part played by each (Baden, 1970; Eccles, 1982b). Thus, the use of the term tooth wear has been increasing in the last few years (Smith, 1989). In the literature the terms "tooth surface loss", "occlusal wear" and "dental wear" also have been used (Dahl *et al.*, 1993). It would be reasonable to use the terms attrition, abrasion and erosion only after there is a clear indication of the specific aetiology in the case under investigation (Smith, 1989).

1.3.2.1. Attrition

Attrition stems from the latin word *attero* which means to rub upon or against (Baden, 1970). Smith (1989) defined attrition as the physical wear of one tooth surface against another. It is considered to be a result of tooth-to-tooth contact (Baden, 1970; Shafer, 1974; Carlsson and Ingervall, 1988; Milosevic, 1993). Thus, tooth tissue loss occurs at the contacting surfaces. Accordingly, slight wear could occur at the proximal contact points but principally tooth tissue loss occurs occlusally and incisally (Smith, 1989). The palatal and labial surfaces of maxillary and mandibular anterior teeth, respectively, could also be affected (Baden, 1970; Sarkar, 1980; Eccles, 1982b; Johansson and Omar, 1994).

The loss of tooth hard tissue could occur to varying degrees, according to Pindborg (1970). Three types of attrition have been described : physiological attrition, defined as the gradual and regular loss of tooth substance as a result of natural mastication;

intensified attrition, defined as more extensive attrition than would normally be expected; and pathological attrition, defined as extreme wear of one single tooth or groups of teeth because of malfunction or malposition of teeth. Indeed, it is often difficult to draw a clear line between physiological and pathological attrition (Pindborg, 1970).

1.3.2.2. Abrasion

Abrasion stems from the latin *abrado* which means to rub off or to scratch off (Baden, 1970). Pindborg (1970) defined abrasion as pathologic tooth wear caused by friction from a foreign body, independent of occlusion. Smith (1989) defined it as physical wear by objects other than another tooth. Examples of the objects are toothbrushing, habits and foodstuffs (Milosevic, 1993). Dental materials scientists use the term abrasion to describe the wear of restorations at non-contacting sites, which manifests as loss of substance across the whole restoration surface with subsequent exposure of the enamel margins (the so-called "submerging surface") (Mair, 1992).

1.3.2.3. Erosion

Erosion stems from the latin *erodo*, which means to wear off or to consume (Baden, 1970). Erosion is defined as the loss of tooth hard tissue as a result of a chemical process not involving bacteria (Pindborg, 1970; Shafer, 1974; Kidd and Smith, 1990). The causative agent is usually an acid (Kidd and Smith, 1990). However, physical wear is probably necessary to rub away the softened, decalcified surface (Smith, 1989). Therefore, Smith (1989) considered that these lesions should always be attributed to erosion/abrasion or erosion/attrition. Nonetheless, when the principal

aetiology is chemical rather than physical, it is common practice to use the term erosion on its own.

Perimylolysis or perimolysis is a special type of erosion which is thought to be caused by low pH along the tongue border. This occurs as a result of the reflux of gastric juices into the mouth, which accumulates between the papillae of the tongue, combined with muscle hyperactivity of the tongue. Thus, it is a combination of erosive and mechanical action against the palatal surfaces of the maxillary teeth, in particular. Clinically, the tuberculum of the incisor becomes indistinct and the premolars and molars become rounded (Pindborg, 1970; Dahl *et al.*, 1993).

According to the aetiology erosion can be classified as :-
regurgitation erosion; dietary erosion; industrial erosion and occasionally medication-induced erosion (Kidd and Smith, 1990; Milosevic, 1993).

1.3.3. Aetiological Factors in Tooth Wear

The terms attrition, abrasion and erosion are used in dentistry to describe tooth wear. These mechanisms tend to occur concurrently, and progressive tooth wear appears to have a multifactorial aetiology (Carlsson and Ingervall, 1988; Johansson *et al.*, 1993a,b; Dahl *et al.*, 1993; Johansson and Omar, 1994). Poynter and Wright (1990) in a clinical study of 100 subjects aged between 46-85 years, found 82% of the subjects were allocated to a combined aetiological grouping of attrition, dietary erosion and abrasion; 14% attrition and dietary erosion; 2% attrition alone; 1% dietary erosion

and 1% regurgitation erosion. Thus, the aetiological factors appear to have a complex interdependence.

In restorative dentistry whenever severe worn teeth are going to be restored, the aetiological factors involved must be considered thoroughly (Dahl *et al.*, 1993). Moreover, when treating patients with severe tooth wear, it is essential to find the most important aetiological factor(s) in order to select the most effective treatment (Carlsson *et al.*, 1985). However, it is often difficult to see the borderline between physiological and pathological conditions for many of these factors (Carlsson and Ingervall, 1988). Despite the known complexities, clinically it remains necessary to identify the causes and effects of advanced tooth wear and its potential for progression if scientific and predictable therapy is to be prescribed for such patients (Johansson *et al.*, 1993b).

1.3.3.1. Age

Tooth wear is, in general, associated with ageing or, more strictly speaking, with the length of time the teeth have been exposed to occlusal function (Carlsson and Ingervall, 1988). Therefore, it is natural for the degree of tooth wear to be proportional to the time of exposure of the teeth to the oral cavity (Dahl *et al.*, 1993). Accordingly, it is not a surprise that all patients show some degree of tooth wear by the time they are advanced in age, when the total cumulative effect of wear is seen (Smith, 1989).

Molnar *et al* (1983) studied the tooth wear rates using dental casts of 64 Australian aborigines in three age groups of 7, 18 and 25 years. Using a depth gauge method, the authors measured the cusp height to the deepest part of the central pit of the first molar. They found that cusp height was highly correlated with age, varying from 2.7mm for intact cusps at age 7 to 0.6mm and 1.3mm for male and female patients, respectively at 25 years of age. By 18 years of age, an average of 0.5mm of cusp height was lost. Interestingly, in males the maxillary teeth lost more cusp height than did mandibular teeth, whilst in females teeth in both arches were worn to about the same degree.

In a study by Pöllmann *et al.* (1987) , 3667 patients, attending an outpatient dental clinic, were examined for tooth wear and the results indicated that the degree of tooth wear increases with age and this correlation was found to be highly statistically significant. Furthermore, a significant correlation of tooth wear with age has been supported by many subsequent studies (Ekfeldt *et al.*, 1990; Poynter and Wright, 1990; Johansson *et al.*, 1993 a,b).

1.3.3.2. Gender

The relation between tooth wear and gender has been investigated and some studies claim that the degree of occlusal tooth wear is more extensive in males than in females (Pöllmann *et al.*, 1987; Seligman *et al.*, 1988; Ekfeldt *et al.*, 1990; Poynter and Wright, 1990; Johansson *et al.*, 1993 a,b). However, these reports are in contrast to the study by Dahl *et al.* (1989).

1.3.3.3. Bite Force

The literature presents opposing views on the influence of bite force on tooth wear. Dahl *et al.* (1985) found that there is no difference in maximum bite force between subjects with extensive tooth wear and a control group, while Carlsson *et al.* (1985) found that subjects with extensive tooth wear had higher bite force values in the anterior part of the mouth than the control group, whereas the opposite was found for the most posterior region. However, when the patient group was divided into two groups in respect to the degree of wear, no significant differences were found with regard to maximum bite force.

In contrast, other studies have reported a positive correlation between bite force and tooth wear (Helkimo and Ingervall, 1978; Nyström *et al.*, 1990; Johansson *et al.*, 1993b). Indeed, increased bite force was assumed to be the reason for the greater tooth wear in men than in women (Shafer *et al.*, 1974; Ekfeldt, 1989; Poynter and Wright, 1990).

1.3.3.4. Occlusal Conditions

It is usually cited that reduced occlusal table (i.e. number of teeth) could increase tooth wear. The term 'loss of posterior support' indicates that all the masticatory force is imposed on the remaining anterior teeth (Milesoveic, 1993). Claims have been made that a reduced number of occluding teeth will lead to increased tooth wear (Eccles, 1982b; Carlsson and Ingerval, 1988) This was confirmed by Ekfeldt *et al.* (1990) and Johansson *et al.*(1993a). The findings of Robb and Smith (1992) and Smith and Robb (1996) do not support the hypothesis that the loss of posterior teeth

leads to an increase in anterior tooth wear. Moreover, it has been claimed that in cases where the anterior teeth are in a potential edge to edge relationship, this may in time lead to advanced tooth wear (attrition) (Eccles, 1982b). In an anthropological study of the skull of an aboriginal Californian population, Reinhardt (1983) found a strong negative correlation between overjet and attrition. However, the author believed that the incisor relationship changes from one of positive overjet to edge to edge bite as occlusal attrition progresses. Krogstad and Dahl (1985) found a larger interincisal angle in patients with advanced tooth wear than in the normal population. They also found a negative correlation between the anterior tooth wear and the gonial angle. This was assumed to be associated with strong masticatory muscles.

The tooth surface morphology could also have an effect on the degree of tooth wear. Moon and Draughn (1982) claimed that a sharp tooth cusp promotes wear and a rapid change in the occlusion.

1.3.3.5. Hyperfunction

In an empty mouth, tooth to tooth contact which leads to occlusal tooth wear may occur during bruxism (Milosevic, 1993). Bruxism is defined as a compulsory gnashing, grinding, or clenching of the teeth for nonfunctional purposes (Ash and Ramfjord, 1995) or it could be defined as the frequent clenching and grinding of the teeth at times and for purposes other than for the mastication of food (Xhonga, 1977). It has been reported that the prevalence of bruxism in a population is between 4-23% (Seligman *et al.*, 1988). The correlation between tooth wear and bruxism has also been reported (Smith and Knight, 1984b; Egermark-Eriksson *et al.*, 1987; Rugh and

Ohrbach, 1988; Kidd and Smith, 1990; Ekfeldt *et al.*, 1990; Ash and Ramfjord, 1995). Normal vertical loss of enamel because of natural tooth wear has been estimated to be about 65μm per annum (Dahl *et al.*, 1993), but this was found to be three to four times greater in bruxists (Xhonga, 1977). Excessive tooth wear has often been observed in mentally retarded people and this has usually been ascribed to bruxism (Lindqvist and Heijbel, 1974; Richmond *et al.*, 1984; Øilo *et al.*, 1987, 1990). However, some authors believe that bruxism has been overestimated as a causative factor in tooth wear (Johansson and Omar, 1994).

Another factor that should be highlighted as being important in the development of tooth wear is the total contact time between opposing teeth (Dahl *et al.*, 1993). It has been estimated that the average time necessary for teeth to be in contact during normal function, such as mastication and deglutition, is 17.5min per day (Graft, 1969). There is no doubt that this value is greatly exceeded by most bruxists (Clark *et al.*, 1981; Clarke and Townsend, 1984). Moreover, it has been reported that the forces expended in clenching bruxism are high relative to muscular forces employed during normal function, and in some cases could exceed the maximal conscious clenches (Clarke *et al.*, 1984).

1.3.3.6. Diet

One of the other aetiological factors of tooth wear that should be considered is the physical and chemical effect of the diet (Carlsson and Ingervall, 1988). The physical effect of food for the development of tooth wear is not well understood (Kidd and Smith, 1990). Some studies have reported a correlation between abrasiveness of food

and tooth wear. It has been found that Eskimos from East Greenland, surviving on the typical Eskimo diet, show more occlusal wear on their first permanent molars than do the Eskimos from West Greenland who had almost abandoned their native diet and subsisted largely on a Western diet (Davies and Pederson, 1955). Intense occlusal tooth wear has also been observed among the Bedouins, and it was thought to be caused by the presence of abrasive particles in their food (Rosenzweig, 1968). Animal experiments on rats have shown that the degree of occlusal tooth wear is dependent more on the content of abrasive particles in the food rather than on the consistency of the food (Carlsson *et al.*, 1967). In countries where the habit of betel nut chewing is practised, heavy tooth wear is often observed (Pindborg, 1970).

In modern societies, the effect of food composition in the development of tooth wear could be important. Wear has been observed in some vegetarians and in those who frequently consume pickles (Smith and Knight, 1984b; Linkosalo and Markkanen, 1985; Kidd and Smith, 1990). It has been reported that a more fibrous and acidic diet could lead to excessive tooth wear (Dimmer, 1986). Many soft drinks which are consumed in modern societies contain citric, phosphoric, carbonic and other acids (Järvinen *et al.*, 1991). The pH value of these drinks is often less than 4.0 (Eccles and Jenkins, 1974; Rytömaa *et al.*, 1988), while the critical pH for enamel dissolution is 5.5 (Meurman *et al.*, 1987; Järvinen *et al.*, 1988). It has been shown *in vitro* that acidic products with a pH below 4.0 cause distinct erosion (Rytömaa *et al.*, 1988). Davis and Winter (1980) found that after exposure of the enamel surface to grapefruit/whole saliva mixture (pH 3.5) for 45 seconds at 25°C, 0.3μm was removed from the surface. Excessive consumption of citrus fruits, some fruit juices and

carbonated drinks with low pH, especially the colas, were reported to cause tooth wear (Pindborg, 1970; Lewis and Smith, 1973; Eccles and Jenkins, 1974; Smith and Knight, 1984b; Järvinen *et al.*, 1991; Dahl *et al.*, 1993). More recently a report was published in the Sunday Times where government scientists blamed fizzy drinks for eroding children's' teeth throughout Britain. Government investigations of 17000 schoolchildren aged 5-15 years, revealed that half of 5-year-olds and a third of young teenagers showed signs of eroded teeth, apparently caused by the acid in canned drinks (Connor 1996). It is predictable that when enamel is subjected to acid attack, acid erosion of some tissue from the surface will occur together with sub-surface softening. Therefore, the situation becomes worse when the acid attack is combined with mechanical action (Davis and Winter, 1980). Smith (1975) reported that acid erosion may make the tooth surface more susceptible to attrition and abrasion. Case reports have been published showing the relationship between dietary erosion and attrition in extensive tooth wear, and the suggestion is that a combination of chemical and mechanical factors is likely to be responsible for the tooth wear cases (Lewis and Smith, 1973). Basically, the acid effect from some foods and drinks with a low pH is to demineralise and soften the tooth surface. Their effects are intensified by superimposed abrasion or attrition. Therefore, the patient should be informed that such foods and drinks should be consumed in moderation (Eccles, 1982b).

1.3.3.7. Gastrointestinal Disturbances

Dental erosion can have extrinsic or intrinsic causes. The extrinsic causes include acid attack from foods and drinks (dietary erosion), some medicines and exposure of the teeth to atmospheric acids (industrial erosion). The intrinsic causes are from sources

within the body, namely regurgitation of gastric contents into the oral cavity (Eccles, 1979; Järvinen *et al.*, 1991). These include perimylolysis which is the reflux of gastric juices into the oral cavity combined with hyperactivity of the tongue (Dahl *et al.*, 1993). Regurgitation of gastric contents could be because of some abnormality in the gastrointestinal tract, such as hiatus hernia, gastro-oesophageal reflux disease, gastritis in gastric ulcer and duodenal ulcer. These are considered risk factors in dental erosion (Allan, 1969; Howden, 1971; Eccles, 1982 a,b; Järvinen *et al.*, 1988; Smith, 1989; Järvinen *et al.*, 1991; Bartlett *et al.*, 1996). Regurgitation could also be provocated by heavily spiced or fatty meals (Bartlett *et al.*, 1997). Patients with chronic alcoholism, where there was a history of chronic gastritis or other digestive disturbances, were reported to suffer from dental erosion (Smith and Knight, 1984b; Simmons and Thompson, 1987; Smith and Robb, 1989; Robb and Smith, 1990, 1996a). Regurgitation could also occur in some of the physiological conditions, for example in women who suffer from morning sickness during pregnancy and who may suffer from regurgitation erosion (Smith, 1989).

Other instances when gastric juices may come into contact with the oral cavity causing erosion of teeth are in recurrent vomiting or when the individual carries out forced vomiting as a result of psychological disorders (Järvinen *et al.*, 1991). These include anorexia nervosa and bulimia nervosa (binge eating followed by vomiting) (Eccles, 1982b; Smith and Knight, 1984b; Carlsson and Ingervall, 1988; Roberts and Li, 1987; Milosevic and Slade, 1989; Järvinen *et al.*, 1991; Robb and Smith, 1996b). Anorexia nervosa is a psychosomatic disease with oral manifestations such erosion of the teeth, reduced salivation and sometimes an increased incidence of caries (Dahl *et*

al., 1993). Clinically, the primary oral manifestations of endogenous erosion include loss of enamel and dentine from the palatal surfaces of maxillary teeth, thinning of maxillary incisal edges, dentine sensitivity, and absence of staining (Simmons and Thompson, 1987). This type of erosion has been classified as regurgitation erosion (Kidd and Smith, 1990; Milosevic, 1993).

1.3.3.8. Environmental and Occupational Factors

Some industrial environments may predispose to tooth wear by the chemical (acid) effect from the environmental field causing what is termed industrial erosion (Kidd and Smith, 1990; Milosevic, 1993). In 1959, the British Dental Association published a memorandum on the erosion of teeth and listed a number of occupations associated with an acid environment and warned employees that work in contact with it carried a real risk of severe tooth erosion (Boyes *et al.*, 1959). In a survey carried out on 555 workers during the years 1962-1964 in three British industrial cities (Glasgow, Manchester and Wolverhampton) 31.7% of the employees exhibited tooth erosion which affected particularly the labial surfaces of the upper and lower incisors(ten Bruggen Cate, 1968). Thus, industrial dental erosion affects the tooth surfaces most often exposed to the atmosphere. These include the incisal one third to one half of the labial surface of the front teeth (Petersen and Gormsen, 1991). Factors influencing the degree of erosion were found to be the acid concentration in the atmosphere, the length of exposure and lip level. The prevalence and incidence of dental erosion was particularly high among battery-making workers, galvanisers and picklers (ten Bruggen Cate, 1968). Similar findings have been reported more recently showing a

significantly high prevalence of tooth erosion in such workers in Finland and Germany (Tuominen *et al.*, 1989; Petersen and Gormsen, 1991).

Moreover, in his survey ten Bruggen Cate (1968) observed that the prevalence of tooth attrition increased strikingly among the workers who suffered from a severe grade of tooth erosion. He also reported that acid-eroded enamel was more susceptible to attrition than normal enamel. This was supported later by Petersen and Gormsen (1991). Dental erosion was also observed among swimmers who swam frequently in chlorinated swimming pools (Centerwall *et al.*, 1986).

The occupational environment can cause not only tooth erosion but also abrasive tooth wear (Milosevic, 1993). It has been reported that occlusal tooth wear was significantly greater in miners than in controls(Enbom *et al.*, 1986). Similar conclusions have been reported by Pällmann *et al.* (1987) who considered that increased tooth wear may be because of the presence of foreign bodies (dust) in the mouth during clenching or merely the result of bruxism whilst working under physical or mental stress. Moreover, Pöllmann and co-workers (1987) found that tooth wear increased when the patient was exposed to professional vibration (i.e.. truck-drivers) during daily work. Other reports have shown that a dusty environment adds to the wear of teeth, as seen in quarry men and cement factory workers (Petersen and Henmar, 1988; Tuominen and Tuominen, 1991).A high prevalence and severity of tooth wear was also observed in a population in Saudi Arabia. It was suggested that the sandy and harsh desert environment probably accounts for this tooth wear in

Saudi Arabians (Fareed *et al.*, 1990; Johansson *et al.*, 1991; Johansson and Omar, 1994).

1.3.3.9. Saliva

Saliva has an important influence on the wear of both teeth and dental restorations in the mouth. It acts as a lubricant between the contacting surfaces, therefore reducing the wear on the surface (Bloem *et al.*, 1988; Mair, 1992). Animal studies have shown that the degree of occlusal tooth wear is significantly more in rats with salivary gland ligation than non-ligated controls and this was ascribed to the reduced secretion of saliva (Carlsson *et al.*, 1965 and 1966).

Magnusson (1991) studied the abrasive effect of oral snuff and concluded that the use of this material was not an important risk factor in occlusal wear. The wear of the polyvinyl chloride plate (Bruxcore plate) that was used to cover the maxillary teeth while the candidate (snuffing volunteer) was chewing snuff was significantly less compared to the plate used while chewing with nothing in the mouth. Oral snuff reduced the wear by stimulating the salivary flow. Furthermore, the buffering capacity of the saliva has an important role in reducing tooth wear by buffering ingested acid (Eccles, 1982b). It has been claimed that dental erosion might be increased in patients with dry mouths after surgical excision of one or more salivary glands and/or radiotherapy. It has been suggested that dental erosion may increase in these patients because acids in the mouth are less well buffered and not diluted by saliva (Smith, 1989). Wöltgens *et al.* (1985) reported that in eleven patients with dental erosion the resting salivary flow was decreased. Järvinen and co-workers (1991) also found that

the risk of dental erosion was five times greater in patients with a low unstimulated salivary flow rate than those with higher flow rates of saliva. It has been found that at normal salivary flow rates, acidic drinks are eliminated from the mouth in about ten minutes and the pH at the tip of the tongue remains low for only two minutes after the drink has been consumed (Meurman *et al.*, 1987). However, in patients with low salivary flow rates, the pH remains low for much longer (Tenovuo and Rekola, 1977). Johansson *et al.* (1993b) reported that a significantly lower secretion rate of stimulated saliva was found in high tooth wear subjects, and the low buffer capacity was significantly correlated with a high degree of wear. This finding gave rise to speculation that the ion exchange and re- and demineralisation between the tooth surface and the saliva may be disturbed as a result of low buffering capacity. This produces a more acidic environment, reduced salivary ion concentration, and increased tooth surface loss.

1.3.3.10. Medication

It has been reported that dental erosion could be related to some medications as a result of their chemical effects on the teeth e.g. chewable aspirin tablets, chewable vitamin C tablets and effervescent vitamin C preparations (Sullivan and Kramer, 1983; Giunta, 1983; Meurman and Murtomaa, 1986). In their study Sullivan and Kramer (1983) reported that of 42 children with juvenile rheumatoid arthritis who had been prescribed chewable aspirin tablets, 25 were found with high levels of dental erosion. They believed that salicylic acid has the potential to produce a low pH in the mouth, although the influence of any abrasive effect from the other constituents of the tablets were not considered (Milosevic, 1993). Dental erosion has been observed in a patient

who was taking hydrochloric acid for the treatment of achlorhydria. However, the progression of dental erosion was arrested when the patient started taking the hydrochloric acid in capsule form (Smith and Knight, 1984b). The correlation between some medications and tooth wear is also evident through the influence on salivary flow. It has been reported that neuroleptics, tricyclic antidepressants, and antihypertensives cause a statistically significant reduction in the salivary flow rate (Parvinen *et al.*, 1984). Järvinen and co-workers (1988) reported that of seven patients with a gastrointestinal disorder and dental erosion, three had a distinctly reduced salivary secretion rate, and two of these patients were taking medications such as diuretics, antihypertensive drugs, tranquillisers and antidiabetics.

1.3.3.11. Habits

A V-shaped lesion of wear on the cervical area of the teeth is commonly believed to be because of toothbrush abrasion. The lesion could be found in particular on the buccal surfaces of the canines and premolars, with the greatest prevalence in the maxillary teeth (Pindborg, 1970; Milosevic, 1993). It is usually ascribed to the use of an intensive horizontal or excessive toothbrushing with abrasive toothpaste (Pindborg, 1970; Shafer *et al.*, 1974; Carlsson and Ingervall, 1988; Johansson and Omar, 1994). It has been claimed that most often the lesions are found on the teeth on the left side in right-handed patients but in left-handed patients the lesions are most marked on the right (Pindborg, 1970; Shafer *et al.*, 1974). However, these lesions are sometimes located subgingivally, beyond the influence of toothbrush abrasion and they have also been found in individuals who seldom brush their teeth. Moreover, these lesions also have been observed in horses and cows implying another, or possibly an additional

explanation for the occurrence of such lesions (Johansson and Omar, 1994). It has been suggested that strain microfractures along the buccal cementoenamel junction could be generated due to the heavy stressing of teeth (mastication and malocclusion), which could possibly make the cervical area more susceptible to destruction (Lee and Eakle, 1984; Braem *et al.*, 1992; Bevenius *et al.*, 1993; Johansson and Omar, 1994; Lee and Eakle, 1996). The improper use of toothpicks and dental floss may also produce abrasion lesions on the proximal exposed root surfaces (Shafer *et al.*, 1974). Abrasion tooth wear may also occur incisally as a notch as a result of habitual behaviour, such as frequent opening of hair pins using incisor teeth, biting sewing thread or fishing lines or holding a pipe stem between the teeth (Pindborg, 1970; Smith, 1989; Johansson and Omar, 1994). Incisal notch abrasion is also observed among the people of some countries where a widespread habit of consuming several kinds of roasted and salted seeds (e.g. watermelon and pumpkin seeds). A seed is placed vertically between the incisal edges of the maxillary and mandibular incisors, the consumer then presses his teeth until the seed shell is split open, the seed inside is eaten and the shell is discarded (El-Mowafy, 1988). Incisal notch abrasion may occur because of some other habits which may be related to some occupations. Tailors, carpenters, shoemakers and hairdressers who hold pins, nails or hair grips between their teeth may experience abrasion (Pindborg, 1970; Shafer *et al.*, 1974; Carlsson and Ingervall, 1988). Abrasion may also occur among glass-blowers and musicians who use wind instruments (Pindborg, 1970). Recently, a case of tooth wear was reported in a dental technician who habitually licked the brush that he used during porcelain work to keep it moist and in a fine pointed shape. The porcelain powder, which is extremely abrasive, acted as a grinding powder between his maxillary and mandibular

anterior teeth. The wear affected the palatal aspects of the maxillary anterior teeth and the labial and incisal aspect of the mandibular anterior teeth (Beckett *et al.*, 1995).

1.3.3.12. Dental Restorations

Apart from the factors discussed previously, the wear rate of human teeth can be disturbed by introducing different restorative materials in the mouth, especially if these materials have different wear properties from the tooth structure they replaced. Excessive wear of natural tooth structures caused by opposing conventional (quartz-filled) composite restorations have been observed clinically (Chapman and Nathanson, 1983; Lambrechts *et al.*, 1987). The sharp edges of quartz crystals are much harder than enamel and contact might have an abrasive sandpaper-like effect on the opposing dentition, thus causing a marked destruction to the tooth structure (Lambrechts *et al.*, 1987). The potential damaging effect of the conventional (quartz-filled) composite resin by abrading the opposing human tooth structure has been also demonstrated in laboratory studies (Suzuki and Leinfelder, 1993; Jagger and Harrison, 1995a). The extent of abrasion appears to be dependent on the size and hardness of the composite filler particles (Suzuki and Leinfelder, 1993). In a recent *in vitro* study, Suzuki and co-workers (1996) evaluated the wear of human enamel against ten commercially available posterior composite resin systems and concluded that composite resins containing zirconium silicate or quartz fillers had a significantly higher potential to wear the opposing enamel than composite resins containing microfillers or barium silicate fillers. The potential abrasive effect of restorative materials in abrading the opposing natural teeth was mainly of concern when the natural teeth were opposed by ceramic restorations. The damaging effect of porcelain restorations on the opposing

natural teeth clinically has been documented (Wiley, 1989) and also demonstrated in laboratory studies (Jacobi *et al.*, 1991; Ratledge *et al.*, 1994; Jagger and Harrison, 1995a). Moreover, the porcelain restorations occasionally require occlusal adjustment at the chairside or intraorally, thus removing the glaze of the surface and producing a rough surface which is highly abrasive and more destructive to the opposing teeth (Monasky and Taylor, 1971). Therefore, some clinicians feel that cast metal occlusal surfaces are preferable to porcelain (Wiley, 1989). The abrasivity of dental ceramics against natural teeth will be discussed in more detail later in this review.

Other factors that have been found to correlate with increased tooth wear are decreased occlusal tactile sensitivity (occlusal perception of thickness) and increased endurance time (Johansson *et al.*, 1993b). It appears that tooth wear has a multifactorial aetiology and in most cases of advanced tooth wear a combination of more than one factor is almost always involved (Dahl *et al.*, 1993).

1.3.4. Tooth Wear Indices

The multifactorial character of tooth wear makes it difficult to determine the aetiological factors responsible, in any individual case (Ekfeldt *et al.*, 1990). Moreover, the severity and the progression of tooth wear varies from one individual to another. It is thus important to monitor the progression of the wear of teeth. This can be achieved by using a scale/index which facilitates an evaluation of the changes in the tooth wear between serial examinations. This is combined with a complete patient history, the identification, if possible, of the causative factors and the degree to which these contribute to deterioration of the dentition may be determined. Once these

aetiological factors have been identified, suitable treatment can be initiated (Johansson and Omar, 1994). Many indices have been developed to evaluate the wear of teeth. They have been designed for use in: epidemiological studies; long-term monitoring of tooth wear in individual patients and research into the aetiology, prevention and management of tooth wear problems (Smith and Knight, 1984a). In general, tooth wear indices are based on a qualitative evaluation of the wear process (Ekfeldt *et al.*, 1990). This is often combined with an estimation of the degree of worn enamel, the size of the exposed dentine, and the reduction in length of the clinical crown (Dahl *et al.*, 1993). Such a classification system was reported in 1879 by Broca (Pindborg, 1970), Broca's index classified occlusal wear in the following degrees:

0 : no attrition (no wear);
1 : attrition of enamel, cusps still visible;
2 : dentine is exposed;
3 : occlusal relief is worn away leaving enamel rim peripherally;
4 : crown worn down close to collum dentis.

The shortcomings of Broca's classification is that it does not register specifically the degree of attrition resulting in perforation of the pulp (Pindborg, 1970).

A tooth attrition grading was used by Whittaker *et al.*(1982) which was based on that devised by Davies and Pedersen (1955) where pulp exposure is considered. In this classification the tooth attrition was graded on a scale of 0-4 as follows:

0 : no attrition;
1 : attrition into enamel;
2 : attrition just involving dentine;
3 : attrition into secondary dentine;
4 : exposure to pulp.

Another index which also grades the occlusal/incisal wear of the teeth into five grades has been reported in the literature (Carlsson *et al.*, 1985; Johansson *et al.*, 1993 a,b; Johansson and Omar, 1994). These five grades are as follows:

0 : no visible facets in enamel; occlusal/incisal morphology intact;
1 : marked wear facets in enamel; occlusal/incisal morphology altered;
2 : wear into dentine which is exposed occlusally/incisally and/or adjacent tooth surface; occlusal/incisal morphology changed in shape with height reduction of tooth;
3 : extensive wear into dentine; larger dentine area (>2mm^2) exposed occlusally/ incisally and/or adjacent tooth surface; occlusal/incisal morphology totally lost locally or generally; substantial loss of crown height;
4 : wear into secondary dentine.

In combination with this grading of wear, a scale for monitoring or scoring the progression of occlusal/incisal tooth wear has been suggested. Four grades are given as follows:

0 : no visible change;
1 : visible change, such as increase of facet areas, without measurable reduction of tooth length; occlusal/incisal morphology changed in shape compared to the first examination;
2 : measurable reduction of tooth length <1mm;
3 : marked reduction of tooth length ≥1mm.

The authors suggested that assessment and monitoring of tooth wear is best accomplished by intraoral examination combined with a diagnostic cast examination and intraoral photographs.

Indices of tooth wear concerned with the erosion process also have been reported. ten Bruggen Cate (1968), in his study of dental erosion in industry, suggested the following grading system of dental erosions:

Etching : dull, ground-glass appearance of the enamel surface without loss of contour;
Grade 1 : loss of enamel only;
Grade 2 : loss of enamel with involvement of dentine;
Grade 3 : loss of enamel and dentine with exposure of secondary dentine;
Grade 4 : loss of enamel and dentine resulting in pulpal exposure.

Eccles (1979, 1982b) suggested a classification of erosion due to non-industrial causes. The erosion lesion was classified into three classes with reference to the severity of the lesion. Letters were also used to refer to the site of the lesion on each tooth:

Classification of Dental Erosion (Eccles, 1979, 1982b)

Class	Type of lesion
I	Superficial - enamel only
II	Localised - into dentine <1/3 of the surface
III	Extensive - into dentine >1/3 of the surface

Letter	Surface denoted
a	Labial
b	Lingual or palatal
c	Occlusal or incisal
d	Multi-surface

A classification system was developed by Kitchin (1941) particularly for grading the cervical abrasion lesion. Four grades were used as follows:

Grade I	:	visible abrasion - depth $\leq$ 0.5mm
Grade II	:	depth > 0.5mm but $\leq$ 1.0mm
Grade III	:	depth > 1.0mm but $\leq$ 1.5mm
Grade IV	:	depth > 1.5mm

A box periodontal probe was used to measure the depth of the abrasion lesion.

Despite the terminology of attrition, erosion and abrasion, a more sophisticated index has been proposed by Smith and Knight (1984a) which records the degree of tooth wear caused by attrition, erosion, abrasion and combinations of these conditions.

Separate records were used for the cervical surface, the remainder of the buccal or labial surface, the lingual or palatal surface, and the occlusal or incisal surface. The approximal surfaces, heavily restored surfaces and missing teeth were not recorded. Five scores were used namely: (Smith and Knight, 1984a)

Score*	Surface	Criterion
0	B/L/O/I	No loss of enamel surface characteristics.
	C	No change of contour.
1	B/L/O/I	Loss of enamel surface characteristics.
	C	Minimal loss of contour.
2	B/L/O	Loss of enamel exposing dentine for less than one third of the surface.
	I	Loss of enamel just exposing dentine.
	C	Defect less than 1mm deep.
3	B/L/O	Loss of enamel exposing dentine for more than one third of the surface.
	I	Loss of enamel and substantial loss of dentine, but not exposing pulp or secondary dentine.
	C	Defect 1-2mm deep.
4	B/L/O	Complete loss of enamel, or pulp exposure, or exposure of secondary dentine.
	I	Pulp exposure or exposure of secondary dentine.
	C	Defect more than 2mm deep, or pulp exposure, or exposure of secondary dentine.

*In case of doubt a lower score is given.
B = buccal or labial; L = lingual or palatal; O = occlusal; I = incisal; C = cervical.

A special chart was designed to record these scores of tooth wear index.

Since there is no established criteria to guide the dentist in drawing a line between normal and pathological tooth wear according to the patient's age, Smith and Knight

(1984a) proposed a set of maximum acceptable tooth wear scores for each decade of age. This enabled the dentist to see the extent and distribution of pathological tooth wear, if that were the case, by comparing of the proposed set with a patient's score index.

Furthermore, an index was proposed by Øilo *et al.* (1987) which assisted in the decision as whether there is a need for treatment or not. This index was concerned with the occlusal / incisal tooth wear. The index was developed from an earlier system (Ryge and Snyder, 1973), where the decision as to the necessity for treatment was a basic criterion. The index consists of three categories of satisfactory degrees of wear: R (Romeo), S (Sierra), and M (Mike), and two categories of not acceptable degrees of wear: T (Tango) and V (Victor). These categories describing the clinical situations of tooth wear ranging from satisfactory to not acceptable were as follows:

Satisfactory

R	No visible wear, or change in anatomical form.
S	Limited (normal) wear, limited change in anatomical form.
M	Considerable wear with obvious change of anatomical form, but without need for treatment.

Not acceptable

T	Considerable wear with marked change in anatomical form. Further damage to the tooth and/or its surrounding tissues is likely to occur.
V	Excessive wear. Extreme change of anatomical form, aesthetics, and function. Pain on chewing. Damage to the tooth and/or its surrounding tissues is now occurring.

All categories except (R) contain subcategories as follows:

Categories	Subcategories	Occlusal Wear
Satisfactory	(Code)	
R	----	No visible wear
S	SOF	Occlusal or incisal wear facets in enamel
	SDF	Small areas of exposed dentine without change of hardness or sensitivity.
M	MLR	Obvious length reduction of tooth
	MED	Large areas of exposed dentine, discoloured, but without change of hardness or sensitivity.
Not acceptable		
T	TLR	Considerable length reduction of tooth
	TED	Large areas of exposed dentine which is discoloured, soft and/or sensitive.
V	VLR	Marked length reduction of tooth
	VTF	Tooth structure and/or restorations fractured due to excessive wear.
	VSD	Softening of exposed dentine
	VPE	Pulp exposure from wear
	VCA	Pain on chewing
	VGM	Irritation of gingiva and/or oral mucous membranes

In order to overcome the problem of grading the wear of restorations two extra subcategories were introduced later (Dahl *et al.*, 1989) in category M, in addition to those described previously. The two subcategories are :

MWR : Large wear facets in restorative material;
MED-P : Perforation of crown with hard, non-sensitive dentine exposed.

According to the authors' classification the wear of restorations has been classified under category M - no need for treatment. In their opinion, large wear facets in restorative materials do not need treatment, and there is no absolute need for

replacement of a perforated crown nor for any other kind of treatment as long as the dentine exposed is hard and no caries can be detected (Dahl *et al.*, 1989).

Another occlusal wear index which also scores both wear of natural teeth and restorations in the mouth has been proposed by Ekfeldt *et al.* (1990). Four scores were used to evaluate the extent of incisal or occlusal wear for each single tooth, according to the following criteria:

Score 0 : no wear or negligible wear of enamel.

Score 1 : obvious wear of enamel or wear through the enamel to the dentine in single spots.

Score 2 : wear of the dentine up to one-third of the crown height.

Score 3 : wear of the dentine up to more than one-third of the crown height; excessive wear of tooth restorative material or dental materials in crown and bridgework, more than one-third of the crown height.

Furthermore, to make these scores more useful in epidemiological studies, the authors created an individual incisal and occlusal tooth wear index (I_A) on the basis of the scores of incisal or occlusal wear for each tooth of the individual.

$$I_A = \frac{10xG_1 + 30xG_2 + 100xG_3}{G_0 + G_1 + G_2 + G_3}$$

I_A : Individual incisal and occlusal tooth wear index.
$G_0 + G_1 + G_2 + G_3$: number of teeth with scores of 0, 1, 2, 3, respectively.
10, 30, 100 : constants, chosen to strengthen the differences in wear between teeth with scores 1, 2 and 3, respectively.

In conclusion, from the examples of tooth wear indices described above, it is clear that tooth wear indices, in general, are based on a qualitative evaluation of the wear process (Ekfeldt *et al.*, 1990). This is often combined with an estimation of the degree

of worn enamel, the size of the exposed dentine, and the reduction in length of the clinical crown (Dahl *et al.*, 1993). Enamel and dentine are anatomical structures of the natural teeth, but dental restorations are often found in the mouth, and as long as the teeth, together with any restoration, move in contact with one another, wear is inevitable (Mair, 1992). Therefore, wear could occur on the natural teeth and on the restorative materials as well. Accordingly, the last two indices described previously (Dahl *et al.*, 1989 and Ekfeldt *et al.*, 1990) included an assessment of the wear of restorative materials. This was also a qualitative evaluation.

A large wear facet in the restoration and crown perforation were used as a criterion in the study by Dahl *et al.* (1989), while the criteria in the study by Ekfeldt *et al.* (1990) was based on an evaluation of the crown height reduction, evaluated as score 3. Ekfeldt *et al.* (1990) admitted that their index had the limitation of not discriminating between incisal and occlusal wear of restorative materials with degrees of 0, 1 and 2, which limits the possibility of ranking slight to moderate tooth wear in individuals with occlusal restorations. Since the wear process affects both natural teeth and restorative materials, many studies have been carried out, to investigate and test the wear properties of different dental materials and their potential effect on the wear of natural teeth.

1.3.5. Wear Testing

Clinical studies on the evaluation of wear of dental materials and human teeth have some limitations and in order to obtain valid *in vivo* values, a large number of test subjects must be included in the study. This would involve serious economic, practical

and ethical problems (Dahl *et al.*, 1993). Moreover, the variation of the factors affecting wear among patients makes the interpretation of the results more difficult (Moon and Draughn, 1982). Therefore, many researchers have directed some of their work towards developing machines which simulate the oral cavity and its environment, to enable them to test the wear of different dental materials and their potential abrasive effects on the natural teeth under controlled conditions. Thus, a measurable amount of wear can be obtained and compared in a shorter time than that needed in *in vivo* studies.

1.3.5.1. Masticatory Cycle

To develop a machine which simulates the oral cavity for wear testing, the force and movements found during mastication must be duplicated (DeLong and Douglas, 1983). The masticatory cycle (chewing cycle) can be divided into the following phases (Murphy, 1965): (i) the preparatory phase - this is a free movement of the mandible away from the maxilla to the degree just sufficient to grasp the food bolus; (ii) the crushing phase - the closing of the mandible which lasts from contact with the food bolus until contact with the teeth; and (iii) the grinding phase - this phase begins with tooth contact and ends in centric occlusion, the mandible in this phase moves upwards and towards the position of centric occlusion along a constant slope. However, the slope outlined is not precisely a straight line, which suggests that fine particles of food between the teeth play a part (Murphy, 1965). The duration of the occlusal contact (occlusal phase) in the chewing cycle has been found to be in the range of 0.21 to 0.35 seconds, representing 31 % of the mean duration of the chewing cycle which was 0.87 second (Jemt *et al.*, 1979). Thus, the average time for one complete chewing

cycle is just less than one second and a chewing rate of 60 to 80 cycles per minute has been reported as an acceptable average (Harrison and Lewis, 1975). The latter was supported by Bates and co-workers (1975) who reviewed the literature and reported that 80 cycles per minute is a reasonable estimate of the chewing rate. It is noteworthy that the speed of the mandible is directly proportional to the distance travelled (Murphy, 1965).

Many studies have been published in the literature using various methods and different kinds of foods to record occlusal forces generated during mastication (Anderson, 1956a,b; Anderson and Picton, 1958; De Boever *et al.*, 1978; Helkimo and Ingervall, 1978; Gibbs *et al.*, 1981). However, the results show substantial disagreement. De Long and Douglas (1983) reviewing the literature , reported that the magnitude of these forces lies in the range of 9 to 180 N (2-40 lb).

Thus, the principle in developing a wear testing machine, is to design a piece of equipment which can produce alternate stroke and sliding contact, with a rate of 60-80 cycles per minute and generate a force between 9 to 180 N.

1.3.5.2. Wear Testing Machines

With the ever-increasing number of restorative materials available, the quest for a wear machine which would predict clinical performance has been the dream of many researchers. The development of wear machines is an attempt to simulate the clinical masticatory cycle and oral environment (Mair *et al.*, 1996), so that the wear resistance of different restorative materials and their potential abrasivity on the opposing natural

teeth can be investigated under standard conditions. Many wear machines have been described in the literature and some researchers have adapted different dental devices for this purpose.

Boddicker (1947) used a Kelley grinder which is a type of modified dental hinge articulator to test different types of artificial teeth. Complete dentures were used which consisted of porcelain teeth on one denture and acrylic, gold or porcelain teeth on the other. Occlusal contact between the two dentures was maintained by applying a force of 6 to 25 lb (26.5 - 110.3 N), the test being run under continuous contact. The author observed that under the conditions of the study the porcelain teeth cracked and shattered.

Slack (1949) adapted the Taber abraser (Taber Instrument Corporation, North Tonawanda, N.Y., USA), and suggested that it was necessary to use a standard instrument so that others could repeat the test. He also pointed out that the purpose of his study was not to compare abrasion on the abraser with that which actually occurs in the mouth, but to compare all objects (materials) with each other by means of a common abrasive substance, in this case 220 grit carborundum.

Taketa and co-workers (1957) designed a wear testing machine consisting of a rotating grinding belt and aluminium specimen holder which held the test specimen of the material at the desired angle against the grinding belt. Thus, the machine was only of use in measuring relative wear of the materials against the grinding belt, since no clinical parameters were considered in the design. Later on a wear testing machine

that adopted the same principle was used by McLundie and Patterson (1982) to compare the wear resistance of different composite resins. The specimens were tested against an abrasive paper strip passing at a rate of 0.33m per minute in a water bath which had a constant flow of water. Again, no clinical parameters were considered in the design of this machine.

Lugassy and Greener (1972) used a commercial abrasion tester to evaluate reinforced and unfilled resins. The machine consisted of grinding wheels which rotated over the surface of flat specimens. The speed of rotation of the wheel was 30 cm per second. Jones *et al.* (1972) used a simple abrasion test to evaluate different restorative materials. The authors used a standard commercial mechanical mixer normally used for mixing dental restorative materials. The test was carried out by vibrating the specimens with a quantity of abrasive in the mixer.

Overall, the machines described above did not attempt to simulate the masticatory cycles and the oral environment. However, Cornell and co-workers (1957) stipulated the basic requirement of a wear test for plastic teeth. Despite the type of test materials, their suggestions are worthy of consideration in the development of any wear machine:

1. The test should relate as closely as possible to clinical conditions and should measure comparative wear of tooth material.
2. The test should produce results relating closely to clinical observation of various tooth materials where such data are available.

3. The test should produce a wear pattern on the tooth tested similar to that seen on teeth present over a long period of time in the human mouth.

4. All artificial teeth tested should be put through a preparatory routine which subjects them to the same conditions encountered in the processing and use of artificial dentures.

5. The test should be constructed either without abrasives or with very mild abrasives, since it is well-known that the human oral mechanism tends to reject gritty particles automatically.

6. the test should be rapid enough to be useful in screening materials, but not so accelerated as to lose its relationship to conditions of use.

7. The test should be rapid enough that the development of statistically significant data would be feasible, even though large numbers of materials are being tested.

Generally, the wear testing machines described in the literature could be classified in four categories:

- Pin-on-disc;
- Sliding (reciprocating, intermittent);
- Wheel to wheel;
- Artificial mouth concept.

1.3.5.2.1. Pin-on-disc Machines

Generally, pin-on-disc wear machines consist of a pin of tooth specimen, contacting, under load, a disc of restorative material. Wear is produced by rotating either the disc or the pin resulting in the production of a wear track in the form of a circular groove

on the restorative material disc. Pin-on-disc machines are considered to be the simplest machines designed (Mair *et al.*, 1996) and have been used extensively for wear testing by many authors (Powell and Dickson, 1975; Dickson, 1979; McKinney and Wu, 1982; Rice *et al.*, 1982; Fisher *et al.*, 1983; Mueller *et al.*, 1985; Palmer *et al.*, 1991; Hacker *et al.*, 1996).The pin-on-disc method is essentially a two-body wear test, with water or saliva being used as the lubricating medium. However, a three-body wear testing machine was developed by Hengchang *et al.* (1990) where a slurry of fluorite (fluorspar) powder and carboxymethyl cellulose mixed with water was used as the medium. The modifications used by Hengchang *et al.* were that the materials to be tested were prepared in the form of a cylindrical shape, representing the pin, and the disc consisted of a rubber plate. The other change in this machine was that the material specimen (pin) could move up and down once during a cycle, thereby undergoing both compressive and impulsive forces. Both the material specimen and rubber plate were rotated during the test. However, the drawback of this system was that the machine design enabled ranking of the restorative materials in accordance to their wear resistance only.

1.3.5.2.2. Sliding Machines

Sliding machines generally provide a sliding motion between the two specimens tested to a certain distance whilst with pin-on-disc machines the specimen slide over each other through a full circular motion (rotation). The sliding machines can operate either with an intermittent sliding action or with a reciprocating sliding mechanism. Monasky and Taylor (1971) used the former machine type to study the wear of porcelain, enamel and gold. The machine provided an intermittent contact between the

specimens which were immersed in artificial saliva, to which white flour was added to provide a mild abrasive action. The enamel samples were prepared from the labial surface of the upper central incisors and together with the porcelain and gold specimens were prepared in the form of flat plates. A force of 1 lb (4.45 N) was applied over the specimens tested. Another example of the intermittent sliding machine was that developed by Harrison and Lewis (1975), who attempted to simulate the human masticatory cycle. The specimens were in the form of a pin and plate, with a frequency of contact of 70 per minute under a load of 50-1000 g (0.49-9.8 N). Ratledge *et al.* (1994) also developed a machine to investigate the effect of different restorative materials on the wear of human enamel. The machine produced 70 strokes per minute under a load of 40 N and the test was carried out in tap water or in citric acid (pH 4) for a total of 25000 cycles.

Powell *et al.* (1975) developed a two-body wear testing machine to study the wear response of composite resin, amalgam and enamel. The machine was designed initially to produce a reciprocal sliding contact between an enamel specimen and restorative material specimen on one side of the machine while simultaneously, on the other side, another enamel specimen was made to impact onto the surface of another restorative material specimen. However, the impact test failed to produce any meaningful results, thus, the impact testing phase of the investigation was discontinued, and the study was continued considering the reciprocating sliding test only. The test was later run for 25,000 cycles at a cycling rate of 80, 150 and 235 cpm under a load of 1 Kg/mm^2. The contact zone was flushed continuously with distilled water at 37^0C.

Smalley and Nicholls (1986) described a wear machine that produced a continuous reciprocal sliding contact between specimens at a rate of 45 cpm under a load of 0.3 Kg/mm^2. The restorative material specimens were prepared in pin form with 1mm diameter and opposing plates of human tooth enamel were prepared from the labial surfaces of maxillary central and lateral incisors. The specimens were continuously bathed in distilled water at 37^0C.

Jacobi *et al.* (1991) used another reciprocating sliding wear machine to compare the abrasiveness of six ceramics and gold against extracted human canines. The test was carried out in tap water at room temperature under a load of 4Kg (39.2N) and a cycle rate of 58 cpm. The authors pointed out that the load of 4Kg used was within the range of force encountered in function.

1.3.5.2.3. Wheel to Wheel Machine (ACTA Wear Machine)

The wheel machine was developed by De Gee *et al.* in 1986. It consists of two cylindrical wheels (stainless steel) of different diameter, driven by two motors and rotating against each other in opposite directions in a bowl containing a third body medium. The wheel with the larger diameter was made with rectangular grooves to accommodate the test samples. The second wheel which was smaller in width had a scaled surface to enable more grip on the three-body slurry. The scaled wheel functioned as the antagonist cusp and was pressed by a spring force of 15N against the sample wheel. The smaller width of the antagonist wheel caused the wear area to be situated only in the middle of the samples. Thus, the outermost unworn areas served as reference planes. The relative speeds of the wheels could be adjusted to any

desired speed gradients, which subsequently affected the film of thickness of the third-body medium between the sample wheel and the antagonist wheel. The thickest film is dragged between the wheels when the surface velocities of both wheels are equal, which represents 0% slip. To decrease the film thickness, the slip is increased by slowing down the rotational speed of the antagonist wheel, while the sample wheel is maintained at one revolution per second. The more slip, the higher the shear stress of the medium exerted on the samples. Up to approximately 45% slip the wheel remained separated by a film of food and the wear will be solely of an erosive nature. Beyond 45% slip, the wheels were not able to drag the slurry through the area of the junction and the wheels touch. Thus the wear will be via direct contact between the wheels instead of through the three-body slurry. For permanent homogeneity of the slurries used, a stirrer was mounted underneath the sample wheel (Pallav *et al.*, 1993; De Gee and Pallav, 1994).

So far the restorative materials tested in the wheel to wheel machine consisted of different types of composites and amalgam, and the third body medium used slurries consisting of different components. At first, De Gee *et al.* (1986) and Pallav *et al.* (1988) used a mixture of millet seeds and PMMA (polymethyl methacrylate) beads in water. Later De Gee *et al.* (1990) used millet seeds/water only. Sarrett and Ray (1994) also used millet seeds mixed with deionised water. However, Pallav *et al.* (1993) reported that the use of millet seeds sometimes disturbed the wear test in the later stages of the experiment when the fat in the seeds separated from the slurry and deposited as a waxy layer on the wheel surfaces. Therefore, to overcome this problem, a slurry consisting of rice (fat content 1% compared to 3-4% for millet

seeds) with millet seed shells in water was used. The wheel to wheel machine design was also used by Finger and Thiemann (1987) who also investigated the wear of composite and amalgam in a wear machine similar to the ACTA machine described above. However, the three-body medium that was used consisted of an aqueous slurry of poppy seeds and the load was 10 N.

In a recent review of the ACTA machine, De Gee and Pallav (1994) reported that the load of 15 N, used in all their experiments, was below the level necessary to induce contact stresses for surface fatigue phenomena.

1.3.5.2.4. Artificial Mouth Concept

This system was developed by DeLong and Douglas (1983) which reproduced both the movement and force of mastication against anatomically correct samples, using servo-hydraulics. The three-dimensional motion of the masticatory cycle has been approximated by the use of vertical and horizontal actuators and a judicious rotation of the horizontal and frontal planes. A constant occlusal force could be generated from 1 to 1000 lb (4.45 - 4450 N) and could follow any shape of occlusal anatomy. The system was used in different studies using natural extracted teeth against artificial teeth or different restorative materials (Coffey *et al.*, 1985; DeLong *et al.*, 1985; Sakaguchi *et al.*, 1986; DeLong *et al.*, 1986; DeLong *et al.*, 1989; DeLong *et al.*, 1992). Overall, the parameters used most often were: occlusal force of 13.4 N; cuspal contact time of 0.23 sec; chewing rate of 4 Hz for a total of 300,000 cycles. Deionised water was continually circulated over the wear surfaces.

In addition to the four types of machines described above, there are some other wear machines that do not fit into these categories. Ehrnford *et al.* (1980) developed a machine to study the wear of composite resin materials. The machine consisted of four arms that were attached to the lower side of a horizontally rotating circular disc. The restorative material specimens were mounted onto the end of the four arms and the samples were seated into a beaker containing a slurry medium. The slurry consisted of soda-lime glass pearls (1mm diameter) and aluminium oxide powder in water. When the machine was activated, the arms with the restorative material specimens started rotating in the slurry medium. Thus, the principle of the wear test was a two-body type of contact between the restorative material specimens and the particles of the slurry medium. Another machine was developed by Leinfelder *et al.* (1989) who investigated the wear of composite resin restorative materials. The principle of the wear test consisted of an intermittent contact between a stylus or cusp with a restorative material specimen. For each contact/cycle the stylus first stroked and then rotated onto the surface of the restorative material specimen. During upward movement the stylus counter-rotated to its original position to start a new cycle/contact. The contact between the stylus and the material specimen was through a polyethylene tape. Therefore, the test was described as a three-body wear system. The stylus was contacting the surface of the specimen under a load of 55N. The machine was made with a thermocycling system, thus the test was carried out with alternately heated and refrigerated water.

Finally, the most relevant wear machines have been described in this chapter, and indeed it has been commented by Roulet (1987) that "there were almost as many wear

testing devices as there were scientists who are interested in wear" (Mair *et al.*, 1996).

1.3.5.3. Measurement of Wear

The method of wear evaluation for clinical studies involves either clinical categorisation or indirect methods which measure the wear from replicas. Tooth wear can be evaluated qualitatively by different indices, as described earlier. For restorations, the United States Public Health Service (USPHS) system evaluates the wear of the restoration on the basis of anatomical form and marginal integrity of the cavity. The system (USPHS) classifies the amount of enamel exposed at the cavity margin as: alpha - no wear; bravo - wear which causes a detectable catch at the margin; and charlie - wear which exposes the amelodentinal junction (dentine or base is exposed) (Cvar and Ryge, 1971). This system is also a qualitative evaluation and does not give a quantitative measurement for the wear of the restoration. However, with replica models there are a number of measurement systems that could evaluate the wear quantitatively, the majority of which compare the marginal enamel step with standard reference models (Leinfelder *et al.*, 1986) or with calibrated reference steps (Moffa and Lugassy, 1986; Taylor *et al.*, 1990; Mair, 1990). The major disadvantage of these systems is that they assess only the wear of the restoration margin and, therefore, give no indication of wear which may be occurring at other sites (Mair *et al.*, 1996). However, there are other methods that evaluate quantitatively the wear of both tooth and restorative materials. These methods were mainly used for *in vitro* studies, although some can also be adopted for *in vivo* studies depending on their suitability.

1.3.5.3.1. Weight / Volume

The principle of this method is to determine the weight loss by weighing the specimen before and after the wear test. The weight loss can also be converted to volume loss if the density of the material of the specimen is known. This method has been used in different laboratory studies by different groups to determine the wear of enamel, porcelain, gold, acrylic, composite, amalgam and cast ceramics (Monasky and Taylor, 1971; Mahalick *et al.*, 1971; McCabe and Smith, 1981; Hengchang *et al.*, 1990; Jacobi *et al.*, 1991). The disadvantage of this method was the continual evaporation of moisture, particularly from the teeth after positioning on the scales, which made the accurate weight determination difficult (Jacobi *et al.*, 1991). To overcome this problem, Monasky and Taylor (1971) heat-dried the tooth before weighing. However, Jacobi *et al.* (1991) pointed their fear that dehydration might affect the wear characteristics of the teeth. Thus, in their study, a damp towel was placed in the scale enclosure to reduce the evaporation.

Vrijhoef *et al.* (1985) described how the weight method could be used for quantitative *in vivo* wear measurement on class I and class II restorations. Cast silver caps were made over the occlusal surface of the teeth after relieving the surface of the inlay restoration with tinfoil. Wear on the restoration was simulated by grinding away some of the material from the inlay surface. Silicone impressions of the teeth were taken with the caps before and after the wear simulation. The volume and the thickness of the lost material was measured from the weight of the enclosed impression material in the cap before and after the wear test. This was a modification of a method that was

described earlier by Handelman and co-workers in 1978 to assess quantitatively *in vivo* the wear of fissure sealant. The latter used silver copings that were constructed over the occlusal surfaces of resin replicas of the teeth using an electroplating technique. Thus, the wear could be assessed by weighing the amount of impression material trapped under the silver coping constructed at baseline and successive replicas of the teeth over time. The weight was converted to volume, which represented the volume of material wear.

1.3.5.3.2. Height Reduction

This method is used mainly to measure the pin height reduction (wear) in the pin-on-disc or pin-on-plate wear test machines. The principle of the method is based on measuring the pin height from a fixed reference plane, before and after the wear test, the difference between the two measurements being considered as the amount of wear. The method has been used by many authors using different measuring devices. Harrison and Lewis (1975) reported the use of the bench micrometer (Herbert Controls and Instruments Ltd., Letchworth, England, UK) to determine material loss from a circular pin specimen after the wear test, in their pin-plate sliding wear machine (Jagger and Harrison, 1994 and 1995 a,b). Smalley and Nicholls (1986) and Burgoyne *et al.* (1991) used an X-Y table with digital readout micrometers to measure the wear loss of cylindrical pin restorative specimens, used in a pin-plate sliding wear machine. The pin specimen, in their mounting blocks, were placed on the X-Y table beneath a microscope. The instrument was zeroed by aligning the X and Y cross hairs with X and Y reference grooves, previously machined in the pin surface of the pin mounting block. Measurements were made from the zero point to the worn

end of the pin. The difference between the initial and final measurements determined the amount of pin wear, in millimetres.

Palmer *et al.* (1991) used a stereomicroscope with a micrometer-calibrated moveable platform (Gaertner Scientific Corp., Chicago, IL, USA) to measure the wear of enamel tooth specimens against ceramic discs in a laboratory wear test, using a pin-on-disc type wear machine. The tooth specimens were prepared from extracted human third molars by grinding the most cervical cusp of each tooth into a cone, while the remaining cusps were cut flat. The wear of the tooth specimen was determined by using the X and Y co-ordinates for each relevant point to find the change in height for each cone and its diameter before and after the wear test. Furthermore, using this data the worn volume was calculated using geometric equations.

Hacker *et al.* (1996) used a stereomicroscope (Stereomicroscope, Zeiss, West Germany) to measure and compare the enamel wear against gold and porcelains, using also a pin-on-disc type wear machine. The enamel abrader specimens were cut from extracted teeth with a diameter of 3mm, then mounted onto the rod of the wear machine against the gold and porcelain discs. A hole was made in the centre of the abrader to serve as a reference point. The amount of wear of the enamel abrader was measured by taking polyvinylsiloxane impressions before and after the wear test. The impressions were sectioned along the long axis and the wear of enamel was determined by comparing the depth of the reference holes before and after the wear test.

1.3.5.3.3. Profilometry

Quantification of the wear can be made by tracing profiles of the surface at the test specimen across the wear area, to determine the depth of the wear track. The depth of the wear is usually compared to an adjacent unworn area which is considered the reference plane for measurement. This method is one of the popular methods used by many groups to evaluate wear *in vivo* (Lutz *et al.*, 1979; Mitchem and Gronas, 1982; Lutz *et al.*, 1984) and *in vitro* (Jagger and Harrison, 1994, 1995 a,b; DeGee *et al.*, 1986; De Gee *et al.*, 1990; Pallav *et al.*, 1993; DeGee and Pallav, 1994; Sarrett and Ray, 1994; Ratledge *et al.*, 1994). The conventional profilometers normally have a mechanical stylus, through which the scan profile can be traced by allowing the stylus to cross the wear area at different points. Mechanical profilometry performs well on flat specimens, however it cannot be used easily on curved surfaces. Laser profilometers have been introduced recently which overcome this problem, and avoid mechanical contact with the specimens. In addition the machine can be adjusted so that many scan profiles can be obtained parallel to each other at certain intervals, and a three-dimensional image of the specimen surface can be obtained on a computer screen, making possible wear measurements at many points (Wassell *et al.*, 1994; Bayne *et al.*, 1994).

1.3.5.3.4. Image Analysis

This method was used by Ratledge *et al.* (1994) to assess the wear of human enamel against different restorative materials using a sliding wear machine. Human premolar teeth were sectioned mesiodistally in the long axis, and then each hemisected crown

was sectioned transversely producing six semicircular sections (each 1mm thick) per tooth. Each section was mounted in a brass specimen holder, with the enamel margin projecting outwards, and tested against the restorative material specimens in the wear machine. To assess the wear of enamel, the tooth specimen holder was fitted onto a specially constructed brass imaging jig to enable the tooth profile to be viewed repeatedly in the same vertical plane, and the assessment of the wear of the enamel specimens was made by measuring the tooth profile reduction with a computer image analysis program (SeeScan Solitaire; SeeScan Imaging, London, UK).

1.3.5.3.5. Three-dimensional Measuring Technique

The method was described by Lambrechts *et al.* (1984) for *in vivo* quantitative evaluation of the wear of composite and amalgam restorations. Tooth replicas were produced from silicone polyvinylsiloxane impressions taken at different intervals during the experiment. The repositioning/reorientation of the replicas on the three-dimensional measuring microscope was based on a negative model of the occlusal surface taken at the baseline, together with the use of reference points. The X, Y, Z co-ordinates of the three reference points make up a triangular reference plane, from which the wear points of interest in the restoration was measured. The measurement is based on image focusing by the vertical movement (Z axis) of the viewing head of the microscope. The difference between the baseline Z value and the second focused Z value was recorded by the length-measuring gauge and represented the loss of material at that particular point.

1.3.5.3.6. Surface Mapping

This system assesses the wear quantitatively by contouring / scanning the surface of interest at the initial stage and at different intervals during the experiment, using different technologies which usually employed computer-aided analysis programs. The method was used for *in vivo* and *in vitro* studies of wear measurement. Replicas for the *in vivo* studies were made with a reference point / plane system for repositioning / reorientation regimes. The following surface mapping / contouring methods have been used by researchers studying the wear process:

1. Laser

Atkinson *et al.* (1982) and Williams *et al.* (1983) described the use of laser contouring maps for measurement of the wear of dental restorations. Tooth impressions were made before and after the simulated wear test. Each impression was projected by a laser beam passing through a prismatic beam splitter. The interference fringes were seen as a series of light and dark lines. The object (the tooth impression) was viewed using a camera at an angle to the plane of the fringes and the image was recorded on a photographic film. Photographic prints of the contour patterns were obtained and the pre-wear and post-wear contour maps were compared quantitatively to find the shape, depth and volume of any wear scars. The authors suggested three methods for contour map comparison: fringe displacement method; Moiré method; and computer-aided analysis. The latter was reported to be the most accurate method (2-5% accuracy) and the difference between pre- and post- wear surfaces were obtained by digitising the contour maps, thus the change in volume can be calculated. All the

impressions were made from polyvinylsiloxane, and the material accuracy and precision was found to be adequate.

Subsequently Mair *et al.* (1990) used this technology (laser interferometry) to measure the wear occurring on a number of composite and amalgam restorations placed *in vivo*. Successive replica models at different time intervals were used for measurement, and the computer was programmed to calculate the maximum depth of wear with respect to the baseline.

2. Computer Graphics

Surface mapping by computer graphics was described by DeLong *et al.* (1985). The method employed the servohydraulics mechanism, described previously in the artificial mouth concept (DeLong and Douglas, 1983), together with computer graphics technology. A stylus was connected to an extensometer, and the tip of the stylus was in contact with the surface of the specimen, which could be an extracted tooth or a replica of the tooth. The specimen was mounted on the servohydraulics table and thus was free to move in a three dimensional space, under the tip of the stylus. The stylus was scribed on the surface and the co-ordinates on each point on the surface were fed into an array in the microcomputer. Each pass across the surface gave one profile. A large number of profiles were generated at known intervals, assembled by computer graphics as an image of the surface contour on the computer screen. For wear measurement, the digitised surface contours, before and after the wear test, can be compared using a computer program written for this purpose. The area with any change in surface contour can then be identified and the mean depth, maximum depth

and volume of any change in the contour can be calculated. The method accuracy for volume measurement was found to be 2.5 - 12%.

The use of computer graphics for surface mapping has also been reported by McDowell *et al.* (1988). A three-dimensional plot (contour) was obtained by digitising and scanning the specimen surface using a co-ordinate measuring machine digitiser (Mitutoyo-MX203; Mitutoyo Mfg. Co., Tokyo, Japan) with a computer system. The three-dimensional image at the surface was obtained through a number of scans across the specimen surface. The computer program allows the samples to be measured at different times from the same reference plane. Thus, the wear can be determined through the computer program and reported as volume loss.

3. Reflex Microscope

Adams and Wilding (1988) described the use of the reflex microscope to generate contour maps of a tooth surface from which wear can be measured. The reflex microscope is an optical three-dimensional measuring device. The objective stage of the microscope can be moved along a X and Y axis, while the viewing head can be moved vertically along the Z axis. The observer is able to record the height of the object by focusing a spot of light onto the image of the object. The data of the chosen points is transformed into digital values of the X, Y, and Z co-ordinates and can be stored in a computer file. Subsequently, software programmes can calculate distances, areas and volumes from the stored data. By graphical representation of the stored data points a contour map can be drawn, or a computer model of the object can be plotted. Comparisons between the distances, areas and volumes at successive observations

allows changes to be measured, provided a minimum of three reference points are available to mathematically orientate the object each time it is measured (Adam and Wilding, 1988). To test the accuracy of the method the authors (Adam and Wilding, 1988) cast in lead an impression of a complete denture, and the tooth wear was produced artificially by reducing the occlusal surfaces of a number of teeth. The reference points were scribed in the cast and the amount of tooth material wear was measured using the reflex microscope, and also through a gravimetric method using the weight of the material removed from each tooth. The X, Y and Z co-ordinates at the reference points were recorded and at least 150 points for each tooth before and after the wear. The graphics package was used to interpret contour plots for each tooth. The contours within each region were digitised, and the volumes of the occlusal surfaces above the datum level were calculated. The volumes before and after the wear test were compared and the volume of the material lost was determined. Subsequently the mean depth of each volume difference was calculated. Moreover, with this method the distribution of wear can be assessed quantitatively by studying a contour map made from the plot of the differences. The authors concluded that the reflex microscope is capable of measuring tooth wear *in vitro* provided stable reference points are available, and any differences in depth greater than 10μm can be attributed to tooth wear. The method was used later to assess quantitatively the *in vivo* wear of denture teeth. The reference points were obtained by placing three amalgam markers in the denture base, and measurement was carried out using casts made from impressions of the dentures. The method is also called the biostereometric method (Adams *et al.*, 1989; Adams *et al.*, 1996).

In addition to these quantitative measurement methods, the wear facets have been examined in many studies using scanning electron microscopy (SEM) which helped to distinguish the wear mechanism of different restorative materials. SEM was used for both *in vitro* (DeLong *et al.*, 1986, 1989, 1992; Krejci *et al.*, 1993, 1994, Ratledge *et al.*, 1994) and *in vivo* studies, using tooth replicas (Ekfeldt and Øilo, 1988, 1989, 1990; Mair *et al.*, 1990; Mörmann and Krejci, 1992). Teaford and Tylenda (1991) reported that the SEM micrographs could also be used to detect the microscopic changes in wear patterns on human teeth in a matter of days using tooth replicas (epoxy casts). Thus, daily or weekly changes in rates of wear can be documented for specific locations on teeth. However, they admitted that monitoring the creation of new wear featured on the tooth surface may only be a good indication of certain types of wear (e.g. abrasion) and not others (e.g. erosion).

1.4. CERAMICS IN DENTISTRY

The word ceramic is derived from the Greek "Keramikos" which means "earthen". Therefore, ceramic is an earthy material, usually of a silicate nature (McLean, 1979). Dental ceramics can be defined as a compound of metals (such as aluminium, calcium, lithium, magnesium, potassium, sodium, tin, titanium, and zirconium) and nonmetals (such as silicon, boron, fluorine, and oxygen) that may be used as a single structure component, such as when used in CAD-CAM restorations, or as one of several layers that are used in the fabrication of ceramic-based prostheses. Conventional dental porcelain is a vitreous ceramic based on a silica (SiO_2) network and potash feldspar ($K_2O.Al_2O_3.6SiO_2$) or soda feldspar ($Na_2O.Al_2O_3.6SiO_2$) or both (Anusavice, 1996). Metal oxides (glass modifiers) such as sodium, potassium, and calcium oxides are

added as well as boric oxide to lower the softening (firing) temperature by reducing the amount of cross-linking between the oxygen and the silicon in the glass network (SiO_2) of the porcelain, but at the same time decreasing the viscosity. Therefore, aluminium oxide is added to increase the viscosity and the hardness. Pigmenting oxides are also added to obtain the various shades needed to simulate the colour of natural teeth (McLean, 1979; Anusavice, 1996). Porcelain is supplied in the market as a powder with a mixing liquid (water). Porcelain paste (slurry) is produced by mixing the porcelain powder with liquid (water) from which the anatomy of the crown can be built and carved. The porcelain paste is usually applied onto a cast metal substructure (metal-ceramic crown) or on a platinum foil matrix (jacket crown) that were formed on a die from an impression of the patient's prepared tooth. However, some systems use a refractory die onto which the porcelain paste is applied and condensed directly. Porcelain is built in layers and in case of metal-ceramic crowns the first layer is called opaque porcelain which is applied to hide the colour of the metal oxides on the metal casting. For the jacket crown an aluminous porcelain core material is first built onto the platinum foil to provide the strength for the crown. Both the opaque porcelain and the aluminous core porcelain have to be condensed and fired. This is then followed by body porcelain layers (mainly dentine porcelain then enamel porcelain) of the desired shade from which the anatomy of the crown is built and carved. These layers will be also condensed and fired again in the porcelain furnace (Craig *et al.*, 1987). Densification of the porcelain during firing occurs by the process of sintering, which involves partial fusion and bonding of adjacent surfaces of particles rather than complete melting (Craig *et al.*, 1987). Sintering was also defined as the "transformation of an originally porous compact to a strong dense ceramic" (Kingery

et al., 1976). During sintering the density of porcelain greatly increases and is associated with a volume shrinkage of between 30 - 40% (Denry, 1996). After the correct size and shape of the porcelain crown is achieved the porcelain has to be fired again at a specific temperature and time to produce a glazed surface which is formed as a result of the flow of the fused porcelain over the surface. The glaze gives the porcelain surface the gloss necessary to simulate the natural tooth surface (Craig *et al.*, 1987). During the glaze firing procedure, a thin external layer of glassy material is formed at a temperature and time that causes localised softening of the glass phase and settling of crystalline particles within the surface region (Anusavice, 1996). This procedure is called self-glazing. Glazing may also be accomplished by firing a layer of a low-fusing glass on the porcelain surface. The colour or shade of the porcelain may also be modified in this step by using coloured glazes (Craig, *et al.*, 1987). The latter technique is called add-on glaze. The add-on glaze slurry material contains more glass modifiers and thus has a lower firing temperature. However, a higher proportion of glass modifiers tend to reduce the resistance of the applied glazes to leaching by oral fluids. Therefore, to ensure adequate chemical durability, a self-glaze of porcelain is preferred to an add-on glaze (Anusavice, 1996).

Dental porcelains are classified according to their firing temperature as follows: high fusing, 1300^{0}C; medium fusing, 1101-1300^{0}C; low fusing, 850-1100^{0}C; ultra-low fusing, < 850^{0}C. The high fusing and medium fusing types are used for the production of denture teeth. The low fusing and ultra-low fusing porcelains are used for crown and bridge construction. However, because commercial dental laboratories do not produce denture teeth for complete or partial removable dentures, it has become more

common to classify crown and bridge porcelains as high fusing (850-1100^{0}C) and low fusing (<850^{0}C), although this change in classification has not been adopted universally (Anusavice, 1996).

1.4.1. Ceramics as a Restorative Material

Natural teeth have been acknowledged by most cultures throughout the centuries as an integral facial structure for health, youth, beauty, and dignity. Therefore, it is almost universal that the loss of tooth structure and in particular missing anterior teeth create functional and physical problems and often psychological and social disturbances as well (Kelly *et al.*, 1996). The desire for a durable and aesthetic material to replace the lost tooth structure is ancient. During the 18th century (when the use of porcelain for making artificial teeth was first suggested), the candidate materials for artificial teeth were human teeth, animal teeth, ivory and "mineral" porcelain teeth. Apart from human teeth which were both costly and scarce, the selection of artificial tooth material was based on their mechanical versatility and biological stability. Animal teeth were not satisfactory because of their size, large pulp, and the work required to cut and carve them to the size and shape of human teeth. They were also unstable in the saliva. Ivory, specially hippopotamus ivory, was used more than any of the dental substitutes. Elephant ivory and bone was used in cheaper prosthetic restorations, but not satisfactorily. The pores in the ivory and bone caused these materials to stain easily (Johnson, 1959; Kelly *et al.*, 1996). Moreover, because of their porosity they also absorbed mouth fluid and thus became very unhygienic. It was reported that George Washington used to soak his ivory dentures in port to make them taste less foul (Jones, 1985).

In 1774, Alexis Duchateau, a French apothecary, was very dissatisfied with his stained ivory dentures. He had noticed that the glazed ceramic utensils that he used every day for mixing and grinding his various chemicals, resisted staining with a relatively non porous surface and were also resistant to abrasion. Thus, he began experimenting with minerals, and with the help of porcelain manufacturers, he succeeded in making himself the first set of all mineral dentures. Duchateau had little success and later collaborated with a Parisian dentist named Nicholas Dubois De Chemant who considerably improved the methods of fabrication. Being a dentist, De Chemant made dentures for some of his patients from these minerals. He is given credit for being the first dentist to successfully insert mineral teeth in the human mouth. De Chemant was granted an inventors patent by Louis XVI, and soon after that in 1792 he left France and settled in England where he continued making his porcelain dentures (Johnson, 1959; Jones, 1985; Ring, 1985). In England De Chemant was supplied with porcelain powder from the Wedgwood factory (Messrs, Josiah Wedgwood and Sons Ltd., of Barleston, Stoke-on-Trent, UK). Evidence has been published to show that Messrs Wedgwood were supplying pastes of porcelain teeth not only to De Chemant from 1800 but also to Robert Blake from 1810 and Joseph Fox from 1813 (Cohen, 1975; Jones, 1985). De Chemant played a major role in the advancement of prosthetic dentistry. His dentures remained popular until the introduction of individually packed porcelain teeth by the Italian dentist Gioseppangelo Fonzi in 1808. Fonzi's teeth had platinum brackets packed into the porcelain and were subsequently soldered with gold to the platinum denture base (Johnson, 1959; Ring, 1985; Jones, 1985). However, enamelling of metal for dentures was described as early as 1728 by a French dentist Pierre Fauchard, the father of

modern dentistry (Prinz, 1923; Ring, 1985; Jones, 1985). Fauchard was credited with recognising the potential of porcelain enamels and initiating research with porcelain to initiate colour of teeth and gingival tissues (Johnson, 1959; Jones, 1985; Kelly *et al.*, 1996).

Individual porcelain inlays and crowns were not developed until the late 1800's. An early technique for porcelain inlays was by grinding a porcelain rod to be fitted and cemented into a prepared cavity into the natural tooth (Jones, 1985). In 1882 Herbst of Germany introduced the glass inlays, crushed glass frit fired in moulds made of plaster and asbestos. Single tooth porcelain restorations were first introduced in about 1844. They became more popular after 1860 when the English tube tooth was first placed on the market. The tube teeth had a hole that was intended to allow them to be riveted onto an ivory or metal plate of a full denture. However, the hole made it possible to adapt them for use as an individual post crown for attachment to the roots of natural teeth by means of a hickory wood pivot (Jones, 1985). In 1885 Logan resolved the retention problem encountered between the porcelain crowns and the wooden post by fusing the porcelain to a platinum post (the Richmond crown). One year later, in 1886 Land, of Detroit, introduced the first fused feldspathic porcelain inlays and crowns by burnishing platinum foil to make a matrix for fusing the porcelain with the aid of a gas furnace. Land also tried to use gold foil as the matrix but found that the porcelains used at this time fused at too high a temperature for the gold foil (Jones, 1985; Kelly *et al.*, 1996).

Over the years changes in chemical composition have been made in order to improve or modify the properties of dental porcelain (Jones, 1985). Porcelain composition suitable for metal-ceramic restorations were introduced in 1962 (Weinstein *et al.*, 1962; Weinstein and Weinstein, 1962) and led to the success of this technology to form complete crowns and fixed partial dentures (Kelly *et al.*, 1996; Denry, 1996). However, all ceramic crowns, despite their aesthetic advantages, failed to gain widespread popularity until the introduction of aluminous porcelain in 1965 by McLean and Hughes. The application of high technology processes to dental ceramics in the 1980's has allowed further development of new ceramic materials and systems that are used at the present time.

1.4.2. Ceramic Materials and Systems

1.4.2.1. Metal-Ceramics

In 1962 Weinstein, Katz and Weinstein addressed the problem of thermal expansion coefficient mismatch between porcelain and the metal substructure (Piddock and Qualtrough, 1990). Weinstein *et al.* (1962) first described the production of metal-ceramic restorations using porcelain powders containing 11-15% K_2O frits. Glass in the Na_2O- K_2O- AL_2O_3- SiO_2 system, containing not less than 11% K_2O when subjected to heat treatment at temperatures from 700-1200°C produced high-expansion glass suitable for bonding to metal (McLean, 1991). The nature of the porcelain used for metal-ceramic restorations is similar to the regular feldspathic porcelain with the exception of their alkali content. The soda and potash content of these porcelains is higher than regular porcelain in order to raise the thermal expansion to be compatible with the metal substructure. Increasing the potash (K_2O)

content of the porcelain will move the composition into the leucite field and will increase the tendency to crystallise. Since leucite is a very high expansion phase, its crystallisation in a porcelain made to match the high gold alloys is valuable. However, this crystallisation can be undesirable if it increases the opacity of the porcelain (McLean, 1979).

Generally, crystalline mineral leucite is included in porcelain for metal-ceramic restorations to elevate their thermal expansion coefficient to match that of casting alloys, and to minimise residual thermal stresses (Kelly *et al.*, 1996). Alloys used for metal-ceramic restorations must have high temperature strength and produce thin films of oxide for porcelain bonding. Dental porcelain will wet and adhere to any clean, gas free metal, provided that the metal is covered with an adherent layer of oxide, and the temperature is raised to the point where this oxide partially dissolves into the porcelain (McLean, 1991).

1.4.2.2. Aluminous Porcelain

Great improvements in the strength of all-ceramic crowns accompanied the development of aluminous porcelain by McLean and Hughes in 1965. A high strength core porcelain was made containing up to 50% (by weight) fused alumina crystals, on to which a matched expansion veneer porcelain was baked (McLean, 1988). The veneer porcelain powders were made from high alumina content glasses which overlay the high-strength core and give colour and translucency to the porcelain crown (jacket crown) (McLean, 1967; McLean, 1979). Platinum foil swaged to the die of a tooth was used on to which the porcelain core and veneer were built (McLean, 1967).

Compared with the porcelain used for metal-ceramic restorations the aluminous porcelain contains less alkali and the high combined alumina content produces a very stable glass, much less prone to devitrification (crytallisation) (McLean, 1979). The strength and opacity of aluminous porcelain is related to the grain size of the alumina crystals used. The finer the crystal size the greater the strength and opacity (McLean and Hughes, 1965). Pre-fritting of fused alumina crystals in a glass melt can also improve both translucency and strength. This work resulted in the production of a number of commercial aluminous porcelains, the first being Vitadur-N (Vita, Zahanfabrik, Säckingen, Germany), followed by NBK 1000 (DeTrey/Dentsply, Dreieich, Germany) and subsequently Hi-Ceram (Vita Zahanfabrik, Säckingen, Germany) (McLean, 1991). The Hi-Ceram is a more recent development, in which the aluminous core porcelain is now baked directly onto a refractory die (McLean *et al.*, 1994).

Another commercial aluminous porcelain name that was introduced recently in the market is Vitadur Alpha (Vita Zahanfabrik, Säckingen, Germany) which is replacing the Vitadur-N. Vitadur Alpha has also been referred to as an Opalescent porcelain. Opalescence in dental porcelain is a light-scattering effect achieved with the addition of minute concentration of high index of refraction oxides in a size range near the wavelength of visible light (Kelly *et al.*, 1996). Opalescent formulations have been introduced in a number of incisal porcelains for both all-ceramic restorations (Vitadur Alpha) and metal-ceramic restorations like Omega porcelain (Vita Zahanfabrik, Säckingen, Germany) which has been introduced to replace the VMK68 (Vita Zahanfabrik, Säckingen, Germany) metal-ceramic porcelain. According to Kelly *et al.*

(1996) these new products do not differ markedly from traditional porcelains and thus their physical properties are similar.

1.4.2.3. Slip-Casting Ceramics (In-Ceram)

The development of In-Ceram ceramic crowns was based on the slip-casting technique which has been used in forming clay bodies for at least the past 200 years. The technique was refined by Sadoun in 1989 to produce a high-strength alumina coping that is now marketed under the trade name In-Ceram (Vita Zahanfabrik, Säckingen, Germany) (McLean, 1991). Slip-casting involves the condensation of an aqueous porcelain slip on a refractory die. The porosity of the refractory die helps condensation by absorbing the water from the slip by capillary action (Denry, 1996). To produce the In-Ceram crown, a pure alumina slip-cast coping is made on a special gypsum die of the tooth preparation. The resultant condensed alumina is dried and slowly brought to a temperature of 1100°C. At this firing process the alumina grains partially fuse at their boundaries forming necks between touching particles. The gypsum die shrinks during the firing process, and the coping may then be lifted off the die. This porous and partially sintered alumina is then infiltrated with a low-viscosity, specially prepared low-fusing glass of matching thermal expansion (Lanthanum aluminosilicate with small amounts of sodium and calcium). The glass melts at 800°C and when the temperature is raised to 1100°C diffuses through the porous alumina by capillary action to yield a ceramic coping of high density and strength (McLean, 1991; Kelly *et al.*, 1996). The coping is then veneered with an aluminous veneer porcelain like Vitadur-N or Vitadur Alpha (Mclean, 1991; Anusavice, 1996). The reason for using the aluminous type porcelain is because of their high resistance to devitrification

(crystallisation) during repeated firings and their matching thermal expansion to pure alumina. The In-Ceram coping contains at least 70% pure alumina making it one of the strongest pure ceramic crowns (flexural strength 450 MPa) (Mclean, 1991; Seghi and Sorensen, 1995). Substitutions of magnesium aluminate spinel for the aluminium oxide has been used to improve its translucency (In-Ceram Spinel, Vita) (Kelly *et al.*, 1996). However, the spinel-based core ceramic was not as strong as the alumina-based material (Seghi and Sorensen, 1995).

Although the slip-casting technique produces a high-strength ceramic crown, McLean (1991) expressed doubts about the success of the in-ceram material for fixed partial dentures (bridges), because its fracture toughness still does not compare with the cast metal alloys. Laboratory techniques and clinical use of In-Ceram ceramics for crown and bridge restorations have been described (Pröbster and Diehl, 1992). No failures were recorded for 21 anterior and 40 posterior In-Ceram crowns during service of 4 to 35 months (Pröbster, 1993). However, the clinical failure of In-Ceram ceramic bridges (FPDs) was found to have originated from their connectors, often internally at the interface between the core ceramic and veneering porcelain (Kelly *et al.*, 1995). High failure rates because of fracture of the resin-bonded In-Ceram ceramic bridges have been reported after the first year of a clinical trial (Dürr *et al.*, 1993). The use of In-Ceram for resin-bonded bridgework is not recommended by the manufacturer (Kelly *et al.*, 1996). Slip-casting is not an easy technique and requires considerable practice. However, when the copings are well-made they are quite accurate and excellent aesthetic results can be obtained (McLean, 1991).

1.4.2.4. Magnesia Core Ceramic

Magnesia core ceramic of high thermal expansion was described by O'Brien in 1985. Magnesia crystals were used to reinforce a high expansion coefficient glass, resulting in a core porcelain with flexural strength similar to that of alumina-reinforced porcelain (131MPa) (Piddock and Qualtrough, 1990). The core material is made by reacting magnesia with a silica glass within the 1100 - 1150°C temperature range, which leads to the formation of forsterite (Mg_2SiO_4). The proposed strengthening mechanism is the precipitation of fine forsterite crystals in the glass matrix surrounding unreacted magnesia (O'Brien *et al.*, 1993; Denry, 1996). The relatively high expansion coefficient of the magnesia-reinforced material made the magnesia core thermally compatible with body porcelains normally used for metal-ceramic restorations, offering the possibility of improved shade matching with such restorations. However, one possible result from using a high expansion magnesia core is that the porcelain will be more liable to thermal shock on cooling (Piddock and Qualtrough, 1990).

1.4.2.5. Shrink-Free Ceramics

Porcelain shrinkage that occurs during the firing process of the porcelain jacket crowns, can lead to distortion of the platinum foil matrix and marginal inaccuracy (Sozio and Riley, 1983). In an attempt to overcome these problems Cerestore (Coors Biomedical, Lakewood, Colo., USA) has been introduced as a shrink-free ceramic core material. Sozio and Riley (1983) described the use of a shrink-free ceramic coping which is formed on a special epoxy die by a transfer moulding process. The unfired ceramic contains a mixture of alumina, magnesia, aluminosilicate glass frit,

wax and silicon resin plasticiser. The moulded core is subjected to a lengthy heat treatment during which the alumina reacts with magnesium oxide to form magnesium aluminate spinel crystals. This reaction is accompanied by an increase in volume which offsets the sintering shrinkage (Hullah and Williams, 1987; Piddock and Qualtrough, 1990). Finally the Cerestore coping is veneered with a matched-expansion veneer porcelain to create the tooth form (McLean, 1991). The veneer porcelain used has similar properties to those of a conventional dental aluminous porcelain, and it is applied and fired in the conventional manner (Sozio and Riley, 1983). The Cerestore product, however, has been withdrawn from the market (Anusavice, 1993), and, according to McLean (1991), the Cerestore crown failed for two main reasons; high cost and inadequate strength when compared with metal-ceramic restorations.

Alceram is another shrink-free ceramic with a higher strength core that was marketed to replace the Cerestore crown. The former is also believed to have been withdrawn from the market (Anusavice, 1993).

1.4.2.6. Cast Glass-Ceramics

A glass-ceramic is a material that is formed into the desired shape as a glass, then subjected to a heat treatment to induce partial devitrification (crystallisation) (Anusavice, 1996). MacCulloch in 1968 was the first to report the use of glass-ceramics in dentistry. He used a continuous glass-molding process to produce denture teeth. MacCulloch also suggested the fabrication of crowns and inlays by centrifugal casting of molten glass (McLean, 1988; Anusavice, 1996). In general, glass-ceramics can be obtained with a wide variety of composition, leading to a wide range of

mechanical and optical properties, depending on the nature of the crystalline phase nucleation and growing within the glass (Denry, 1996). In dentistry the most widely used glass ceramic product is a silica material that crystallises to form mica upon heat treatment (Craig, 1989). Dicor is a mica-based glass-ceramic which was the first commercially castable ceramic material for dental use. It was developed by Corning Glass Works in America (Corning Glass Works, Corning, NY, USA) and marketed by Dentsply International (Anusavice, 1996). The material contains tetrasilicic fluormica crystals ($K_2Mg_5Si_8O_{20}F_4$) which because of their flexibility plate-like morphology added strength and resistance to fracture propagation. The tetrasilicic mica system nucleates readily at a temperature of 650°C to 1075°C. The residual glass phase occupies approximately 45% (volume) of the glass-ceramic (McLean, 1991). Micas are classified as layer-type silicates. Cleavage planes are situated along the layers. This crystal structure dictates the mechanical properties of this mineral. crack propagation is not likely to occur across the mica crystals and is more probable along the cleavage planes of these layered silicates. In the glass-ceramic material the mica crystals are usually highly interlocked within the glassy matrix. The interlocking of the crystals is a key factor in the fracture resistance of the glass-ceramic, and their random orientation makes fracture propagation equally difficult in all directions (Adair and Grossman, 1984; Denry, 1996).

Dicor is a castable glass that can be formed into an inlay, facial veneer, or full-crown restoration by the traditional lost-wax casting process similar to that employed for cast metals (Anusavice, 1996). Adair and Grossman (1984) described the clinical and laboratory procedures for Dicor crown construction. Briefly, the wax pattern of the

crown is spured and invested with a phosphate-bonded investment. After burning out procedures, the glass is cast centrifugally at 1370°C into the mould. Following devesting the glass crown is sandblasted to remove residual casting investment and the sprues are cut away. The crown is then embedded in a special investment and subjected to a heat treatment at a temperature of 1075°C for the nucleation and growth of the mica crystals, a process called ceramming. The resulting cerammed crown is cloudy white in appearance with a high degree of translucency (McLean, 1988, 1991; Piddock and Qualtrough, 1990). Thus, the Dicor ceramic system was intended originally to be shaded with a thin surface layer (50-100μm) of colourant glasses (Kelly *et al.*, 1996). External colouration is considered not as natural and durable as porcelain with pigments dispersed throughout the material (Craig, 1989). Therefore, Dicor Plus (Dentsply Int.) was introduced and launched to overcome this problem. The material is used as a cast coping and veneered with a matched expansion feldspathic porcelain of the aluminous type, offering the technician the opportunity of building the porcelain colour in depth (McLean, 1991).

1.4.2.7. Leucite-Reinforced Porcelain (Optec HSP)

Optec HSP (Jeneric/Pentron Inc., Wellington, CT, USA) is a leucite-reinforced feldspathic porcelain and the restoration is made from powder that is condensed and sintered by the same process used for traditional dental porcelain (Anusavice, 1996; Kelly *et al.*, 1996). The leucite concentration in Optec material was reported as 50.6 wt % appreciably greater than traditional metal-ceramic porcelain (eg. Vita VMK68, 19.3 wt % and Ceramco II, 21.5 wt %) (Denry *et al.*, 1994; Mackert and Russel,

1995; Kelly *et al.*, 1996) which gives the Optec material higher strength than the traditional metal-ceramic porcelain (Anusavice, 1996). The large amount of leucite in the Optec material contributes to a high thermal contraction coefficient, and the mismatch of the thermal contraction between leucite (22 to 25 x 10^{-6}/°C) and the glassy matrix (8 x 10^{-6}/°C) results in the development of tangential compressive stress in the glass around the leucite crystals on cooling. These stresses can act as crack deflectors and contribute to increasing the resistance of the weaker glassy phase to crack propagation (Denry, 1996).

The advantages of Optec HSP are the lack of a metal or opaque substructure, good translucency, moderate flexural strength, and there is no need for special laboratory equipment. The disadvantages are potential marginal inaccuracy caused by porcelain sintering shrinkage and its potential to fracture in posterior teeth. Optec HSP can be made in a refractory die for inlays, onlays, low-stress crowns and veneers (Anusavice, 1996).

1.4.2.8. Heat-Pressed Ceramics (IPS Empress)

IPS Empress (Ivoclar USA, Amherst, NY, USA) is a precerammed glass-ceramic that is heated in a cylinder form and injected under pressure and high temperature into a mould. Like Optec HSP it is basically a feldspathic porcelain containing a high concentration of leucite crystals that increase the resistance to crack propagation (Anusavice, 1996). To produce IPS Empress ceramic crowns, the wax pattern of the crown is placed on a specially designed cylindrical crucible former and invested using a phosphate-bonded investment. The wax is burnt out and the cylindrical opening into

the mould is filled with the IPS Empress ceramic ingot and an aluminum oxide pushing rod. The assembly is placed in a specially designed automatic press furnace which heats up to the programmed press temperature of 1150°C. After a 20 minute holding time at this temperature, the ceramic material is then pressed (under pressure of 0.3 to 0.4 MPa) into the mold (Dong *et al.*, 1992). The resulting crown form can be finished either by staining or glazing techniques or a layering technique involving the application of veneer porcelain (Dong *et al.*, 1992; Denry, 1996). Subsequent heat treatment that simulates surface colouration and glaze firing or veneer application firing was found to further increase the material strength (160 to 180 MPa) (Dong *et al.*, 1992). The advantages of the IPS Empress are its lack of metal or an opaque ceramic core, moderate flexural strength, excellent fit and excellent aesthetics. The disadvantages are its potential to fracture in posterior areas and the need for special laboratory equipment (Anusavice, 1996).

1.4.2.9. Hydrothermal Ceramics

This is a new category of dental ceramics developed from industrial ceramics by introducing hydroxyl groups into the ceramic structure under heat and steam, from which the term hydrothermal ceramic is derived (Komma, 1993; Mattmüller *et al.*, 1996). Ducera Dental GmbH (Rosbach, Germany) have adopted this technology and introduced Duceram-LFC for the first time in 1989 as a hydrothermal low fusing ceramic to be used for all-ceramic restorations, ceramic and metal-ceramic inlays and partial crowns (Mattmüller *et al.*, 1996). Komma (1993) reported the structure and the characteristics of this new ceramic material compared with the regular feldspathic porcelain. Regular metal-ceramic feldspathic porcelains consist of two phases. The

"crystal phase" is composed of leucite crystals, and the "glass phase" surrounds the leucite crystal with glass. In contrast to leucite-containing metal-ceramic, there is no crystal phase in the production of Duceram-LFC, the latter is a one-phase material defined as a glass. As stated earlier, dental porcelain is a vitreous ceramic having the basic silicon-oxygen network as the glass-forming matrix (McLean, 1979; Anusavice, 1969). Fused silica is a high-melting material. Its high-melting temperature is attributed to the three-dimensional network of covalent bonds between silica tetrahedra, which are the basic structural units of the glass network (Anusavice, 1996). Alkali metal oxides (glass modifiers) are added to lower the softening temperature of the glass by reducing the amount of cross-linking between the oxygen and the silicon. Oxygen-silicon bonds are interrupted because of the oxygen atoms in the added alkali oxides. As a result, the three-dimensional silica network contains many linear chains of silica tetrahedra that are able to move more easily at lower temperatures than the atoms that are locked into the three-dimensional structure of silica tetrahedra (McLean, 1979; Anusavice, 1996). Thus, the alkali oxides widen the network of the glass and as their levels increase, the melting temperature decreases and the expansion increases. However, in practice there are application limits to this widening process of the silicate structure which lies at about 22 - 25 % of alkali addition. At this point glasses are no longer chemically resistant and water leaches them out (Komma, 1993). Based on earlier industrial studies that were carried out in the early 1960's at the Max-Plank-Institute, Würzburg, the research department of Ducera had managed to introduce hydroxyl groups to the glass network under heat and steam. The result of their research is a dental ceramic with a low fusing

temperature (660-680°C) with high hydrolytic resistance, known as Duceram-LFC (Komma, 1993).

The level of decrease in the fusing temperature is proportional to the amount of hydrothermally introduced OH-groups in the glass network which can be expressed in the following formula (Bartholomew, 1983):

$$\equiv Si - O - Si \equiv + H_2O \rightarrow 2 \equiv Si - OH$$

The resultant structure with OH-groups have a lower binding energy, thus low firing temperatures are sufficient to break down the chemical connection of these hydroxyl glasses. As a result they soften at low firing temperatures (Komma, 1993). The firing temperature for Duceram-LFC lies between 660°C and 680°C. With such a low firing temperature it was possible to fire the Duceram-LFC over a conventional metal-ceramic porcelain base (Duceram metal-ceramic porcelain) without affecting the form nor the accuracy of the conventional porcelain base, with a strong and permanent bond to it (Komma, 1993). This is an important issue for the construction of all-ceramic inlays, onlays and veneers. To make an inlay or onlay from the Duceram-LFC, a refractory die is made by duplicating the original master die. A thin base of regular Duceram metal-ceramic porcelain is fired onto the refractory die. The base is then returned to the master model and completed using Duceram-LFC and fired on a sagger tray. The difference of 270°C in the firing temperature between the regular Duceram metal-ceramic porcelain (about 930°C) and Duceram-LFC (about 660°C) guarantees an exact fit even with difficult inlays, as the regular Duceram ceramic base is not affected by the firings. This has given the following advantages to the Duceram-LFC as reported in the Ducera publication (Frechter, LFC working instructions):

perfect marginal fit; precise occlusion and contact points; special model systems are no longer necessary; less refractory and duplicating material is needed. The manufacturers also claim that the Duceram-LFC increases its strength from 110N/mm^2 up to 160N/mm^2 after insertion in the mouth. This increase in strength was attributed to the surface layer formed with many OH-groups, built through alkali and hydroxyl exchange.

$$\equiv Si - O - Na^+ + H_2O \rightarrow \equiv Si - OH + Na^+ + OH^-$$

The surface Si-hydroxyl layer is thus more flexible and can, so-to-speak, heal surface flaws. Laboratory tests (hydrolytic tests) showed that the growth of the Si-hydroxyl layer was more intense at the start and then slowed down, reaching a maximum thickness of 3μm. Therefore, if this layer is taken off the surface by mechanical force as may occur in the mouth, a new hydroxyl layer is built up quickly. Thus, the Duceram-LFC structure provides a continuous "self-healing" process because of the build-up of a Si-hydroxyl layer on the surface which seals micro flaws continuously. The Ducera research group also reported that Duceram-LFC was less brittle than the regular dental ceramics and the Si-hydroxyl layer showed signs of plastic deformation which also protects the surface from damage (Komma, 1993). However, a disadvantage of the Duceram-LFC is that it cannot be directly sintered on a metal substructure because of the low coefficient of expansion. Therefore, an inner lining of conventional high-fusing ceramic (Ducera metal-ceramic) on the metal substructure is required (Mattmüller *et al.*, 1996).

Another hydrothermal dental ceramic that has been introduced by the same company is a bonded ceramic, Duceragold. The latter, however, in contrast to the leucite free

Duceram-LFC has leucite crystals that had been evenly distributed and integrated during the hydrothermal glass phase. The firing temperature of Duceragold lies between 760-780°C. The leucite has been added to its structure to increase the thermal expansion coefficient to be suitable to bond and sintered on a specially deep gold-coloured type IV alloy called Degunorm that was developed and marketed by Dugussa. Because of the common hydrothermal glass phase in both Duceram-LFC and Duceragold, they have similar characteristics since both are able to build the Si-hydroxyl layer which heals micro flaws (Komma, 1993). The use of the hydrothermal ceramic Duceragold with Degunorm alloy together has been called the "Golden Gate System" and their use has been supported in a recent clinical report by Mattmüller *et al.* (1996).

1.4.2.10. Machinable Ceramics

The evolution of machining and computer aided technology for production of machined ceramic restorations has added a new option to restorative dentistry, and has led to the development of a new generation of machinable ceramics (Denry, 1996). There are two common systems that are commercially available: Cerec CAD-CAM system and copy-milling Celay system (Kelly *et al.*, 1996).

1.4.2.10.1. Cerec CAD-CAM System

The word Cerec stands for **ce**ramic **rec**onstruction (Smith and Cardwell, 1989). While CAD-CAM stands for computer aided designing - computer aided machining (Krejci *et al.*, 1994; Anusavice, 1996). With the Cerec system (Siemens, Benheim, Germany) the ceramic restoration (inlays, onlays, crowns) are ground from manufactured

ceramic blocks with diamond discs or other instruments to the dimensions obtained from a scanned image of the tooth preparation (Anusavice, 1996). The Cerec machine consists of three main elements; hand-held video camera, computer, and three-dimensional milling machine. Briefly, the video camera produces an image of the prepared tooth which is recorded by the computer, the picture of the tooth will then be displayed on the monitor. The camera records data about the tooth in all three planes. This information is used by the operator in addition to the computer programme which designs the ceramic restoration. After the computer finishes the design of the restoration, it produces instructions for the milling machine. The latter mills a ceramic block which had been mounted into it using a diamond disc. The grinding is carried out under a water spray and the shape of the restoration is produced by up and down movement of the milling head while the ceramic block is rotated and advanced into the disc (Smith and Cardwell, 1989). Thus the ceramic block is being ground by a diamond disc with translation of movement guided by computer-controlled signals, based on the restoration design (Anusavice, 1996). However, the Cerec machine does not produce a finished occlusal surface, since the restoration is ground by means of a disc and hollows such as fossae cannot be milled. Therefore, the occlusal surface of the restoration has to be finished in the mouth using rotating diamond finishing instruments (Smith and Cardwell, 1989; Rekow, 1991). The Cerec CAD-CAM system has been used in clinical dentistry for more than 10 years. Throughout this time, the hardware as well as the software have been improved to enhance the grinding precision and the accuracy of fit of the Cerec restorations. The original machine was called Cerec 1 and this was succeeded by three generations of Cerec 1, carrying the same name. Later, a completely redesigned machine named

Cerec 2 was introduced, capable of producing inlays, onlays, veneer and full crowns with the aim of achieving an even higher accuracy of fit than the previous models. A bur has been added to the milling machine which works in synchrony with the grinding disc to allow grinding of the occlusal morphology. Moreover, an extrapolation design mode can be used that generates an individualised occlusal-surface morphology automatically, including the central main fissure and cusp slopes. The grinding precision of the Cerec 2 unit was found to be 2.4 times greater that of Cerec 1, and the accuracy of fit of Cerec 2 generated inlays was improved by 30% compared with that generated by Cerec 1 (Mörmann and Schug, 1997). In addition, some authors have reported further development of the CAD system particularly for the full-crown restorations. Sohmura and Takahashi (1995) reported a development of the CAD system for a clinical crown restoration. Data from a typical crown form was acquired and stored, then applied to the imaged tooth preparation. The occlusal morphology was established from both static and functional occlusal records. The completed design can then be used to produce a full crown restoration by the CAM system. The program is based on a computer graphic drawing technique and it is not clear if this CAM program will be suitable for the Cerec system.

The ceramics from which the Cerec restorations can be produced are manufacturer-made and supplied as blocks of different shades and size. These are Cerec Vita Mark I (Vita Zahnfabrik), a traditional coarse porcelain; Cerec Vita Mark II (Vita Zahnfabrik), a fine particle size porcelain material; and Dicor MGC (DeTrey/Dentsply), a glass ceramic (Krejci *et al.*, 1994). Cerec Vita Mark I was found to be more abrasive against the opposing enamel than Cerec Vita Mark II

(Krejci *et al.*, 1994), therefore the latter is more desirable and can be considered as a replacement for the Vita Mark I. As a structure, Cerec Vita Mark II blocks are made from fine particle size (4μm) feldspathic porcelain enriched with aluminium oxide (20-23%) (Vita product information). It contains sanidine ($KAlSi_3O_8$) as a major crystalline phase within a glassy matrix, which might explain the lack of translucency of this material (Denry, 1996). Dicor MGC is a machinable glass-ceramic similar to Dicor, with the exception that the material is cast and cerammed by the manufacturer. The glass ceramic contains 70 vol% of the crystalline phase, colourants have been added to match tooth colour (Denry, 1996).

Overall, the disadvantages of Cerec CAD-CAM restorations include: the need for costly equipment; the technique-sensitive nature of surface imaging that is required for the prepared teeth; and lack of computer-controlled processing support for occlusal adjustment (Anusavice, 1996). The advantages of the system include: a chairside ceramic restoration in one visit; freedom from making an impression; and saving the time of laboratory assistance (Smith and Cardwell, 1989; Anusavice, 1996). Moreover, since these systems use a manufactured ceramic, thus removing the ceramic processing, and hence microstructural control, from the dental laboratory and places it within the jurisdiction of the manufacturer. A ceramic manufacturer can generally provide a superior material compared with a dental laboratory (Kelly *et al.*, 1996). In a recent report, the accuracy of fit for Cerec 2 generated inlays that were made from Vita Mark II was found to be 56 ± 27μm which was considered an excellent accuracy by the authors (Mörmann and Schug, 1997) and so this system appears to have a very promising future.

1.4.2.10.2. Celay System

The Celay system (Mikrona Technology, Spreitenbach, Switzerland) uses a copy-milling technique to produce ceramic inlays or onlays from resin analogues (McLaren and Sorensen, 1994; Denry, 1996). The system is based on a mechanical device that is used to trace the surface of a prefabricated pattern of the designed restoration made from a blue resin-based composite (Celay-Tech, ESPE, Seefeld-Oberbay, Germany). The resin pattern can be produced directly on the prepared tooth or indirectly on the master die made from an impression. As the tracing tool passes over the resin pattern, a milling machine duplicates these movements as it grinds a copy of the pattern from a ceramic block by means of a diamond instrument (Eidenbenz *et al.*, 1994; Anusavice, 1996). The ceramic available that can be used with the Celay system is Vita-Celay (Vita). This material contains sanidine as the major crystalline phase within a glassy matrix (Denry, 1996). Recently, In-Ceram pre-sintered slip-cast alumina blocks (Vita) have been introduced which can be machined with a Celay copy-milling system to generate copings for crowns and bridges (McLaren and Sorensen, 1995). Currently, it is possible to machine Celay In-Ceram or In-Ceram spinell material and then infiltrate the pattern with a sodium-lanthanum glass in a manner similar to that used for conventional In-Ceram crown cores or bridge frameworks (Anusavice, 1996). The time for infiltration is only a few minutes compared with 4 hours for dental laboratory In-Ceram ceramic. Both types of glass-infiltrated alumina are veneered with Vitadur Alpha porcelain (Anusavice, 1996). The marginal accuracy of Celay In-Ceram restorations is within 50μm (Denry, 1996). The advantages of the Celay system are reported as: (1) no specific preparation design is needed; (2) short fabrication times

including occlusal surfaces; (3) precise fit with industrial ceramic based on a simple and reproducible technique; (4) chairside restorations in one visit are possible (Eidenbenz *et al.*, 1994). However, there are a number of disadvantages: pre-restoration fabrication (resin pattern) is needed, which may be difficult especially for the direct method and substantial investment is needed (Eidenbenz *et al.*, 1994). Indeed, another development of this system which could be considered as an advantage is the introduction of the Celay In-Ceram technique for crown cores and bridge frameworks which are then veneered with a conventional technique using Vitadur Alpha porcelain (Anusavice, 1996) which may give more control over the shade of the restoration.

Finally, despite the development and introduction of these systems and different types of dental ceramics over the last few years, thereby providing a broader spectrum of restorative materials for dental practice, dentists remain suspicious about the structural longevity of the ceramic restoration, their fit, and their potential abrasivity against the natural dentition (Kelly *et al.*, 1996).

1.5. WEAR OF CERAMICS AND OPPOSING TOOTH STRUCTURE

Dental ceramics are perhaps the most commonly used aesthetic material for indirect restorations (Christensen, 1986; Wiley, 1989; Jagger and Harrison, 1995), although their potential destructive abrasive effect against opposing natural teeth has been clinically documented (Wiley, 1989). This has influenced greater research interest in this area. *In vivo* investigations are time-consuming since at least 6 to 12 months is required to produce a reasonable amount of wear (Ratledge *et al.*, 1994). Therefore,

wear machines, that are supposed to simulate the oral environment, have been developed to accelerate the wear rate, so that meaningful results can be obtained in a shorter time. However, the oral environment is complex, consisting of fluids with changing composition and pH, cyclic thermal conditions, cyclic mechanical forces exerted during mastication and the nature of the diet consumed. All of these factors may have marked effects on the wear of hard dental tissues and restorative materials (Moon and Draughn, 1982). Therefore, these factors should be considered when the result of a wear test *in vitro* is interpreted. Surface roughness was also reported as a factor which affects the wear process. This is because only the high spots of the surface are in contact producing high localised stress and thus increasing wear and indeed this is a matter which must be considered during porcelain restoration adjustment (Monasky and Taylor, 1971; Moon and Draughn, 1982). Wear also depends on the microstructural elements of the ceramic and its fracture toughness as well as its hardness (Larsen-Basse, 1994), although Seghi *et al.* (1991) found no correlation between the ceramic hardness and the opposing enamel wear rate. The size and shape of abrasive fissures that develop on a dental ceramic surface during contact appeared critical for determining enamel wear (Kelly *et al.*, 1996). The character of the abrasive surface is known to be a function of the fracture toughness of the ceramic, the size of its microstructure (grains, filler particles, pores), and local property variations in its microstructure (Larsen-Basse, 1994; Kelly *et al.*, 1996).

Studies *in vitro* have investigated not only the enamel-ceramic wear but also the wear of different restorative material against different dental ceramics as well as the effect of surface finishing of the ceramics. Monasky and Taylor (1971) studied the wear of

enamel, porcelain and gold in a wear machine which produced an interrupted sliding contact under a load of 1 lb (4.45N). The test was carried out in a medium of artificial saliva, in which white flour was added to provide a mild abrasive action. All the specimens, enamel, porcelain and gold were in the form of flat plates. The enamel specimens were prepared from the labial surfaces of upper central incisors. The porcelain (Ceramco) specimen surfaces were prepared with various finishes, as experimental variables. The results indicated a definite correlation between the roughness of the porcelain surfaces and the resultant rate of tooth wear. Both glazing and polishing of rough surfaces tended to reduce the wear. From the results it was concluded that the rougher the porcelain surface, the higher the rate of tooth wear. Tooth structure in contact with a rough porcelain surface tend to wear rapidly at first until a "polish" of the porcelain surface is obtained. This functional polishing of the porcelain reduced the wear rate on opposing teeth. Moreover, it was found that gold also wore down rapidly against the porcelain. The latter was also found by Mahalick *et al.* (1971) who studied the wear resulting from the combination of gold, acrylic resin, porcelain (Ceramco) and enamel. The test was carried out in a wear machine with a load of 13.5 lb (60N). They found that all the materials showed low wear rates when they were tested against gold. Porcelain-enamel and porcelain-gold produced higher wear rates than gold-enamel and gold-gold combinations. The authors suggested that gold may be the most satisfactory restoration of any occlusal surface and it may be more satisfactory to fabricate porcelain bonded to gold restorations with no more porcelain than that needed for aesthetics.

Fisher *et al.* (1983) reported that porcelain was found to be less resistant to wear than metal when both were abraded by human enamel specimens (lingual cusp of maxillary premolars). The specimens were in a disc shape with one half of metal (Jalenko 'O' and Microbond N/P2) and the second half was porcelain (Ceramco) that was packed and fired to the same level as the metal. The tooth cusp was rotated against the metal-porcelain specimen using a pin-on-disc-like wear machine under a load of 3 kg (29.4N). The test was carried out in distilled water at 37°C. After 10000 cycles at a speed of 130 cycles/minute the porcelain half of the specimens had a deeper and wider wear track than its metal counterpart. No mention was made about the rate of tooth wear.

The wear mechanism of dental porcelain against human teeth has been studied by DeLong *et al.* (1986) using the artificial mouth concept that was described previously. The maxillary element was the palatal cusp of the maxillary third molar and the mandibular element was porcelain (Ceramco II, Ceramco, New York, NY, USA) fused to a metal disc. The test was carried out with a maximum occlusal force of 13.35 N in deionised water at 37°C , for a total of 500,000 cycles. Under the condition of the artificial mouth the authors stated that the brittle fracture wear mechanism of the porcelain was not involved extensively. The porcelain wear track exhibited smooth wear grooves at the edge of the track with pits/lacunae, which appear to have resulted from frequently observed small areas of fracture, across the worn surface of the porcelain. The authors also reported that the wear mechanism of dental porcelain was an abrasive rather than an adhesive wear process, and the

amount of abrasive ploughing would be controlled by the hardness of the enamel surface.

The artificial mouth was used later (DeLong *et al.*, 1989) to study the wear of enamel (maxillary molar samples) against three ceramic systems namely Cerestore, Dicor, and porcelain-fused to metal (Ceramco II body porcelain). None of the ceramic samples had external shading and the conventional porcelain (Ceramco) samples were used with a glazed surface. The test was carried out for 300,000 cycles under the same parameters described before. The wear was evaluated for both ceramic specimens and tooth enamel specimens by measuring the volume loss as well as the maximum depth of wear using the surface mapping technique (DeLong *et al.*, 1985). Overall, the enamel-Dicor pairing showed significantly less wear than either than the enamel-Cerestore or the enamel-Ceramco (porcelain fused to metal). No significant difference was found between the enamel-Cerestore or the enamel-Ceramco pairings. The authors commented that this difference was because of the nature of the wear process which was affected by the hardness of material (knoop hardness for: feldspathic porcelain, 460; Dicor, 362; enamel, 343). Thus the enamel-porcelain couples had experienced what is called "hard" abrasive wear, while the enamel-Dicor couples experienced "soft" abrasive wear (DeLong *et al.*, 1989). A further study (DeLong *et al.*, 1992) with the artificial mouth was carried out under the same conditions with the aim to determine if external shading of the ceramic would alter the wear of enamel. In this study the ceramic system (mandibular element) included Dicor with and without shading and porcelain-fused-to-metal (Ceramco II body porcelain), with and without shading. Gold specimens were included as a control. It was found that the external

shading of the ceramics caused an elevation in the wear of enamel 2 to 5 times more than that of unshaded ceramics, and 10 to 15 times greater than that of enamel opposing gold. The materials tested were ranked according to the volume loss of the enamel as:

gold ≤ Dicor < porcelain < Dicor with shading < porcelain with shading.

According to the combined vertical height loss the ranking was:

gold < Dicor < porcelain = Dicor with shading = porcelain with shading.

The authors suggested that the elevation in enamel wear after the ceramic shading might be attributed to the microstructure of the shading materials and to the porosity that might be incorporated after shading.

The fact that unshaded Dicor hardness is similar to the hardness of enamel, and the thought that this might be a factor in the reduction of the enamel wear produced by unshaded Dicor (DeLong *et al.*, 1989 and 1992) has initiated research to assess the relationship between enamel wear rates and the hardness of opposing dental ceramics. Seghi *et al.* (1991) investigated the wear of human enamel against various dental ceramics. A wear machine that produced a continuous sliding contact between enamel cylinders and ceramic discs was used. The enamel specimens were obtained from extracted human maxillary molars and tested against five different ceramic systems namely: Dicor; Dicor with shading porcelain; glass slide; Vita VMK 68 (a metal-ceramic feldspathic porcelain); and Optec HSP (a leucite-reinforced glass). The authors included manufacturer-supplied glass slides for the purpose of comparison with a presumption that the slides were largely free of the types of defects (surface roughness, pores, inhomogeneity of microstructure, non-parallel surface) that might

occur when dental ceramics are hand made. All the ceramic specimens (discs) were made according to the manufacturers' recommendations. The test surfaces for all the ceramic discs had received the same treatment which ended by polishing with 0.1μm diamond polishing paste. The enamel specimens were tested against the ceramic discs under a load of 0.65 N in distilled water. The enamel wear was determined by measuring the height reduction of the enamel cylinders. The hardness of the ceramic specimens was also measured to assess the relationship between enamel wear and ceramic hardness. The results showed that Dicor and Dicor with shading had caused the least amount of enamel wear. Optec HSP was found to be the most abrasive material. There was a poor correlation between ceramic hardness and the amount of enamel wear. The authors stated that the difference in wear could be because of the microstructural differences between the materials.

The wear of enamel against castable ceramic Dicor was investigated by other researchers who were also interested if the shading affected the wear rate of enamel. Palmer *et al.* (1991) tested the enamel of third molar cusps against ceramic discs made from conventional metal-ceramic Vita porcelain, Dicor without shading, and Dicor with shading. The test was carried out in a pin-on-disc type wear machine under a load of 3.015 kg (30N) under a flow of distilled water at 37°C. The results showed that Dicor with shading produced significantly greater wear of enamel than the Dicor without shading and conventional metal-ceramic porcelain. However, in contrast to the previous studies (DeLong *et al.*, 1989 and 1992) the wear of enamel produced by Dicor without shading did not differ significantly from that produced by conventional metal-ceramic porcelain.

Jacobi *et al.* (1991) investigated the abrasiveness of the Dicor system in compared to the conventional metal-ceramic porcelain (VMK68) and gold. Surface finishing had also been included in the study as another variable, namely Dicor polished, Dicor polished with shading, Dicor cerammed with shading, Dicor cerammed and unshaded, porcelain polished, porcelain polished and glazed, and gold polished. The material specimens were in the form of slabs and those designated as polished were abraded with progressively finer silicon carbide paper up to 600 grit, including the gold specimens. The specimens were tested against human extracted canines in an alternating sliding wear machine under a load of 4 kg (39.2N), in tap water at room temperature. The material specimens were moved against the teeth back and forth 4000 times at 58 cycles per minute. The volume loss for both tooth and material was calculated by weighing the specimens before and after the test and using the density to convert the weight loss to volume. According to their results the materials were ranked from least to most abrasive as: gold; Dicor polished; porcelain polished; Dicor polished and shaded; porcelain polished and glazed; Dicor cerammed skin shaded; and Dicor cerammed skin unshaded. On the other hand the ranking of materials from the most wear-resistant to the least wear-resistant was reported as: gold; Dicor cerammed; Dicor cerammed and shaded; porcelain polished; porcelain polished and glazed; Dicor polished and shaded; Dicor polished. The results of this study led the authors to conclude that Dicor shading porcelain had approximately the same abrasiveness as VMK68 glazed porcelain. Dicor ceramic without skin or shading was the least abrasive ceramic material but the most subject to wear. The cerammed skin of Dicor material was the most abrasive and wear resistant of the ceramic surfaces. Gold was found to be the least abrasive and under the conditions of the study the

glazed porcelain was found to be more abrasive than polished porcelain. Based on this study it appears that a shaded Dicor restoration is as abrasive as conventional glazed porcelain and since the shade is applied over the Dicor cast ceramic to build the colour of the restoration, the resultant restoration did not reduce the risk of wear of the opposing tooth structure.

The wear of porcelain and some other restorative dental materials have also been investigated *in vivo*. Ekfeldt and Øilo (1988) investigated *in vivo* the wear of gold (type III and IV), porcelain (metal-ceramic Vita VMK), light-cured resin (Denta colour, Kulzer and Co. GmbH) and heat-cured resin (Biodent K+B, DeTrey) in occlusal contact against a complete denture made with acrylic resin teeth (SR Orthotyp, Ivoclar) and with porcelain (Vita Lumin VaKuum) denture teeth. The materials tested were made as removable segments in the form of double crowns for each segment of either side replacing the mandibular premolars. A bruxer patient was used as the model in this study. The wear was evaluated quantitatively from the weight loss of the segment that was then converted to volume loss, and qualitatively by scanning electron microscopy using replica models made from epoxy resin. The wear was assessed after one month and then after two months for each segment, thus the volume loss per month was calculated. The result showed that all the materials tested had the greatest loss (wear) when they were opposed by the porcelain denture teeth. The heat-cured unfilled resin was the least wear-resistant material followed by light-cured resin, porcelain and gold. The heat-cured (unfilled resin) showed a combined tribochemical and fatigue type of wear. The light-cured resin showed mainly a fatigue type of wear. Porcelain also showed mainly a fatigue type wear (pits

and fracture lines), and in porcelain-porcelain contact, scratches were observed and some of them exhibited a special type of multiple small brittle fractures. Gold showed a combined abrasive and fatigue type of wear. A further report (Ekfeldt and Øilo, 1989) showed that the wear of both porcelain and resin denture teeth was also mainly a fatigue type with some abrasion where hard particles were part of the wear debris.

In addition, Ekfeldt and Øilo (1990) published another *in vivo* study where three patients were involved. Removable crowns were fitted over existing natural teeth that were first crowned with fixed gold crowns. Removable crowns of the materials to be tested were fixed over these gold crowns using a temporary cement. The removable crowns were made from type III gold, type IV gold, metal-ceramic porcelain (Vita VMK porcelain fused to metal substructure) and Isosit (Ivoclar) microfilled resin (over a metal substructure, with mechanical retention). The opposing teeth were restored with metal-ceramic restorations and for one patient the removable crowns were used in both arches for material combination assessment. The wear was assessed quantitatively and qualitatively as in the authors' previous studies. It was found that the wear rate of gold and porcelain had equal values antagonising metal-ceramic crowns in all three patients and the microfilled resin (Isosit) wear rate was three to four times higher. No statistically significant differences in wear resistance were found between type III and type IV gold alloys. When identical materials were in contact in the patient with removable crowns in both arches, it was found that both gold alloy types III and IV had the lowest amount of wear. The wear seen with porcelain and microfilled composite resin (Isosit) were three and ten times higher, respectively, than gold. The type of wear mechanisms was reported as fatigue in the porcelain

specimens, showing several lacunaes in the wear area, combined fatigue and abrasion for gold, and, for the microfilled resin, mainly fatigue with some tribochemical reaction.

All the above *in vivo* studies (Ekfeldt and Øilo, 1988, 1989, 1990) investigated the wear of different restorative materials against another material, in other words material to material study of wear. None of them reported the wear of the natural dentition against restorative materials.

By contrast, the wear of tooth against materials has been reported in many *in vitro* studies using wear machines in an attempt to simulate the oral cavity as discussed previously. A series of three studies had been reported by Jagger and Harrison (1994, 1995a,b) to investigate the wear of human teeth against different restorative materials using a wear machine which provided an intermittent sliding contact. The machine was originally developed by Harrison and Lewis (1975). In their first study, Jagger and Harrison (1994) investigated the wear effect of porcelain surface finish on human enamel. The porcelain specimens were prepared from Vitadur-N porcelain (Vita). The specimens were prepared and fired in the form of studs and then divided into three groups. One group was left as it was and was referred to as unglazed porcelain. The second had received an extra two minutes firing to produce a glazed surface and referred to glazed porcelain, while the specimens in the third group were polished with a series of sandpaper discs of increasing fineness. The porcelain studs were tested against enamel plates that were prepared from the buccal surface of human permanent incisors, canines and premolars. The specimens were abraded for 62 hours,

under 0.4 MPa force, in water at 37°C. Wear was evaluated by measuring the length changes of the porcelain studs using a bench micrometer, and for enamel wear by measuring the maximum depth of the wear track on the enamel plates using surface profilometry. It was found that the glazed and unglazed porcelain produced similar amounts of enamel wear, however that produced by polished porcelain was substantially less. The wear of porcelain was almost similar for the three groups with no significant differences. In their second report Jagger and Harrison (1995a) tested specimens of amalgam (Dispersalloy; Johnson and Johnson, Ascot, Berkshire, UK); conventional composite (Concise; 3M Dental Products, St Paul, MN, USA); microfine composite (Herculite; Kerr, Romulus, MI, USA) and gold. The specimens were prepared in the form of studs in addition to the glazed and unglazed porcelain stud specimens that were reported in the previous study. The materials were tested against the enamel plates using the same methodology reported previously by Jagger and Harrison (1994). The authors showed that enamel demonstrated good abrasion resistance against amalgam and microfine composite and moderate abrasion resistance against gold. Marked destruction of enamel was produced by conventional composite and the greatest amount of enamel wear was produced by porcelain. Furthermore, the same wear test was performed again, but the enamel plates were replaced by dentine plates (Jagger and Harrison, 1995b) to compare the wear resistance of dentine to that of enamel. It was found that dentine was substantially less wear resistant than enamel. Conventional composite resin produced extreme destruction of dentine, and glazed porcelain produced the greatest amount of dentine wear (unglazed porcelain was not included in this study).

In summary, these three studies (Jagger and Harrison, 1994, 1995 a,b) confirmed that porcelain is abrasive and potentially destructive against human enamel and can even elicit extreme destruction to the tooth tissue if it comes into direct contact with dentine.

The wear properties of three ceramic systems were investigated by Krejci *et al.* (1993) using a wear machine which produced a maximum load of 49 N. The palatal cusp of maxillary molars were tested against ceramic inlays that were cemented into mandibular molars and mounted in the wear machine. The ceramic inlays were made from: Dicor, cast glass ceramic (DeTrey/Dentsply, Dreieich, Germany); Biodent, sintered feldspathic porcelain (DeTrey/Dentsply, Dreieich, Germany); and IPS Empress, pressed glass ceramic (Ivoclar, Schaan, Leichtenstein). The surface of the inlays for Dicor and Biodent were polished while the IPS Empress inlays were tested with a polished as well as a glazed surface. The wear was quantified by measuring the vertical loss of the specimen at the contact area using a three-dimensional scanner. The polished sintered feldspathic porcelain (Biodent) was found to cause the highest amount of enamel wear followed by polished Dicor, glazed IPS Empress and polished IPS Empress. Polished Dicor was found to be the least resistant to wear followed by polished Biodent porcelain, glazed IPS Empress and polished IPS Empress. Overall, the difference between the polished porcelain (Biodent) and polished Dicor was not significant nor the difference between the glazed and polished IPS Empress.

Ratledge *et al.* (1994) also investigated the wear properties of the IPS Empress ceramic system against opposing enamel and compared that to Vitadur-N porcelain

and some other restorative materials, a wear machine that provided sliding contact was used with a rate of 70 strokes per minute under a load of 40N for a total of 25,000 cycles. The enamel specimens were prepared from the buccal and lingual surfaces of extracted human premolars and tested against: human dental enamel - as the control; Amalcap amalgam (Ivoclar-Vivadent, Schaan, Liechtenstein); conventional composite (concise; 3M Dental Products Division); inlay/onlay microfilled composite (SR-Isosit; Ivoclar-Vivadent); Vitadur-N glazed porcelain (Vita); and unglazed IPS Empress metal-free ceramic (Ivoclar-Vivadent). The specimens were prepared in the form of discs and were then embedded in a cylindrical specimen holder of the wear machine. The test was carried out in tap water and in citric acid solution buffered at pH 4.0. The wear was evaluated by measuring the profile reduction of the enamel specimens, and the depth of the wear scars on the material specimens which was measured by profilometry. It was found that, overall, the testing in citric acid significantly increased the wear of enamel. Amalgam produced the least amount of enamel wear and some transfer of amalgam was observed on opposing enamel specimens. However, Vitadur-N porcelain was found to be the most abrasive material followed by IPS Empress ceramic. The conventional composite produced greater enamel wear than the microfilled material. Based on the scanning electron microscopy observation, the authors stated that large quartz filler particles in the conventional composite resin had been plucked out and given rise to three-body abrasive wear, thus creating greater wear of the enamel specimens. It was also found that enamel-enamel combinations produced a high rate of wear. It was suggested that this could be also attributed to a three-body wear mechanism resulting from some chipping of the enamel specimens during the test. Furthermore, analysis of

material wear scar depth showed a significantly reduced depth of wear scar for enamel plate (the control), IPS Empress and Vitadur-N. Greater scar depth was found for the microfilled and conventional composite. The amalgam wear scar depth was not as great as that found for the composite materials. The authors also reported their support to the claim that porcelain occlusal surfaces may be damaging to opposing enamel surfaces (Ratledge *et al.*, 1994).

The introduction of machinable ceramics has added a new category of dental ceramics that also have been tested and evaluated in regard to their wear resistance and abrasivity against human teeth. In a five year clinical study Mörmann and Krejci (1992) reported that the Cerec inlays that were made from Vita Mark I ceramic blocks (Vita) showed excellent clinical performance. No wear or loss of contour were observed on the occlusal surfaces. However, it was reported that the occlusal contact point surfaces of some inlays were partially roughened. The authors also stated that the development of Vita Mark II (fine-particle porcelain) and Dicor MGC (Dentsply) glass ceramic may further improve the long-term performance. Indeed, a more recent 4 year clinical study also reported good clinical performance of the Cerec inlays made from Dicor MGC material. The latter has also been reported to demonstrate excellent wear resistance (Heymann *et al.*, 1996). Both Vita Mark I and Dicor MGC have been investigated *in vitro* (Krejci *et* al., 1994) and compared to the more recently introduced Vita Mark II, the fine particle sized porcelain, using a wear machine with a maximum chewing load of 49N. The ceramic specimens were prepared as inlay restorations and cemented into extracted mandibular molars. The occlusal surface of the ceramic inlays were polished and the specimens were tested

against the palatal cusps of maxillary molars. The wear was assessed by vertical loss and compared also to other data that included enamel-enamel combinations. It was found that the wear rate of all ceramic materials except Dicor MGC was less than that of human enamel. Furthermore, the abrasivity against opposing enamel cusps was high with Dicor MGC and Vita Mark I and moderate with the Vita Mark II. It was concluded that as far as occlusal contact wear is concerned, the fine-particle size porcelain, Vita Mark II, seems to be the material of choice for the machinable Cerec ceramic restoration (Krejci *et al.*, 1994). Later reports also found that the wear of Dicor MGC was greater than that of Vita Mark II (Estafan *et al.*, 1996). However, in contrast to the conclusion of the report by Krejci *et al.* (1994), Ramp *et al.* (1996) compared the amount of enamel wear produced by Dicor MGC and Vita Mark II to that produced by IPS Empress and cast type III gold. They found that Dicor MGC and gold produced a similar wear of enamel which was significantly less than the enamel wear produced by IPS Empress and Vita Mark II which were also found to produce similar amount of enamel wear.

While searching for less abrasive ceramic materials, Hacker *et al.* (1996) recently compared the wear of enamel produced by Procera all-ceramic low-fusing porcelain (Procera, Sandvik AP, Stockholm, Sweden) with that produced by conventional feldspathic porcelain, (Ceramco; Ceramco Inc., Burlington, NJ, USA) and gold alloy (Olympia ; J.F.Jelenko and Co., Armonk, NY, USA). The enamel specimens were cut from extracted teeth with a diameter of 3mm and then were attached to rods of the wear machine. The latter was a pin-on-disc type wear machine, thus the material specimens were prepared in a disc form and tested against the enamel abrader under a

load of 1 lb (4.45N) in a medium of fresh natural saliva, for a total of 10,000 cycles. The wear was determined by assessing the height loss of the enamel abrader and the depth of the wear track of the restorative material discs. A substantial difference was found in the amount of enamel wear produced by the three materials. The greatest amount of enamel wear was found to be caused by the conventional porcelain Ceramco, followed by the low-fusing porcelain Procera, and then gold. The all-ceramic low-fusing porcelain was found to be causing 74% less wear of enamel than the conventional feldspathic porcelain. Furthermore, the wear of both porcelains were not significantly different from each other, yet both were significantly less resistant to wear than gold. The authors stated that the smaller amount of enamel wear caused by the low-fusing porcelain compared to the conventional porcelain is an obvious advantage in situations were aesthetic demands call for porcelain occlusal surfaces. Thus these types of porcelain, with significantly lower abrasivity, have a promising future (Hacker *et al.*, 1996).

The Procera all-ceramic porcelain was designed to be compatible with the aluminum oxide core for restoring the Branemark system (Cera-One; Nobelpharma AB, Göteborg, Sweden) abutment with an all-ceramic implant-retained crown. Recently its application has been extended for single crown restoration cases. Computer-controlled technology is used to scan the master die of the prepared tooth. The stored data is transmitted to the Procera work station, where a high-purity aluminum oxide powder is pressed under high pressure onto an enlarged die. The latter is used to compensate the subsequent shrinkage of the aluminum oxide ceramic after firing. The resultant core (coping) is then veneered with a Procera all-ceramic porcelain

(Gottlander *et al.*, 1994; Hegenbarth, 1996). Other low-fusing ceramic systems with specific applications that have been marketed are Procera and Duceratin ceramics (Ducera Dental, Rosbach, Germany). Both are also low-fusing ceramics that have been developed to veneer titanium copings (Nilson *et al.*, 1994; Gottlander *et al.*, 1994; Esquivel *et al.*, 1996). Their low-fusing temperature has attributed to the introduction of hydroxyl groups into the glass matrix, which was found to successfully lower the fusing temperature without adversely affecting their physical properties, particularly their chemical solubility (Esquivel *et al.*, 1996). The technique of introducing the hydroxyl groups into the glass matrix initiated the new category of dental ceramics known as hydrothermal ceramics, discussed previously. Duceram-LFC is a low-fusing hydrothermal ceramic with a wide spectrum of use. It has the ability to bond to conventional metal-ceramic substructure porcelain without affecting the form or the accuracy of the conventional porcelain substructure. The manufacturers claim that the material has interesting properties such as Si-hydroxyl surface layer formation which is claimed to protect the surface and heal the micro flaws providing the material a self-healing process (Komma, 1993). These claims make this material of interest for investigation of the wear properties and its abrasivity in opposition to natural teeth.

Although many studies have been undertaken to investigate the wear of tooth structure and dental ceramics, there are still many questions which have not yet been addressed. Firstly, the variation in the porcelain surface investigated have been based on non-clinical finishing techniques. No consideration has been taken to simulate the clinical adjustment of the porcelain surface that is usually carried out by a rotating

diamond instrument rather than grinding a porcelain specimen against a flat surface, as in previous studies. Secondly, there is no data available at present on the wear properties (abrasivity and wear resistance) of the hydrothermal ceramic Duceram-LFC. Both Duceram-LFC and Vita Mark II are newly introduced ceramics which are supposedly less abrasive than conventional porcelains. There is not enough data to support this claim and it is now timely to investigate this further. Thirdly, increased consumption of carbonated beverages have been known to increase tooth wear rates. Up to now there has been no investigation of the wear properties of Duceram-LFC and Vita Mark II in an acidic environment. Finally, a good model system for three-body wear of tooth vs ceramic has not been established. With all these points in mind, this study was undertaken to address all the above questions. Thus, the objective of the present study was to investigate the wear of human enamel against dental ceramics in a wear machine, developed to simulate the chewing cycle. The study was also to elucidate further the effects of porcelain types and finishing surface on the wear of tooth structure, investigate the effect of carbonated drinks on tooth and porcelain wear, and, lastly, attempt to develop a satisfactory model for three-body wear that simulated oral conditions.

CHAPTER 2

GENERAL
MATERIALS AND METHODS

Chapter 2: General Materials and Methods

2.1. Preparation of Material Specimens

The materials used in this study were an alumnious porcelain, Vitadur Alpha (Vita Zahnfabrik, Bad Säckingen, Germany), a bonded-to-metal porcelain, Omega (Vita Zahnfabrik, Bad Säckingen, Germany), a low fusing hydrothermal ceramic, Duceram-LFC (Ducera Dental GmbH, Rosbach, Germany), a machinable ceramic, Cerec Vita Mark II (Vita Zahnfabrik, Bad Säckingen, Germany), and a cast gold (Kenbridge 71% gold; The Scientific Metal Co. Ltd, London, UK). All the ceramic materials were shade A3, and the material specimens were constructed according to the following method. All the specimens except the Vita Mark II specimens were constructed in the form of a circular cap with a flat surface, 18mm in diameter and 1mm thick for the Alpha, Duceram-LFC and gold specimens and 1.5mm for the Omega specimens (0.5mm metal and 1mm porcelain). A special die was constructed from autopolymerising acrylic resin (Formatray; Kerr, Romulus, MI, USA) for this purpose. The die was constructed as a cylinder with a diameter of 18mm. A shoulder was prepared around the upper surface of the die to a depth of 2.5mm and width of 1mm. Five rings were constructed that fitted accurately around the die and exceeded its height by (1) 0.4mm, (2) 1mm, (3) 0.5mm, (4) 0.9mm, and (5) 1.5mm (Fig. 2.1). The rings enabled control over the thickness of material for the different stages of construction of each specimen. The specimens were constructed according to clinical laboratory procedures. For Alpha porcelain specimens, platinum foil (Skillbond Direct Ltd., High Wycombe, Bucks, UK) was moulded to the die, and then a layer of core Alpha porcelain was applied 0.4mm thick (ring 1). This was then fired in a porcelain furnace at 1120°C, and a layer of dentine Alpha porcelain was condensed over the

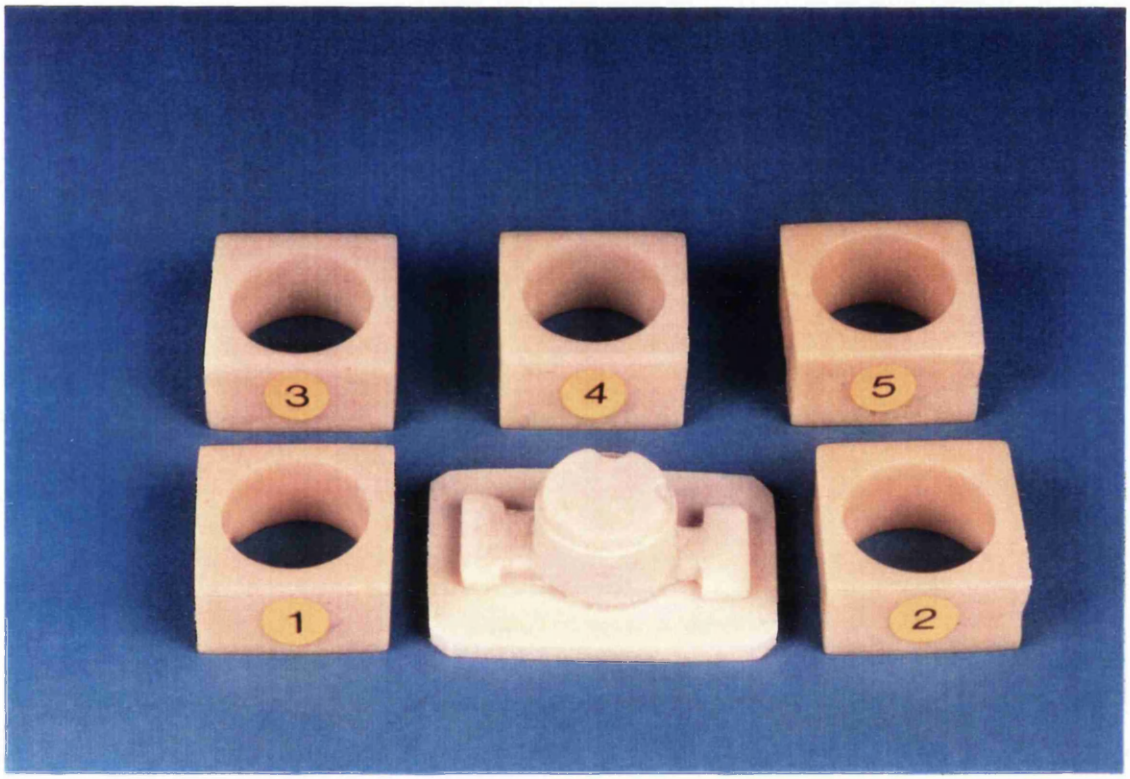


Fig. 2.1. Die for the preparation of restorative material specimens with rings (1-5) of different height.

core to a thickness of 0.6mm (ring 2) and fired in the furnace at 960°C. The specimen was then checked for an even thickness of 1mm, and placed again into the furnace for glazing (autoglaze) at 940°C for 1minute.

Metal substructures of Wiron 88 alloy (BEGO, Metrodent Ltd, Huddersfield, UK) were cast from wax patterns 0.5mm thick that were carved onto the die (ring 3) for Omega porcelain specimens. The metal caps were then placed over the die and a 0.4mm thick (ring 4) layer of opaque Omega porcelain was applied to the metal and fired at 930°C. A 0.6mm thick layer of dentine Omega porcelain was then condensed over the opaque layer (ring 5) and fired again at 930°C in the porcelain furnace. The specimen was then checked for an even thickness of 1.5mm and placed again into the furnace for glazing (autoglaze) at 930°C for 1minute.

The Duceram-LFC specimens were built onto platinum foil that was moulded to the die in a full thickness of 1mm (ring 2) and fired in the porcelain furnace at 660°C as recommended by the manufacturer. Each specimen was checked for an even thickness of material and placed again into the furnace for glazing (autoglaze) at 650°C for 2.5minutes. For all the porcelain specimens described above, the preglaze finishing was carried out using a silicon-carbide abrasive green stone (732, Chaperlin & Jacobs Ltd., Sutton, Surrey, UK). The specimens were then rinsed under tap water and placed in the furnace for glazing (autoglaze). All procedures for firing and glazing were carried out according to the manufacturers' recommendations, using a Vacumat 100 furnace (Vita Zahnfabrik, Bad Säckingen, Germany).

For the gold specimens , wax patterns 1mm thick were carved onto the die (ring 2). The wax patterns were then invested and cast in Cristobalite investment (Whip Mix Corp., Louisville, KN, USA) using a conventional lost-wax technique. The specimens were sandblasted (50μm aluminium oxide) to remove the investment material and polished using brown and green abrasive wheels (Shofu Dental Corporation, Menlo Park, CA, USA).

For the Cerec Vita Mark II specimens, manufactured blocks of the material were sliced into plates 18mm long, 12mm wide and 3mm thick using a water-cooled edge coated diamond blade (continuous rim disc 4" diameter and 250μm thickness) (D.K. Holdings Ltd., Staplehurst, Kent, UK) mounted in a Labcut 1010 machine (Agar Scientific Ltd., Stansted, Essex, UK) running at 400rpm (Fig. 2.2). Since Cerec restorations are cut clinically with a so-called "half-occlusion" morphology, which does not include occlusal fissures, the fine establishment of the occlusal morphology has to be done with a rotating diamond coated instrument (Krejci *et al.*, 1994). Therefore, to simulate clinical conditions, one side of each plate was adjusted by grinding slightly until the surface gloss was removed totally using a fine grit (red band) diamond bur (8879L; Komet, Brasseler Co., Lemgo, Germany) followed by a super-fine (yellow band) diamond bur (859GKEF; Komet) in a speed-increasing handpiece (1:3) under constant water coolant spray (120,000 rpm). The surface was then polished using porcelain finishing wheels (RUWA, Ceram-Pol wheels, Howmedica International Ltd., London, UK), followed by a diamond polishing paste (Chaperlin & Jacobs Ltd., Sutton, Surrey, UK) in a felt wheel. The plates were then rinsed under tap water.

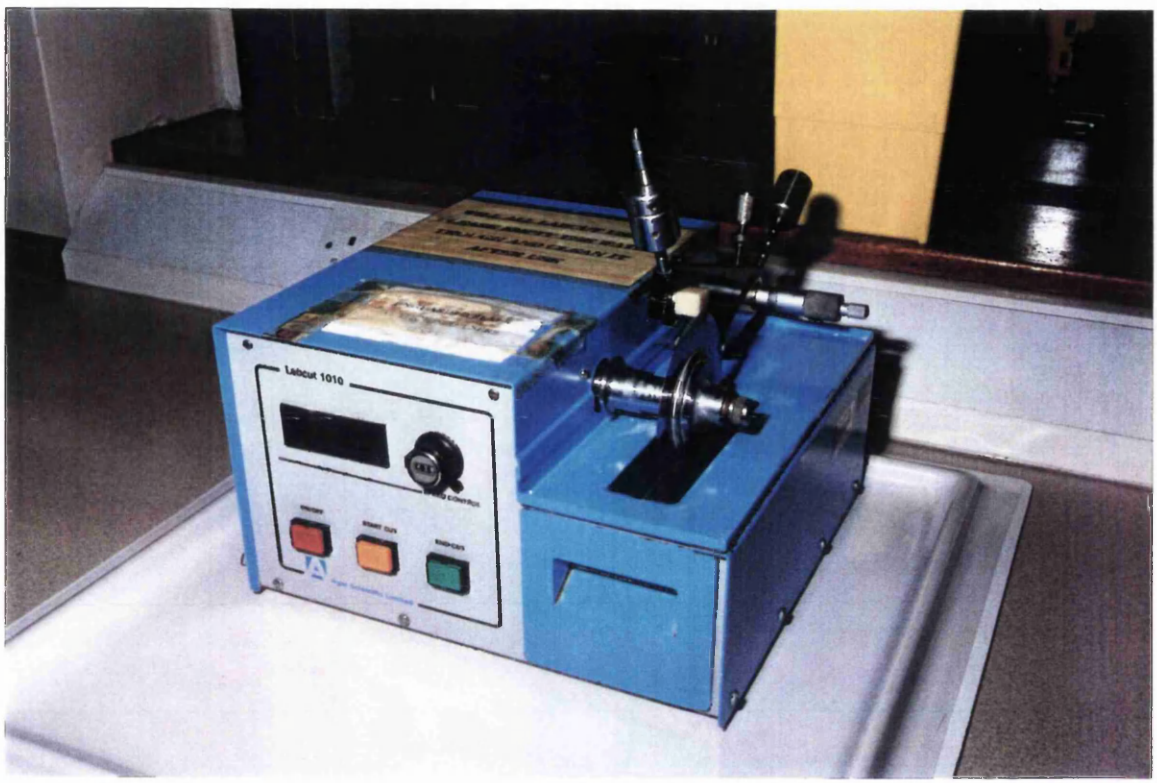


Fig. 2.2. The Labcut 1010 machine with a diamond blade used to slice the Cerec Vita Mark II block.

Figure 2.3 shows the five restorative material specimens, constructed as described above. The specimens were mounted onto the lower specimen holder of the wear machine. The lower specimen holder was in the form of a bolt with a cupped head, onto which a positive replica of the fitting surface of the material specimen was produced from autopolymerising acrylic resin (Fig 2.4). The material specimen was then cemented onto this replica using polycarboxylate cement (Poly-F plus; Dentsply Ltd., Weybridge, Surrey, UK) (Fig. 2.5). However, the Vita Mark II specimens (plates) were embedded directly into the autopolymerising acrylic resin with the polished surface upwards (Fig. 2.6).

2.2. Surface Roughness Measurement

Prior to the wear test, and before the restorative material specimens were mounted onto the specimen holder, they were subjected to average surface roughness measurements. A Dektak 3ST surface profile measuring system (Veeco, Sloan Technology, Santa Barbara, CA, USA) was used for this purpose (Fig. 2.7). The machine consisted of a stylus mounted above the machine stage where the specimen was placed for measurement. The Dektak 3ST operates using a computer with Microsoft Windows programme. By placing the specimen on the stage below the stylus, the specimen image appears on the screen of the computer monitor. Thus the stylus can be brought onto the surface of the specimen at any desired point and a scan profile can be traced across the surface for any required length. The profile trace appears on the monitor screen, and the two cursors of the monitor are then placed at the extremities of the profile trace. The profile trace is levelled and the average surface roughness is calculated by the software program and displayed on the screen

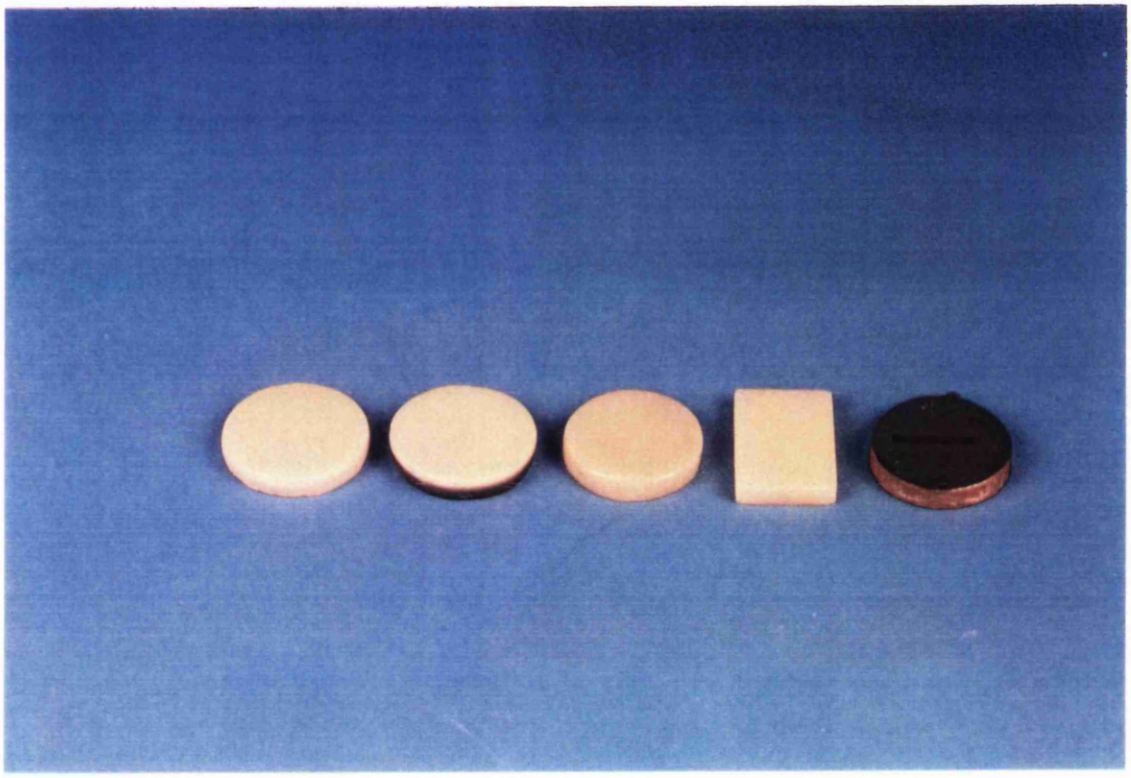


Fig. 2.3. Restorative material specimens; left to right: Alpha porcelain; Omega porcelain; Duceram-LFC; Vita Mark II; gold.

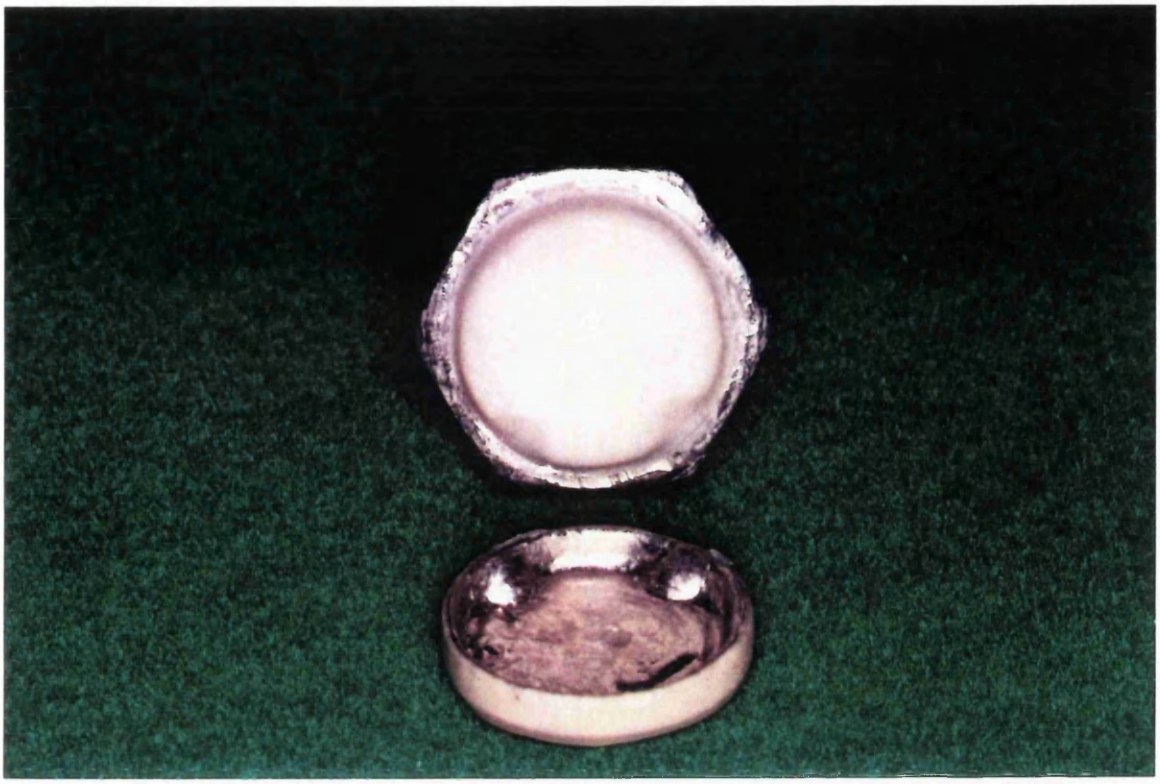


Fig. 2.4. Positive replica of the fitting surface of the restorative material specimen on the holder with the completed specimen.

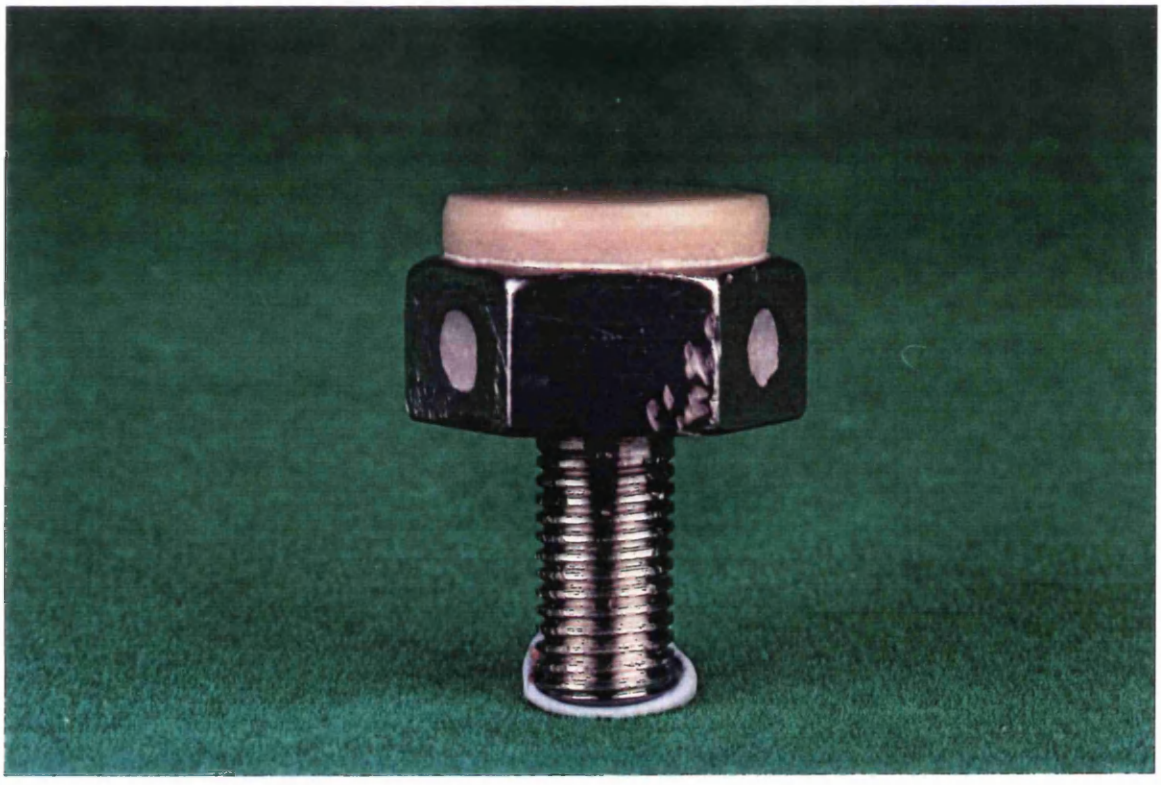


Fig. 2.5. Cemented restorative material specimen on the holder.

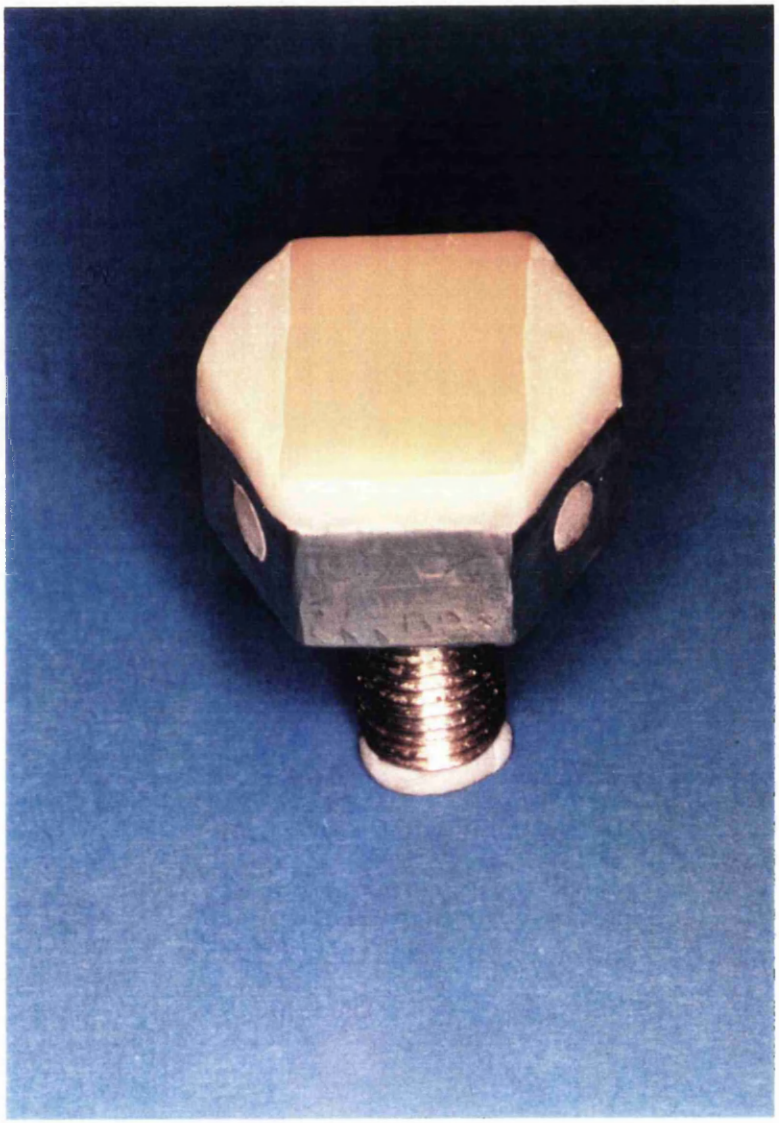


Fig. 2.6. Vita Mark II specimen mounted on the holder.

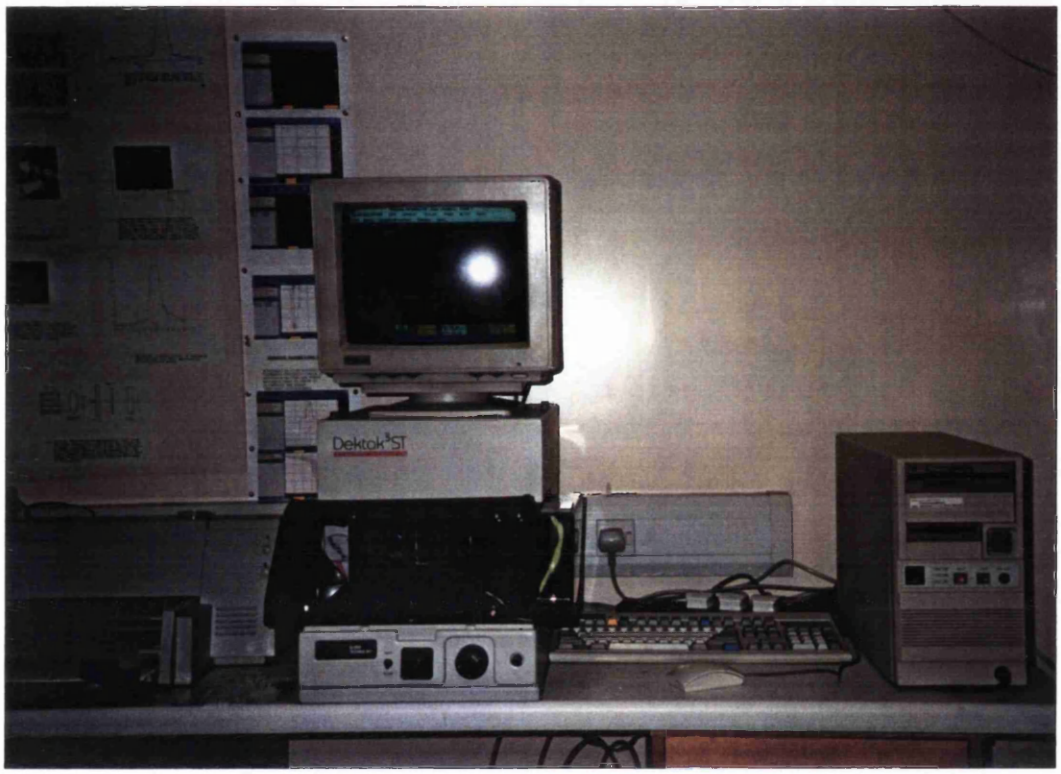


Fig. 2.7. Dektak 3ST surface profile measuring system.

in Angstroms which was then converted to micrometers. Average roughness (Ra) of five surface profile tracings were recorded for each specimen, and the mean of the five readings was considered as the surface roughness for that particular specimen. Each of the five profiles was 2mm in length (stylus speed 12 seconds, data points 1000) and traced across the potential wear track on the surface of the material with an approximate distance of 2mm between each of the five profile tracings. Average roughness (Ra) is the arithmetic average deviation from the mean line (Dektak 3ST, operation manual, Veeco, Sloan Technology, Santa Barbara, CA, USA), and in the present study all the values were calculated from the raw, unfiltered data (without cut-off). It was felt that any deviation from the mean line (horizontal, or centre line) whether large or small should be included in the calculation of surface average roughness value since this may affect the wear process.

2.3. Preparation of Teeth

Extracted caries-free human mandibular premolars were stored in 0.12% thymol. Teeth were prepared by grinding the lingual cusp(s), if necessary, to leave only the buccal cusp. Each tooth was then sectioned in half in a bucco-lingual direction, through the buccal cusp tip, using the Labcut 1010 machine with a water-cooled edge-coated diamond blade described previously (section 2.1). Care was taken to ensure that the cut was made in the long axis of the tooth. Thus, two specimens were obtained from each tooth (Fig. 2.8). Sof-lex finishing discs (3M Dental Products, St. Paul, MN, USA) of increasing fineness were used to smooth the sharp margins of the enamel (avoiding the cusp tip), where the tooth had been sectioned initially. The root of each tooth specimen was embedded into the upper cylindrical specimen holder of

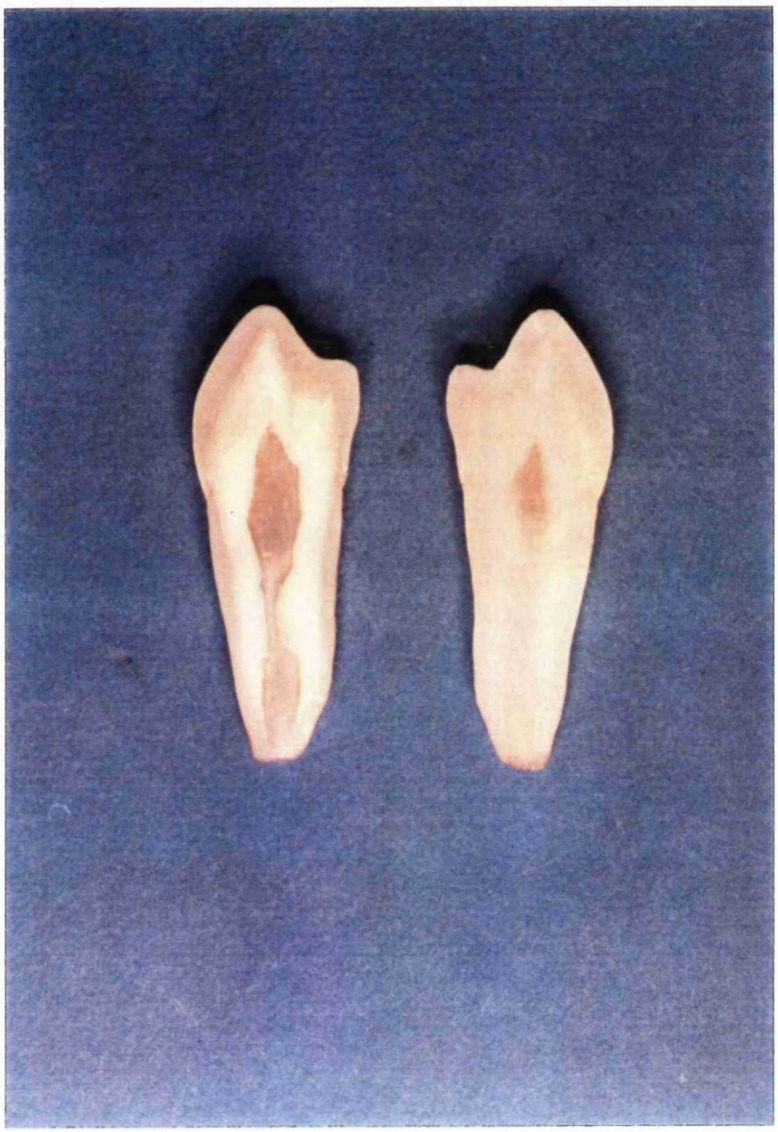


Fig. 2.8. A mandibular premolar sectioned in two halves. Each half was used as one specimen.

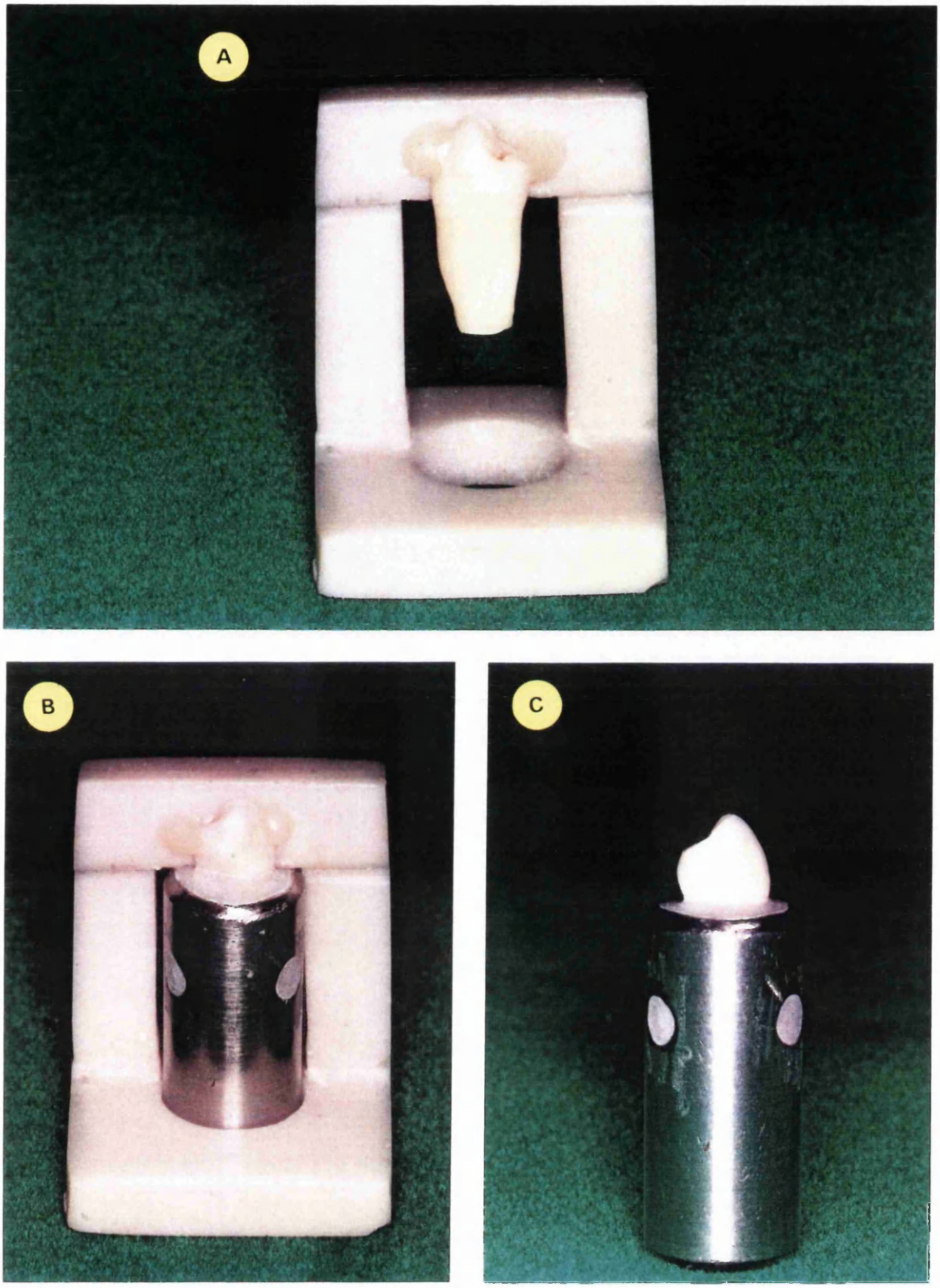


Fig. 2.9. (A) Tooth specimen attached to an acrylic jig with wax, (B) the root of the tooth specimen embedded into the holder filled with acrylic resin, (C) tooth specimen mounted in the holder.

the wear machine using autopolymerising acrylic resin (Formatray). An acrylic jig was constructed to ensure that the insertion of the tooth was made in the same axis of the holder ensuring that the cusp tip of the tooth was perpendicular to the horizontal plane (Fig. 2.9).

2.4. Wear Test Procedure

The wear machine used in this study is shown in Fig. 2.10(a and b) and consisted of an electrically driven motor (A) connected through a rotating disc to a horizontal arm (B). At the end of the arm was a clamp with a slot (C), into which the upper specimen holder containing the tooth could be inserted and tightened. The upper part of the slot had a screw by which the specimen could be adjusted vertically. The clamp design enabled the removal and replacement of the upper specimen holder in the same adjusted position. The horizontal arm was suspended centrally by a rocking arm through which a desired load could be applied to the upper specimen by means of a preloaded spring cell (D). Both tooth and material specimens were kept in distilled water at room temperature for 24 hours before the wear test was carried out. The lower specimen holder with the material sample mounted onto it (E) was then threaded into a stainless steel support on the base of the dental wear machine. The upper specimen holder containing the tooth (F) was inserted and tightened into the horizontal arm clamp. Both the upper (tooth) and lower (material) specimens were seated in a waterbath. The level of the media immersing the specimens was kept at a constant level and volume (50mL) by means of an overflow pipe (G).

The wear machine was connected to the electrical supply through a control box (Fig. 2.11) from which the rate of cycling could be set and the number of cycles monitored

through a digital counter device. The horizontal arm of the wear machine was connected to the side of the rotating disc through a 10mm diameter cylindrical bar. The connection of the bar to the rotation disc was eccentric in such way that the inner side of the bar diameter was at the centre of rotation while the opposite (outer) side was 10mm from it. The horizontal arm was supported in the middle by the rocking arm where the preloaded spring cell unit was fitted. Thus when the machine was activated, the rotating movement of the disc was transmitted to the horizontal arm making the tooth, which was attached to the clamp at the opposite end of the horizontal arm, move upwards, forwards, and then downwards impacting the surface of the material specimen, at the start of the tooth sliding path. After this, the horizontal arm was pulled backwards, sliding the tooth for 10mm along the test material. Both the impact and sliding motion was at a preset load determined by adjustment of the spring cell unit. The tooth was then lifted by the movement of the horizontal arm and brought again to the starting point for a new cycle. Thus each cycle consisted of an impact action followed by sliding motion under a constant preset load. The spring cell unit was fitted with a precision position switch could sense if the load failed during the test and in that event the cycle counter and the machine stopped. The tip of the tooth cusp was brought into contact with the surface of the material specimen using a slotted grub screw before the machine was switched on. The clamp was tightened, and the cycles rate was adjusted at 80 cycles per minute. Thus, as the machine was activated, the cusp of the tooth slid across the surface of the restorative material for a distance of 10mm and at a rate of 80 cycles per minute. Each specimen was tested for a total of 25000 cycles under a load of 40 N (Jacobi *et al.*, 1991; Ratledge *et al.*, 1994).

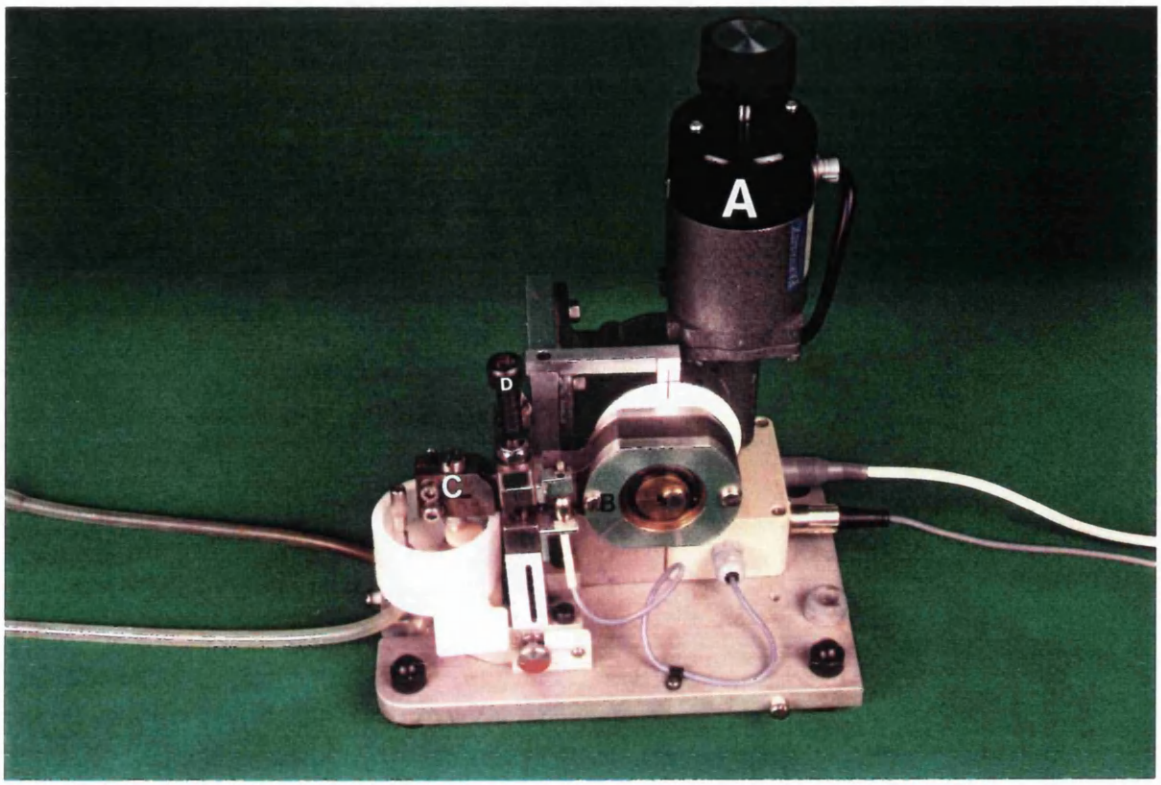


Fig. 2.10a. Dental wear machine showing: A, electric motor; B, horizontal arm; C, clamp for the tooth specimen; D, preloaded spring cell.

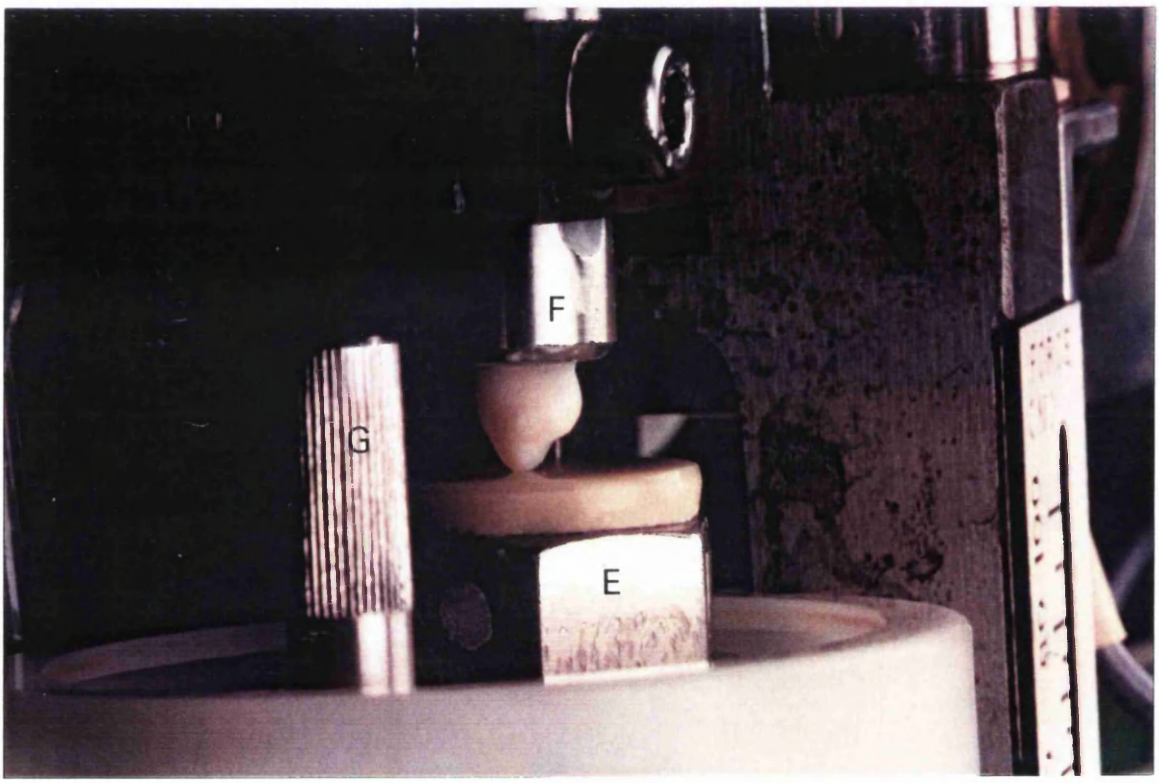


Fig. 2.10b. Close up of tooth-material specimen: E, lower material specimen holder; F, upper tooth specimen holder; G, overflow pipe.

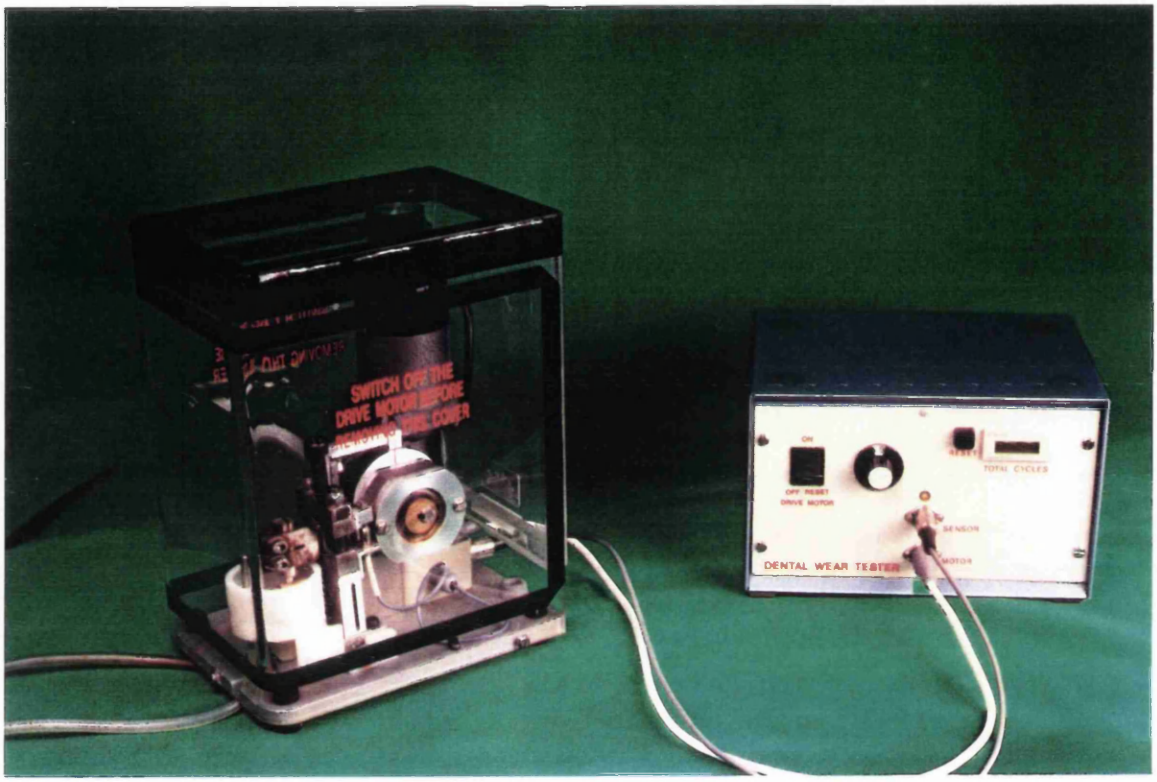


Fig. 2.11. Dental wear machine with the control box.

2.5. Wear Measurement

2.5.1. Tooth Enamel Wear

A reflex microscope (Reflex Measurement Ltd., Butleigh, UK) (Fig. 2.12) was used to determine the amount of wear of the tooth specimens by measuring the reduction in the tooth cusp height. Before the tooth was placed in the wear machine, a horizontal line was traced on the flat surface (cut surface) of the tooth, 4mm from the tip of the cusp. The line was traced using a silicon carbide Ultra-thin end cutter disc (Dedeco International Inc., Long Eddy, NY, USA) mounted on a milling machine (F1, Degussa AG, Frankfurt, Germany) (Fig. 2.13). Using a special jig the tooth specimen could be placed repeatedly in the same position on the reflex microscope stage. The tooth position was adjusted so that the traced line coincided with the X axis of the microscope. The traced line was thus a reproducible reference line from which the furthest point of the tooth enamel could be measured (Fig. 2.14). Tooth specimens were measured at 0, 5000, 15000 and 25000 cycles. The cusp reduction (enamel wear) was determined by subtraction of the worn cusp distance from the initial baseline measurement.

2.5.2. Restorative Materials Wear

For the measurement of wear of the materials, two marks were traced at the margin of each specimen before the wear machine was switched on. The line connecting these two marks was perpendicular to the potential wear track direction, and crossed it at the midpoint of the sliding distance. At the end of the wear test and before the specimen was removed from the machine, an impression was taken of the worn surface using a polyvinylsiloxane impression material (President; Coltène AG,

Altstätten, Switzerland) putty-wash technique in a special acrylic tray constructed for this purpose. An epoxy resin (Epofix; Struers, Rødovre, Copenhagen, Denmark) replica was then produced from each impression to be used for measurement of the wear depth track of the restorative materials. Wear track depth was measured from each replica at five points, namely at the midpoint and 2mm and 4mm above and below the midpoint, across the wear track (Fig. 2.15), using the Dektak 3ST surface profile measuring system. The stylus was positioned at one side of the wear track corresponding to the five points of measurement, and a scan profile was traced for each point by allowing the stylus to travel for a distance of 4mm (stylus speed 10 seconds, data points 800) from one side of the wear track to the opposite side across the wear track. Thus, the profile of the wear track was traced on the computer screen, and by placing the two cursors (R and M) of the monitor screen at the margins of the wear track, R (reference cursor) at the right side and M (measurement cursor) at the left side of the wear track, the two margins were levelled to the zero line using the software levelling command. By moving the M cursor to intersect with the profile trace of the wear track at the deepest point, the vertical distance between the M cursor at the deepest point of the profile trace and the R cursor at the zero level will be displayed automatically on the screen in Angstroms (Fig. 2.16) and then the values were converted to micrometers. Values were determined at the 5 points of measurement for each specimen. All the results were recorded and the deepest measurement was chosen to represent the amount of wear for that particular specimen.

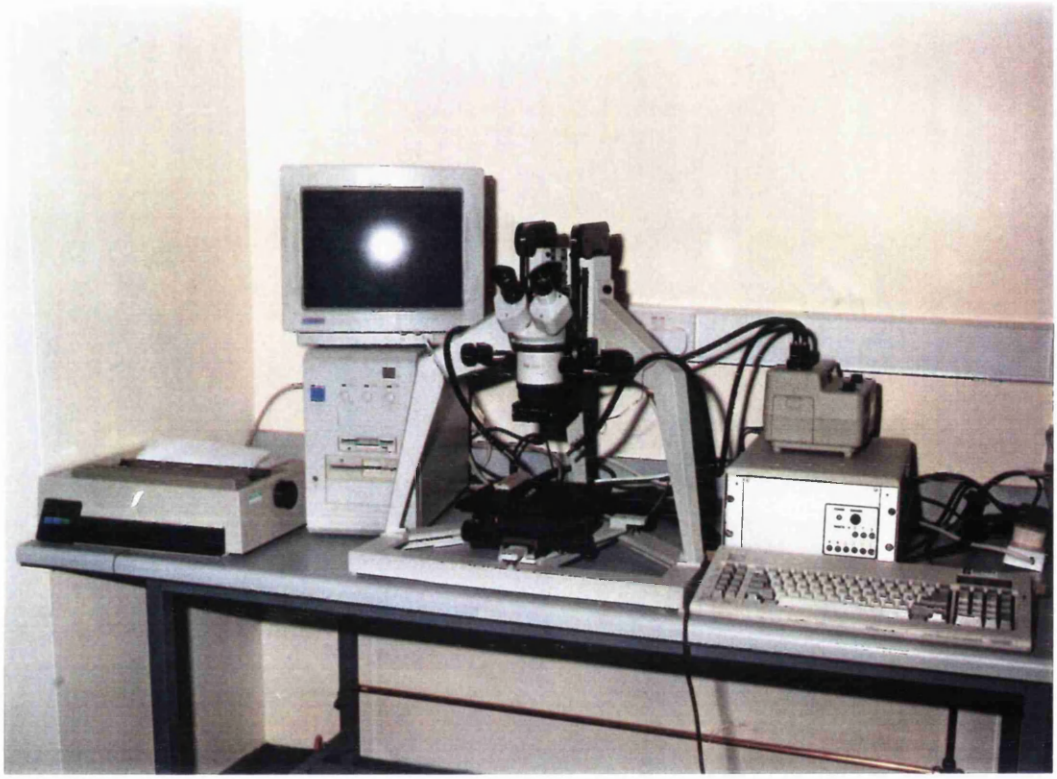


Fig. 2.12. Reflex microscope connected to a microcomputer, used to measure the reduction in tooth cusp height.

Fig. 2.13. F1 Degussa milling machine with a silicon carbide disc used to trace the reference measurement line on the tooth specimen.

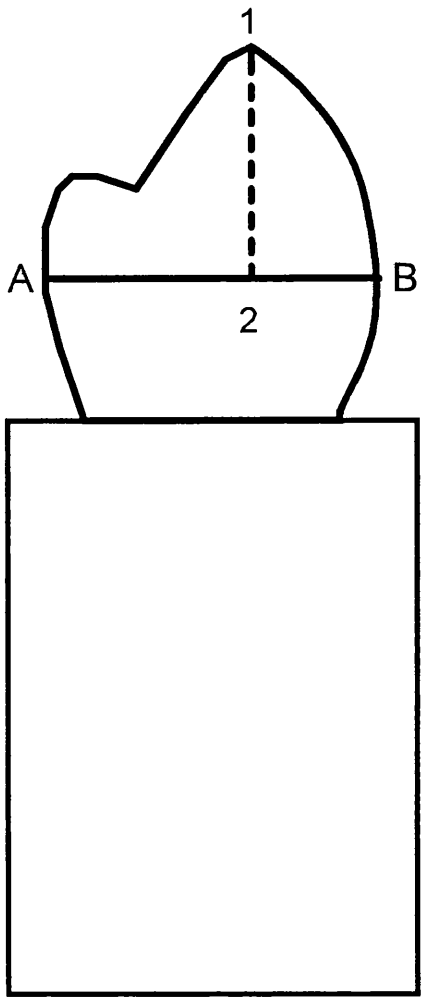


Fig. 2.14. Diagram showing the axial view of tooth in holder. Line AB represents the reference line and measurement was made from 1-2.

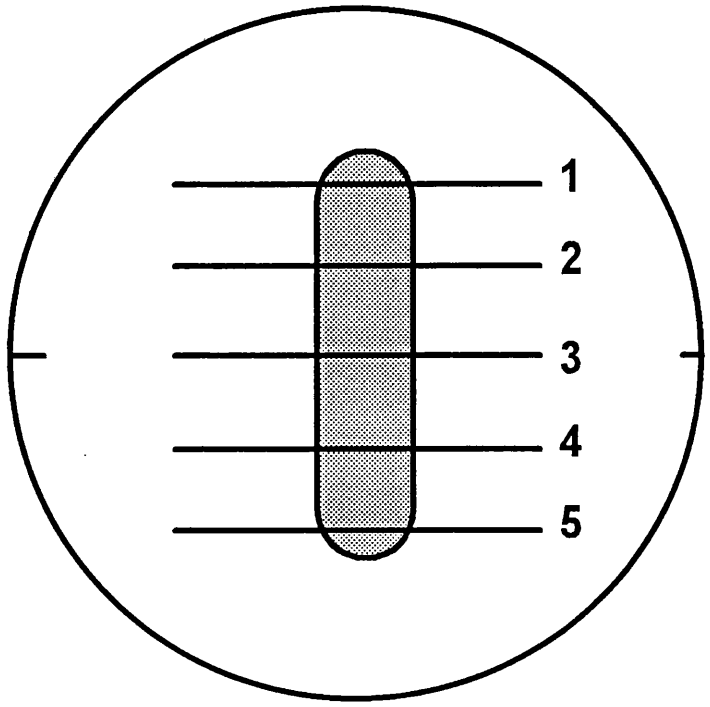


Fig. 2.15. Diagram showing the restorative material replica with the wear track. Lines 1-5 represents the scan profile trace at which the wear track depth was measured. Line 3, midpoint; lines 2 and 4, 2mm above and below the midpoint, and lines 1 and 5, 4mm above and below the midpoint respectively.

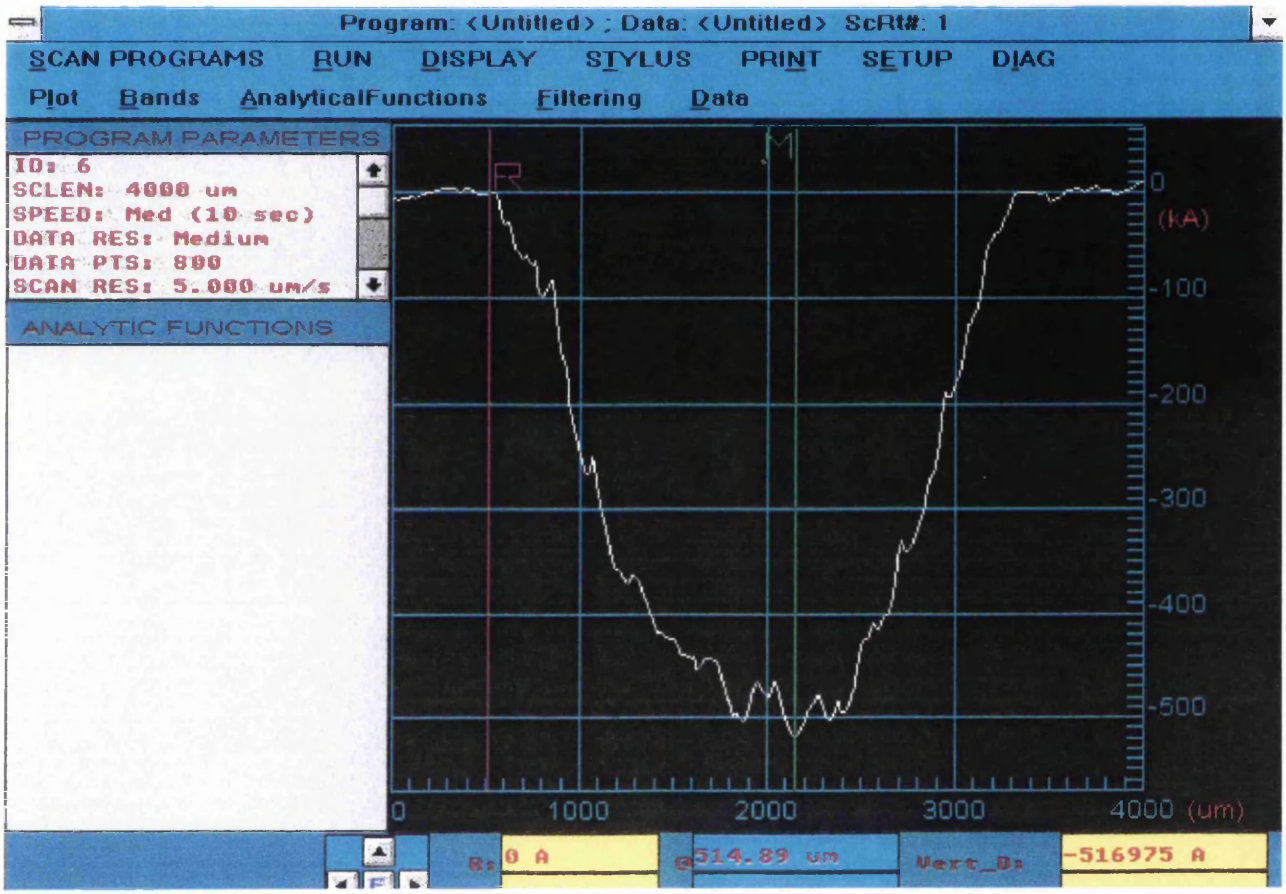


Fig. 2.16. Scan profile of the wear track of the restorative material obtained using the Dektak 3ST profilometer: R = reference cursor placed at the left margin of the wear track; M = measurement cursor intersecting the wear track profile at the deepest point.

CHAPTER 3

The Effect of Porcelain Surface Finishing on the Wear of Human Enamel

Chapter 3: The Effect of Porcelain Surface Finishing on the Wear of Human Enamel

3.1. Introduction

Porcelain is considered to be the material of choice for indirect restorations where aesthetics are of concern (Jagger and Harrison, 1994). Occasionally a glazed porcelain restoration requires adjustment at the chairside, or intraorally, producing a surface that may be highly abrasive and potentially destructive to the opposing natural teeth (Monasky and Taylor, 1971; Wiley, 1989). This adjustment removes the glazed surface of the porcelain producing a rough surface which may increase wear (Moon and Draughn, 1982). To overcome this, the roughened surface of porcelain must be reglazed or polished, after adjustment, to produce the smoothest surface possible (Raimondo *et al.*, 1990). However, reglazing is not always possible. Therefore, different polishing methods have been used and evaluated in an attempt to restore the appearance and smoothness of the porcelain surface (Smith and Wilson, 1981; Sulik and Plekavich, 1981; Klausner *et al.*, 1982; Newitter *et al.*, 1982; Raimondo *et al.*, 1990; Brewer *et al.*, 1990; Goldstein *et al.*, 1991; Patterson *et al.*, 1991). Methods employing finishing wheels followed by pumice or porcelain polishing paste have been reported to aid the production of smoother surfaces (Newitter *et al.*, 1982).

One of the other factors that has been reported to play a role in the wear process is the chemical environment in the mouth (Moon and Draughn, 1982). There are many soft drinks consumed with pH values often less than 4.0 (Eccles and Jenkins, 1974; Rytömaa et al., 1988). Excessive consumption of such drinks have been reported to cause tooth wear (Lewis and Smith, 1973; Eccles and Jenkins, 1974; Smith and

Knight, 1984b; Järvinen *et al.*, 1991). The acid in these drinks demineralise and soften the tooth surface and their effects are intensified by superimposed abrasion or attrition (Eccles, 1982b).

The aim of this study was to investigate the abrasive effects of glazed, unglazed and polished porcelain on the wear of human tooth enamel and the influence of carbonated soft drinks on the rate of wear.

3.2. Materials and Methods

Preparation of Porcelain specimens

Sixty specimens of aluminous Vitadur alpha porcelain were constructed with a glazed (autoglaze) surface as described previously (section 2.2). Thirty specimens of the 60 were separated randomly into 3 groups of 10. The first group was referred to as glazed porcelain and left with the glaze intact. All the visible glaze was removed from the second group using a new fine grit (red band) diamond bur (8879L; Komet, Gebr. Brasseler GmbH & Co. KG, Lemgo, Germany) followed by a new super-fine (yellow band) diamond bur (859GKEF; Komet) using a speed-increasing handpiece (1:3) under constant water coolant spray (120,000 rpm). This was the unglazed porcelain group and corresponded clinically to chairside-adjusted porcelain. The third group was processed as the unglazed group but the surface was then polished using porcelain finishing wheels (RUWA, Ceram-Pol wheels; Howmedica International Ltd., London, UK). This was followed by a diamond polishing paste (Chaperlin & Jacobs Ltd., Sutton, Surrey, UK) in a felt wheel. This was the polished porcelain group and corresponded clinically to chairside adjusted and polished porcelain. Every

effort was made to simulate clinical circumstances when applying each surface finish, and all adjustments were made by one operator. These 3 groups were tested in the dental wear machine against tooth specimens in distilled water. The remaining 30 porcelain specimens were also divided randomly in 3 groups of 10 and treated exactly in the same manner as described above and tested with intermittent exposure to a carbonated beverage (Coca Cola; Coca Cola and Schweppes Beverages Ltd., Uxbridge, UK). Five specimens were selected randomly per group from each of the six groups of porcelain, before the wear test, for average surface roughness measurement. The Dektak 3ST surface profile measuring system was used for this purpose. Average roughness (Ra) of five surface profile tracings per specimen were recorded as described previously (section 2.2), and the mean of the five readings was considered as the surface roughness for that particular specimen. Overall, the porcelain specimen assignment and the selection for average surface roughness measurements was carried out randomly. This was achieved by turning the porcelain specimens upside down, so that the operator was not able to see the porcelain surface during the selection of specimens from each group.

Preparation of Teeth

Tooth specimens were prepared from 30 extracted caries-free human mandibular premolars as described previously (section 2.3), thus 30 pairs of tooth specimens were obtained by sectioning each tooth in half in a bucco-lingual direction, through the buccal cusp tip. The 30 pairs of tooth specimens were divided into 6 groups, 5 pairs in each group, thus 10 specimens were obtained per group. Each specimen was mounted, in turn, into the wear machine specimen holder, and the latter fitted tightly

into the clamp slot on the horizontal arm of the dental wear machine above the porcelain specimen.

Wear Test Procedure

Porcelain specimens were tested against their antagonist tooth specimens for a total of 25000 cycles in the wear machine. The first 30 samples were tested in distilled water, which was renewed after each 5000 cycles. The second group of 30 samples was tested with an intermittent exposure to Coca Cola for 5000 cycles in Coca Cola, and 5000 cycles in distilled water alternately up to 25000 cycles (ie. 3 times in Coca Cola and twice in distilled water), 50mL of liquid either Coca Cola or distilled water were used each time to fill the water bath of the wear machine. The pH of the Coca Cola was determined using a pH meter (MI410; Microelectrodes Inc., Bedford, NH, USA) each time a new bottle was used, and was found to be in the range of 2.28-2.37.

Wear Measurement

The amount of wear for both tooth as well as porcelain specimens was measured in this study after 5000, 15000, and 25000 cycles. A reflex microscope was used to determine the amount of enamel wear of the tooth specimens by measuring the reduction in the tooth cusp height, as described previously (section 2.5.1).

For the measurement of porcelain wear, a series of impressions were taken of the porcelain specimens at each measurement time in this study (after 5000, 15000 and 25000 cycles) using a putty-wash technique with polyvinylsiloxane (President) impression material. An epoxy resin replica was then produced from each impression to be used for measurement of the porcelain wear at all intervals. Wear track depth

was measured from each replica at five points, using the Dektak 3ST surface profile measuring system, as described previously (section 2.5.2) after the requisite number of cycles. The deepest measurement was chosen to represent the amount of wear. The accuracy of the replica in reproducing the porcelain wear track was determined by measuring the wear track depth at the midpoint from a group of 10 specimens, after 25000 cycles, from the resin replica, and from their original porcelain specimens, and these measurements were compared.

Statistical Analysis

One-way analysis of variance (ANOVA) was used to explore the surface roughness data for statistically significant differences between porcelain groups. Postanalysis paired comparisons of groups were then carried out using Bonferroni multiple comparisons method (95% confidence interval level). Enamel and porcelain wear data were analysed using repeated measures ANOVA to explore the data for statistically significant effects of porcelain finishing surface, media (water vs. cola) and number of cycles. Appropriate follow up comparisons were then carried out using Bonferroni multiple comparisons method to produce sets of simultaneous 95% confidence intervals (Altman, 1991).

3.3. Results

Table 3.1 shows the mean surface roughness of the porcelain specimen groups. One-way ANOVA revealed a significant difference in surface roughness between the groups ($p<0.001$). Table 3.1 shows that the smoothest surface was the glazed group followed by the polished while the unglazed demonstrated the roughest surface.

Bonferroni multiple comparisons showed that both glazed and polished surfaces were significantly smoother than the unglazed surface ($p<0.05$), while the difference between glazed and polished surfaces was not statistically significant ($p>0.05$).

Table 3.2 shows the mean values for tooth cusp reduction (enamel wear) after 5000, 15000 and 25000 cycles. These results are also illustrated graphically in Fig. 3.1, showing that the greatest amount of enamel wear was produced by unglazed porcelain, followed by polished and then glazed porcelain, and this was observed at every measurement time. The amount of enamel wear was increased when the test was carried out with exposure to the carbonated drink. Fig. 3.2 shows the cumulative enamel wear rate against glazed, unglazed and polished porcelain in distilled water and Coca Cola. The cumulative enamel wear rate in water vs. cola against glazed, unglazed and polished porcelain are shown in Fig. 3.3. Overall, the graphs (Fig. 3.2 and 3.3) show that the cumulative enamel wear rate increased with increasing number of cycles.

Repeated measures ANOVA (Table 3.3) showed a highly significant effect of media (water vs. cola), porcelain finishing surface and number of cycles on the wear of tooth enamel ($p<0.001$). The interaction between media*surface, surface*cycles and the three-way interaction between media*surface*cycles were not significant, while the media*cycles interaction was highly significant ($p<0.001$).

Bonferroni multiple comparisons were used to compare the mean wear of enamel for the three surfaces and the two media groups at each measurement time (after 5000, 15000 and 25000 cycles). These showed (Table 3.4) that after 5000 and 15000 cycles

a significant difference in the amount of enamel wear was found between all three surfaces with the unglazed group having the highest mean wear followed by the polished group, with the glazed group having the lowest mean wear. After 25000 cycles the unglazed group had significantly higher mean wear than the polished or glazed groups, while the difference between polished and glazed groups was not quite significant. When the groups of different media were compared, overall, the amount of enamel wear in the Coca Cola group was significantly higher than the water group, and the mean size of this difference increased with increasing number of cycles (significant media*cycles interaction).

Tables 3.5 - 3.10 show the five measurements of the wear depth track of the porcelain specimens after 5000, 15000 and 25000 cycles, when the test was carried out in water only and in Coca Cola/water alternately. The tables show that the deepest point of the wear track was not constantly at same point throughout the test. Furthermore its position varied from one specimen to another, but for most of the specimens it was found mainly at point 2, 3, or 4. For comparison, the mean of the deepest points for each group was considered to represent the amount of wear for that group.

Table 3.11 summarises the mean wear depth track of the porcelain specimens after 5000, 15000 and 25000 cycles for the six groups. These results are also illustrated graphically in Fig. 3.4. Figure 3.5 summarises the cumulative porcelain wear rate for the three finishing surfaces in distilled water and Coca Cola. The cumulative porcelain wear rate in water vs. cola for the glazed, unglazed and polished surfaces are shown in Fig. 3.6. Overall, the graphs show that the amount of porcelain wear was higher in

the water groups than in the Coca Cola groups, the cumulative wear rate increased with increasing number of cycles. Repeated measures ANOVA (Table 3.12) showed a highly significant effect of media and number of cycles on porcelain wear ($p<0.001$), whilst the surface finishing had no significant effect on wear of the porcelain ($p=0.46$). None of the interaction terms was significant. Bonferroni multiple comparisons (Table 3.13), confirmed no significant difference overall between the three surface groups (glazed vs. unglazed, glazed vs. polished, unglazed vs. polished) at any of the three measurement times. However, there was a significant difference in the amount of porcelain wear between the water group and the Coca Cola group, with the mean size of this difference being similar at each of the three measurement times (no significant interactions)

Table 3.14 shows the depth of wear track at midpoint for 10 specimens of porcelain measured from the replicas (resin) and from the original (porcelain) specimens after 25000 cycles, as well as the difference between the two measurements. The maximum observed difference in this sample of 10 was 1.90μm. The 95% limits of agreement between the two measurements were calculated (mean of difference ± 2SD) (Bland, 1995) and were found to be -1.52 to 2.36μm, which is an acceptable level of agreement relative to the depth of wear track measured.

Table 3.1. Mean (μm, ± SD) of surface roughness (Ra) of porcelain specimens.

Group	N	Glazed	Unglazed*	Polished
Water	5	0.68 ± 0.17	1.56 ± 0.15	0.73 ± 0.08
Cola	5	0.66 ± 0.14	1.50 ± 0.25	0.79 ± 0.04
Total	10	0.67 ± 0.15	1.53 ± 0.19	0.76 ± 0.07

* The difference with glazed and polished was statistically significant after applying Bonferroni multiple comparisons (95%).

Table 3.2. Mean wear of enamel(mm, ± SD) after 5000, 15000 and 25000 cycles.

Cycles	Media	Glazed	Unglazed	Polished
5000	Water only	0.547 ± 0.103	0.710 ± 0.077	0.605 ± 0.112
	Cola/water	0.623 ± 0.110	0.768 ± 0.104	0.691 ± 0.057
15000	Water only	0.777 ± 0.125	0.918 ± 0.086	0.813 ± 0.117
	Cola/water	0.897 ± 0.124	1.037 ± 0.112	0.997 ± 0.064
25000	Water only	0.927 ± 0.151	1.057 ± 0.088	0.938 ± 0.106
	Cola/water	1.104 ± 0.136	1.232 ± 0.115	1.190 ± 0.055

N = 10 specimens per group

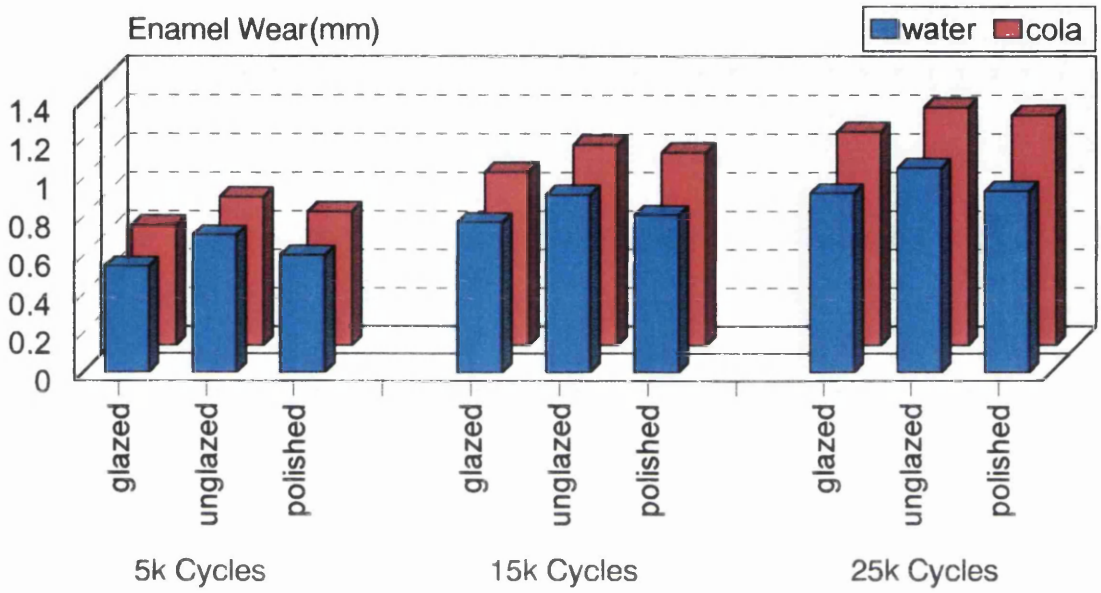
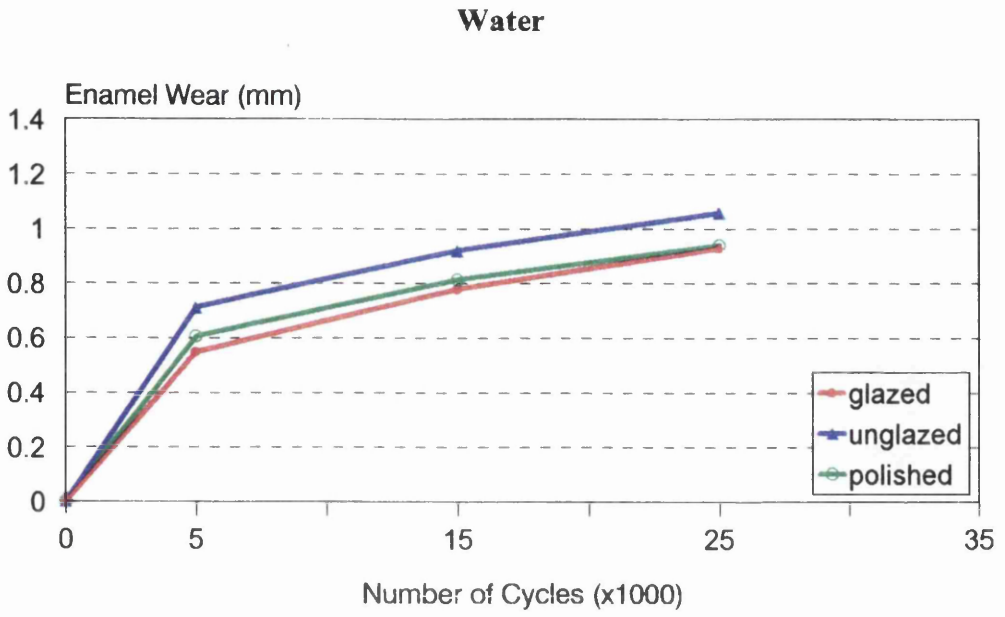


Fig. 3.1. Mean wear of enamel after 5000, 15000 and 25000 cycles against; glazed, unglazed and polished Alpha porcelain.



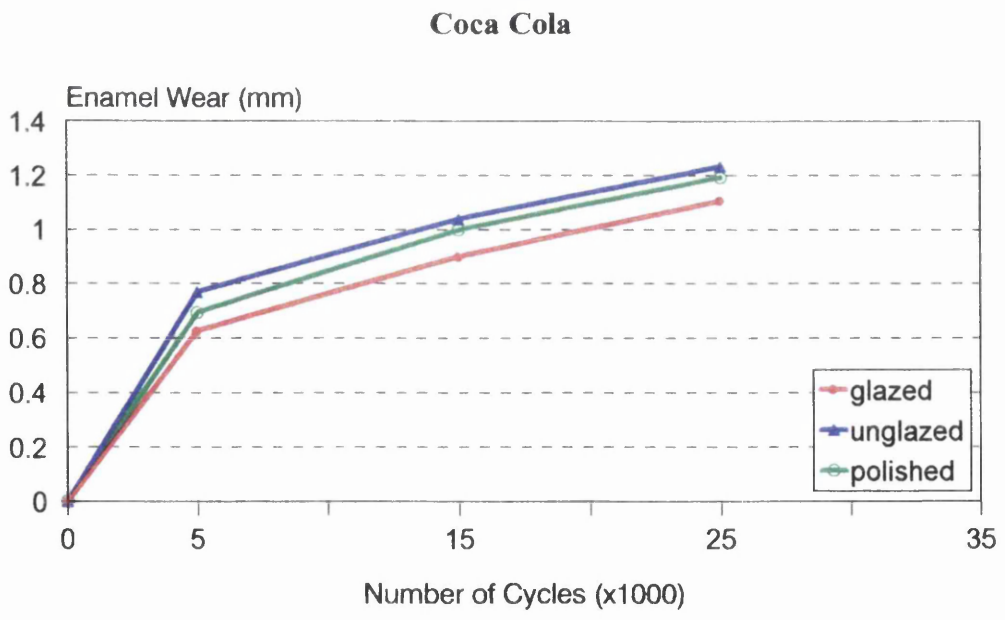


Fig. 3.2. Cumulative mean wear rates of enamel for water and Coca Cola groups.

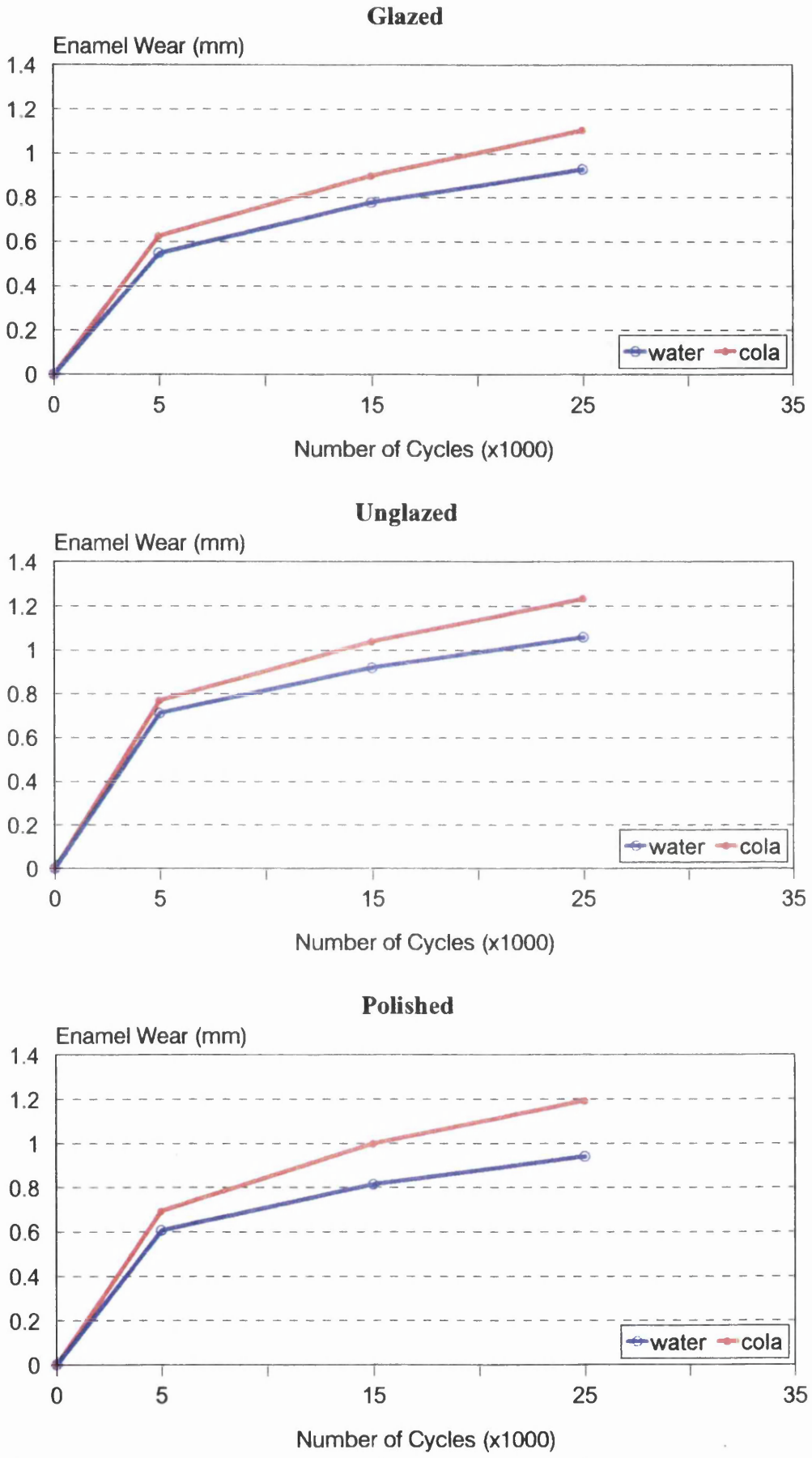


Fig. 3.3. Cumulative mean wear rates of enamel against Alpha porcelain groups; glazed, unglazed and polished in water and in Coca Cola.

Table 3.3. Repeated measures analysis of variance for enamel wear.

Source	DF	SS	MS	F	P
Media	1	0.86209	0.86209	27.46	< 0.001
Surface	2	0.60361	0.30180	9.61	< 0.001
Cycles	2	5.29590	2.64795	2684.79	< 0.001
Media*Surface	2	0.02898	0.01449	0.46	0.63
Media*Cycles	2	0.12159	0.06079	61.64	< 0.001
Surface*Cycles	4	0.00446	0.00112	1.13	0.35
Media*Surface*Cycles	4	0.00649	0.00162	1.64	0.17
Specimen (Media Surface)	54	1.69551	0.03140	31.84	< 0.001
Error	108	0.10652	0.00099		
Total	179	8.72516			

Table 3.4. Bonferroni multiple comparisons: simultaneous 95% confidence intervals for differences in mean enamel wear between surfaces and between media groups.

Factor	Groups	Interval Estimate*		
		5000 Cycles	15000 Cycles	25000 Cycles
Surface	Glazed-Unglazed	(-0.214, -0.094)^{s}	(-0.209, -0.073)^{s}	(-0.201, -0.057)^{s}
	Glazed-Polished	(-0.123, -0.003)^{s}	(-0.136, -0.000)^{s}	(-0.120, 0.023)^{ns}
	Unglazed-Polished	(0.030, 0.151)^{s}	(0.005, 0.141)^{s}	(0.009, 0.152)^{s}
Media	Water-Cola	(-0.133, -0.014)^{s}	(-0.208, -0.073)^{s}	(-0.272, -0.130)^{s}

* Difference between groups is significant if 95% confidence interval for difference in means does not overlap zero: s = significant; ns = not significant.

Table 3.5. Wear depth track (μm) of glazed alpha porcelain tested in water.

5000 Cycles

Point	Specimen Number										Mean	SD
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**		
i	27.13	19.28	23.80	34.02	19.78	26.28	33.33	33.77	18.20	37.69	27.33	7.06
ii	16.58	34.51	29.42	40.36	29.05	26.75	37.01	42.35	25.80	42.98	32.48	8.47
iii	21.70	35.76	32.49	31.66	25.98	28.04	37.39	41.58	27.14	44.32	32.61	7.19
iv	23.69	25.69	37.84	28.44	23.84	19.84	32.73	36.21	25.71	38.52	29.25	6.62
v	14.72	19.80	26.25	22.88	18.19	14.55	25.20	28.63	24.05	32.10	22.64	5.80
DP*	i	iii	iv	ii	ii	iii	iii	ii	iii	iii		
VDP*	27.13	35.76	37.84	40.36	29.05	28.04	37.39	42.35	27.14	44.32	**34.94**	6.60

15000 Cycles

Point	Specimen Number										Mean	SD
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**		
i	39.53	40.99	33.77	53.38	41.60	38.81	47.04	51.61	39.90	50.71	43.73	6.52
ii	39.47	57.76	42.32	66.38	49.54	48.79	71.08	70.13	43.73	76.78	56.60	13.63
iii	46.64	50.32	51.38	55.67	47.87	47.56	68.07	71.03	48.49	72.78	56.38	10.31
iv	42.56	52.47	48.24	53.44	44.38	42.94	58.49	60.46	43.78	58.43	50.52	7.04
v	30.73	44.21	47.54	51.08	30.44	29.44	46.08	50.54	30.26	47.72	40.70	9.46
DP*	iii	ii	iii	ii	ii	ii	ii	iii	iii	ii		
VDP*	46.64	57.76	51.38	66.38	49.54	48.79	71.08	71.03	48.49	76.78	**58.79**	11.44

25000 Cycles

Point	Specimen Number										Mean	SD
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**		
i	42.85	55.09	45.05	70.58	42.24	45.28	67.05	66.12	45.89	61.60	54.17	11.23
ii	67.10	82.19	68.91	86.67	59.13	64.29	89.23	88.18	59.31	89.81	75.48	12.88
iii	67.14	79.10	71.14	80.93	59.25	65.61	89.30	87.37	61.06	89.23	75.01	11.64
iv	63.56	78.97	65.96	79.04	53.97	59.09	79.41	79.49	54.42	77.41	69.13	10.88
v	46.54	64.72	59.07	67.25	32.87	44.53	54.17	64.39	39.80	60.98	53.43	11.85
DP*	iii	ii	iii	ii	iii	iii	iii	ii	iii	ii		
VDP*	67.14	82.19	71.14	86.67	59.25	65.61	89.30	88.18	61.06	89.81	**76.04**	12.39

*DP deepest point and VDP value of the deepest point

Table 3.6. Wear depth track (μm) of unglazed alpha porcelain tested in water.

5000 Cycles

Point	Specimen Number										Mean	SD
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**		
i	24.48	21.63	28.75	33.08	32.12	35.25	31.87	21.12	21.79	33.02	28.31	5.52
ii	24.12	23.03	21.59	40.65	37.24	37.28	33.02	21.79	23.63	40.97	30.33	8.23
iii	24.60	31.53	21.92	39.80	40.03	38.59	42.22	27.54	26.28	29.68	32.22	7.36
iv	35.37	31.25	28.23	49.18	40.71	28.27	32.08	26.73	20.74	30.26	32.28	7.94
v	12.79	21.51	14.31	25.31	22.09	26.23	13.39	16.11	20.19	20.86	19.28	4.86
DP*	iv	iii	i	iv	iv	iii	iii	iii	iii	ii		
VDP*	35.37	31.53	28.75	49.18	40.71	38.59	42.22	27.54	26.28	40.97	**36.11**	7.49

15000 Cycles

Point	Specimen Number										Mean	SD
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**		
i	37.09	39.07	31.55	53.38	47.28	46.01	33.34	40.15	43.71	59.59	43.12	8.78
ii	38.15	44.90	42.82	76.53	73.25	51.88	49.73	41.65	38.40	56.53	51.38	13.72
iii	43.36	59.40	39.55	73.11	67.69	51.40	61.07	50.24	49.41	53.88	54.91	10.47
iv	48.35	56.05	40.23	68.44	61.05	46.13	53.31	51.87	41.43	58.35	52.48	8.91
v	16.71	39.82	24.76	39.08	41.86	35.96	25.89	32.95	35.30	36.67	32.90	7.98
DP*	iv	iii	ii	ii	ii	ii	iii	iv	iii	i		
VDP*	48.35	59.40	42.82	76.53	73.25	51.88	61.07	51.87	49.41	59.59	**57.42**	10.85

25000 Cycles

Point	Specimen Number										Mean	SD
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**		
i	40.19	52.63	38.71	66.74	49.90	53.49	44.70	52.97	57.30	76.50	53.31	11.57
ii	44.29	58.74	57.10	99.87	77.42	78.72	63.19	60.41	57.30	72.10	66.91	15.59
iii	56.58	72.32	52.47	98.82	81.02	79.03	79.96	75.66	69.11	70.94	73.59	13.04
iv	54.37	74.68	55.68	90.22	69.45	65.37	65.97	71.30	58.24	75.00	68.03	10.77
v	19.27	57.32	31.56	51.24	47.54	51.42	39.43	47.32	50.76	51.41	44.73	11.50
DP*	iii	iv	ii	ii	iii	iii	iii	iii	iii	i		
VDP*	56.58	74.68	57.10	99.87	81.02	79.03	79.96	75.66	69.11	76.50	**74.95**	12.44

*DP deepest point and VDP value of the deepest point

Table 3.7. Wear depth track (μm) of polished alpha porcelain tested in water.

5000 Cycles

Point	Specimen Number										Mean	SD
	1	2	3	4	5	6	7	8	9	10		
i	28.88	18.13	22.95	23.90	22.56	27.97	38.01	24.74	29.67	37.81	27.46	6.47
ii	44.13	26.48	33.46	21.93	27.90	22.33	25.47	18.88	19.79	33.90	27.43	7.82
iii	40.60	20.95	25.60	25.01	35.29	27.01	32.57	28.12	21.08	50.19	30.64	9.24
iv	37.91	27.09	20.02	40.65	32.92	35.23	33.10	19.76	22.21	40.65	30.95	8.16
v	29.34	15.32	19.74	19.63	21.96	18.92	21.87	16.66	17.31	26.90	20.76	4.45
DP*	ii	iv	ii	iv	iii	iv	i	iii	i	iii		
VDP*	44.13	27.09	33.46	40.65	35.29	35.23	38.01	28.12	29.67	50.19	**36.18**	7.32

15000 Cycles

Point	Specimen Number										Mean	SD
	1	2	3	4	5	6	7	8	9	10		
i	43.95	33.26	37.70	33.27	50.69	41.22	60.23	35.96	42.28	52.69	43.13	8.95
ii	64.54	46.86	45.38	45.86	46.35	48.92	37.24	40.68	32.06	51.39	45.93	8.70
iii	64.38	39.59	41.57	53.10	51.90	51.64	61.36	35.24	32.77	64.31	49.59	11.78
iv	53.30	46.54	41.65	63.43	55.50	64.15	58.70	32.56	33.12	67.23	51.62	12.64
v	42.14	32.46	35.85	40.05	39.92	45.05	35.89	27.16	26.17	39.33	36.40	6.22
DP*	ii	ii	ii	iv	iv	iv	iii	ii	i	iv		
VDP*	64.54	46.86	45.38	63.43	55.50	64.15	61.36	40.68	42.28	67.23	**55.14**	10.34

25000 Cycles

Point	Specimen Number										Mean	SD
	1	2	3	4	5	6	7	8	9	10		
i	59.81	40.72	39.86	43.03	62.81	49.70	72.66	61.31	54.43	65.53	54.99	11.31
ii	77.91	53.00	59.15	60.99	67.36	71.03	58.87	63.51	43.47	62.84	61.81	9.48
iii	82.24	49.31	59.51	70.58	72.71	74.52	81.29	54.68	42.57	83.61	67.20	14.76
iv	66.02	58.59	61.81	73.67	75.99	83.31	76.95	58.64	44.14	78.29	67.74	12.03
v	51.01	39.66	52.97	40.04	62.54	46.84	48.10	41.74	37.92	47.58	46.84	7.51
DP*	iii	iv	iv	iv	iv	iv	iii	ii	i	iii		
VDP*	82.24	58.59	61.81	73.67	75.99	83.31	82.29	63.51	54.43	83.61	**71.94**	11.34

*DP deepest point and VDP value of the deepest point

Table 3.8. Wear depth track (μm) of glazed alpha porcelain tested in cola/water.

5000 Cycles

Point	Specimen Number										Mean	SD
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**		
i	13.10	11.89	7.05	9.33	10.08	22.97	8.65	15.44	14.70	12.52	12.57	4.52
ii	17.12	11.15	8.01	10.13	13.17	26.56	11.52	11.34	21.84	13.47	14.43	5.78
iii	23.77	12.76	8.56	16.61	16.84	27.76	16.50	13.28	25.30	19.65	18.10	6.04
iv	25.97	12.07	7.93	17.32	12.08	21.43	13.80	12.23	25.46	15.70	16.40	6.09
v	15.18	9.80	5.82	8.47	12.09	18.62	9.81	8.20	18.58	12.56	11.91	4.37
DP*	iv	iii	iii	iv	iii	iii	iii	i	iv	iii		
VDP*	25.97	12.76	8.56	17.32	16.84	27.76	16.50	15.44	25.46	19.65	**18.63**	6.15

15000 Cycles

Point	Specimen Number										Mean	SD
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**		
i	33.09	27.43	8.58	22.43	28.64	39.10	22.35	21.10	35.96	18.96	25.76	9.02
ii	40.03	32.33	15.36	30.59	27.76	51.46	31.99	21.80	49.27	25.02	32.56	11.49
iii	43.34	29.32	15.13	38.02	28.71	48.32	37.78	28.09	48.02	28.65	34.54	10.47
iv	42.45	22.83	11.36	32.01	27.33	40.73	32.58	26.09	45.17	24.30	30.49	10.34
v	39.06	23.05	11.18	23.06	33.14	37.25	28.53	25.76	39.07	21.12	28.12	9.07
DP*	iii	ii	ii	iii	v	ii	iii	iii	ii	iii		
VDP*	43.34	32.33	15.36	38.02	33.14	51.46	37.78	28.09	49.27	28.65	**35.74**	10.75

25000 Cycles

Point	Specimen Number										Mean	SD
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**		
i	44.54	53.44	21.32	39.21	34.03	46.67	33.13	28.79	46.27	26.31	37.37	10.34
ii	59.42	54.94	32.54	46.92	39.24	65.31	49.91	36.59	69.04	35.81	48.97	12.96
iii	61.87	46.71	32.32	51.60	41.09	63.37	56.79	41.21	71.74	40.25	50.69	12.52
iv	61.49	37.74	24.00	45.84	37.72	56.37	47.22	38.44	64.77	33.25	44.68	13.01
v	56.47	39.44	22.62	37.04	44.05	49.23	38.08	39.75	57.08	27.35	41.11	11.19
DP*	iii	ii	ii	iii	v	ii	iii	iii	iii	iii		
VDP*	61.87	54.94	32.54	51.60	44.05	65.31	56.79	41.21	71.74	40.25	**52.03**	12.44

*DP deepest point and VDP value of the deepest point

Table 3.9. Wear depth track (μm) of unglazed alpha porcelain tested in cola/ water.

5000 Cycles

Point	Specimen Number										Mean	SD
	1	2	3	4	5	6	7	8	9	10		
i	19.39	18.94	24.57	20.40	10.41	12.09	17.17	23.39	18.42	7.58	17.24	5.55
ii	38.29	12.34	10.69	19.72	10.39	16.50	18.77	27.19	17.72	16.36	18.80	8.44
iii	22.58	22.99	9.21	22.80	13.88	12.11	20.48	23.52	22.89	13.19	18.36	5.58
iv	25.17	25.09	12.57	20.33	18.51	16.46	26.62	26.45	23.26	14.81	20.93	5.13
v	14.29	19.13	6.87	15.37	10.07	8.56	21.56	19.63	15.45	9.87	14.08	5.08
DP*	ii	iv	i	iii	iv	ii	iv	ii	iv	ii		
VDP*	38.29	25.09	24.57	22.80	18.51	16.50	26.62	27.19	23.26	16.36	**23.92**	6.41

15000 Cycles

Point	Specimen Number										Mean	SD
	1	2	3	4	5	6	7	8	9	10		
i	44.01	41.45	44.74	35.52	18.72	25.60	27.00	44.46	35.05	20.74	33.73	10.07
ii	57.78	35.22	19.93	37.78	18.11	27.69	43.30	46.33	35.86	19.62	34.16	13.00
iii	41.56	47.02	29.00	41.89	30.35	19.42	48.45	45.51	42.02	23.63	36.88	10.38
iv	47.96	51.12	27.27	39.72	32.59	32.54	55.70	43.32	38.73	30.45	39.94	9.49
v	25.53	36.56	21.11	28.79	27.67	20.54	41.10	36.95	34.50	23.70	29.65	7.22
DP*	ii	iv	i	iii	iv	iv	iv	ii	iii	iv		
VDP*	57.78	51.12	44.74	41.89	32.59	32.54	55.70	46.33	42.02	30.45	**43.52**	9.63

25000 Cycles

Point	Specimen Number										Mean	SD
	1	2	3	4	5	6	7	8	9	10		
i	52.86	44.75	67.66	40.70	27.41	29.12	39.55	50.25	42.60	35.55	43.05	11.88
ii	62.25	58.99	43.01	49.92	27.72	30.21	55.67	61.37	48.61	24.31	46.21	14.33
iii	56.21	64.28	48.64	54.35	45.10	24.03	68.69	60.76	62.84	40.24	52.51	13.43
iv	62.77	71.58	46.68	53.65	47.76	43.88	70.93	59.09	54.76	43.56	55.47	10.44
v	38.44	46.48	38.83	41.77	43.25	33.08	58.72	46.43	45.50	33.15	42.57	7.53
DP*	iv	iv	i	iii	iv	iv	iv	ii	iii	iv		
VDP*	62.77	71.58	67.66	54.35	47.76	43.88	70.93	61.37	62.84	43.56	**58.67**	10.67

*DP deepest point and VDP value of the deepest point

Table 3.10. Wear depth track (μm) of polished alpha porcelain tested in cola/ water.

5000 Cycles

Point	Specimen Number										Mean	SD
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**		
i	31.97	14.99	13.00	12.53	12.44	15.21	18.19	23.94	11.97	26.04	18.03	6.95
ii	33.53	17.61	9.76	6.95	14.10	9.19	19.03	24.62	13.29	18.51	16.66	7.98
iii	34.47	22.55	11.48	7.16	14.79	14.70	21.84	29.46	24.77	27.04	20.83	8.61
iv	38.27	22.46	12.35	13.43	26.84	21.49	21.18	30.49	26.30	25.16	23.80	7.63
v	23.49	17.78	8.49	11.15	16.82	17.73	16.47	20.82	14.69	12.60	16.00	4.47
DP*	iv	iii	i	iv	iv	iv	iii	iv	iv	iii		
VDP*	38.27	22.55	13.00	13.43	26.84	21.49	21.84	30.49	26.30	27.04	**24.13**	7.56

15000 Cycles

Point	Specimen Number										Mean	SD
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**		
i	46.47	44.98	18.48	20.16	24.57	27.82	42.63	50.58	20.57	39.82	33.61	12.46
ii	65.98	42.65	25.50	15.30	27.69	21.90	52.70	56.20	31.17	39.74	37.88	16.46
iii	64.65	47.12	26.23	20.51	34.19	31.18	53.69	61.00	46.25	48.78	43.36	14.80
iv	61.90	44.88	31.64	30.23	41.10	36.97	49.52	57.54	40.19	48.61	44.26	10.38
v	34.89	35.54	20.17	26.17	28.22	31.80	35.11	41.92	31.03	26.05	31.09	6.19
DP*	ii	iii	iv	iv	iv	iv	iii	iii	iii	iii		
VDP*	65.98	47.12	31.64	30.23	41.10	36.97	53.69	61.00	46.25	48.78	**46.28**	11.79

25000 Cycles

Point	Specimen Number										Mean	SD
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**		
i	61.74	51.50	25.20	23.47	29.65	37.15	47.67	59.88	29.90	52.01	41.82	14.45
ii	81.32	64.59	38.04	23.16	37.31	33.62	70.89	75.29	46.98	55.06	52.63	19.80
iii	82.86	69.10	39.39	32.93	50.72	46.31	73.22	80.76	60.26	68.44	60.40	17.36
iv	78.62	63.12	41.29	45.37	55.98	56.37	60.21	75.35	54.98	63.61	59.49	11.65
v	54.64	48.19	25.43	35.16	41.76	49.91	41.33	55.37	44.01	40.16	43.60	9.09
DP*	iii	iii	iv	iv	iv	iv	iii	iii	iii	iii		
VDP*	82.86	69.10	41.29	45.37	55.98	56.37	73.22	80.76	60.26	68.44	**63.37**	13.99

*DP deepest point and VDP value of the deepest point

Table 3.11. Mean wear of Alpha porcelain (μm, ± SD) after 5000, 15000 and 25000 cycles.

Cycles	Media	Glazed	Unglazed	Polished
5000	Water only	34.94 ± 6.60	36.11 ± 7.49	36.18 ± 7.32
	Cola/water	18.63 ± 6.15	23.92 ± 6.41	24.13 ± 7.56
15000	Water only	58.79 ± 11.44	57.42 ± 10.85	55.14 ± 10.34
	Cola/water	35.74 ± 10.75	43.52 ± 9.63	46.28 ± 11.79
25000	Water only	76.04 ± 12.39	74.95 ± 12.44	71.94 ± 11.34
	Cola/water	52.03 ± 12.44	58.67 ± 10.67	63.37 ± 13.99

N = 10 specimens per group.

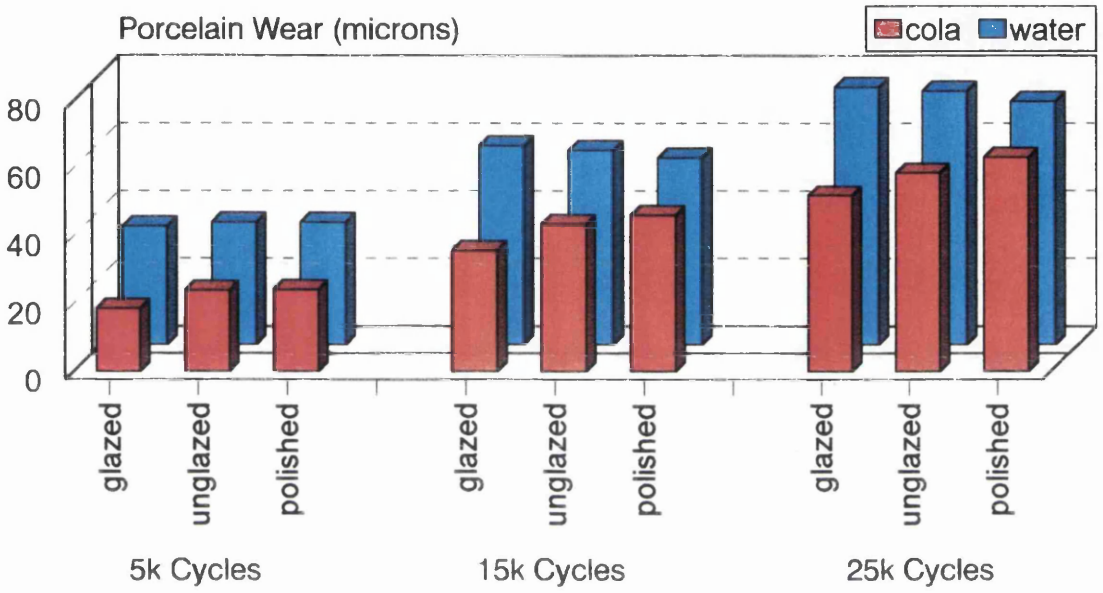
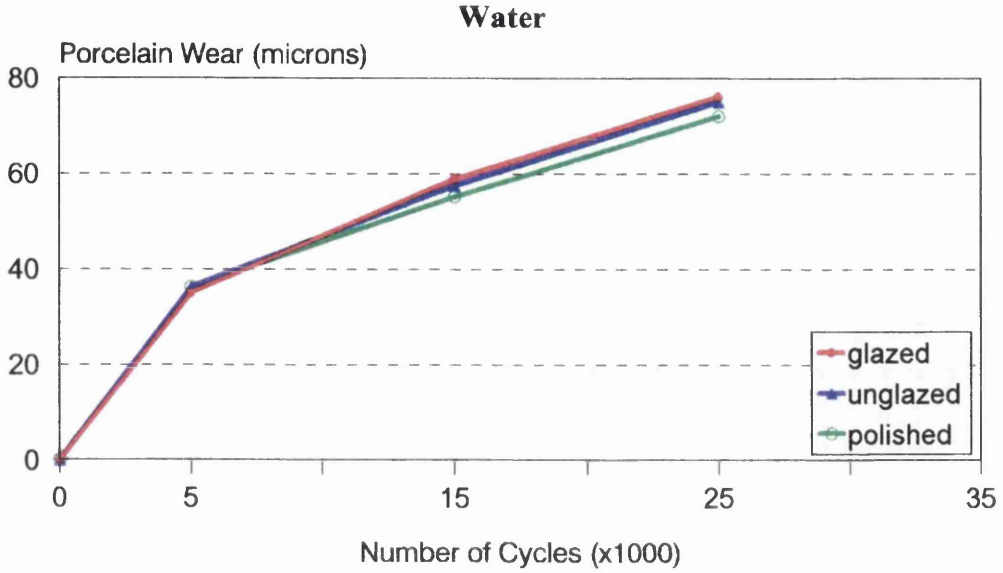


Fig. 3.4. Mean wear of Alpha porcelain after 5000, 15000 and 25000 cycles.



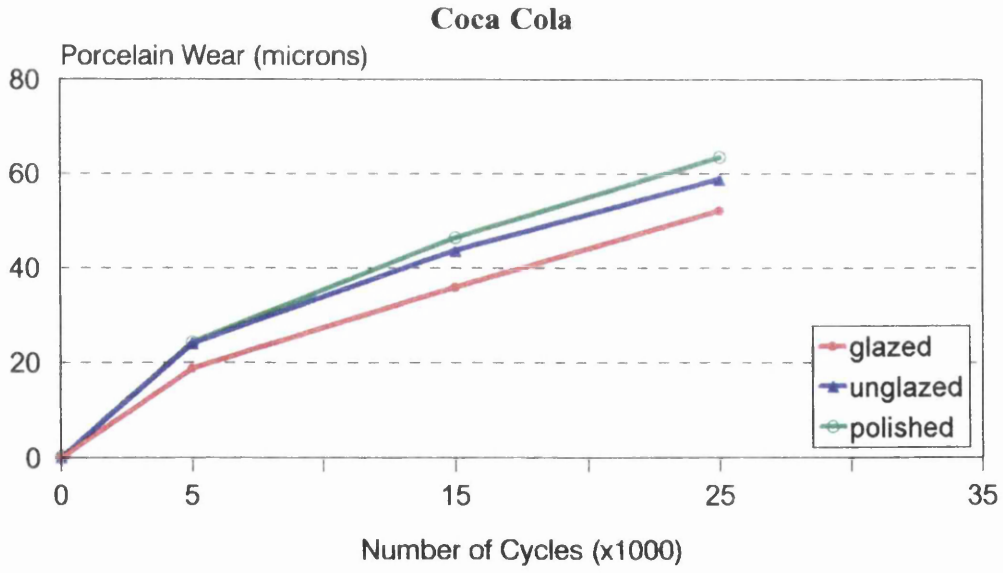


Fig. 3.5. Cumulative mean wear rates of Alpha porcelain for water and Coca Cola groups.

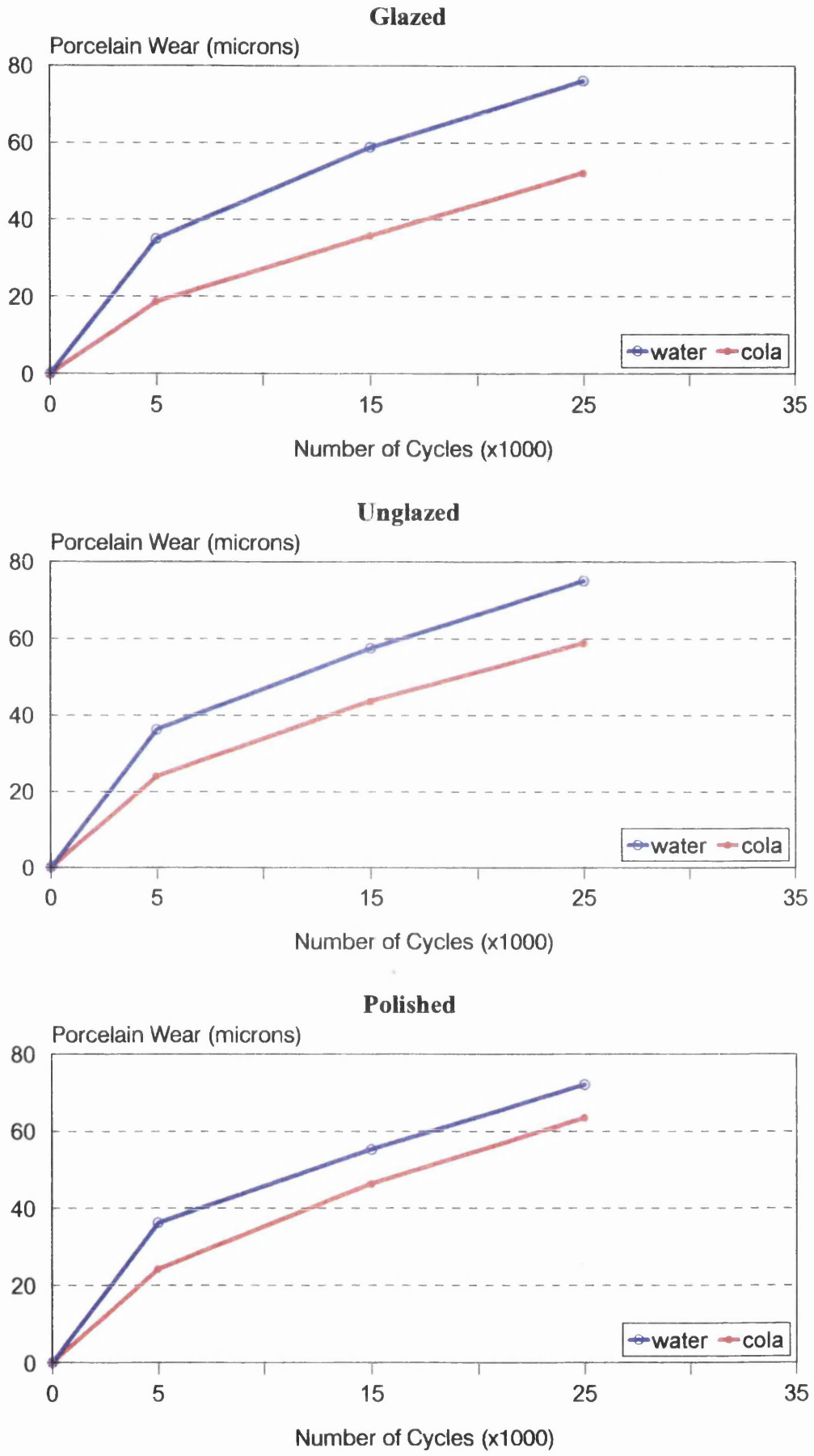


Fig. 3.6. Cumulative mean wear rates of Alpha porcelain groups; glazed, unglazed and polished in water and in Coca Cola.

Table 3.12. Repeated measures analysis of variance for porcelain wear.

Source	DF	SS	MS	F	P
Media	1	10161.18	10161.18	37.07	< 0.001
Surface	2	434.09	217.04	0.79	0.46
Cycles	2	41619.45	20809.72	1004.99	< 0.001
Media*Surface	2	973.46	486.73	1.78	0.18
Media*Cycles	2	58.74	29.37	1.42	0.25
Surface*Cycles	4	3.02	0.76	0.04	0.99
Media*Surface*Cycles	4	196.38	49.10	2.37	0.06
Specimen (Media Surface)	54	14800.29	274.08	13.24	< 0.001
Error	108	2236.30	20.71		
Total	179	70482.91			

Table 3.13. Bonferroni multiple comparisons: simultaneous 95% confidence intervals for differences in mean porcelain wear between surfaces and between media groups.

Factor	Groups	Interval Estimate*		
		5000 Cycles	15000 Cycles	25000 Cycles
Surface	Glazed-Unglazed	$(-7.632, 1.163)^{ns}$	$(-10.252, 3.850)^{ns}$	$(-10.732, 5.176)^{ns}$
	Glazed-Polished	$(-7.770, 1.025)^{ns}$	$(-10.494, 3.608)^{ns}$	$(-11.577, 4.332)^{ns}$
	Unglazed-Polished	$(-4.535, 4.259)^{ns}$	$(-7.293, 6.809)^{ns}$	$(-8.799, 7.110)^{ns}$
Media	Water-Cola	$(9.152, 17.892)^{s}$	$(8.262, 22.277)^{s}$	$(8.384, 24.193)^{s}$

* Difference between groups is significant if 95% confidence interval for difference in means does not overlap zero: s = significant; ns = not significant.

Table 3.14. Midpoint wear depth track of porcelain, measured (μm) from the replicas and their original porcelain specimens.

Specimen Number	Replica	Original	Difference (Replica-Original)
1	82.86	82.86	0.00
2	69.10	68.24	0.86
3	39.39	38.86	0.53
4	32.93	33.86	-0.93
5	50.72	48.82	1.90
6	46.31	46.26	0.05
7	73.22	74.27	-1.05
8	80.76	79.18	1.58
9	60.26	59.17	1.09
10	68.44	68.22	0.22
Mean	60.40	59.97	0.42
SD	17.36	17.24	0.97

3.4. Discussion

The porcelain specimens were constructed according to clinical laboratory procedures, and surface finishing was made to simulate clinical conditions. The results showed that the unglazed surface was significantly rougher than the glazed surface. Polishing the unglazed surface of porcelain (adjusted porcelain) using a porcelain finishing wheel and diamond paste was found to reduce the surface roughness significantly but not to the same extent as a glazed surface, although the difference between glazed and polished surfaces was not statistically significant. The difference in surface roughness between the porcelain groups could be responsible for the variation in the amount of enamel wear among the porcelain groups with different finishing surfaces. It can be seen from Fig. 3.1 that the greatest wear of enamel was against unglazed porcelain, followed by polished and glazed porcelain. This is in agreement with previous studies (Monasky and Taylor, 1971) but in disagreement with the study by Jagger and Harrison (1994), who found that the amount of enamel wear produced by both glazed and unglazed porcelain was similar whilst that produced by polished was substantially less. However, the difference between their study and the present study may be due to the way in which the porcelain specimens were prepared. The only difference between the glazed and unglazed specimens in the study by Jagger and Harrison (1994) was that the unglazed specimens were not fired to produce a glaze. In other words, no surface adjustment was carried out, in contrast to the present study. Indeed, the results of the present study show that the amount of enamel wear produced by polished porcelain after 25000 cycles was significantly less than that produced by the unglazed porcelain. In fact in the water group, the amount of enamel wear produced by polished porcelain (0.938 ± 0.106) was similar to that

produced by the glazed group (0.927 ± 0.151). The polishing procedure thus reduced the initial abrasiveness of the adjusted porcelain surface. Klausner *et al.* (1982) found no significant difference between the final polished surface and the initial autoglazed surface with regard to surface roughness.

The results show that the enamel wear increased when the wear test was carried out with exposure to the Coca Cola. It appears that the acidic effect of the Coca Cola may have demineralised the tooth enamel and made it more susceptible to the abrasive effect of the porcelain (Eccles, 1982b). The finishing surface of the porcelain was also seen to have an effect when the test was carried out with exposure to the Coca Cola, and again the greatest amount of enamel wear was produced by unglazed porcelain followed by polished and then glazed. In contrast, the finished surface of the porcelain did not affect its wear. However, the amount of wear of the porcelain in the water group was significantly higher than in the Coca Cola group. This could be again because of the acidic effect of the carbonated beverage in demineralising and softening the tooth enamel (Eccles, 1982b) as supported by an *in vitro* study by Lussi *et al.* (1993) where a significant decrease in enamel hardness was found after exposure to acidic beverages, including Coca Cola. Subsequently, tooth enamel softened by exposure to the carbonated beverage would not have the same capacity to abrade the porcelain surface as an enamel which had not been softened by acid exposure.

The results of this study showed that the surface adjustment did not affect the porcelain wear, however, it did affect the enamel wear significantly. By removing the glazed layer during porcelain adjustment, microporosities on the porcelain surface are

exposed (Patterson *et al.*, 1991). These porosities are not completely eliminated by polishing the porcelain surface (Sulik and Plekavich, 1981; Patterson *et al.*, 1991). Patterson *et al.* (1991) found that polishing of adjusted porcelain using a commercial porcelain refinishing kit that incorporates diamond paste reduced the surface roughness significantly but it was unable to restore the surface smoothness to that of the originally glazed porcelain, which concurs with the present study. In the present study, however, the difference in roughness between the polished and the original glazed surface was not statistically significant.

The results show (Fig. 3.2 and 3.5) that the rate of enamel and porcelain wear was high in the initial stages up to 5000 cycles, after which the degree of wear decreased gradually with time as shown in a previous study by DeLong *et al.* (1992). This may be because, at an early stage the contact area between the tooth cusp and the porcelain surface was small, and the load was distributed over that small area. Since the cusp had a cone shape, (half cone in the present study), with a reduction in height of the tooth cusp because of wear, the surface area increased gradually, and the load became distributed over a larger area. Thus, this may explain the more gradual decrease in the rate of wear after 5000 cycles. This supports the claim that a sharp tooth cusp with a small contact area promotes a greater degree of wear (Moon and Draughn, 1982).

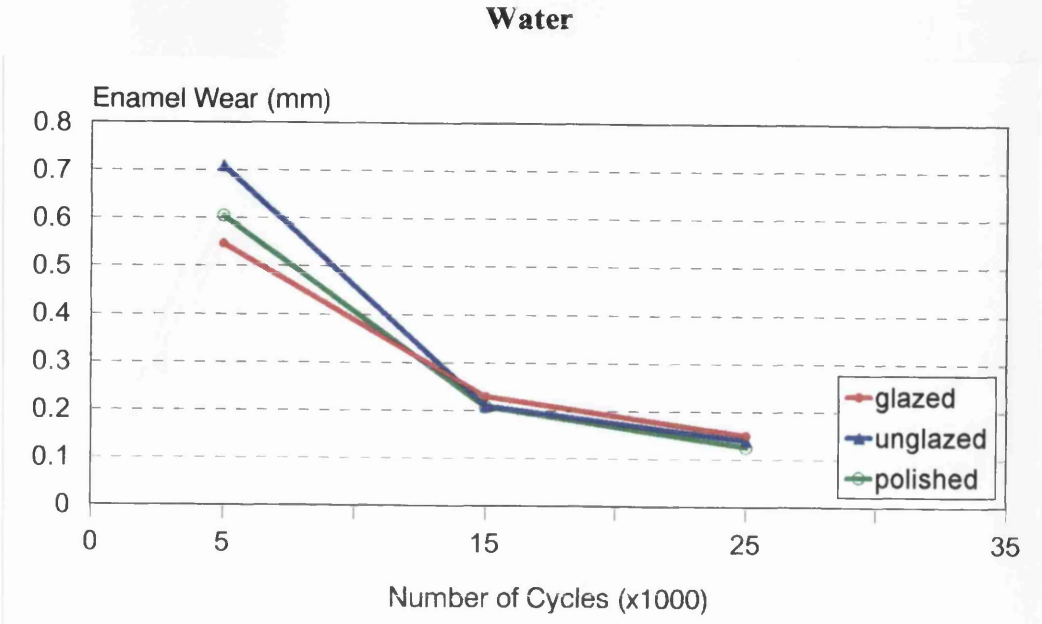
The graph lines of the cumulative enamel wear rate in Fig. 3.2 for the three surfaces are almost parallel. This may mean that the differences between the three surfaces was initiated at an early stage of the wear test, up to 5000 cycles, after which the

differences become less. Thus the abrasive effect of the rough surface becomes less with increasing the number of cycles. It was observed by visual examination that the wear track on the surface of the unglazed porcelain specimen appeared to become more and more polished with an increase in the number of cycles. Thus, the rate of enamel wear became slower and the effect of the finishing surface became more or less the same. This is shown more clearly in Fig. 3.7 which represents the individual (non cumulative) amount of enamel wear between each time period (namely wear from: 0-5000 cycles; 5000-15000 cycles and 15000-25000 cycles). This self polishing of the porcelain has been reported previously (Monasky and Taylor, 1971).

Repeated measures analysis of variance for enamel wear showed that the interaction between media*cycles (time) was significant. This means that the trend in mean enamel wear over time was significantly different for the two media (water vs. cola). Therefore, the graph lines in Fig. 3.3 are divergent. The fact that the three-way interaction was not significant suggests that pattern is the same for all three surfaces, which is in agreement with Fig 3.3. Thus, the difference in the rate of enamel wear between the water and Coca Cola groups increased with time. This could be due to the Coca Cola demineralising the enamel more and more with repeated exposure. The pH value of Coca Cola used in this study ranged from 2.28 to 2.37. The critical pH for enamel demineralisation is 5.5 (Meurman *et al.*, 1987; Järvinen *et al.*, 1988). An enamel surface which has been etched by acid is more susceptible to the effect of mechanical force (Eccles, 1982b).

The results of this study are in agreement with reports in the literature that acid exposure accelerates the rate of enamel wear (Lewis and Smith, 1973; Davis and Winter, 1980; Eccles, 1982b; Ratledge *et al.*, 1994) and supports the claim that the acid in some carbonated drinks demineralises and softens the tooth surface and their effects are intensified by superimposed abrasion or attrition (Eccles, 1982b). Thus, acid erosion may make the tooth surface more susceptible to attrition and abrasion (Smith, 1975).

This study also indicates the potential damage of porcelain on tooth enamel and suggests that whenever a porcelain restoration requires chairside adjustment, the resulting unglazed surface must be either reglazed or polished in order to produce the smoothest surface possible and to reduce the potential destructive abrasive effect of the porcelain on the opposing natural teeth. The following study investigated whether different porcelain types were as abrasive as the Vitadur Alpha porcelain tested in this study.



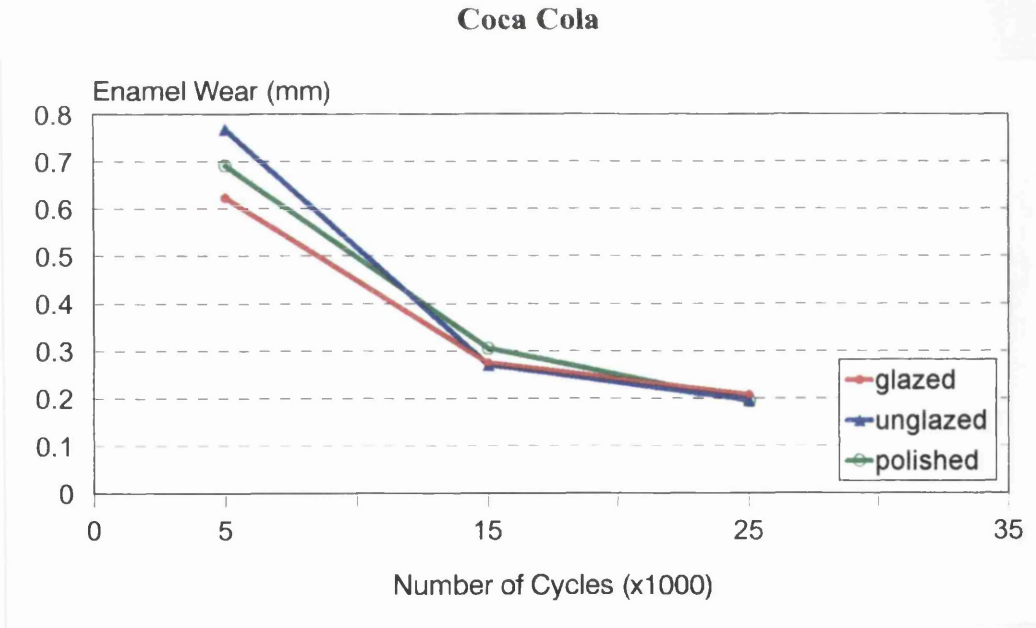


Fig. 3.7. Individual (non cumulative) mean wear rates of enamel against Alpha porcelain in water and in Coca Cola.

3.5. Conclusion

Under the conditions of this study the following points were concluded;

1. Polishing an unglazed porcelain surface (adjusted porcelain) with a finishing wheel and diamond paste reduced the surface roughness significantly, such that the difference in roughness between the resulting polished surface and the original glazed surface was not statistically significant.

2. Unglazed porcelain surface produced the highest amount of enamel wear, followed by polished and then glazed porcelain. After 25000 cycles the difference between glazed and polished groups was no longer significant, yet both produced significantly less enamel wear than the unglazed group.

3. Exposure to a carbonated beverage significantly accelerated the wear rate of enamel for the three surface finishes of porcelain.

4. The porcelain surface finish did not affect the wear of porcelain.

CHAPTER 4

Wear Of Human Enamel Against Dental Ceramics and Gold

Chapter 4: Wear Of Human Enamel Against Dental Ceramics and Gold

4.1. Introduction

Although the routine use of ceramics in restorative dentistry is a recent phenomenon, the desire for a durable and aesthetic material to restore the dentition is ancient (Kelly *et al.*, 1996). Patient demand for dental restorations that simulate the beauty of natural teeth and mask any metal substructure has contributed to the use of porcelain as a covering material (Hacker *et al.*, 1996). Dentists have provided their patients with porcelain-fused-to-metal restorations from the time they were introduced in dentistry in 1962 (Weinstein *et al.*, 1962; Weinstein and Weinstein, 1962). Very shortly after this introduction, in 1965, the aluminous porcelain was developed by McLean and Hughes (1965) from which the aluminous porcelain jacket crown was constructed (McLean, 1967), and the latter has since become an alternative option where aesthetics is of greater concern for the anterior teeth. However, reports have shown that dental ceramics are abrasive and potentially destructive to the opposing natural teeth (Wiley, 1989; Ratledge *et al.* 1994).

Previous studies have demonstrated that enamel wear when opposed by dental ceramics was substantially greater than when opposed by gold (Mahalick *et al.*, 1971; Jacobi *et al.*, 1991; Jagger and Harrison, 1995a). Nevertheless, according to a survey published by Christensen in 1986, the use of dental porcelain by dentists on occlusal surfaces of patients' teeth was found substantially more than the use of metal. The use of less abrasive ceramics would offer excellent aesthetics whilst minimising the wear

of the opposing natural teeth and would be a valuable addition to the dentists' selection of materials (Hacker *et al.*, 1996).

Duceram-LFC and Cerec Vita Mark II are two dental ceramics that have recently been introduced in dentistry. The novelty in their structure is that the Duceram-LFC is a hydrothermal ceramic, hydroxyl groups have been introduced into the glass network of the ceramic, and as a result the fusing temperature of the material is lowered (Komma, 1993). The Cerec Vita Mark II, a machinable ceramic, is marketed in the form of blocks made from fine particle feldspathic porcelain for use with CAD-CAM systems (i.e. Cerec system).

The aim of this study was to compare the wear of human enamel against two conventional ceramics (aluminous and bonded to metal porcelain), low fusing hydrothermal ceramic (Duceram-LFC), machinable ceramic (Cerec Vita Mark II) and cast gold.

4.2. Materials And Methods

Preparation of Material Specimens

The material specimens were constructed from: Vitadur Alpha porcelain (aluminous porcelain); Omega porcelain (bonded-to-metal porcelain); Duceram-LFC ceramic (low fusing hydrothermal ceramic); Cerec Vita Mark II (machinable ceramic); and cast gold (Kenbridge). All the ceramic materials were shade A3. Ten specimens of each material were produced according to the previous protocol (section 2.1). Specimens of Alpha porcelain, Omega porcelain and Duceram-LFC ceramic were

glazed, whilst the surface for Vita Mark II and gold specimens were polished as described previously (section 2.1).

Prior to the wear test, five specimens were selected randomly from each of the groups of the materials for average surface roughness measurement using the Dektak 3ST surface profile measuring system. Average roughness (Ra) of five surface profile tracings were recorded for each specimen as described previously (section 2.2), and the mean of the five readings was considered as the surface roughness for that particular specimen.

Preparation of Teeth

Tooth specimens were prepared from 25 extracted caries-free human mandibular premolars, as described in section 2.3. Thus 25 pairs of tooth specimens were obtained by sectioning each tooth in half in a bucco-lingual direction, through the buccal cusp tip. The 25 pairs of tooth specimens were divided into 5 groups, with 5 pairs in each group, thus 10 specimens were obtained per group. The root of each tooth specimen was embedded into the upper cylindrical specimen holder of the wear machine using autopolymerising acrylic resin (Formatray) (section 2.3).

Wear Test Procedure

The restorative material specimens were mounted onto the lower specimen holder of the wear machine. Both tooth and material specimens were kept in distilled water at room temperature for 24 hours before the wear test was carried out. The lower specimen holder with the material sample mounted onto it was then threaded into a

stainless steel support on the base of the dental wear machine. The upper specimen holder containing the tooth was inserted and tightened into the horizontal arm clamp. Both the upper (tooth) and lower (material) specimens were seated in a waterbath filled with distilled water. The level of the distilled water immersing the specimens was kept at a constant level and volume (50mL) by means of an overflow pipe. Material specimens with their antagonist tooth specimens were tested in the wear machine as described previously (section 2.4). Each tooth-material sample was tested under a load of 40 N at a rate of 80 cycles per minute and for a total of 25000 cycles. The samples were tested in distilled water, which was renewed after each 5000 cycles.

Wear Measurement

The amount of tooth enamel wear was measured after 5000, 15000, and 25000 cycles. A Reflex microscope was used to determine the amount of enamel wear of the tooth specimens by measuring the reduction in the tooth cusp height.

For the measurement of wear of the material specimens, at the end of the wear test and before the specimen was removed from the machine, an impression was taken *in situ* using a polyvinylsiloxane impression material (President) putty-wash technique. An epoxy resin replica was then produced from each impression from which the depth of the wear track was measured. Wear track depth was measured from each replica at five points across the wear track, using the Dektak 3ST surface profile measuring system, as described previously (section 2.5.2). The deepest measurement was chosen to represent the amount of wear for that particular specimen, and this was determined for each specimen. The accuracy of the replica in reproducing the material wear track was determined by comparing the wear track depth at the midpoint of five gold

specimens picked randomly, after the 25000 cycles of wear testing, to that measured from their resin replicas.

Statistical Analysis

The data for the surface roughness and the wear of the restorative materials was analysed with one way analysis of variance (ANOVA), while repeated measures ANOVA was used to analyse the data of the enamel wear. Overall, follow up comparisons were then carried out using the Bonferroni method to produce sets of simultaneous 95% confidence intervals (Altman, 1991).

4.3. Results

Table 4.1 shows the mean of surface roughness of each of the materials prior to wear testing. One way ANOVA revealed a significant difference in surface roughness among the groups ($P<0.001$). Follow up Bonferroni multiple comparisons (Table 4.2) showed that the differences in surface roughness between the ceramic groups were not statistically significant ($p>0.05$), whilst the gold group was significantly smoother than all the ceramic groups.

Table 4.3 shows the mean values for tooth cusp reduction (enamel wear) after 5000, 15000 and 25000 cycles. Fig. 4.1 illustrates graphically the means of enamel wear after 25000 cycles. The greatest amount of enamel wear was produced by Omega porcelain followed by Alpha porcelain, Vita Mark II and Duceram-LFC, and the least wear was produced by gold. Fig. 4.2 shows the cumulative wear rate of enamel after 5000, 15000 and 25000 cycles, exhibiting the same ranking of the groups at every

measuring interval. Fig. 4.2 also shows that the cumulative enamel wear rate increased with the increase in the number of cycles for all the groups, but this was less distinct for the gold group.

Repeated measures ANOVA (Table 4.4) showed highly significant effects of material and number of cycles on the wear of tooth enamel ($p<0.001$), as well as the interaction between material and cycles ($p<0.001$). Bonferroni multiple comparisons were used therefore to compare the amount of enamel wear produced by the different restorative material groups at each measurement time (after 5000, 15000 and 25000 cycles). The comparisons showed (Table 4.5) that at all intervals the amount of enamel wear in the Alpha and Omega groups was significantly higher than in the Duceram-LFC and Vita Mark II groups, while the enamel wear produced by gold was significantly lower than all the ceramic groups. There was no significant difference in the amount of enamel wear produced by Alpha and Omega porcelain, nor between Duceram-LFC and Vita Mark II, at all time intervals ($p>0.05$).

Table 4.6a-e show the values of the wear depth track of the restorative material specimens, at the five points of measurement, after 25000 cycles. Table 4.7 shows the mean wear of restorative materials (wear track depth) after 25000 cycles. These results are also illustrated graphically in Fig 4.3, which shows that Alpha porcelain had the deepest wear track, this was followed in order by Omega, Duceram-LFC, Vita Mark II and gold which had the shallowest wear track. One way analysis of variance (ANOVA) showed a highly significant difference among the groups ($p<0.001$). Bonferroni multiple comparisons follow-up showed (Table 4.8) that Alpha

and Omega porcelain groups had significantly greater wear than Duceram-LFC, Vita Mark II and the gold groups. However, the differences in wear between the pairs Alpha and Omega, Duceram-LFC and Vita Mark II and between Vita Mark II and gold were not statistically significant ($p>0.05$). The wear in the Duceram-LFC group was significantly greater than in the gold group.

Table 4.9 shows the depth of wear track at the midpoint for 5 specimens of gold measured from the resin replicas and from the original gold specimens, as well as the difference between the two measurements. The maximum observed difference in this sample of 5 was 0.56μm. The 95% limits of agreement between the two measurements were calculated (mean of difference ± 2SD) (Bland, 1995) and found to be -0.80μm to 0.56μm, which is an acceptable level of agreement relative to the depth of wear track measured.

Table 4.1. Mean ± SD of surface roughness (Ra) of restorative materials prior to the wear test.

Restorative Material	Surface Finishing	N	ROUGHNESS (Ra) (μm)
Alpha Porcelain	glazed	5	0.68 ± 0.17
Omega Porcelain	glazed	5	0.72 ± 0.10
Duceram-LFC	glazed	5	0.63 ± 0.07
Vita Mark II	polished	5	0.58 ± 0.10
Gold	polished	5	0.22 ± 0.06

Values connected by vertical lines were not significantly different ($p>0.05$) after applying Bonferroni multiple comparisons.

Table 4.2. Bonferroni multiple comparisons: simultaneous 95% confidence intervals for differences in mean surface roughness (Ra) of restorative materials.

Material	Omega	Duceram-LFC	Vita Mark II	Gold
Alpha	(-0.250, 0.178)	(-0.160, 0.268)	(-0.108, 0.320)	(0.248, 0.676)*
Omega		(-0.124, 0.304)	(-0.072, 0.356)	(0.284, 0.712)*
Duceram-LFC			(-0.162, 0.266)	(0.194, 0.622)*
Vita Mark II				(0.142, 0.570)*

* Significant, difference between materials is significant if 95% confidence interval for difference in means does not overlap zero.

Table 4.3. Mean wear of enamel ± SD after 5000, 15000 and 25000 cycles against restorative material groups.

Material Groups*	Enamel Wear (mm)		
	5000 Cycles	15000 Cycles	25000 Cycles
Alpha Porcelain	0.547 ± 0.103	0.777 ± 0.125	0.927 ± 0.151
Omega Porcelain	0.608 ± 0.134	0.835 ± 0.187	0.958 ± 0.197
Duceram-LFC	0.315 ± 0.061	0.448 ± 0.116	0.543 ± 0.152
Vita Mark II	0.406 ± 0.072	0.553 ± 0.132	0.653 ± 0.163
Gold	0.046 ± 0.018	0.071 ± 0.024	0.086 ± 0.026

*N = 10 specimens per group

Values connected by vertical lines were not significantly different ($p>0.05$) after applying Bonferroni multiple comparisons.

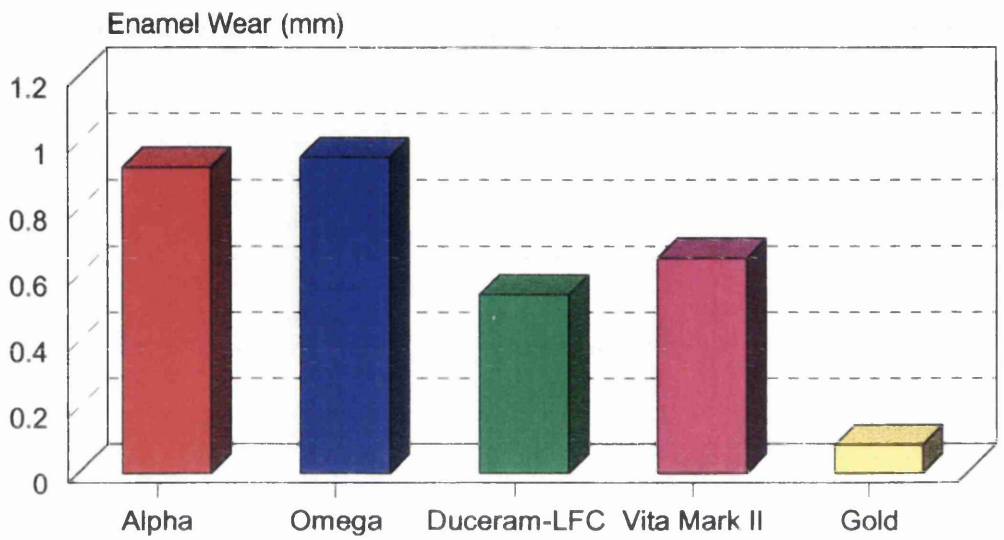


Fig. 4.1. Mean enamel wear after 25000 cycles against ceramics and gold.

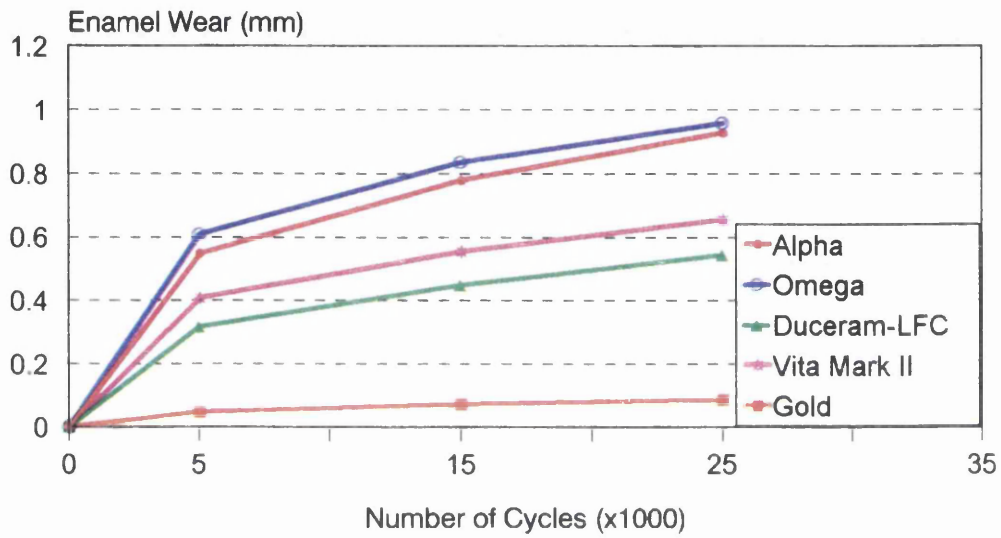


Fig. 4.2. Cumulative mean wear rate of enamel against ceramics and gold.

Table 4.4. Repeated measures analysis of variance for enamel wear.

Source	DF	SS	MS	F	P
Material	4	10.30346	2.57586	61.82	< 0.001
Cycles	2	1.57899	0.78950	340.80	< 0.001
Material*Cycles	8	0.36606	0.04576	19.75	< 0.001
Specimen (Material)	45	1.87502	0.04167	17.99	< 0.001
Error	90	0.20849	0.00232		
Total	149	14.33202			

Table 4.5. Bonferroni multiple comparisons: simultaneous 95% confidence intervals for differences in mean enamel wear between material groups.

Material Groups	Interval Estimate		
	5000 Cycles	15000 Cycles	25000 Cycles
Alpha - Omega	(-0.176, 0.054)	(-0.227, 0.111)	(-0.228, 0.167)
Alpha - Duceram-LFC	(0.117, 0.346)*	(0.160, 0.498)*	(0.187, 0.582)*
Alpha - Vita Mark II	(0.026, 0.255)*	(0.055, 0.393)*	(0.076, 0.472)*
Alpha - Gold	(0.386, 0.616)*	(0.537, 0.874)*	(0.644, 1.039)*
Omega - Duceram-LFC	(0.178, 0.407)*	(0.218, 0.555)*	(0.217, 0.612)*
Omega - Vita Mark II	(0.087, 0.316)*	(0.113, 0.451)*	(0.107, 0.502)*
Omega - Gold	(0.447, 0.677)*	(0.595, 0.932)*	(0.674, 1.069)*
Duceram-LFC - Vita Mark II	(-0.205, 0.024)	(-0.274, 0.064)	(-0.308, 0.087)
Duceram-LFC - Gold	(0.155, 0.384)*	(0.208, 0.546)*	(0.259, 0.654)*
Vita Mark II - Gold	(0.246, 0.475)*	(0.313, 0.650)*	(0.370, 0.765)*

* Significant, difference between groups is significant if 95% confidence interval for difference in means does not overlap zero.

Table 4.6. Wear depth track (μm) of restorative materials after 25000 cycles.

(a) Alpha porcelain

Point	Specimen Number										Mean	SD
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**		
i	42.85	55.09	45.05	70.58	42.24	45.28	67.05	66.12	45.89	61.60	54.17	11.23
ii	67.10	82.19	68.91	86.67	59.13	64.29	89.23	88.18	59.31	89.81	75.48	12.88
iii	67.14	79.10	71.14	80.93	59.25	65.61	89.30	87.37	61.06	89.23	75.01	11.64
iv	63.56	78.97	65.96	79.04	53.97	59.09	79.41	79.49	54.42	77.41	69.13	10.88
v	46.54	64.72	59.07	67.25	32.87	44.53	54.17	64.39	39.80	60.98	53.43	11.85
DP*	iii	ii	iii	ii	iii	iii	iii	ii	iii	ii		
VDP*	67.14	82.19	71.14	86.67	59.25	65.61	89.30	88.18	61.06	89.81	**76.04**	12.39

(b) Omega Porcelain

Point	Specimen Number										Mean	SD
	1	2	3	4	5	6	7	8	9	10		
i	38.34	18.42	14.74	31.31	41.91	15.12	33.19	35.17	29.48	26.23	28.39	9.59
ii	51.30	26.97	15.49	39.21	77.48	31.46	70.93	29.80	32.73	80.61	45.60	23.16
iii	61.59	40.81	32.20	51.25	93.38	48.31	86.40	41.03	51.86	92.22	59.90	22.69
iv	56.53	39.52	38.62	50.00	85.14	50.59	72.02	53.44	49.50	80.82	57.62	16.27
v	43.10	27.64	29.52	32.81	43.18	36.98	32.84	49.60	42.10	36.76	37.45	6.96
DP*	iii	iii	iv	iii	iii	iv	iii	iv	iii	iii		
VDP*	61.59	40.81	38.62	51.25	93.38	50.59	86.40	53.44	51.86	92.22	**62.02**	20.85

(c) Duceram-LFC

Point	Specimen Number										Mean	SD
	1	2	3	4	5	6	7	8	9	10		
i	18.10	56.99	24.14	25.49	25.13	22.08	15.42	26.36	25.53	34.55	27.38	11.59
ii	14.33	65.45	33.91	15.94	15.84	24.26	28.03	44.44	26.64	48.14	31.70	16.58
iii	18.94	61.63	36.54	16.11	16.95	29.93	30.53	59.27	39.77	69.95	37.96	19.56
iv	28.48	34.25	31.58	17.16	17.89	22.49	30.14	53.85	48.08	69.02	35.29	16.76
v	22.98	27.22	23.39	19.55	14.22	18.81	25.22	40.42	36.72	43.40	27.19	9.78
DP*	iv	ii	iii	i	i	iii	iii	iii	iv	iii		
VDP*	28.48	65.45	36.54	25.49	25.13	29.93	30.53	59.27	48.08	69.95	**41.88**	17.36

*DP deepest point and VDP value of the deepest point.

(d) Cerec Vita Mark II

Point	Specimen Number										Mean	SD
	1	2	3	4	5	6	7	8	9	10		
i	43.15	8.98	28.65	11.85	29.47	16.27	12.10	7.40	15.11	31.28	20.3[illegible]	11.89
ii	28.44	28.75	14.53	11.38	15.81	10.96	18.74	13.26	23.34	41.23	20.64	9.75
iii	23.87	19.23	9.07	6.49	15.49	14.34	19.28	8.02	20.80	21.33	15.79	6.14
iv	31.17	11.52	19.72	12.73	10.85	18.70	17.24	8.88	18.94	23.59	17.33	6.74
v	24.10	8.81	14.85	10.47	8.03	12.67	10.81	7.97	15.48	17.84	13.10	5.11
DP*	i	ii	i	iv	i	iv	iii	ii	ii	ii		
VDP*	43.15	28.75	28.65	12.73	29.47	18.70	19.28	13.26	23.34	41.23	**25.86**	10.52

(e) Gold

Point	Specimen Number										Mean	SD
	1	2	3	4	5	6	7	8	9	10		
I	13.23	13.12	11.51	10.28	21.20	8.21	13.95	9.74	17.29	25.51	14.40	5.44
II	16.42	11.73	11.00	9.70	24.60	6.58	12.67	10.78	16.06	17.02	13.66	5.06
III	18.62	12.92	11.62	12.88	25.23	10.36	17.41	10.26	15.27	14.85	14.94	4.57
IV	17.27	11.52	10.20	9.62	24.47	7.20	13.29	9.54	14.97	15.27	13.34	5.00
V	10.01	6.86	7.31	5.25	16.94	4.26	7.85	4.62	8.66	9.67	8.14	3.68
DP*	III	I	III	III	III	III	III	II	I	I		
VDP*	18.62	13.12	11.62	12.88	25.23	10.36	17.41	10.78	17.29	25.51	**16.28**	5.59

*DP deepest point and VDP value of the deepest point.

Table 4.7. Mean wear of restorative materials ±SD after 25000 cycles.

Restorative Material	N	Wear of Restorative Materials (μm)
Alpha Porcelain	10	76.04 ± 12.39
Omega Porcelain	10	62.02 ± 20.85
Duceram-LFC	10	41.88 ± 17.36
Vita Mark II	10	25.86 ± 10.52
Gold	10	16.28 ± 5.59

Values connected by vertical lines were not significantly different ($p>0.05$) after applying Bonferroni multiple comparisons.

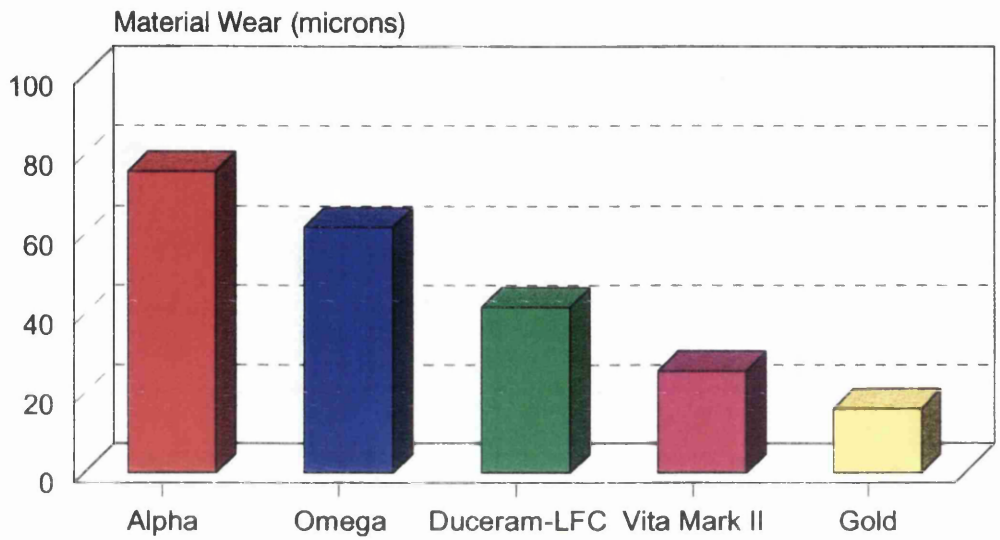


Fig. 4.3. Mean wear of restorative materials after 25000 cycles.

Table 4.8. Bonferroni multiple comparisons: simultaneous 95% confidence intervals for differences in mean of restorative materials wear.

Material	Omega	Duceram-LFC	Vita Mark II	Gold
Alpha	(-4.94, 32.98)	(15.19, 53.11)*	(31.22, 69.14)*	(40.79, 78.72)*
Omega		(1.17, 39.09)*	(17.20, 55.12)*	(26.77, 64.70)*
Duceram-LFC			(-2.93, 34.99)	(6.64, 44.57)*
Vita Mark II				(-9.39, 28.54)

* Significant, difference between materials is significant if 95% confidence interval for difference in means does not overlap zero.

Table 4.9. Midpoint wear depth track, measured (μm) from the replicas and their original gold specimens.

Specimen Number	Replica (Resin)	Original (Gold)	Difference (Replica-Original)
1	10.36	10.28	0.08
2	17.41	17.97	-0.56
3	10.26	10.59	-0.33
4	15.27	15.37	-0.10
5	14.85	14.53	0.32
Mean	13.63	13.75	-0.12
SD	3.18	3.28	0.34

4.4. Discussion

The results of this study show that the gold group had the smoothest surface compared to the ceramic groups, and this was statistically significant. Moreover, the gold produced the least amount of enamel wear, which was also significantly less than all ceramic groups tested. On other hand, there were no significant differences in surface roughness between the ceramic groups, while the amount of enamel wear was significantly different among these groups. Therefore, surface roughness is not the only factor that affected the wear process, but the properties and structure of the materials may play a part. Seghi *et al.* (1991) found that material hardness was poorly correlated with the abrasiveness of ceramic materials on human enamel. They suggested that microstructural differences between different ceramic materials may explain the different amounts of enamel abrasion. The fact that gold produced less enamel wear than dental ceramics has been reported in previous studies (Mahalick *et al.*, 1971; Jacobi *et al.*, 1991; Jagger and Harrison, 1995a; Hacker *et al.*, 1996).

The two conventional high fusing porcelains tested in the present study, the aluminous Alpha and bonded-to-metal Omega, showed a similarity in their abrasivity against enamel as well as their resistance to wear. The main difference between aluminous and bonded porcelain lies in the high strength of the aluminous porcelain core, the latter containing up to 50% (by weight) fused alumina crystals (McLean, 1979, 1988). The core of the Alpha porcelain in this study was covered with a dentine layer of Alpha porcelain which probably does not differ much in regard to its abrasivity from the dentine layer of the Omega porcelain. The latter has, however, more alkali in its structure, while the Alpha porcelain dentine has more alumina content (McLean,

1979). The teeth in both groups were abrading against the dentine porcelain layer and the wear did not reach the core of the Alpha porcelain or the opaque material of the Omega porcelain. It appears that the difference between the Alpha and Omega dentine layers did not affect the wear process much, since both groups showed similarity in their resistance to wear and their abrasivity against tooth enamel.

The present study showed that the conventional high fusing porcelains caused significantly more enamel wear than the low fusing ceramic, yet the latter still caused significantly more enamel wear than gold. This is in agreement with a study by Hacker *et al.* (1996). Furthermore, they reported that gold exhibited the least amount of wear compared with the conventional and low fusing porcelain, which was also found in the present study. The low fusing porcelain that they used (Procera All-Ceramic Porcelain) demonstrated more wear than the conventional porcelain (Ceramco), although the difference was not statistically significant. However, in the present study the opposite was found in that the low fusing ceramic Duceram-LFC showed significantly less wear than the conventional porcelain (Alpha and Omega). This could be because of the chemical structure and characteristics of the Duceram-LFC. The latter is a leucite-free ceramic consisting of a one-phase glass material. In the production of Duceram-LFC hydroxyl ions are introduced into its structure under heat and steam. Thus, the Duceram-LFC is called an hydrothermal ceramic (Komma, 1993). When the Duceram-LFC comes in contact with water, a layer with many OH-groups is formed on the surface of the ceramic. This layer is built through alkali and hydroxyl exchange. Thus, the surface Si-hydroxyl layer is more flexible and can heal surface flaws. In addition, even when this layer is removed from the surface by

mechanical force, a new layer is built up quickly. Thus, the surface of the Duceram-LFC has an inherent self-healing property. It is also reported that the leucite-free (Duceram-LFC) dental ceramic is less brittle than the known conventional dental ceramics, and the Si-hydroxyl layer shows signs of plastic deformation which also protects the surface from damage (Komma, 1993). In summary, this structure and its characteristics might explain why the Duceram-LFC ceramic was less abrasive on the enamel and, at the same time, had less wear than the conventional Alpha and Omega porcelains. More investigation is required to determine the characteristics of the Duceram-LFC ceramic in greater detail.

The machinable ceramic Vita Mark II also was less abrasive on enamel and had less wear than conventional Alpha and Omega porcelains. Krejci *et al.* (1994) found that Vita Mark II, which is a fine particle-sized porcelain material, was less abrasive on an opposing tooth enamel cusp than the traditional coarse porcelain Vita Mark I. The fact that in the present study the Vita Mark II had less wear than the conventional Alpha and Omega porcelains, might be because of the quality of condensation and the particle size (average 4μm; Vita product information) of the porcelain. Vita Mark II is a factory-made ceramic of small particle size, whilst conventional porcelains are made by hand condensation. The porcelain particles of the conventional porcelains may be comparatively easily loosened and displaced from the porcelain matrix, which may explain why the conventional porcelains exhibited greater wear. Furthermore, this might also contribute to the greater wear of enamel produced by the conventional porcelain groups. Kelly *et al.* (1996) stated that many important physical properties are directly dependent on how the ceramic is made, and a ceramics manufacturer can

generally provide a superior material compared with a dental laboratory. Thus, an advantage of the machinable ceramic systems is the removal of ceramic processing, and hence microstructural control, from the dental laboratory and placing it within the jurisdiction of the manufacturer. However, although Vita Mark II was significantly less abrasive than conventional Alpha and Omega porcelains, it was still significantly more abrasive than gold, which is in agreement with the study by Ramp *et al.* (1996).

Overall, the cumulative wear rate of enamel for all groups increased with an increase in cyclic loading. The graph of enamel wear rate in Fig. 4.2 shows that the rate of wear was maximal in the initial stages of the experiment, up to 5000 cycles, after which the rate decreased gradually. This is in agreement with a study by DeLong *et al.* (1992). This change in the wear rate may be because, at the initial stage the load was distributed over a small contact area between the tip of the cusp and the material specimen surface. With time (cycles) and because of the height reduction (wear) of the tooth cusp (cone shape) the contact area increased gradually, and the load became distributed over a larger area and therefore the rate of wear slowed (Moon and Draughn, 1982). The reduction in the wear rate of enamel was quite obvious when the enamel was opposed to the gold. After the wear test it was noticed in the gold group that the enamel wear facets had greyish-golden patches. This finding was also noticed by Hacher *et al.*(1996), which may be an indication that the gold was adhering to the enamel as a result of an adhesive-wear mechanism. Moreover, it has been claimed that cast metals appear to have the best wear characteristics because they maintain a smooth surface, thus minimising surface friction (Mair *et al.*, 1996).

Finally, the results of the present study confirm that gold is less abrasive than the dental ceramics tested. Duceram-LFC and Vita Mark II were shown to be less abrasive against enamel and less prone to wear than conventional porcelains (Alpha and Omega). The following studies investigated further the wear properties of Duceram-LFC and Vita Mark II under different conditions.

4.5. Conclusion

The following points were concluded from this study:

1. The polished gold had the smoothest surface, whilst the glazed Omega porcelain was the roughest followed by glazed Alpha porcelain, glazed Duceram-LFC, and then polished Vita Mark II, although the difference between the ceramic groups was not statistically significant.

2. The Duceram-LFC (hydrothermal low fusing ceramic) and the Vita Mark II (machinable ceramic) were significantly less abrasive to enamel than conventional Alpha and Omega porcelains. All the ceramic materials tested were significantly more abrasive than gold.

3. Gold was less prone to wear than the dental ceramics tested in this study, although the difference between gold and Vita Mark II was not statistically significant. The Duceram-LFC and Vita Mark II were significantly less prone to wear than Alpha and Omega porcelains.

4. There was no significant difference in either ceramic wear or in enamel wear between the Alpha and Omega groups, nor between Duceram-LFC and Vita Mark II groups.

CHAPTER 5

The Effect of Carbonated Beverages on the Wear of Human Enamel and Dental Ceramics

Chapter 5: The Effect of Carbonated Beverages on the Wear of Human Enamel and Dental Ceramics

5.1. Introduction

Throughout history, ceramics have been found to be resistant to corrosion, abrasion, and dissolution even in an acidic environment. These properties led Fauchard in the early part of the eighteenth century to suggest the use of porcelain for making artificial teeth and since then work has continued on this group of materials leading to the diverse range of dental ceramics in use today (McLean, 1991). Generally, there are two major problems that arise with the use of ceramics in dentistry. Firstly, is their potential for brittle, catastrophic fracture and secondly their potential destructive effect by abrading the opposing natural tooth structure (Rosenblum and Schulman, 1997). Among the new ceramic systems that have been developed and introduced recently to restorative dentistry are the Duceram-LFC (hydrothermal low fusing ceramic) and the Cerec Vita Mark II (machinable ceramic). These two ceramics are found to be less abrasive and more resistant to wear than conventional porcelain (Chapter 4) when tested in distilled water. The low abrasivity on tooth enamel and their resistance to wear may be attributed to their microstructure being different from conventional porcelains.

The aim of the present study was to compare the effect of carbonated beverages with a low pH on the wear resistance of Duceram-LFC and Cerec Vita Mark II, and their abrasivity on human enamel, with that already found with conventional Alpha porcelain (Chapter 3).

5.2. Materials and Methods

Preparation of Ceramic Specimens

Ten specimens of Duceram-LFC (low fusing hydrothermal ceramic) and ten specimens of Cerec Vita Mark II (machinable ceramic) were produced according to the method described previously (section 2.1). Specimens of Duceram-LFC were glazed, whilst the surface for Vita Mark II was polished, as described earlier (section 2.1).

Prior to the wear test, five specimens were selected randomly from each of the two groups of ceramics for average surface roughness measurement, using the Dektak 3ST surface profile measuring system. Average roughness (Ra) of five surface profile tracings were recorded for each specimen (section 2.2), and the mean of the five readings was considered as the surface roughness for that particular specimen.

Preparation of Teeth

Tooth specimens were prepared from 10 extracted caries-free human mandibular premolars (section 2.3). Thus 10 pairs of tooth specimens were obtained by sectioning each tooth in half in a bucco-lingual direction, through the buccal cusp tip. The 10 pairs of tooth specimens were divided into 2 groups, with 5 pairs in each group, thus 10 specimens were obtained per group. The root of each tooth specimen was embedded into the upper cylindrical specimen holder of the wear machine using autopolymerising acrylic resin (Formatray).

Wear Test Procedure

Duceram-LFC and Vita Mark II specimens were mounted onto the lower specimen holder of the wear machine (section 2.1). Both tooth and ceramic specimens were kept in distilled water at room temperature for 24 hours prior to the wear test, after which they were mounted in the wear machine. Each tooth-ceramic sample was tested under a load of 40 N, at a rate of 80 cycles per minute and for a total of 25000 cycles. The tooth-ceramic samples were tested with an intermittent exposure to Coca Cola (pH range 2.28-2.37) for 5000 cycles in Coca Cola, and 5000 cycles in distilled water alternately, up to 25000 cycles (i.e. 3 times in Coca Cola and twice in distilled water). 50mL of either Coca Cola or distilled water was used each time to fill the waterbath of the wear machine.

Wear Measurement

The amount of tooth enamel wear (cusp height reduction) was measured after 5000, 15000, and 25000 cycles, using a reflex microscope, (section 2.5.1). Ceramic material wear was assessed after the completion of the wear test (after 25000 cycles) by determining the deepest point of the wear track measured from the epoxy resin replicas of the ceramic specimens using the Dektak 3ST surface profile measuring system (section 2.5.2).

Statistical Analysis

For reasons of comparison, the glazed Alpha porcelain data (water and cola groups), from Chapter 3, was included as well as the data of the Duceram-LFC and Vita Mark

II groups, from Chapter 4, where the test was carried out in water only. Thus, all the data was analysed together.

One-way analysis of variance (ANOVA) was used to analyse the surface roughness data of the ceramic groups. The enamel wear data was analysed using repeated measures ANOVA to explore the data for any statistically significant effects of material type, media, and number of cycles. Two-way ANOVA was performed to analyse the data for the wear of the ceramic materials to explore the data for any significant effects of material type and media. Overall, postanalysis paired comparisons was carried out with the *t*-test. In view of the number of individual tests done, a Bonferroni approach (Bonferroni correction method) was used (Altman, 1991), in which differences were regarded as statistically significant if the probability (p) was less than 0.017. Differences with p values greater than 0.017 were regarded as not statistically significant.

5.3. Results

Table 5.1 shows the mean surface roughness of the ceramic material groups prior to wear testing. One-way analysis of variance (ANOVA) showed no significant difference in surface roughness between the three ceramic groups (p=0.19).

Table 5.2 shows the mean values for tooth cusp reduction (enamel wear) after 5000, 15000 and 25000 cycles. Figure 5.1 illustrates graphically the means of enamel wear against the ceramic materials after 25000 cycles. Overall, the amount of enamel wear was increased when the test was carried out with exposure to the Coca Cola. Figure

5.2 shows the mean of the cumulative enamel wear rates against the three ceramic materials for the water (media, water only) and Coca Cola (media, cola/water) groups. The graphs (Fig. 5.2) show that when the test was carried out in water only at all the measurement intervals, the greatest amount of enamel wear was produced by Alpha porcelain, followed by Vita Mark II and then Duceram-LFC, which produced the least amount of enamel wear. When the test was carried out with exposure to the Coca Cola at all measurement intervals Alpha porcelain produced the greatest amount of enamel wear and this was followed this time by Duceram-LFC and Vita Mark II, which produced the lowest amount of enamel wear in this event. Figure 5.3 shows the means of the cumulative enamel wear rates in water vs cola against the three ceramic materials separately. Overall, exposure to the Coca Cola accelerated the enamel wear rates. Both Fig. 5.2 and 5.3 show that the cumulative enamel wear rates increased with increasing number of cycles.

Repeated measures ANOVA (Table 5.3) showed a highly significant effect of material type, media (water vs cola) and number of cycles ($p<0.001$). All the interactions were significant and the media*cycles interaction was found to be highly significant ($p<0.001$). The *t*-test was performed to make paired comparisons between the groups (Table 5.4). In the water groups significant differences ($p<0.017$) were found between Alpha porcelain and Duceram-LFC and between Alpha porcelain and Vita Mark II at all measurement intervals. However, the difference between Duceram-LFC and Vita Mark II was significant only at 5000 cycles and no longer significant after 15000 and 25000 cycles. In the cola groups (medium, cola/water) the difference between Alpha porcelain and Duceram-LFC was significant only at 5000 cycles and

no longer significant after 15000 and 25000 cycles. The difference between Alpha porcelain and Vita Mark II was significant at all intervals. However, the difference between Duceram-LFC and Vita Mark II was not significant at all intervals. When the groups of different media were compared, the difference between the Alpha porcelain groups (water vs cola) and between the Vita Mark II groups (water vs cola) were significant only after 25000 cycles. However, for the Duceram-LFC groups the difference between the water vs cola group was significant at all intervals and this difference increased with increasing number of cycles (Fig. 5.3).

Tables 5.5, 5.6 and 5.7 show the wear track depth at the five measurement points for the ceramic specimens (Alpha porcelain, Duceram-LFC and Vita Mark II, respectively) tested in water only and in cola/water media after 25000 cycles. The means of the deepest points for the six groups are presented in Table 5.8 and illustrated graphically in Fig. 5.4 for direct comparisons. Figure 5.4 shows that when the test was carried out in water only, Alpha porcelain had the greatest amount of wear followed by Duceram-LFC and Vita Mark II. However, when the test was carried out with exposure to Coca Cola, Duceram-LFC had the greatest amount of wear followed by Alpha porcelain and Vita Mark II. Furthermore, the wear of Alpha porcelain with exposure to the Coca Cola was less than its wear in water only. In contrast, the wear of Duceram-LFC and Vita Mark II was greater in the groups with exposure to Coca Cola than their wear in water only.

Two-way analysis of variance (Table 5.9) showed that the material type had a highly significant effect ($p<0.001$) while the media effect was not significant, however the

material*media interaction was highly significant ($p<0.001$). The media (cola effect) had affected the material wear in a different way for each type of material which is in agreement with Fig. 5.4. This may explain why the p value for the media effect was not significant. Follow up *t*-test paired comparisons between the groups of the ceramics showed (Table 5.10) that in the water groups significant differences ($p<0.017$) were found between Alpha porcelain and Duceram-LFC, Alpha porcelain and Vita Mark II, whilst the difference between Duceram-LFC and Vita Mark II was not statistically significant ($p>0.017$). In the cola groups the difference between Alpha porcelain and Duceram-LFC was not significant. However, the difference between Alpha porcelain and Vita Mark II, Duceram-LFC and Vita Mark II was statistically significant. When the groups of different media were compared significant differences ($p<0.017$) were found between the Alpha porcelain groups (water vs cola) and between Vita Mark II groups (water vs cola), whilst the difference between the Duceram-LFC groups (water vs cola) was not statistically significant ($p>0.017$).

Table 5.1. Mean (μm, ± SD) of surface roughness (Ra) of ceramic groups prior to wear test.

Group	N	Alpha porcelain	Duceram-LFC	Vita Mark II
Water	5	0.68 ± 0.17	0.63 ± 0.07	0.58 ± 0.10
Cola	5	0.66 ± 0.14	0.62 ± 0.04	0.59 ± 0.06
Total	10	0.67 ± 0.15	0.63 ± 0.06	0.59 ± 0.08

Table 5.2. Mean wear of enamel (mm, ± SD) after 5000, 15000 and 25000 cycles against the ceramic materials.

Cycles	Media	Alpha porcelain	Duceram-LFC	Vita Mark II
5000	Water only	0.547 ± 0.103	0.315 ± 0.061	0.406 ± 0.072
	Cola/water	0.623 ± 0.110	0.456 ± 0.096	0.411 ± 0.078
15000	Water only	0.777 ± 0.125	0.448 ± 0.116	0.553 ± 0.132
	Cola/water	0.897 ± 0.124	0.739 ± 0.152	0.659 ± 0.115
25000	Water only	0.927 ± 0.151	0.543 ± 0.152	0.653 ± 0.163
	Cola/water	1.104 ± 0.136	0.945 ± 0.173	0.856 ± 0.135

N = 10 specimens per group

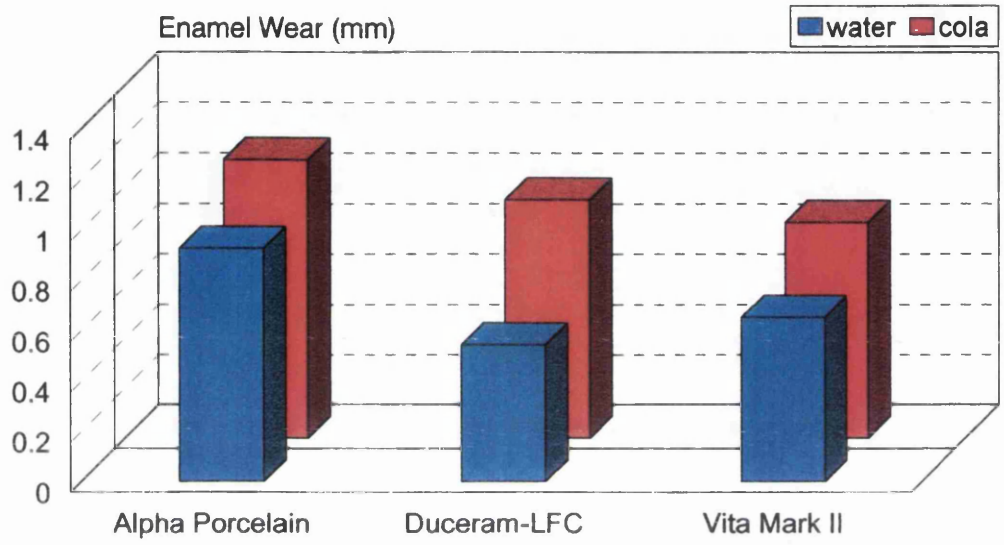
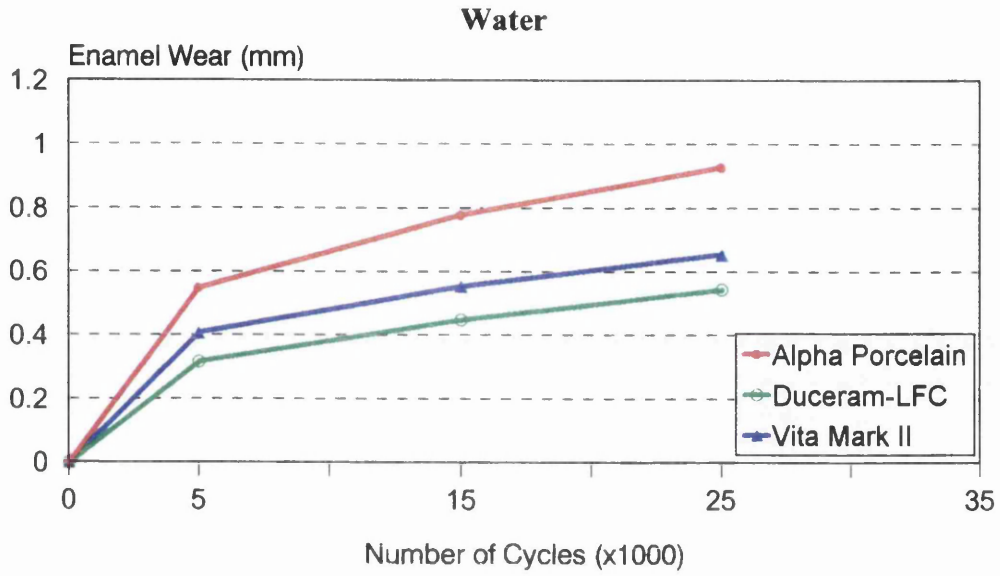


Fig. 5.1. Mean wear of enamel after 25000 cycles against ceramic materials for the water and cola groups.



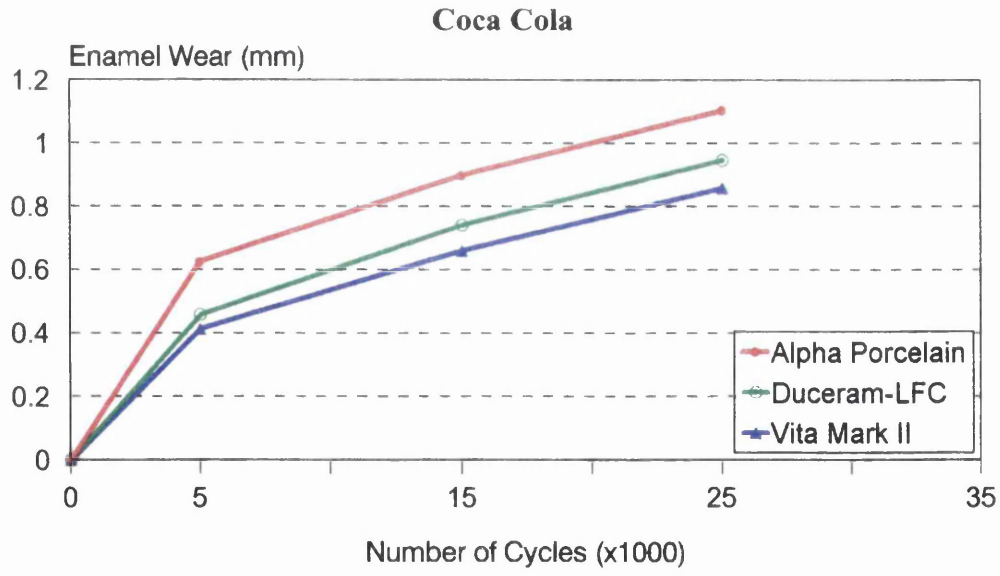


Fig. 5.2. Cumulative mean wear rates of enamel for water and Coca Cola groups.

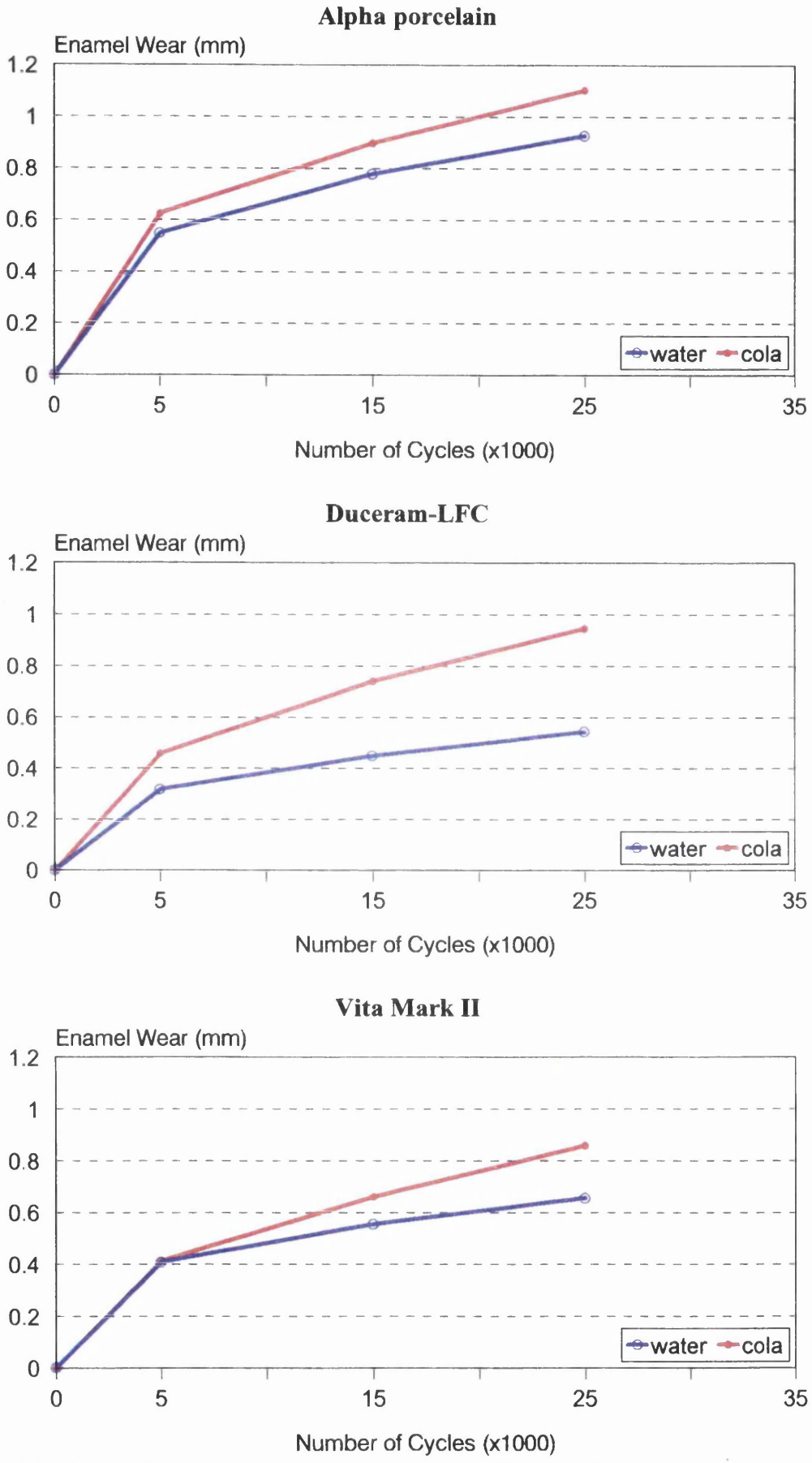


Fig. 5.3. Cumulative mean wear rates of enamel against the three ceramic groups in water and in Coca Cola.

Table 5.3. Repeated measures analysis of variance for enamel wear.

Source	DF	SS	MS	F	P
Material	2	2.12681	1.06341	25.61	< 0.001
Media	1	1.28271	1.28271	30.89	< 0.001
Cycles	2	4.33100	2.16550	738.81	< 0.001
Material*Media	2	0.27161	0.13580	3.27	0.046
Material*Cycles	4	0.04281	0.01070	3.65	0.008
Media*Cycles	2	0.26072	0.13036	44.48	< 0.001
Material*Media*Cycles	4	0.03418	0.00855	2.92	0.025
Specimen (Material Media)	54	2.24207	0.04152	14.17	< 0.001
Error	108	0.31656	0.00293		
Total	179	10.90847			

Table 5.4. *t*-test probability values (p)* of enamel wear for paired comparisons between ceramic groups and media groups.

Cycles	Media Group	Alpha porcelain vs Duceram-LFC	Alpha porcelain vs Vita Mark II	Duceram-LFC vs Vita Mark II
5000	Water	<0.001	0.003	0.007
	Cola	0.002	<0.001	0.26
15000	Water	<0.001	0.001	0.08
	Cola	0.022	<0.001	0.20
25000	Water	<0.001	0.001	0.13
	Cola	0.036	<0.001	0.22

Water groups vs Cola groups

Cycles	Media Group	Alpha porcelain	Duceram-LFC	Vita Mark II
5000	Water vs Cola	0.13	0.001	0.88
15000	Water vs Cola	0.047	<0.001	0.07
25000	Water vs Cola	0.014	<0.001	0.008

*Difference between the groups regarded as statistically significant only if $p<0.017$

Table 5.5. Wear depth track (μm) of alpha porcelain specimens after 25000 cycles.

Medium: water only

Point	Specimen Number										Mean	SD
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**		
i	42.85	55.09	45.05	70.58	42.24	45.28	67.05	66.12	45.89	61.60	54.17	11.23
ii	67.10	82.19	68.91	86.67	59.13	64.29	89.23	88.18	59.31	89.81	75.48	12.88
iii	67.14	79.10	71.14	80.93	59.25	65.61	89.30	87.37	61.06	89.23	75.01	11.64
iv	63.56	78.97	65.96	79.04	53.97	59.09	79.41	79.49	54.42	77.41	69.13	10.88
v	46.54	64.72	59.07	67.25	32.87	44.53	54.17	64.39	39.80	60.98	53.43	11.85
DP*	iii	ii	iii	ii	iii	iii	iii	ii	iii	ii		
VDP*	67.14	82.19	71.14	86.67	59.25	65.61	89.30	88.18	61.06	89.81	**76.04**	12.39

Medium: cola/water

Point	Specimen Number										Mean	SD
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**		
i	44.54	53.44	21.32	39.21	34.03	46.67	33.13	28.79	46.27	26.31	37.37	10.34
ii	59.42	54.94	32.54	46.92	39.24	65.31	49.91	36.59	69.04	35.81	48.97	12.96
iii	61.87	46.71	32.32	51.60	41.09	63.37	56.79	41.21	71.74	40.25	50.69	12.52
iv	61.49	37.74	24.00	45.84	37.72	56.37	47.22	38.44	64.77	33.25	44.68	13.01
v	56.47	39.44	22.62	37.04	44.05	49.23	38.08	39.75	57.08	27.35	41.11	11.19
DP*	iii	ii	ii	iii	v	ii	iii	iii	iii	iii		
VDP*	61.87	54.94	32.54	51.60	44.05	65.31	56.79	41.21	71.74	40.25	**52.03**	12.44

*DP deepest point and VDP value of the deepest point.

Table 5.6. Wear depth track (μm) of Duceram-LFC specimens after 25000 cycles.

Medium: water only

Point	Specimen Number										Mean	SD
	1	2	3	4	5	6	7	8	9	10		
i	18.10	56.99	24.14	25.49	25.13	22.08	15.42	26.36	25.53	34.55	27.38	11.59
ii	14.33	65.45	33.91	15.94	15.84	24.26	28.03	44.44	26.64	48.14	31.70	16.58
iii	18.94	61.63	36.54	16.11	16.95	29.93	30.53	59.27	39.77	69.95	37.96	19.56
iv	28.48	34.25	31.58	17.16	17.89	22.49	30.14	53.85	48.08	69.02	35.29	16.76
v	22.98	27.22	23.39	19.55	14.22	18.81	25.22	40.42	36.72	43.40	27.19	9.78
DP*	iv	ii	iii	i	i	iii	iii	iii	iv	iii		
VDP*	28.48	65.45	36.54	25.49	25.13	29.93	30.53	59.27	48.08	69.95	**41.88**	17.36

Medium: cola/water

Point	Specimen Number										Mean	SD
	1	2	3	4	5	6	7	8	9	10		
i	24.54	40.65	72.34	50.78	37.79	27.51	23.23	63.14	35.33	27.18	40.25	16.88
ii	20.07	62.72	75.15	61.80	49.67	41.79	18.58	80.90	53.76	29.11	49.35	21.82
iii	23.02	66.98	82.39	68.19	48.73	46.75	24.48	79.09	57.87	28.62	52.61	22.00
iv	39.47	58.41	81.98	62.85	59.80	44.71	44.43	70.67	51.37	29.52	54.32	15.59
v	29.56	56.42	57.40	45.95	41.74	45.33	46.64	56.43	33.68	33.51	44.67	10.15
DP*	iv	iii	iii	iii	iv	iii	v	ii	iii	v		
VDP*	39.47	66.98	82.39	68.19	59.80	46.75	46.64	80.90	57.87	33.51	**58.25**	16.68

*DP deepest point and VDP value of the deepest point.

Table 5.7. Wear depth track (μm) of Vita Mark II specimens after 25000 cycles.

Medium: water only

Point	Specimen Number										Mean	SD
	1	2	3	4	5	6	7	8	9	10		
i	43.15	8.98	28.65	11.85	29.47	16.27	12.10	7.40	15.11	31.28	20.34	11.89
ii	28.44	28.75	14.53	11.38	15.81	10.96	18.74	13.26	23.34	41.23	20.64	9.75
iii	23.87	19.23	9.07	6.49	15.49	14.34	19.28	8.02	20.80	21.33	15.79	6.14
iv	31.17	11.52	19.72	12.73	10.85	18.70	17.24	8.88	18.94	23.59	17.33	6.74
v	24.10	8.81	14.85	10.47	8.03	12.67	10.81	7.97	15.48	17.84	13.10	5.11
DP*	i	ii	i	iv	i	iv	iii	ii	ii	ii		
VDP*	43.15	28.75	28.65	12.73	29.47	18.70	19.28	13.26	23.34	41.23	**25.86**	10.52

Medium: cola/water

Point	Specimen Number										Mean	SD
	1	2	3	4	5	6	7	8	9	10		
i	25.18	46.28	28.20	27.64	41.71	35.85	23.19	26.30	28.55	39.94	32.28	8.01
ii	27.09	47.94	22.26	17.92	33.19	43.86	36.20	40.93	32.70	46.13	34.82	10.17
iii	23.69	37.27	13.56	25.01	21.97	40.43	32.39	23.78	25.39	43.69	28.72	9.41
iv	24.72	35.20	21.35	16.66	24.67	37.13	23.78	24.91	25.40	37.62	27.14	7.06
v	17.27	31.59	18.31	8.40	22.91	32.59	15.49	21.29	17.76	24.15	20.98	7.31
DP*	ii	ii	i	i	i	ii	ii	ii	ii	ii		
VDP*	27.09	47.94	28.20	27.64	41.71	43.86	36.20	40.93	32.70	46.13	**37.24**	7.96

*DP deepest point and VDP value of the deepest point.

Table 5.8. Mean wear of ceramic materials (μm, ± SD) after 25000 cycles.

Group	N	Alpha porcelain	Duceram-LFC	Vita Mark II
Water	10	76.04 ± 12.39	41.88 ± 17.36	25.86 ± 10.52
Cola	10	52.03 ± 12.44	58.25 ± 16.68	37.24 ± 7.96

Table 5.9. Two-way analysis of variance for ceramic material wear.

Source	DF	SS	MS	F	P
Material	2	10621.6	5310.8	30.00	< 0.001
Media	1	23.4	23.4	0.13	0.72
Material*Media	2	4844.9	2422.4	13.69	< 0.001
Error	54	9558.6	177.0		
Total	59	25048.4			

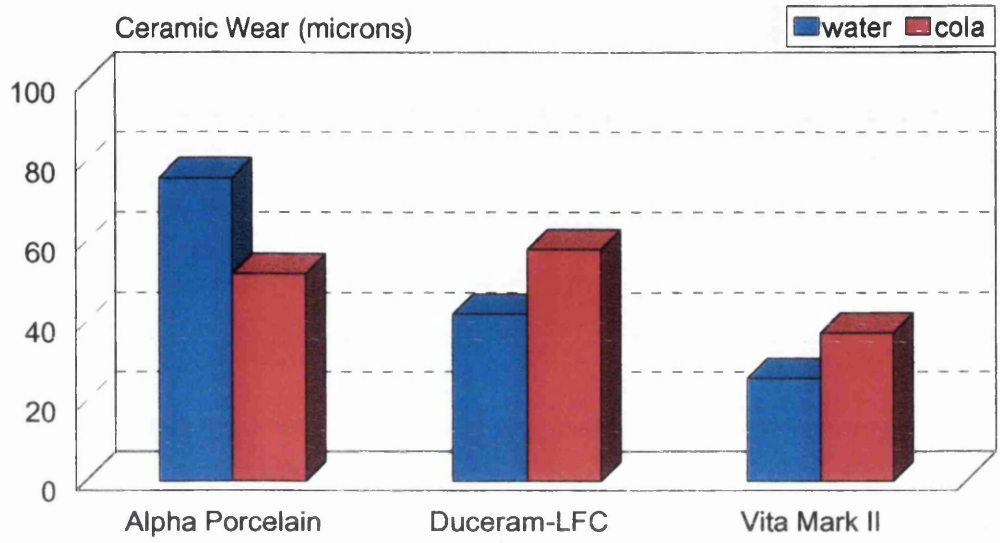


Fig. 5.4. Mean wear of ceramic materials after 25000 cycles for the water and cola groups.

Table 5.10. *t*-test probability values (p)* of ceramic wear for paired comparisons between ceramic material groups and media groups after 25000 cycles

Media Group	Alpha porcelain vs Duceram-LFC	Alpha porcelain vs Vita Mark II	Duceram-LFC vs Vita Mark II
Water	<0.001	<0.001	0.03
Cola	0.36	0.006	0.004

Water groups vs Cola groups

Media Group	Alpha porcelain	Duceram-LFC	Vita Mark II
Water vs Cola	<0.001	0.046	0.015

*Difference between the groups regarded as statistically significant only if p<0.017

5.4. Discussion

It can be seen from Fig. 5.1 that there was greater enamel wear when the test was carried with exposure to Cola Cola (pH range 2.28-2.37). As discussed previously (Chapter 3), it appears that the acidic effect of the Coca Cola may have contributed to this by demineralising the tooth enamel and making it more susceptible to the abrasive effect of the ceramic materials (Eccles, 1982b). Overall, the Alpha porcelain produced the greatest amount of enamel wear for both the water and cola groups. Interestingly, after 25000 cycles and compared to the enamel wear in water, exposure to Coca Cola increased the amount of enamel wear against the three ceramic material groups by 19% for Alpha porcelain, 31 % for Vita Mark II and 74% for Duceram-LFC. These substantial differences between the groups may be attributed partly to the fact that the contact area between the tooth cusps and the Duceram-LFC specimen was smaller (cone-shape cusp) than that between the tooth cusp and ceramic specimen for Vita Mark II and Alpha porcelain since the Duceram-LFC was the least abrasive material when tested in water only. Thus, the acidic effect of the Coca Cola will demineralise and soften the surface layers of the small volume of the cusp tip in the Duceram-LFC group faster than in the Alpha porcelain group where the worn surface of the tooth cusp was much larger. In this event, a volumetric wear measurement would be of greater use to compare the volume loss of the enamel rather than the height reduction. However, the previous explanation cannot be the only reason to cause such a substantial increase in the enamel wear as a result of exposure to Coca Cola in the Duceram-LFC group. Vita Mark II was almost as abrasive as the Duceram-LFC when tested in water (no significant differences between the groups, $p=0.13$). Thus, the contact area of the tooth cusp was comparable to that in the Duceram-LFC group,

and the increase in enamel wear was by 31% which is substantially less than 74% for the Duceram-LFC. Thus, it appears that the effect of Coca Cola was more severe on the Duceram-LFC group than on the Vita Mark II group, which made the Duceram-LFC become more abrasive than Vita Mark II when both were tested with exposure to Coca Cola, although the difference was not statistically significant. This difference can be seen in Fig. 5.2 where the enamel wear rates in the cola group against the Duceram-LFC became greater than that against the Vita Mark II.

Overall, the difference in the enamel wear rates between the water and the Coca Cola groups increased with time (increasing number of cycles) (Fig. 5.3). As stated previously (Chapter 3) this could because of the acidic effect of the Coca Cola in demineralising and softening the tooth enamel more and more with repeated exposure (Eccles, 1982b; Lussi *et al.*, 1993). The pH of the Coca Cola used in this study (2.28-2.37) was lower than the critical pH for enamel demineralisation which is 5.5 (Meurman *et al.*, 1987 and Järvinen *et al.*, 1988). Therefore the results of the present study support the claim that acid erosion may make the tooth surface more susceptible to attrition and abrasion (Smith, 1975). The effect of Coca Cola in relation to time (cycles) was also demonstrated. The trend in mean enamel wear over time was significantly different for the two media (water vs cola). Therefore, the graph lines in Fig. 5.3 are divergent. The fact that the three-way interaction was also significant suggests that the pattern was not the same for the three material groups, which is in agreement with Fig. 5.3. Overall, the results of the present study are in agreement with previous reports that acid exposure accelerates the rate of enamel wear (Lewis and Smith, 1973; Eccles, 1982b; Davis and Winter, 1980; Ratledge *et al.*, 1994).

Moreover, the present study also showed that Coca Cola exposure had affected the wear of the ceramic materials. The wear of Alpha porcelain with intermittent exposure to Coca Cola was found to be less than its wear in water only and this was suggested (Chapter 3) to be because of the acidic effect of the Coca Cola in softening the tooth enamel (Eccles, 1982b; Lussi *et al.*, 1993). Thus the latter would not have the same capacity to abrade the Alpha porcelain surface as that undemineralised enamel tested in water only. Surprisingly the result for the Duceram-LFC and Vita Mark II was different, since both had greater wear in cola than in water. This demonstrates that both Duceram-LFC and Vita Mark II becomes less resistant to wear after exposure to Coca Cola. Duceram-LFC is a hydrothermal ceramic with a property to form a silicon-hydroxyl layer on the surface when in contact with water. The manufacturer claims that the silicon-hydroxyl layer protects the surface of the ceramic from damage by healing the surface micro flaws, thus the Duceram-LFC has what is called a self-healing process (Komma, 1993). This may explain a significantly lower amount of wear of Duceram-LFC in comparison to the wear of Alpha porcelain when the test was carried out in water only. However, it appears that this protection has been affected negatively when the wear test was carried out with exposure to Coca Cola. Unfortunately, there are no published studies in the literature available to compare the results of the present study for the Duceram-LFC apart from the manufacturer's publication (Komma, 1993) which did not cover the wear properties of the material under a dynamic test as in the present study. Engineering and tribologist researchers have investigated the wear of different types of ceramics. Erdemir (1994) stated that under dynamic action of a sliding contact, ceramics have been observed to interact with chemical species (tribochemical interaction) in their surroundings and to undergo

distinct transition in their friction and wear behaviour. These tribochemical interactions of ceramics with the surrounding environment determine the wear of the materials. Such interactions can decrease wear or increase it, depending on the particular ceramic and environment. These phenomena are manifestations of the surface chemistry of ceramics, and the chemical reactions are related to the electronic structure of the materials. When there is an increase in wear, this is usually caused by the chemical attack of the grain boundaries and intergranular fracture on the ceramic materials (Fischer and Mullins, 1994). In the present study it appears that the Coca Cola had increased the wear of the Duceram-LFC through a chemical reaction with materials which makes it more susceptible to wear. This chemical reaction, perhaps, in combination with the dynamic action of the wear test, weakened the ceramic surface and allowed easier breakdown of particles, leaving behind a rough abrasive surface which could have contributed to the substantial increase in the wear of the opposing tooth enamel.

Vita Mark II also had greater wear in Coca Cola compared to water. Interestingly, in the Coca Cola group the deepest point of the wear track was either at point (i) or (ii) (Table 5.7), points corresponding to the impact area of the tooth specimen into the ceramic surface. Perhaps, because of the small particle size of the ceramic and the acidic environment of the Coca Cola, the material becomes more susceptible to an impact wear mechanism, thus showing greater wear in the Coca Cola than in water.

Finally, this study confirms that carbonated soft drinks accelerate the rate of enamel wear. Further investigations are needed to study the properties of Duceram-LFC and Vita Mark II compared with conventional porcelain under controlled variables.

5.5. Conclusion

Under the conditions of this study the following points were concluded:

1. For both media (water only, cola/water) after 25000 cycles, Alpha porcelain was more abrasive than Duceram-LFC and Vita Mark II, although the difference in enamel wear between the Alpha porcelain group and the Duceram-LFC group in Coca Cola was not statistically significant.

2. Exposure to the carbonated beverage (Coca Cola) increased the amount of enamel wear by 19% against Alpha porcelain, 31% against Vita Mark II and 74% against Duceram-LFC, compared to the enamel wear produced in water.

3. The ranking of ceramic materials from most resistant to wear to least resistant was:

(a) Water only - Vita Mark II, Duceram-LFC, Alpha porcelain;

(b) Cola/water - Vita Mark II, Alpha porcelain, Duceram-LFC.

CHAPTER 6

Three-body Wear of Human Enamel and Dental Ceramics

Chapter 6: Three-body Wear of Human Enamel and Dental Ceramics

6.1. Introduction

Previous studies have investigated the wear of human enamel and opposing ceramic materials using distilled water as the medium and this can be considered as a two-body wear test (Chapter 4). However, in the mouth the wear process that occurs between the teeth and their antagonist restorations are a combination of two-body and three-body wear (Harrison, 1978). The 'third body' of the wear process is presented by food particles present between the teeth and their opposing restorations during mastication. *In vitro* studies have used different mixtures of slurries in an attempt to simulate the actual food abrasive effect on the wear process. Some authors have used natural food products, usually mixed with water, to get closer to the consistency of the normal food consumed. These include flour (Monasky and Taylor, 1971), poppy seeds (Finger and Thiemann, 1987), millet seeds (De Gee *et al.*, 1990), and rice (Pallav *et al.*, 1993). However, other studies have used artificial products such as PMMA (polymethyl methacrylate beads) (De Gee *et al.*, 1986; Matsumura *et al.*, 1995), calcium carbonate particles or silicon carbide grit as an abrasive slurry (Sarrett *et al.*, 1991). As early as 1957, Cornell and co-workers stated that if an abrasive medium is used for *in vitro* wear tests, it has to be mildly abrasive, since the human oral mechanisms tend to reject gritty particles automatically. Harrison (1978) studied the wear of different combinations of porcelain and acrylic resin used for denture teeth. He found that the result of the *in vitro* wear test that incorporated calcium pyrophosphate as a mild abrasive medium correlated well with the clinical data. However, the results of the test that was carried out with 600 grit carborundum as a

severely abrasive medium indicated a total reversal of the clinically accepted and observed wear characteristics. This is because severe abrasives are not commonly part of the normal diet. Therefore, it was concluded that *in vitro* wear tests that incorporate an appropriate mild abrasive slurry may effectively duplicate the clinical condition.

The aim of this study is to investigate the wear of human enamel and the opposing ceramic materials in a three-body wear test and to compare the results to that previously obtained for a two-body wear test (Chapter 4).

6.2. Materials and Methods

Preparation of Ceramic Specimens

Ceramic specimens were prepared from Vitadur Alpha porcelain, Duceram-LFC ceramic and Cerec Vita Mark II blocks using the method described previously (section 2.1). Ten specimens from each material were prepared. The specimens for Alpha and Duceram-LFC were prepared with a glazed surface, whilst one side of the Vita Mark II specimens (plates) was polished (section 2.1). Five specimens were selected randomly from each group for surface roughness measurement using the Dektak 3ST machine (section 2.2). Each specimen was then mounted onto the wear machine specimen holder for wear testing (section 2.1).

Preparation of Tooth Specimens

Tooth specimens were prepared from 15 extracted caries-free human mandibular premolars that were divided into three groups of five. Each tooth was then sectioned

in half in its long axis in the bucco-lingual direction, through the buccal cusp tip, thus each group consisted of 10 specimens. Each tooth specimen was then mounted in its holder (section 2.3). Both ceramic and tooth specimens were kept for 24 hours in distilled water before the wear test.

Wear Test Procedure

The wear test was carried out in the wear machine (section 2.4) using the same test parameters, namely a load of 40 N at a rate of 80 cycles per minute and for a total of 25000 cycles. However, in the present study the specimens were tested in a three-body medium to simulate the food slurry. The medium was composed of a mixture of 22g cornmeal grit (East End Foods plc, Birmingham, UK) and 6g wholemeal flour (Allinson; Westmill Foods Ltd., Maidenhead, UK), in 25 mL of distilled water. This quantity was enough to fill the water bath of the wear machine and fully immersed the specimens tested (both tooth and ceramic specimens). A mechanical stirrer was inserted into the waterbath of the wear machine providing a permanent homogeneity of the slurry (Fig. 6.1). The slurry was renewed every 5000 cycles using the same composition and quantity. For optimum experimental reproducibility the same batch of cornmeal grit and wholemeal flour was used throughout the study. The speed of the stirrer was also kept constant.

Wear Measurement

Enamel wear was assessed by measuring the tooth cusp height reduction, after 5000, 15000, and 25000 cycles, using a reflex microscope, as described previously (section 2.5.1). The wear track depth of the ceramic material specimens was measured at the end of the wear test (after 25000 cycles) from their epoxy resin replicas, using the

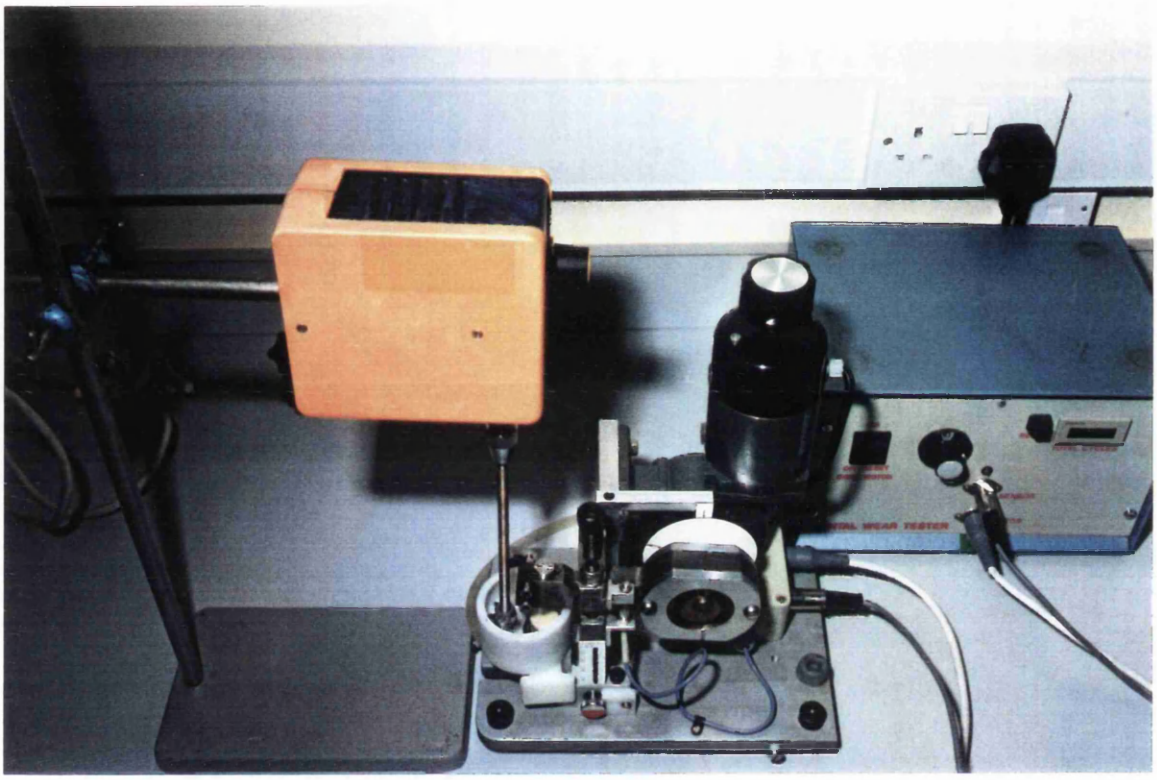


Fig. 6.1. Stirrer inserted into the waterbath of the wear machine.

Dektak 3ST surface profile measuring system, to determine the deepest point of the wear track (section 2.5.2).

Statistical Analysis

To enable comparisons of the three-body wear test with the two-body test the data for the Alpha porcelain, Duceram-LFC and Vita Mark II, tested in distilled water from Chapter 4 were included. Thus, all the data was analysed together.

The surface roughness data of the ceramic groups was analysed by one-way analysis of variance (ANOVA). Repeated measures ANOVA was performed to explore the data of the enamel wear for any statistically significant effect of ceramic material type, media, and number of cycles. The data for the wear of the ceramic materials was analysed using two-way ANOVA to explore the data for any significant effect of material type and media. Overall, postanalysis paired comparisons was carried out with the *t*-test. In view of the number of individual tests done, a Bonferroni approach (Bonferroni correction method) was used (Altman, 1991), in which differences were regarded as statistically significant if the probability (p) was less than 0.017. Differences with p values greater than 0.017 were regarded as not statistically significant.

6.3. Results

The mean surface roughness of the ceramic material groups measured prior to wear testing are shown in Table 6.1. One-way analysis of variance (ANOVA) showed no significant difference in surface roughness between the three ceramic groups (p=0.29).

The mean values of enamel wear (tooth cusp reduction) after 5000, 15000 and 25000 cycles are presented in Table 6.2. The mean enamel wear after 25000 cycles is illustrated graphically in Fig. 6.2. Figure 6.2 shows that the enamel wear in the three-body slurry medium had decreased against Alpha porcelain and Vita Mark II and increased against the Duceram-LFC compared to that produced in water (two-body wear). The means of the cumulative enamel wear rates in water and in the slurry medium are illustrated separately in Fig. 6.3, which shows the change in the material abrasivity ranking of the groups for the two media. At all the measurement intervals, and in both media, Alpha porcelain caused the greatest amount of enamel wear. For the water group this was followed by Vita Mark II and then Duceram-LFC. However, in the presence of food particles the rate of enamel wear against Duceram-LFC became greater than the rate against Vita Mark II. Figure 6.4 shows the means of the cumulative enamel wear rates in water vs slurry media against the three ceramic materials separately. It can be seen that at all intervals the rates of enamel wear against Alpha porcelain and Vita Mark II was greater in water than in slurry medium. In contrast, the enamel wear rates against Duceram-LFC was greater in the slurry medium than in water.

Repeated measures ANOVA (Table 6.3) showed a highly significant effect of material type and number of cycles ($p<0.001$), but the media effect was shown not to be statistically significant. This could be because the enamel wear rates against the three ceramic materials was different in the two media and had decreased for the Alpha porcelain and Vita Mark II groups and increased for the Duceram-LFC group when tested in slurry media. These differences between the groups had compensated

the statistical effect of the media. Therefore, the material*media interaction was significant (p=0.003). Moreover, all the interactions were also found to be significant. The number of cycles had a highly significant effect (p<0.001) with the rates of enamel wear increasing with increasing number of cycles (Figs. 6.3, 6.4). The follow up paired comparison between the groups was performed using the *t*-test with Bonferroni correction method (Table 6.4). For the test carried out in water, significant differences (p<0.017) in the amount of enamel wear was found between Alpha porcelain and Duceram-LFC, and between Alpha porcelain and Vita Mark II at all measurement intervals. However, the difference between Duceram-LFC and Vita Mark II groups was significant only at 5000 cycles and no longer significant after 15000 and 25000 cycles. For the three-body slurry medium test the amount of enamel wear produced by Alpha porcelain at all intervals was not significantly different from that produced by Duceram-LFC, however it was significantly higher than that produced by Vita Mark II. The difference in enamel wear in the slurry medium between Duceram-LFC and Vita Mark II group was not significant at 5000 and 15000 cycles, however it became significant after 25000 cycles. When the groups of different media were compared for each of the three ceramics, the difference between the groups (water vs slurry) was not significant at all intervals, except for the Duceram-LFC group, that was found significant only at 15000 cycles.

Tables 6.5, 6.6 and 6.7 show the depth of the wear track for the ceramic specimens (Alpha porcelain, Duceram-LFC and Vita Mark II, respectively) at the five measurement points after 25000 cycles in water and in slurry medium. The means of the deepest points for the six groups are presented in Table 6.8. For direct

comparisons the means are also illustrated graphically in Fig. 6.5, which shows that the wear of Alpha porcelain and Vita Mark II in slurry medium was less than their wear in water. In contrast, the wear of Duceram-LFC in the slurry medium was not reduced, in fact it was slightly greater than the wear in water. For the ceramic material wear ranking in the water group, Alpha porcelain had the greatest amount of wear followed by Duceram-LFC and Vita Mark II. However, in the slurry medium group, Duceram-LFC had the greatest amount of enamel wear, followed by Alpha porcelain and Vita Mark II. Overall, Vita Mark II had the lowest amount of wear in both media. Two-way analysis of variance (Table 6.9) showed a highly significant effect of ceramic material type and media as well as the interaction between material and media ($p<0.001$). Follow up paired comparisons *t*-test (significant only if $p<0.017$) between the ceramic groups showed (Table 6.10) that in the water groups the wear of Alpha porcelain was significantly greater than the wear of Duceram-LFC and Vita Mark II ($p<0.001$) and the difference between Duceram-LFC and Vita Mark II was not significant ($p>0.017$). In the slurry groups the difference between Alpha porcelain and Duceram-LFC was not significant ($p>0.017$), whilst the wear of Alpha porcelain and Duceram-LFC was significantly greater than the wear of Vita Mark II ($p<0.001$). When the groups of different media were compared for each ceramic material, significant differences ($p<0.017$) were found between the Alpha porcelain groups (water vs slurry) and between Vita Mark II groups (water vs slurry) both having greater wear in water than in slurry medium. However, there was no significant difference between the wear of Duceram-LFC in water and in slurry medium ($p=0.84$).

Table 6.1. Mean (μm, ± SD) of surface roughness (Ra) of ceramic groups prior to wear test.

Group	N	Alpha Porcelain	Duceram-LFC	Vita Mark II
Water	5	0.68 ± 0.17	0.63 ± 0.07	0.58 ± 0.10
Slurry	5	0.58 ± 0.12	0.60 ± 0.08	0.54 ± 0.04
Total	10	0.63 ± 0.15	0.62 ± 0.07	0.56 ± 0.08

Table 6.2. Mean wear of enamel (mm, ± SD) after 5000, 15000 and 25000 cycles against the ceramic materials.

Cycles	Media	Alpha Porcelain	Duceram-LFC	Vita Mark II
5000	Water	0.547 ± 0.103	0.315 ± 0.061	0.406 ± 0.072
	Slurry	0.487 ± 0.085	0.389 ± 0.120	0.370 ± 0.086
15000	Water	0.777 ± 0.125	0.448 ± 0.116	0.553 ± 0.132
	Slurry	0.718 ± 0.108	0.648 ± 0.192	0.468 ± 0.093
25000	Water	0.927 ± 0.151	0.543 ± 0.152	0.653 ± 0.163
	Slurry	0.806 ± 0.126	0.738 ± 0.217	0.497 ± 0.097

N = 10 specimens per group

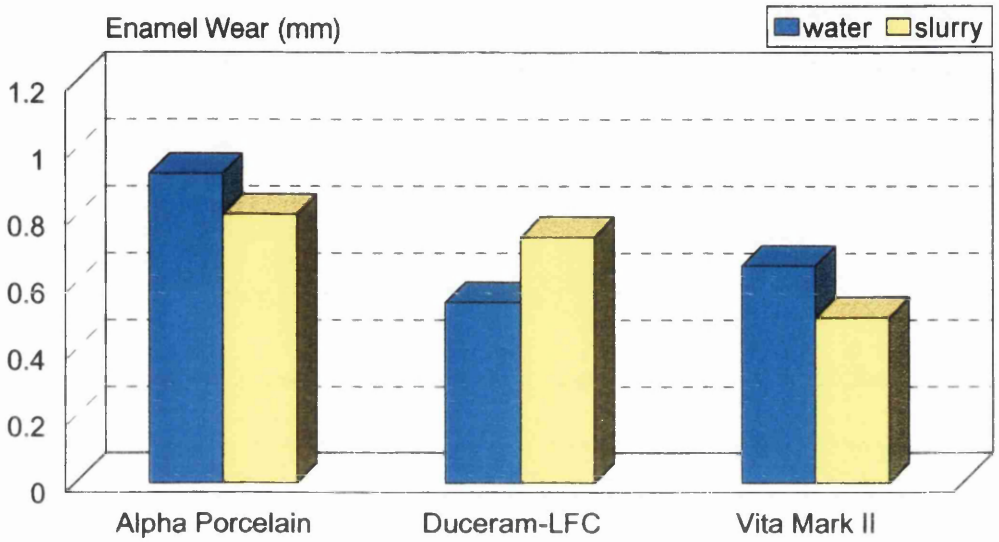
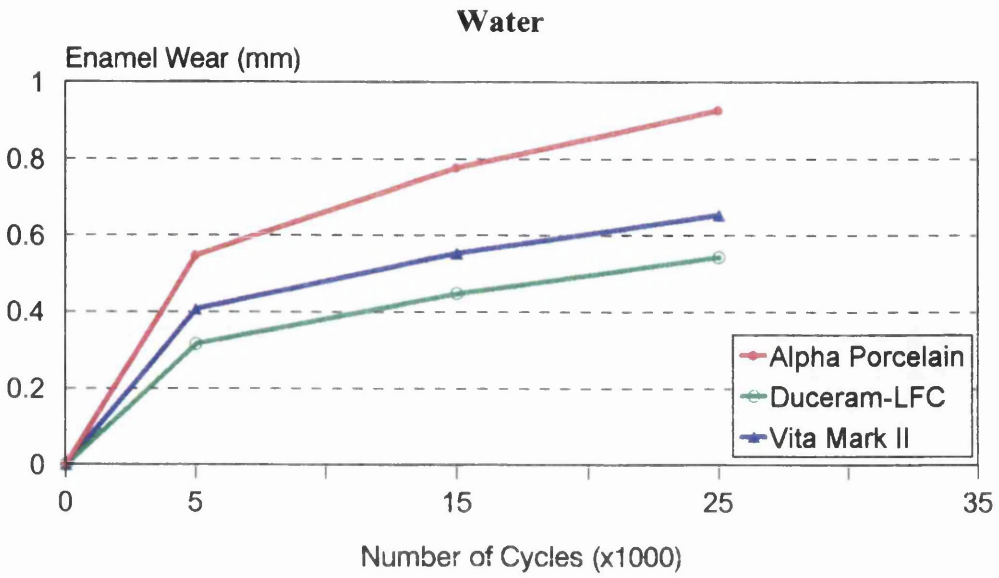


Fig. 6.2. Mean wear of enamel after 25000 cycles against ceramic materials tested in water and in slurry media.



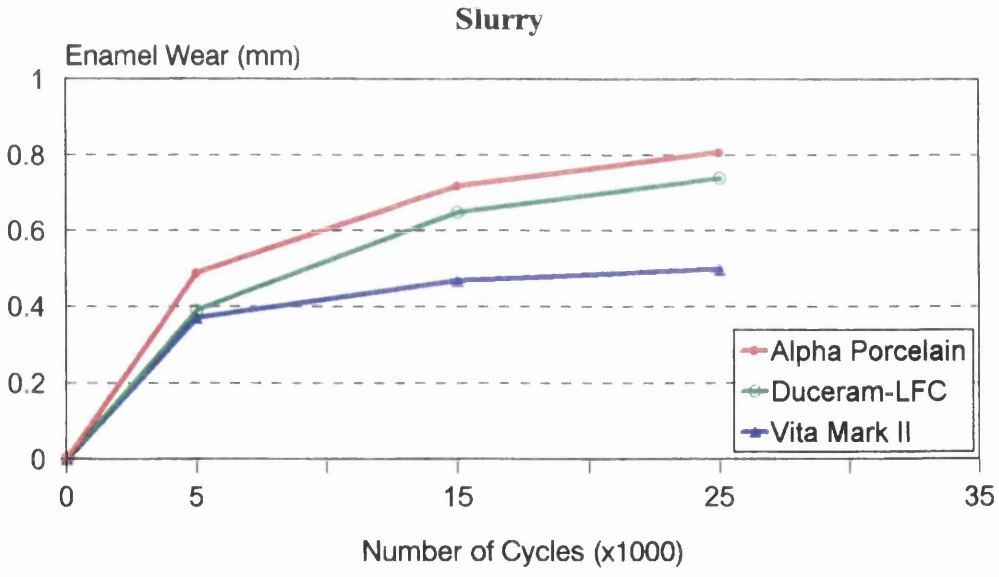


Fig. 6.3. Cumulative mean wear rates of enamel for water and slurry groups.

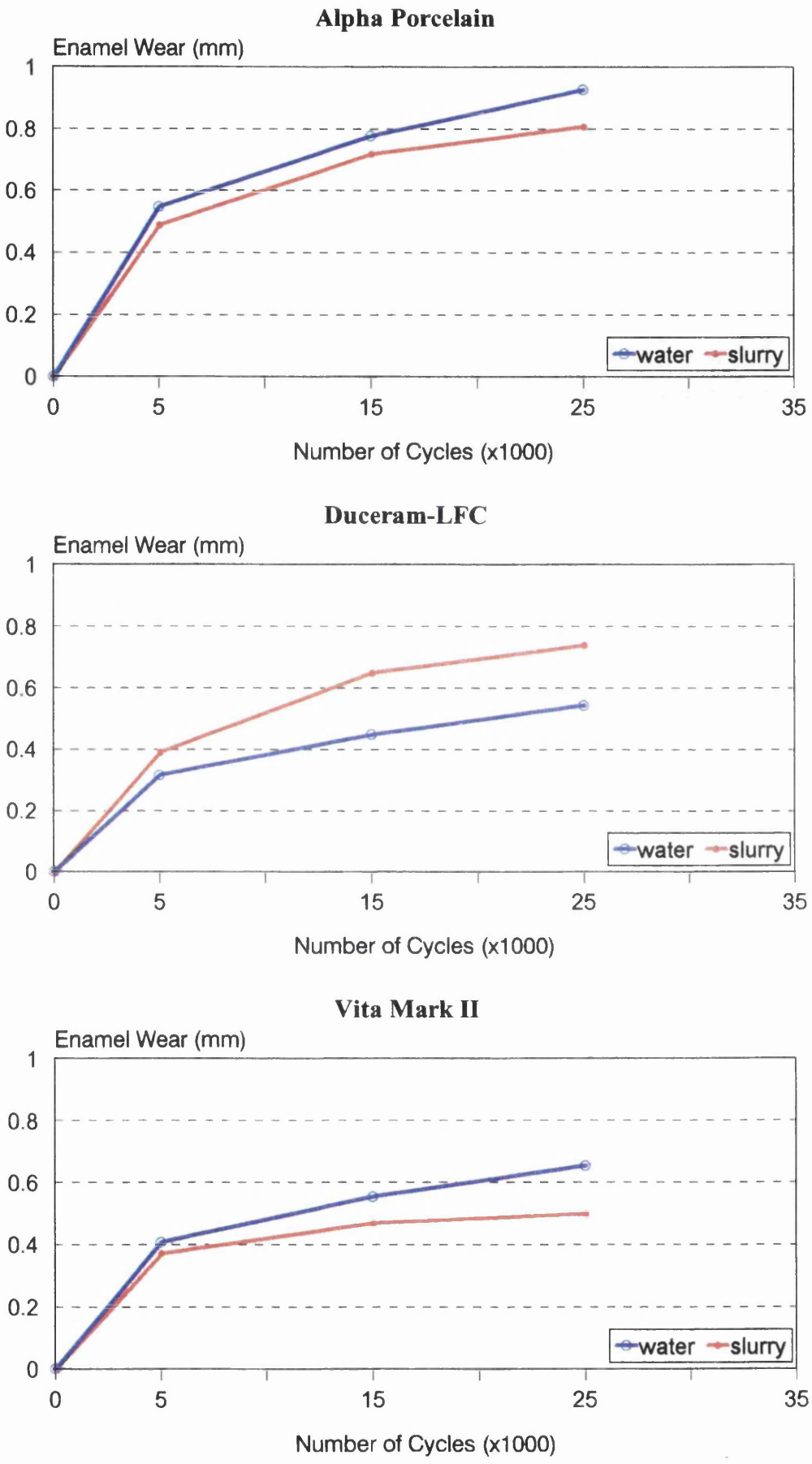


Fig. 6.4. Cumulative mean wear rates of enamel against the three ceramic groups in water and slurry media.

Table 6.3. Repeated measures analysis of variance for enamel wear tested in water and slurry media.

Source	DF	SS	MS	F	P
Material	2	1.74464	0.87232	19.56	< 0.001
Media	1	0.00136	0.00136	0.03	0.862
Cycles	2	2.35499	1.17749	482.80	< 0.001
Material*Media	2	0.59095	0.29547	6.62	0.003
Material*Cycles	4	0.14084	0.03521	14.44	< 0.001
Media*Cycles	2	0.01572	0.00786	3.22	0.044
Material*Media*Cycles	4	0.08432	0.02108	8.64	< 0.001
Specimen (Material Media)	54	2.40845	0.04460	18.29	< 0.001
Error	108	0.26340	0.00244		
Total	179	7.60467			

Table 6.4. *t*-test probability values (p)* of enamel wear for paired comparisons between ceramic groups and media groups tested in water and in slurry media for 25000 cycles.

Cycles	Media Group	Alpha Porcelain vs Duceram-LFC	Alpha Porcelain vs Vita Mark II	Duceram-LFC vs Vita Mark II
5000	Water	<0.001	0.003	0.007
	Slurry	0.05	0.007	0.68
15000	Water	<0.001	0.001	0.08
	Slurry	0.33	<0.001	0.019
25000	Water	<0.001	0.001	0.13
	Slurry	0.41	<0.001	0.008

Water groups vs Slurry groups

Cycles	Media Group	Alpha Porcelain	Duceram-LFC	Vita Mark II
5000	Water vs Slurry	0.17	0.11	0.32
15000	Water vs Slurry	0.27	0.014	0.11
25000	Water vs Slurry	0.07	0.03	0.02

*Difference between the groups regarded as statistically significant only if $p<0.017$

Table 6.5. Wear depth track (μm) of Alpha porcelain specimens after 25000 cycles (water vs slurry media).

Medium: Water

Point	Specimen Number										Mean	SD
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**		
i	42.85	55.09	45.05	70.58	42.24	45.28	67.05	66.12	45.89	61.60	54.17	11.23
ii	67.10	82.19	68.91	86.67	59.13	64.29	89.23	88.18	59.31	89.81	75.48	12.88
iii	67.14	79.10	71.14	80.93	59.25	65.61	89.30	87.37	61.06	89.23	75.01	11.64
iv	63.56	78.97	65.96	79.04	53.97	59.09	79.41	79.49	54.42	77.41	69.13	10.88
v	46.54	64.72	59.07	67.25	32.87	44.53	54.17	64.39	39.80	60.98	53.43	11.85
DP*	iii	ii	iii	ii	iii	iii	iii	ii	iii	ii		
VDP*	67.14	82.19	71.14	86.67	59.25	65.61	89.30	88.18	61.06	89.81	**76.04**	12.39

Medium: Slurry

Point	Specimen Number										Mean	SD
	1	2	3	4	5	6	7	8	9	10		
i	15.43	21.27	17.14	20.04	14.72	18.14	10.58	21.07	15.52	19.90	17.38	3.39
ii	22.83	30.63	26.81	28.35	22.98	25.74	20.09	35.49	25.93	26.70	26.56	4.34
iii	28.38	35.86	32.35	28.75	24.84	23.65	22.58	45.88	27.45	22.79	30.15	7.02
iv	30.20	33.43	25.76	26.15	22.66	24.70	22.34	41.39	27.65	22.08	27.64	6.03
v	25.49	34.50	28.09	21.55	18.10	22.41	17.22	34.08	25.96	20.40	24.78	6.06
DP*	iv	iii	iii	iii	iii	ii	iii	iii	iv	ii		
VDP*	30.20	35.86	32.35	28.75	24.84	25.74	22.58	45.88	27.65	26.70	**30.06**	6.75

*DP deepest point and VDP value of the deepest point.

Table 6.6. Wear depth track (μm) of Duceram-LFC specimens after 25000 cycles (water vs slurry media).

Medium: Water

Point	Specimen Number										Mean	SD
	1	2	3	4	5	6	7	8	9	10		
i	18.10	56.99	24.14	25.49	25.13	22.08	15.42	26.36	25.53	34.55	27.38	11.59
ii	14.33	65.45	33.91	15.94	15.84	24.26	28.03	44.44	26.64	48.14	31.70	16.58
iii	18.94	61.63	36.54	16.11	16.95	29.93	30.53	59.27	39.77	69.95	37.96	19.56
iv	28.48	34.25	31.58	17.16	17.89	22.49	30.14	53.85	48.08	69.02	35.29	16.76
v	22.98	27.22	23.39	19.55	14.22	18.81	25.22	40.42	36.72	43.40	27.19	9.78
DP*	iv	ii	iii	i	i	iii	iii	iii	iv	iii		
VDP*	28.48	65.45	36.54	25.49	25.13	29.93	30.53	59.27	48.08	69.95	**41.88**	17.36

Medium: Slurry

Point	Specimen Number										Mean	SD
	1	2	3	4	5	6	7	8	9	10		
I	21.00	17.56	37.14	21.02	33.48	21.68	18.48	15.86	31.94	16.95	23.51	7.71
II	35.76	34.97	63.34	28.11	53.52	32.04	25.52	22.62	56.05	21.10	37.30	15.02
III	37.74	40.94	76.53	29.16	63.49	38.13	28.03	27.78	64.71	26.39	43.29	18.24
IV	36.58	40.78	75.19	26.83	58.37	33.19	21.01	25.65	61.71	26.97	40.63	18.29
V	23.17	35.80	32.52	18.99	28.04	30.85	22.00	28.93	38.40	27.04	28.57	6.12
DP*	iii	iii	iii	iii	iii	iii	iii	v	iii	v		
VDP*	37.74	40.94	76.53	29.16	63.49	38.13	28.03	28.93	64.71	27.04	**43.47**	18.07

*DP deepest point and VDP value of the deepest point.

Table 6.7. Wear depth track (μm) of Vita Mark II specimens after 25000 cycles (water vs slurry media).

Medium: Water

Point	Specimen Number										Mean	SD
	1	2	3	4	5	6	7	8	9	10		
i	43.15	8.98	28.65	11.85	29.47	16.27	12.10	7.40	15.11	31.28	20.34	11.89
ii	28.44	28.75	14.53	11.38	15.81	10.96	18.74	13.26	23.34	41.23	20.64	9.75
iii	23.87	19.23	9.07	6.49	15.49	14.34	19.28	8.02	20.80	21.33	15.79	6.14
iv	31.17	11.52	19.72	12.73	10.85	18.70	17.24	8.88	18.94	23.59	17.33	6.74
v	24.10	8.81	14.85	10.47	8.03	12.67	10.81	7.97	15.48	17.84	13.10	5.11
DP*	i	ii	i	iv	i	iv	iii	ii	ii	ii		
VDP*	43.15	28.75	28.65	12.73	29.47	18.70	19.28	13.26	23.34	41.23	**25.86**	10.52

Medium: Slurry

Point	Specimen Number										Mean	SD
	1	2	3	4	5	6	7	8	9	10		
i	8.94	10.49	3.84	6.85	5.74	5.24	6.24	8.90	4.55	3.97	6.48	2.29
ii	6.32	13.68	7.51	9.94	7.62	5.69	6.97	10.09	4.79	6.11	7.87	2.66
iii	12.01	9.78	4.97	9.32	8.07	9.37	11.14	7.26	4.62	7.72	8.43	2.41
iv	10.87	11.69	8.11	10.66	7.29	10.65	9.43	9.80	10.21	6.85	9.56	1.62
v	11.17	8.90	6.76	10.88	7.54	7.67	8.46	8.88	9.10	7.46	8.68	1.45
DP*	iii	ii	iv	v	iii	iv	iii	ii	iv	iii		
VDP*	12.01	13.68	8.11	10.88	8.07	10.65	11.14	10.09	10.21	7.72	**10.26**	1.89

*DP deepest point and VDP value of the deepest point.

Table 6.8. Mean wear of ceramic materials (μm, ± SD) after 25000 cycles (water vs slurry media).

Group	N	Alpha Porcelain	Duceram-LFC	Vita Mark II
Water	10	76.04 ± 12.39	41.88 ± 17.36	25.86 ± 10.52
Slurry	10	30.06 ± 6.75	43.47 ± 18.07	10.26 ± 1.89

Table 6.9. Two-way analysis of variance for ceramic material wear in water and slurry media.

Source	DF	SS	MS	F	P
Material	2	12919.6	6459.8	41.18	< 0.001
Media	1	5999.0	5999.0	38.24	< 0.001
Material*Media	2	5801.2	2900.6	18.49	< 0.001
Error	54	8470.6	156.9		
Total	59	33190.3			

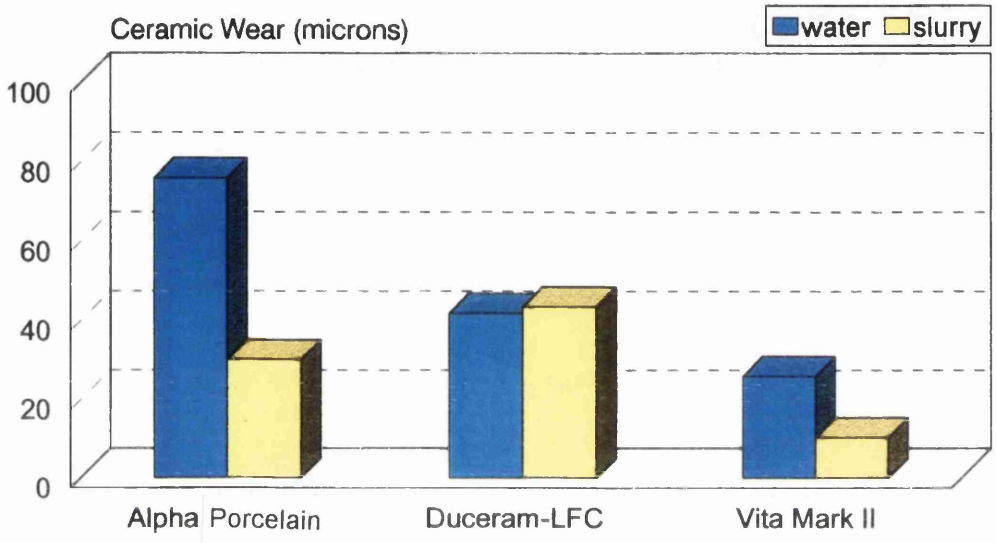


Fig. 6.5. Mean wear of ceramic materials after 25000 cycles tested in water and in slurry media.

Table 6.10. *t*-test probability values (p)* of ceramic wear for paired comparisons between ceramic groups and media groups tested in water and in slurry media for 25000 cycles.

Media Group	Alpha Porcelain vs Duceram-LFC	Alpha Porcelain vs Vita Mark II	Duceram-LFC vs Vita Mark II
Water	<0.001	<0.001	0.03
Slurry	0.05	<0.001	<0.001

Water groups vs Slurry groups

Media Group	Alpha Porcelain	Duceram-LFC	Vita Mark II
Water vs Slurry	<0.001	0.84	0.001

*Difference between the groups regarded as statistically significant only if p<0.017

6.4. Discussion

The use of cornmeal grit with wholemeal flour was an attempt to simulate the texture and the consistency of the natural food consumed. It was surprising that the three-body slurry medium had different effects on the groups tested in the present study. The presence of food particles in the medium was found to reduce the wear of both enamel and the two ceramics, Alpha porcelain and Vita Mark II. However, the reverse was found for the Duceram-LFC group, where the amount of wear increased. Harrison (1978) compared the wear of an acrylic resin against porcelain in a two-body (water medium) and a three-body (abrasive slurry) wear test and found that the introduction of a mildly abrasive medium (calcium pyrophosphate) increased the rate of acrylic resin wear against a glazed porcelain and decreased it against a sandblasted porcelain. Although a direct comparison cannot be made between this and the present study, the results of Harrison (1978) indicate a diverse effect of the three-body medium in the wear process.

It is probable for the Alpha porcelain and Vita Mark II groups, that the cornmeal grit in the slurry acted as a cushion which absorbed the shock of the impact force of the tooth onto the ceramic surface. This can be deduced from the substantial reduction of the wear track depth at points (i) and (ii) (Table 6.5 and 6.7), which correspond to the impact area of the tooth onto the ceramic surface, in particular in the Vita Mark II specimens (Table 6.7).

The reduction in the amount of wear for both enamel and ceramic material for the Alpha porcelain and Vita Mark II groups could also be attributed to the fact that the

sliding contact between the tooth and ceramic was through the slurry particles trapped between the two surfaces. These particles, perhaps, were much softer and more elastic than either the tooth enamel or the ceramic material. Thus the elastic deformation of the slurry particles may also absorb some of the load applied over the samples, during the sliding contact. The presence of the slurry also reduced the frequency of direct contact between the tooth enamel and the asperities of the hard ceramic surface, thus reducing the direct abrasive wear between the two surfaces.

However, in the case of the Duceram-LFC, the presence of the slurry particles between the tooth enamel and the material appeared to have the opposite effect. The Duceram-LFC is a leucite free ceramic which has a homogeneous highly dense structure (Komma, 1993) and this may contribute to its low abrasivity against the tooth enamel in the two-body wear test in water. In addition, the Duceram-LFC has the property to form a silicon-hydroxyl layer on its surface, when in contact with water, making the surface flexible and less brittle than a conventional porcelain (Komma, 1993). These properties may also make the ceramic more resistant to wear and also less abrasive on tooth enamel. It is probable that the presence of the slurry particles between the tooth and the Duceram-LFC surface could have interfered with the formation of the silicon-hydroxyl layer, either mechanically or chemically, thus exposing the surface of the ceramic to come either in direct contact with the tooth or through the slurry particles. Since Duceram-LFC is free of leucite and not strengthened by the aluminium oxide in the same way as the Alpha porcelain and Vita Mark II (Vita product information), the presence of the slurry particles may allow the load to be concentrated over localised small areas on the ceramic surface, and

although these particles are relatively soft and elastic it appears that they did not compensate for the absence of the protective silicon-hydroxyl layer. This may have caused localised cracks either in the surface or in the subsurface, thus weakening the ceramic surface and making it relatively more susceptible to wear, although the increase in the material wear was negligible. The formation of cracks and their further propagation also can result in the formation of loose particles and when these particles are removed by an abrasive wear mechanism, for example, they will leave a rough and abrasive surface. These loose particles will be mixed with the slurry and thence trapped between the surfaces of the tooth enamel and the material specimens tested, thus further increasing the wear of opposing enamel. Interestingly, it was noticed from the raw data that the Duceram-LFC specimens that had showed less wear, also caused reduced tooth enamel wear, which may further support the latter explanation that if a ceramic surface has increased damaged, then it will become rougher and more abrasive.

Figure 6.4 shows that despite the effect of the slurry media in decreasing the enamel wear (Alpha porcelain and Vita Mark II) or in increasing it (Duceram-LFC), the difference between the water group and the slurry group was increased with increasing number of cycles. This is because over time (increasing number of cycles) the contact area of the tooth cusp was increasing because of the wear of the cusp tip (conical shape), subsequently more slurry particles were trapped between the tooth cusp and the ceramic specimen, thus enhancing the effect of the slurry medium.

6.5. Conclusion

After 25000 cycles of the wear test in the three-body slurry medium, compared to a distilled water media, the following can be concluded:

1. Slurry medium decreased the amount of enamel wear against Alpha porcelain and Vita Mark II and increased it against Duceram-LFC, although the differences were not statistically significant.

2. In water medium Alpha porcelain was significantly more abrasive than Duceram-LFC and Vita Mark II. However, in the slurry medium the difference between Alpha porcelain and Duceram-LFC was not significant, yet both were significantly more abrasive than Vita Mark II.

3. The wear of the ceramic materials was significantly less in the slurry medium than in water for the Alpha porcelain and Vita Mark II, whilst the Duceram-LFC had some small increase in wear.

4. In the water test the Alpha porcelain was found to be significantly more prone to wear than Duceram-LFC and Vita Mark II. However, in the slurry medium the wear of Alpha porcelain became less than the wear of Duceram-LFC, yet both were found to be significantly more prone to wear than Vita Mark II.

CHAPTER 7

Scanning Electron Microscopy Evaluation of Tooth Enamel and Restorative Material Wear

Chapter 7: Scanning Electron Microscopy Evaluation of Tooth Enamel and Restorative Material Wear

7.1. Introduction

Scanning electron microscopy (SEM) is a qualitative method for surface image evaluation. It is capable of producing images of high resolution and large depth of field at very high magnifications. The technique of SEM is a well established procedure, although not without its drawbacks. In this technique the specimen is placed in an electron beam and the image is produced by collection of secondary electrons emitted by the surface and volume of the specimen. Therefore, the surface to be examined must be at first electrically conductive. This is generally accomplished by coating with a thin metallic film (normally gold) in a vacuum, a process termed sputter coating. Loss of surface detail is a theoretical consideration during this process, however as the approximal thickness of the metal film is only 30nm, it is generally considered inconsequential (Scott, 1993). However, an important side effect is the potential for desiccation of the specimen when placed under the vacuum which would have a great effect on the tooth structure, particularly the dentine (Barnes, 1978). Subsequently, cracks may be formed in the tooth surface. To overcome this problem, a replica technique can be used. This involves the casting of an epoxy resin replica from an accurate impression of the specimen and the subsequent preparation of the replica for microscopic examination (Barnes, 1978, 1979). The replica technique has been used in many *in vivo* studies since it allows scanning electron microscopy examination of *in vivo* specimens and serial examination of samples at different times (Ekfeldt and Øilo, 1988, 1989, 1990; Mair, 1990; Teaford and

Tylenda, 1991; Mörmann and Krejci, 1992). However, as much as the replica is accurate, perhaps very fine structural detail may be lost with this technique.

Recently, a new scanning electron microscope has been developed which operates at normal pressures and does not require dehydration of samples. This is what is called the environmental electron microscope which may well be able to overcome the problems encountered with the normal machines (Scott, 1993). Nonetheless, SEM remains an excellent way of examining surfaces of dental tissues and restorative materials and is used extensively in dental studies to evaluate qualitatively the surface roughness (Raimondo *et al.*, 1990; Goldstein *et al.*, 1991; Patterson *et al.*, 1991; Ward *et al.*, 1995) and the wear characteristics of different restorative materials (DeLong *et al.*, 1986; Krejci *et al.*, 1993, 1994; Ratledge *et al.*, 1994; Pallav *et al.*, 1993).

The aim of this study is to use the SEM to investigate the wear characteristics of the ceramic materials and their antagonist tooth enamel specimens, which had been tested under different conditions described in the previous chapters.

7.2. Materials And Methods

After the wear test, at least three specimens were selected randomly, from each group of every experiment, with their antagonist tooth specimens, to be examined by scanning electron microscopy. The specimens were rinsed under tap water, then dried gently with air from the dental unit. Specimens were then mounted onto the SEM specimen holder stubs and wiped with alcohol to remove finger grease, or any residual

surface moisture. They were then placed under vacuum and sputter coated with gold. The prepared specimens were viewed by a scanning electron microscope (Joel, JSM-T300, Tokyo, Japan) at different magnifications, at a constant accelerating voltage (30 kV). Photographs were taken for all the specimens at similar magnifications to allow direct comparisons between the resulting photomicrographs.

7.3. Results

7.3.1. Surface finishing of restorative materials

Figure 7.1 shows a scanning electron micrograph of a glazed Alpha porcelain surface exhibiting a relatively smooth surface interrupted only by slight granularity. Figure 7.2 shows a scanning electron micrograph of unglazed Alpha porcelain surface that had been adjusted with a fine and then super-fine diamond bur. Extensive surface disruption is clearly evident with many irregularities with sharp edges. Figure 7.3 shows a scanning electron micrograph of an adjusted Alpha porcelain surface that had been polished using porcelain finishing wheel and diamond polishing paste. The scanning electron micrograph shows a smooth surface with some microporosity that had been opened because of the porcelain adjustment through removal of the glazed surface. Figures 7.4 to 7.5 show scanning electron micrographs of a glazed surface of Omega porcelain and Duceram-LFC, respectively. Figure 7.4 shows that the glazed surface of the Omega porcelain specimen is clearly interrupted by some granularity. Figure 7.5 shows that the Duceram-LFC has a relatively smooth surface. Figure 7.6 shows the surface of Vita Mark II, which had previously been ground with a diamond bur, then polished by porcelain finishing wheels and diamond polishing paste. Numerous microporosities can be seen clearly. Figure 7.7 shows the surface of a

polished cast gold surface which had previously been finished with brown and green abrasive rubber wheels. The scanning electron micrograph shows a smooth surface with thin scratches.

7.3.2. Wear tracks in restorative materials

Figure 7.8 shows a typical representation of the wear track at low magnification (original magnification x15) as represented by an Omega porcelain specimen. The area on the right of the photograph represents the beginning of the wear track corresponding to the point where the tooth specimen first impacts the surface of the material. The arrow indicates the direction of the sliding path of the tooth onto the material specimen.

Figure 7.9 to 7.12 show scanning electron micrographs of the wear track of Alpha porcelain, Omega porcelain, Vita Mark II and Duceram-LFC respectively, at a magnification of (a) x100 and (b) x1000, tested in water. Overall, at the lower magnification the scanning electron micrograph shows multi lacunae (pits) in the surface of the wear track in addition to grooves and ridges that run along the wear track. However, for the Duceram-LFC the lacunae were smaller in size and the general view of the surface of the track was much smoother (Fig. 7.12a). At the higher magnification in all specimens the lacunae were seen to be surrounded by multiple cracks with a tendency to meet each other thus loosening further particles from the surface and increasing the size of the lacunae. For the Duceram-LFC the cracks appeared to be more superficial and relatively shorter in length, compared with

the other ceramics. In addition, the undamaged areas around the lacunae appeared to be quite smooth (Fig. 7.12b).

Figure 7.13 shows a view of the wear track of the gold specimen at a magnification of (a) x100 and (b) x500. Figure 7.13a shows that the wear track surface consists of multiple pits which appear as if the material has been spalled i.e. some fragments have been removed from the material. Figure 7.13b shows the depressions left behind as a result of the fragments that had been removed. Furthermore, it can be seen that some of the fragments were surrounded by cracks suggesting that this is just prior to their removal whilst others had been reattached to the surface. Overall, Fig. 7.13b suggests that the wear of gold seems to occur in layers.

Figure 7.14 to 7.16 show scanning electron micrographs of the wear tracks of Alpha porcelain, Vita Mark II and Duceram-LFC respectively, at a magnification of (a) x100 and (b) x1000, tested with an intermittent exposure to Coca Cola. Figure 7.14a shows the wear track of Alpha porcelain with distinct ridges running along the surface with a substantial reduction in the number of lacunae compared to that observed when tested in water (Fig. 7.9a). At the higher magnification (Fig. 7.14b) particles can be seen at the side of the ridges. The fact that these particles have different contrast may suggest that they originate from different materials. It is probable that some of these particles are from the porcelain itself whilst the others have originated from the opposing enamel surface. Figure 7.15a shows the presence of numerous ridges and grooves on the wear track surface of the Vita Mark II. In addition there are multiple lacunae present. The higher magnification (Fig. 7.15b) shows how these lacunae are

joined together forming a more extensive damaged area with a rougher surface. Figure 7.16a shows a widespread area of lacunae in the wear track of Duceram-LFC, indicating extensive damage to the surface associated with some cracks. Overall, the surface is different compared with that seen in water. At the higher magnification (7.16b) deep crack formation is obvious and indicates that some surface particles have been broken off leaving a rough surface.

Figure 7.17 to 7.19 show scanning electron micrographs of the wear track of Alpha porcelain, Vita Mark II and Duceram-LFC respectively, at a magnification of (a) x100 and (b) x1000, tested in the presence of food particles. Figure 7.17a shows the wear track of Alpha porcelain with a specific pattern of lacunae that were formed and lay in rows. This is most probably because the food particles have been trapped between the tooth surface and the porcelain and dragged along the wear track resulting in such a pattern. There is a substantial reduction in the presence of grooves and ridges which were more prominent when the test was carried out in water. Figure 7.17b shows that lacunae that had formed in the Alpha porcelain were much smaller compared with that seen when the test was carried out in water. The central part of Fig. 7.17b shows an area that appears collapsed perhaps because of the presence of a subsurface void. Passing food particles may have become trapped in this area, causing subsequent collapse. Overall, a much smoother surface can be seen compared with that seen when the test was carried out in water (Fig. 7.9). Figure 7.18a shows that the wear tracks of Vita Mark II was much smoother in the presence of food particles than that seen in water (Fig. 7.11a). At the higher magnification (7.18b) the lacunae are still present, however, they are much smaller in size and they are not as localised as in Fig. 7.11b.

No deep cracks were noticed. Figure 7.19a shows the wear track of Duceram-LFC with a unique wear pattern. Cracks are seen in the form of successive arches with their concave sides radiating towards the direction of slide of the tooth. Lacunae were also noticed mainly lying between these crack lines. Figure 7.19b revealed that these cracks were also connected with micro cracks in between.

7.3.3. Enamel wear facets

Figures 7.20 to 7.25 are scanning electron micrographs of the wear facets of the tooth enamel that were tested either in water or cola/water alternatively, against the Alpha porcelain with different finishing surfaces: glazed (Figs. 7.20, 7.21), unglazed (Figs. 7.22, 7.23) and polished (Figs. 7.24, 7.25). Overall, grooves can be seen running parallel to the sliding path direction of the tooth which may indicate that the wear mechanism was mainly of a two-body abrasive nature. Areas with microcracks are also observed, especially at the edges of the grooves.

Figure 7.26 and 7.27 show scanning electron micrographs of the tooth enamel wear facets that were tested in distilled water against Omega porcelain and Vita Mark II respectively. Again, similar grooves are observed running parallel to the direction of the tooth sliding path, as observed in the enamel wear tested against Alpha porcelain (Fig. 7.20). Some evidence of surface damage are also seen associated with microcracks indicating a fatigue wear process in addition to the abrasive wear. The grooves in the enamel wear facets against Vita Mark II were less distinct or much shallower and generally less frequent than those found against Alpha and Omega porcelain.

Figure 7.28 shows a scanning electron micrograph of the tooth enamel wear facet that was tested in distilled water against Duceram-LFC. Substantial differences were noticed in that the damaged areas or microcracks associated with the localised surface damage (fatigue) were almost absent. The surface had a much smoother appearance compared with the previous groups (Figs. 7.20, 7.26, 7.27). The surface shows the presence of what can be termed shallow scratches rather than deep grooves seen previously. Again these scratches ran parallel to the direction of the tooth sliding path.

Figure 7.29 shows a scanning electron micrograph of tooth enamel wear facet tested in water against gold. No grooves can be seen and in some areas the surface is relatively smooth with dark thin deposits running along microscratches. Other areas show some damage to the enamel structure with some particles which have become attached to the surface. These particles have a different contrast from the tooth enamel surface and probably are gold deposited as a result of adhesive wear mechanisms.

Figures 7.30 and 7.31 show scanning electron micrographs of tooth enamel wear facets tested with intermittent exposure to Coca Cola against Vita Mark II and Duceram-LFC, respectively. Figure 7.30 shows numerous grooves that also run parallel along the tooth sliding path, with distinct edges. Compared to Fig. 7.27, tested in water, the areas of damage with microcracks were much less in Fig. 7.30, and a greater number of deeper grooves were observed, yet not so deep nor as much as those observed in Fig. 7.21 (tooth enamel vs glazed Alpha porcelain in Coca Cola). Figure 7.31 shows that the surface of the tooth enamel (against Duceram-LFC in

cola) is much rougher with areas of damage and irregular patterns of wear, compared with that seen when the test was carried out in water (7.28).

Figures 7.32 to 7.34 show scanning electron micrographs of tooth enamel wear facets tested in food slurry against Alpha porcelain, Vita Mark II and Duceram-LFC, respectively. Both tooth enamel wear facets tested against Alpha porcelain and Duceram-LFC (Figs. 7.32 and 7.34, respectively) showed some similarities i.e. the damaged areas in the enamel structure with numerous grooves. The pattern seen with Vita Mark II (Fig. 7.33), however, shows absence of damaged areas (microcracks) and grooves which are much more shallow and less distinct.

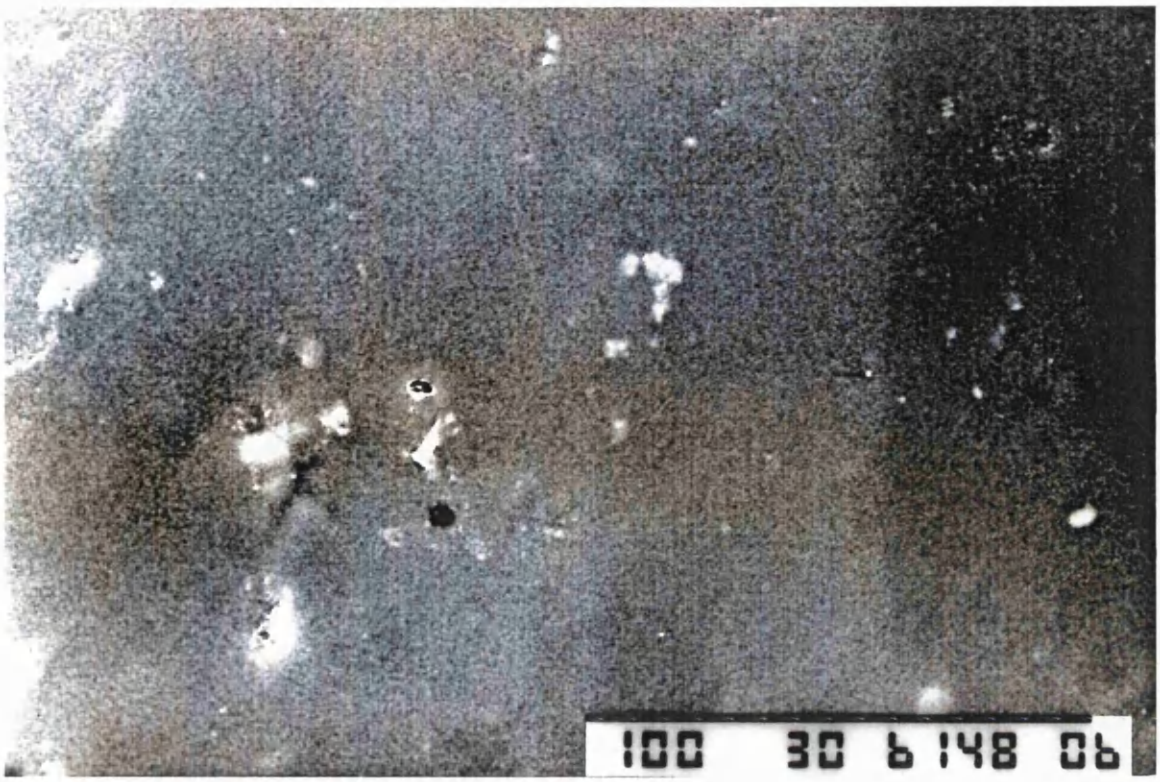


Fig. 7.1. SEM of a glazed Alpha porcelain surface (Original magnification X500; bar = 100μm).

Fig. 7.2. SEM of an unglazed Alpha porcelain surface that had been adjusted with a fine and then super-fine diamond bur. (Original magnification X500; bar = 100μm).

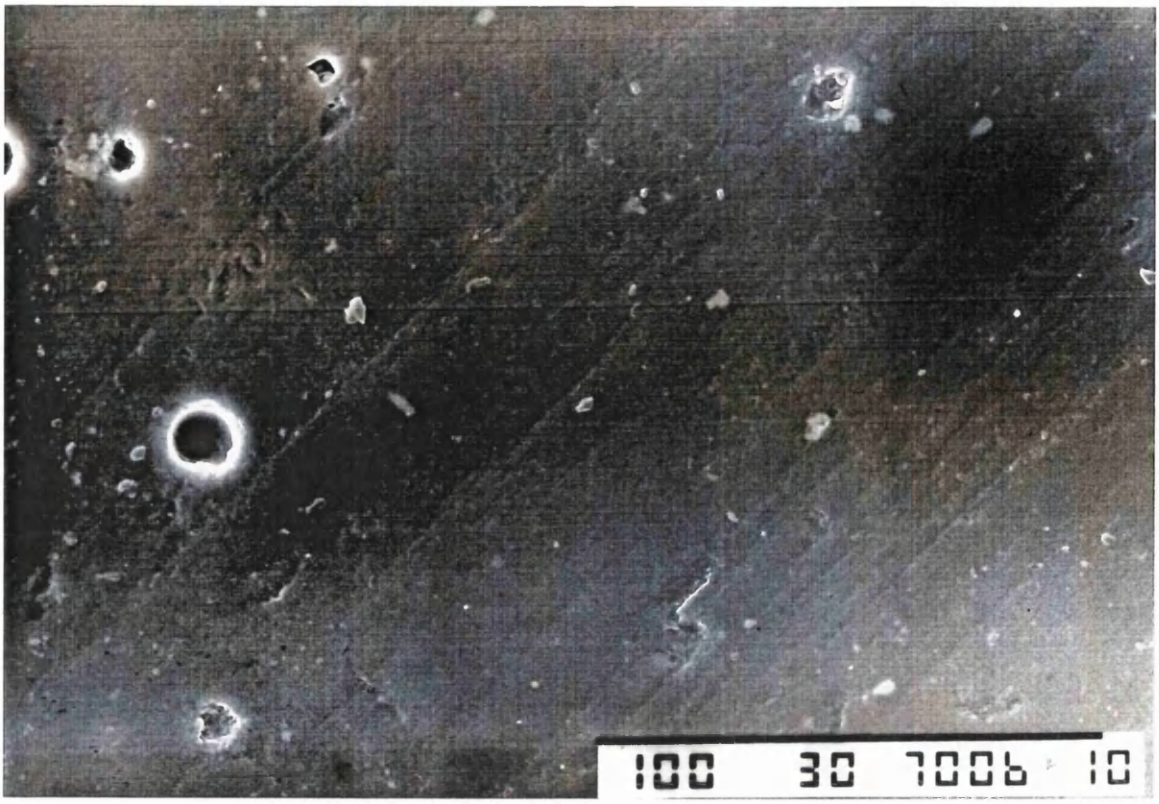


Fig. 7.3. SEM of a polished Alpha porcelain surface. The surface had first been adjusted with diamond burs and then polished using porcelain finishing wheel and diamond polishing paste. (Original magnification X500; bar = 100μm).

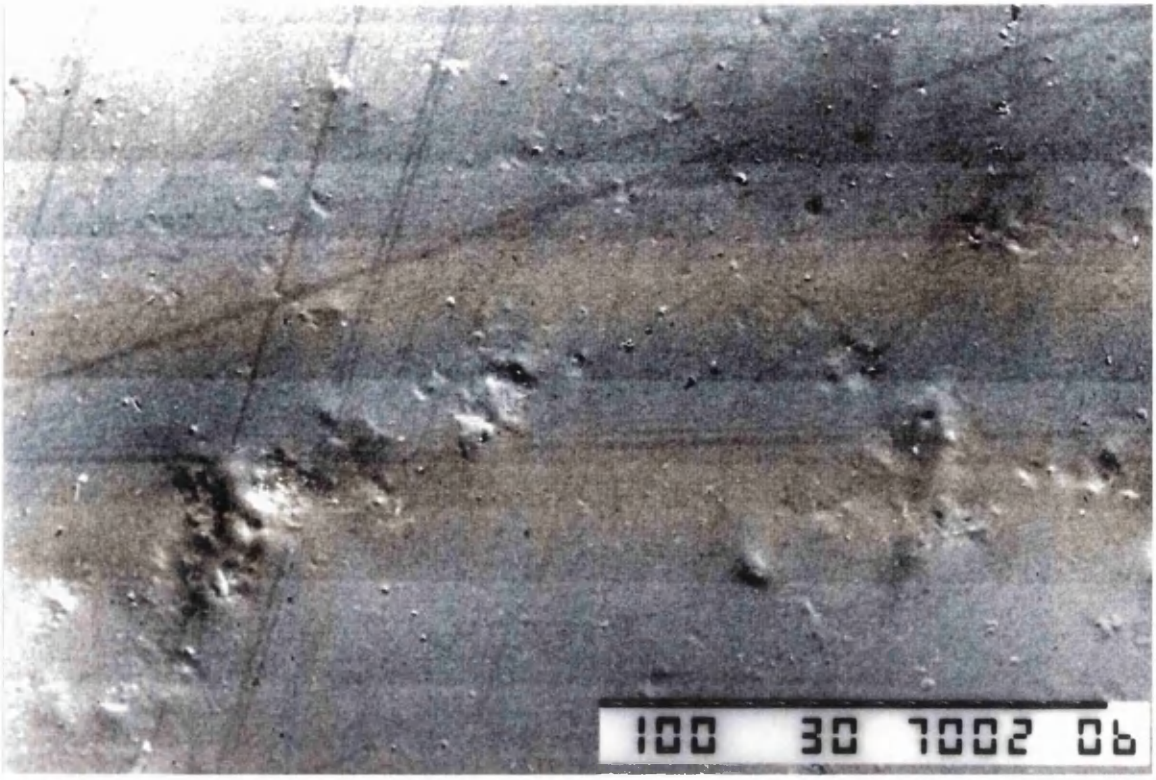


Fig. 7.4. SEM of a glazed surface of Omega porcelain (Original magnification X500; bar = 100μm).

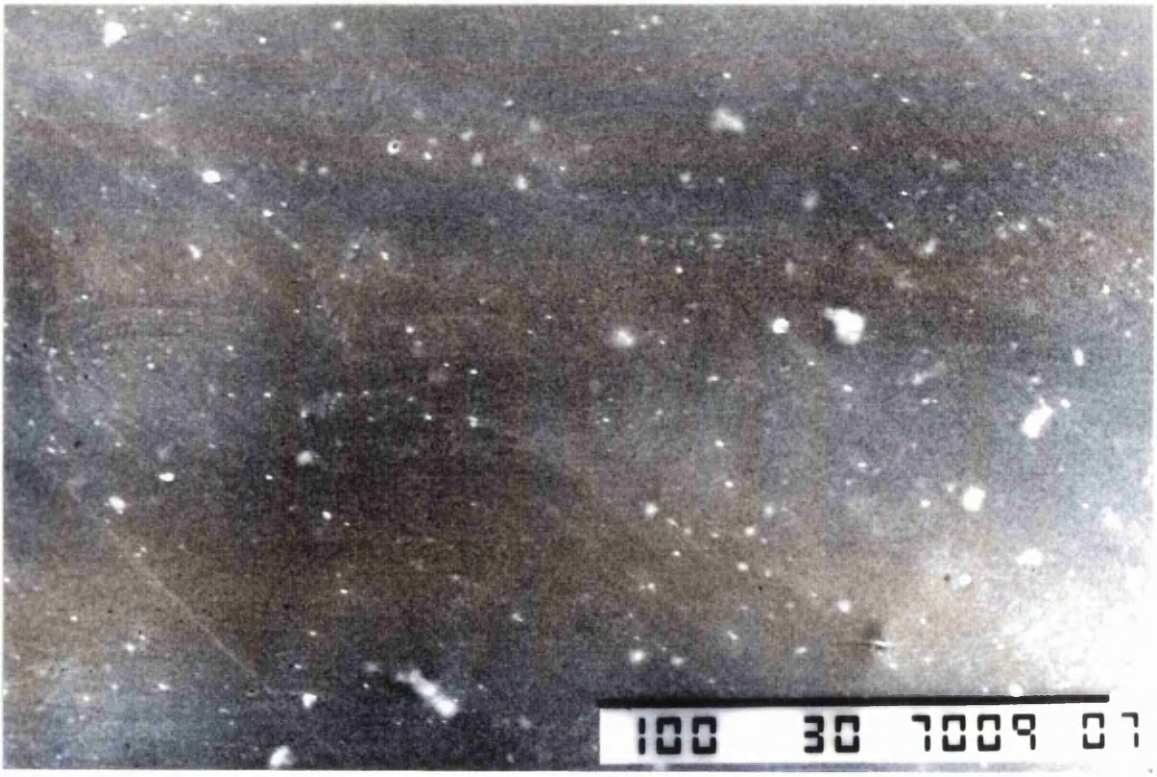


Fig. 7.5. SEM of a glazed surface of Duceram-LFC (Original magnification X500; bar = 100μm).

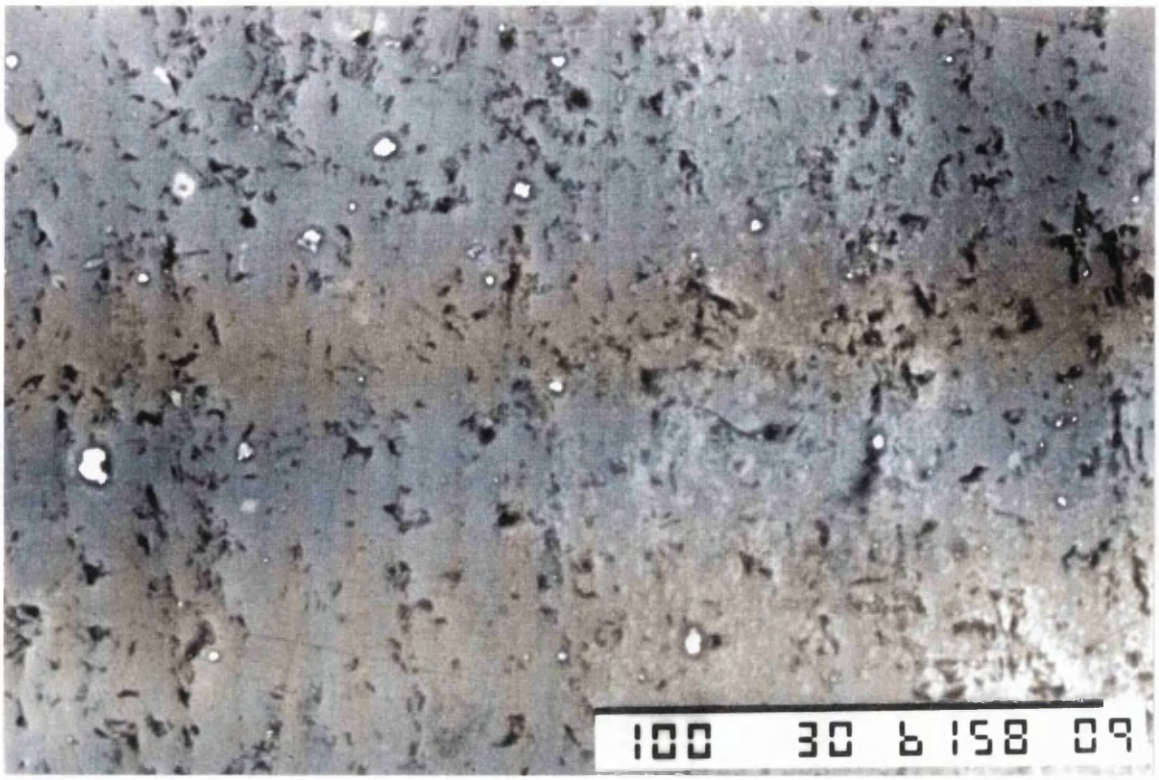


Fig. 7.6. SEM of a polished Vita Mark II surface. The surface had first been adjusted with diamond burs and then polished using porcelain finishing wheel and diamond polishing paste (Original magnification X500; bar = 100μm).

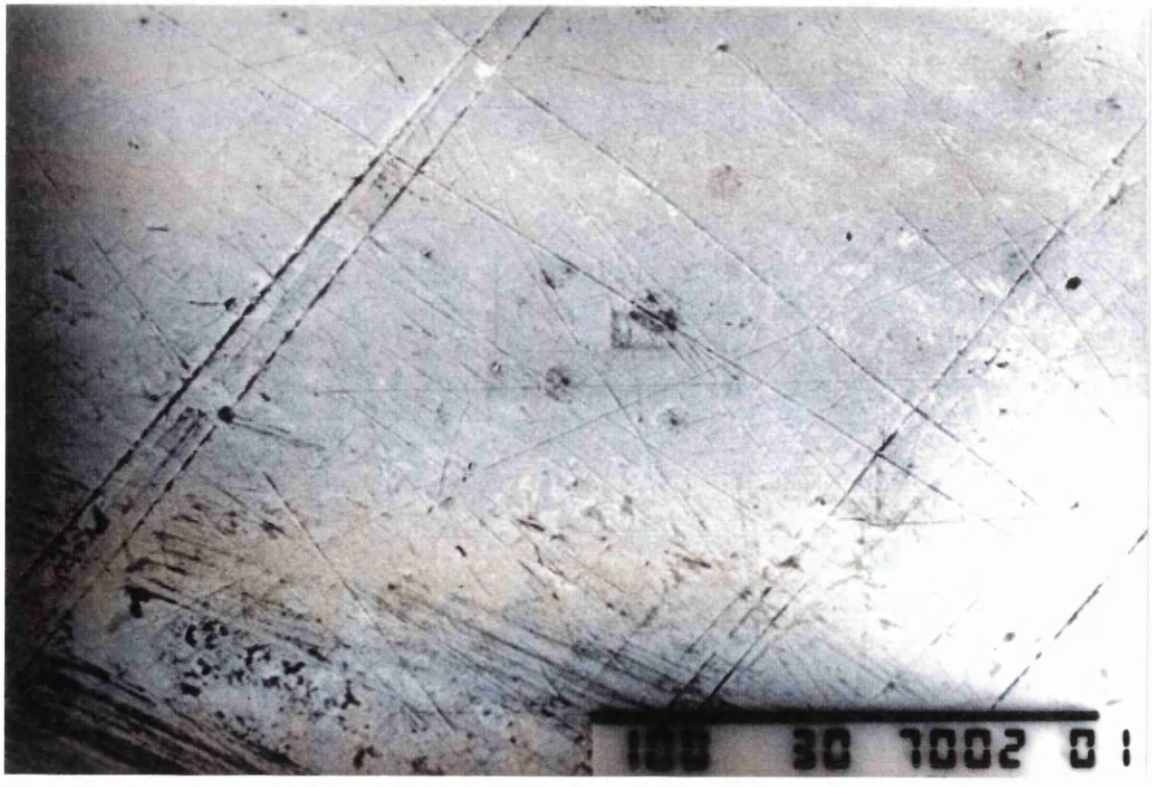


Fig. 7.7. SEM image of a polished cast gold surface which had been finished with brown and green abrasive rubber wheels (Original magnification X500; bar = 100μm).

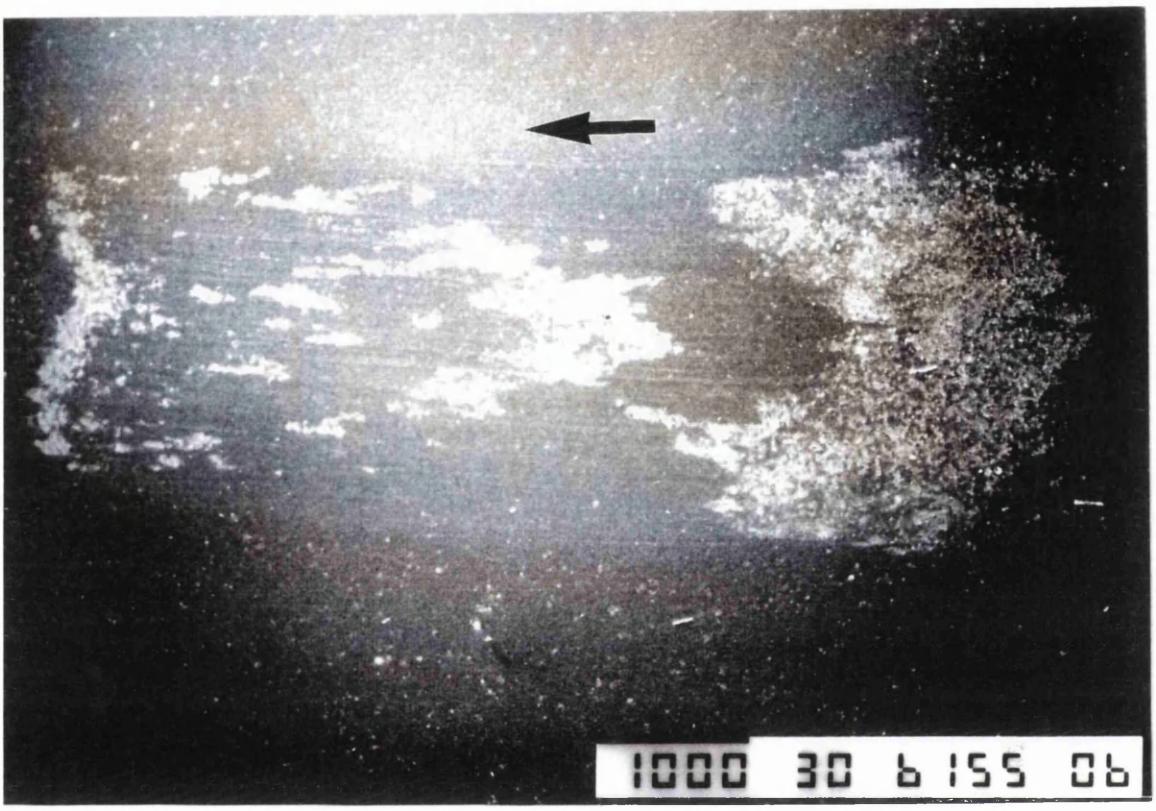


Fig. 7.8. SEM of a typical representation of the wear track as represented by an Omega porcelain specimen. The right end of the wear track is where the tooth specimen first impacts on the surface of the material. The arrow indicates the direction of the sliding path of the tooth (Original magnification X15; bar = 1000μm).

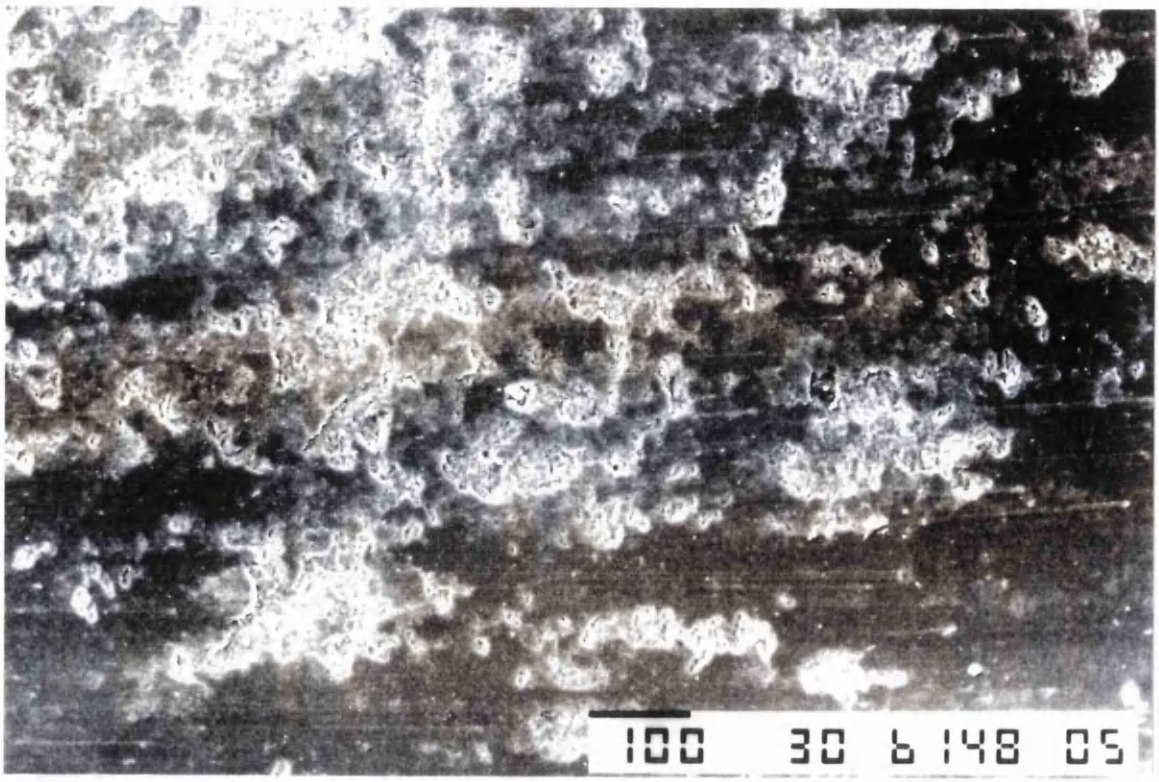


Fig. 7.9a. SEM of the wear track of Alpha porcelain tested in water (Original magnification X100; bar = 100μm).

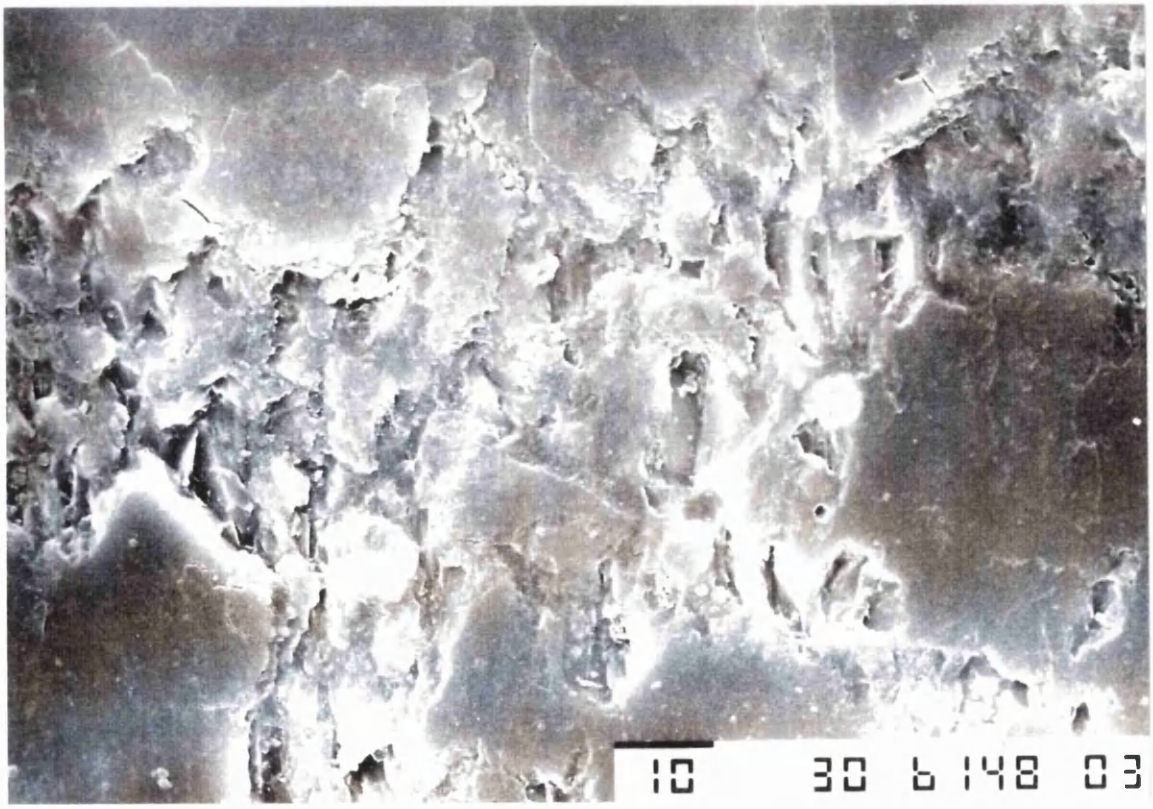


Fig. 7.9b. SEM of the wear track of Alpha porcelain tested in water (Original magnification X1000; bar = 10μm).

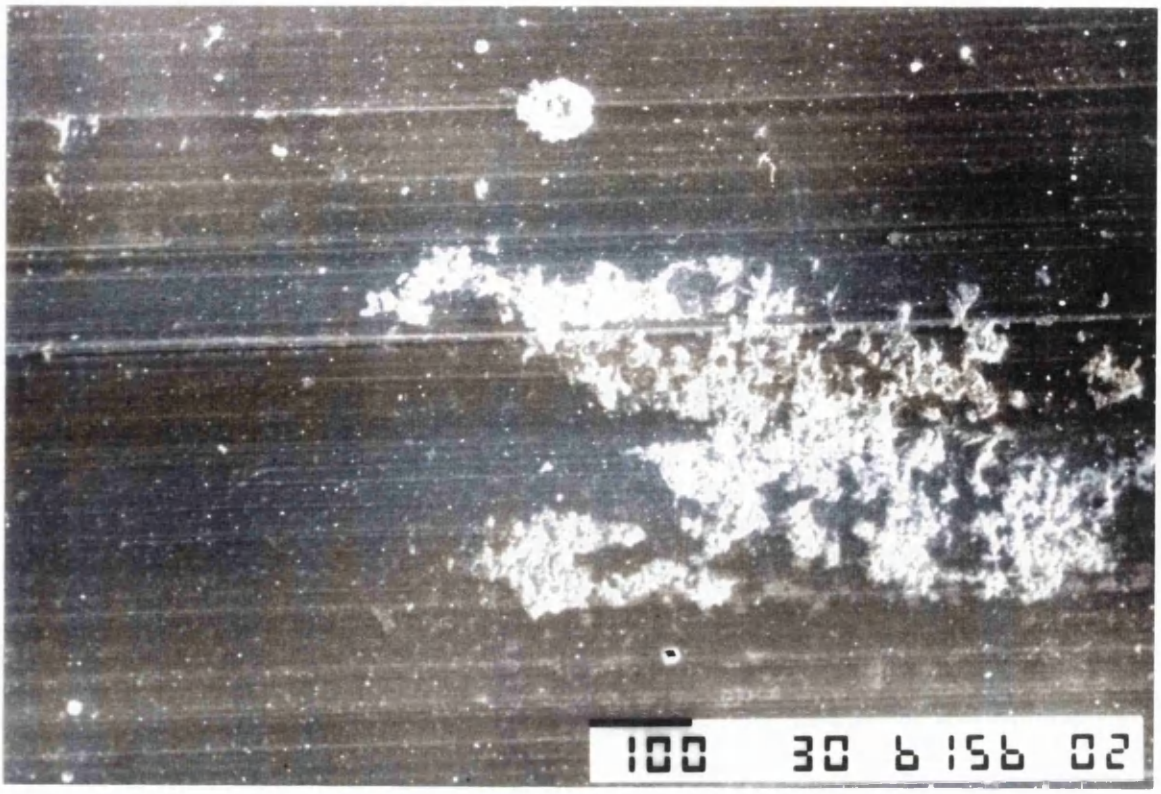


Fig. 7.10a. SEM of the wear track of Omega porcelain tested in water (Original magnification X100; bar = 100μm).

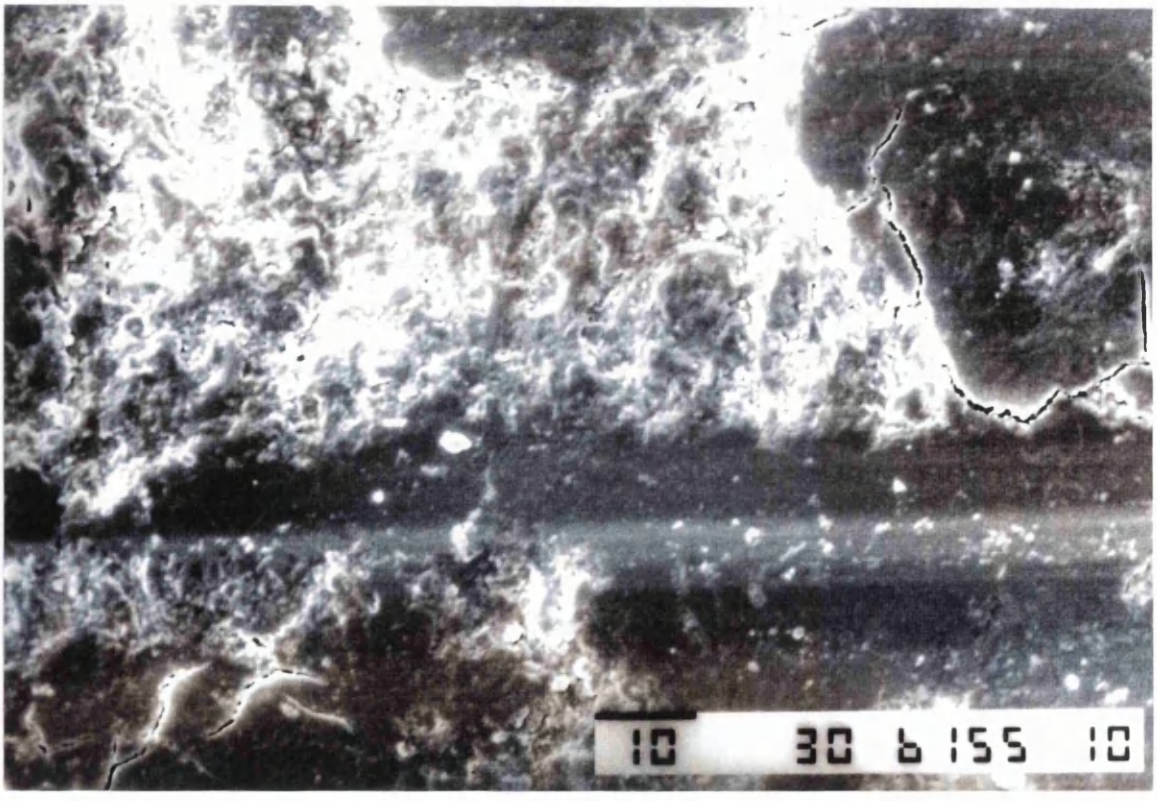


Fig. 7.10b. SEM of the wear track of Omega porcelain tested in water (Original magnification X1000; bar = 10μm).

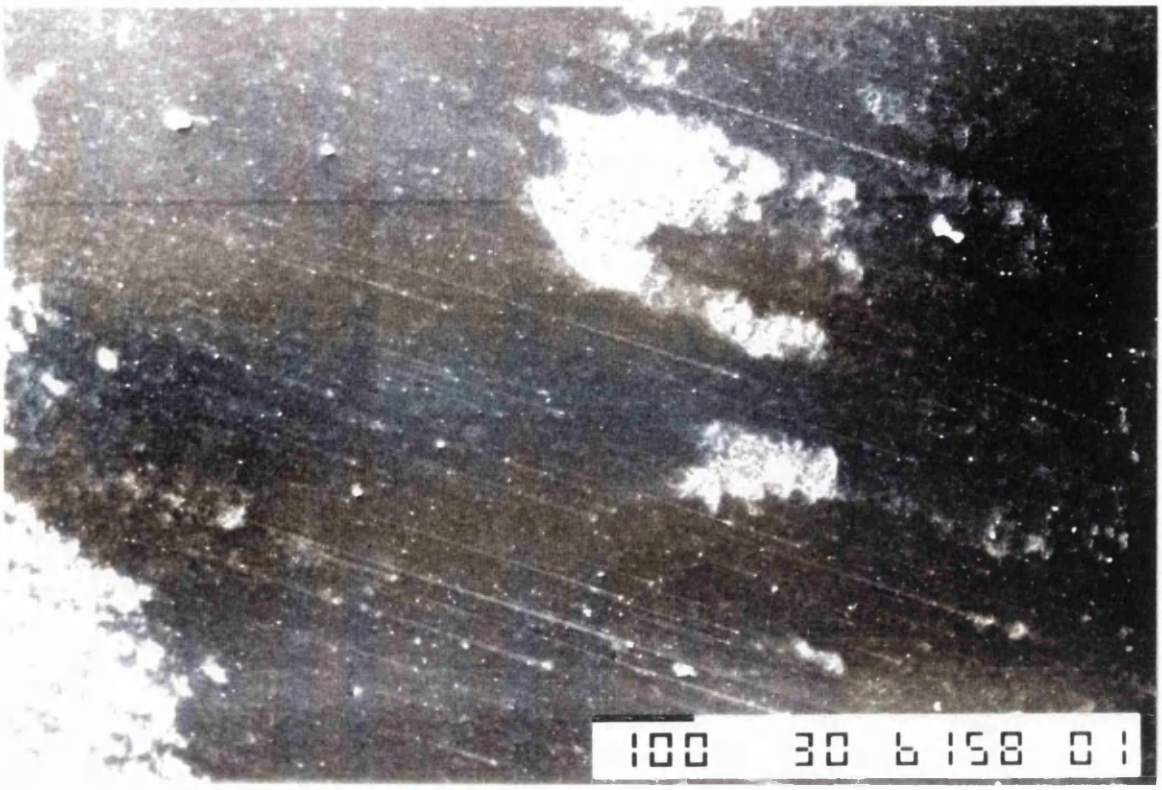


Fig. 7.11a. SEM of the wear track of Vita Mark II tested in water (Original magnification X100; bar = 100μm).

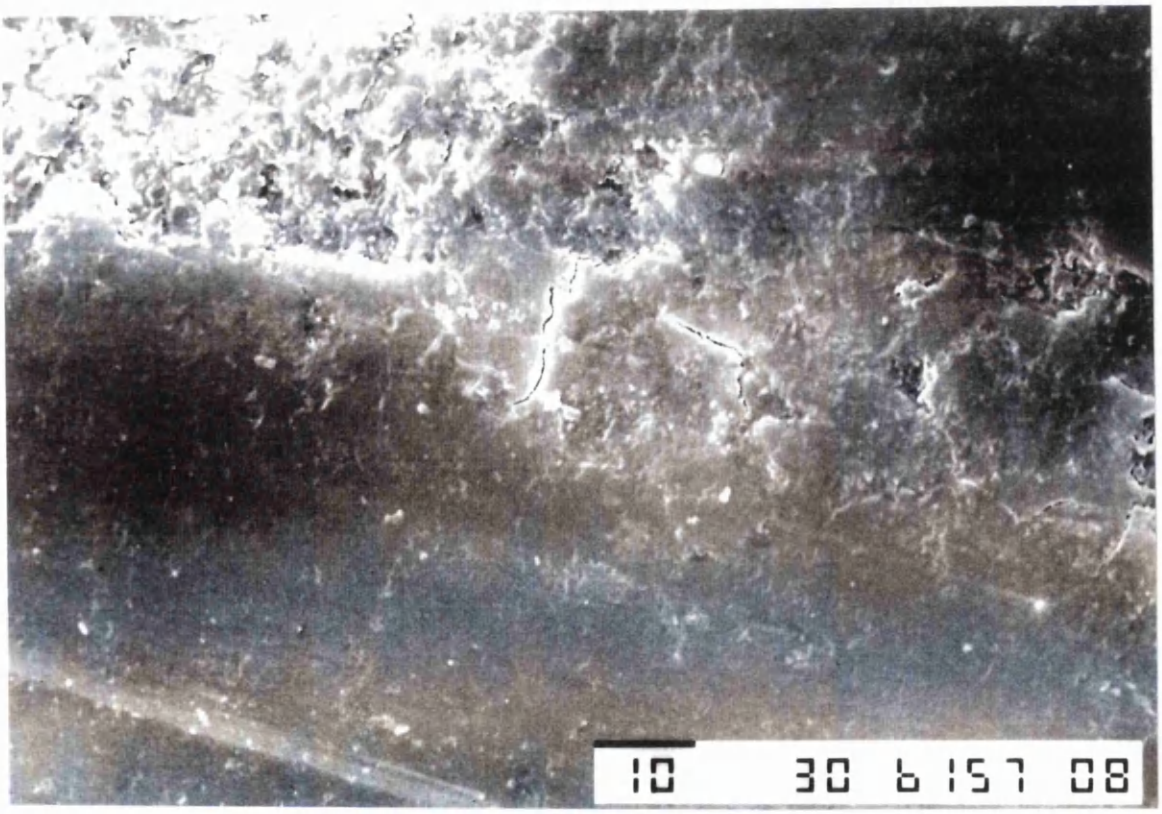


Fig. 7.11b. SEM of the wear track of Vita Mark II tested in water (Original magnification X1000; bar = 10μm).

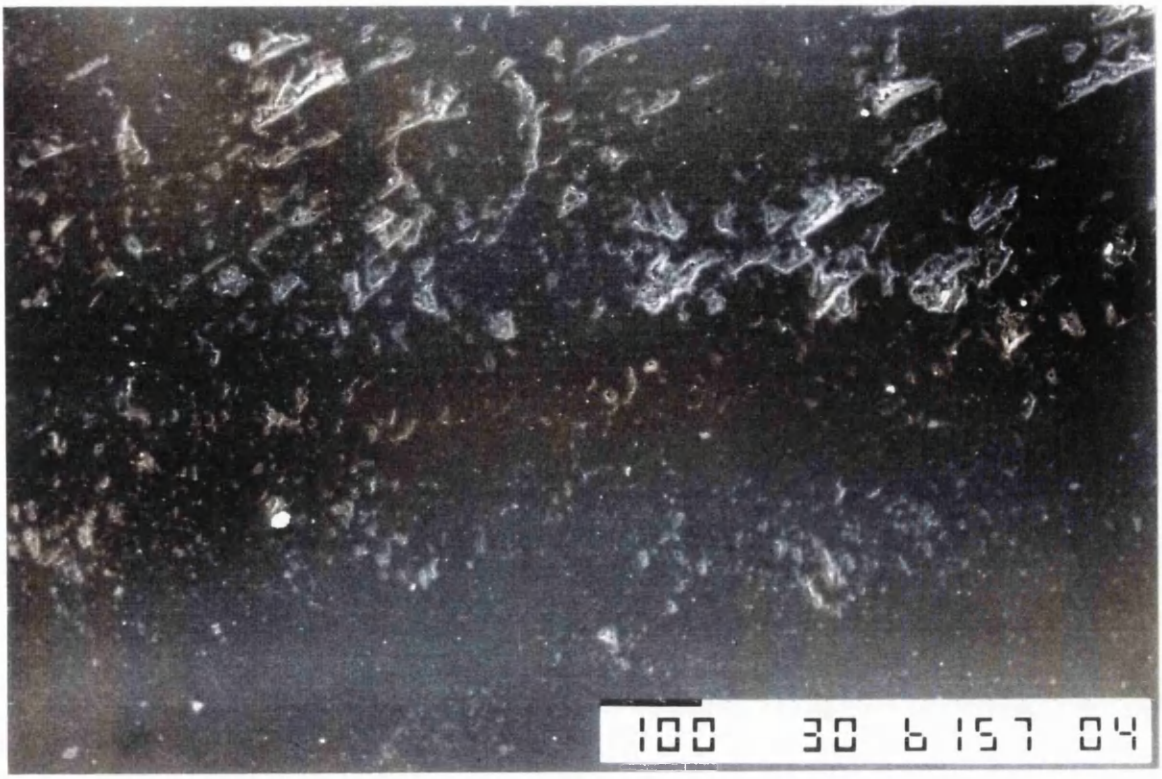


Fig. 7.12a. SEM of the wear track of Duceram-LFC tested in water (Original magnification X100; bar = 100μm).

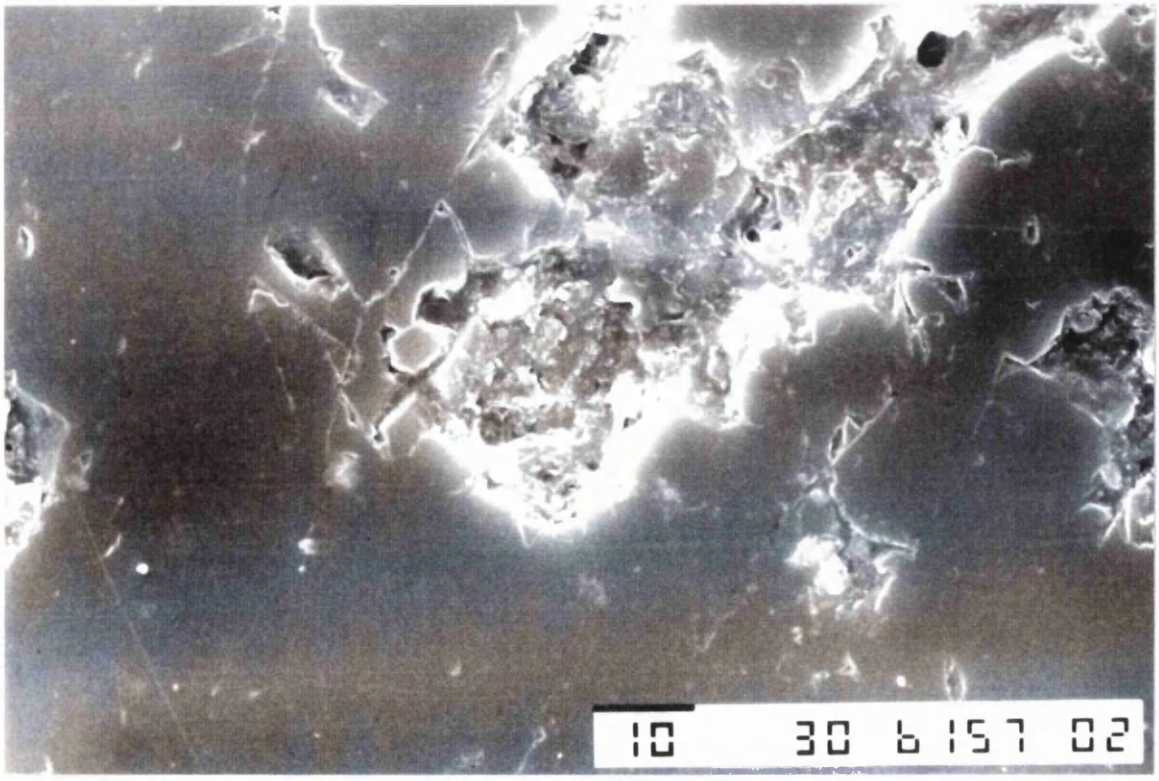


Fig. 7.12b. SEM of the wear track of Duceram-LFC tested in water (Original magnification X1000; bar = 10μm).

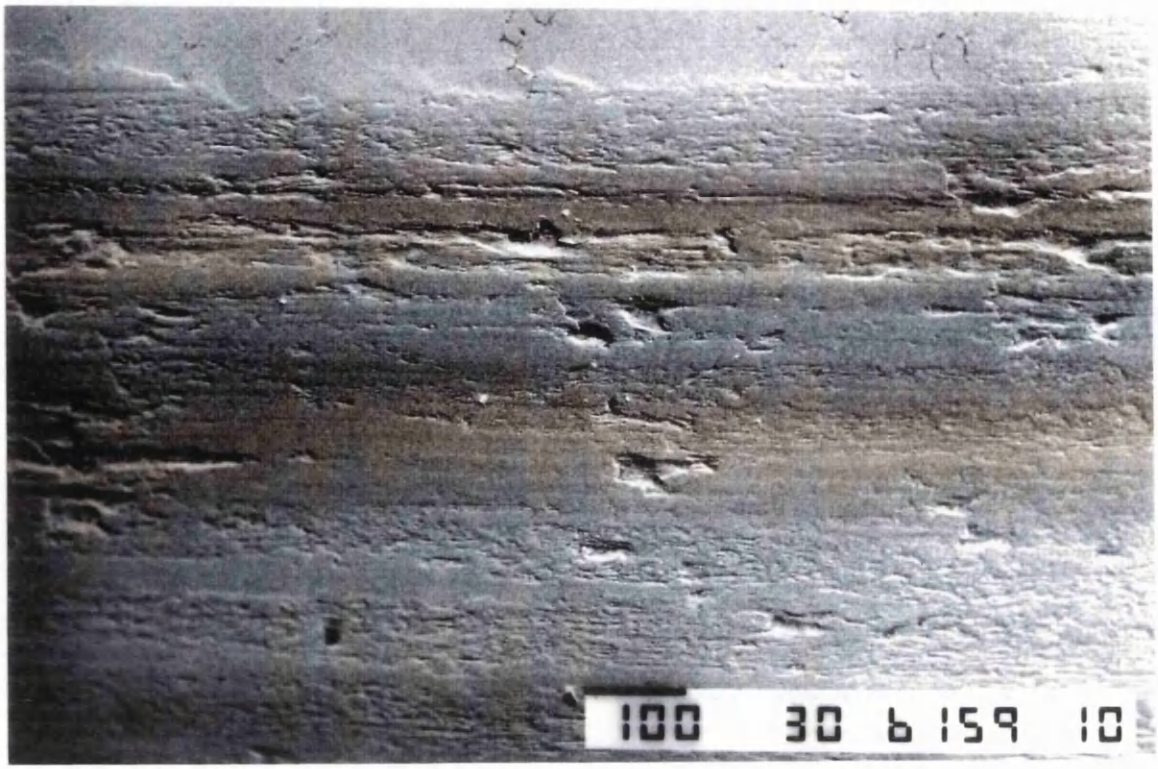


Fig. 7.13a. SEM of the wear track of a gold specimen tested in water (Original magnification X100; bar = 100μm).

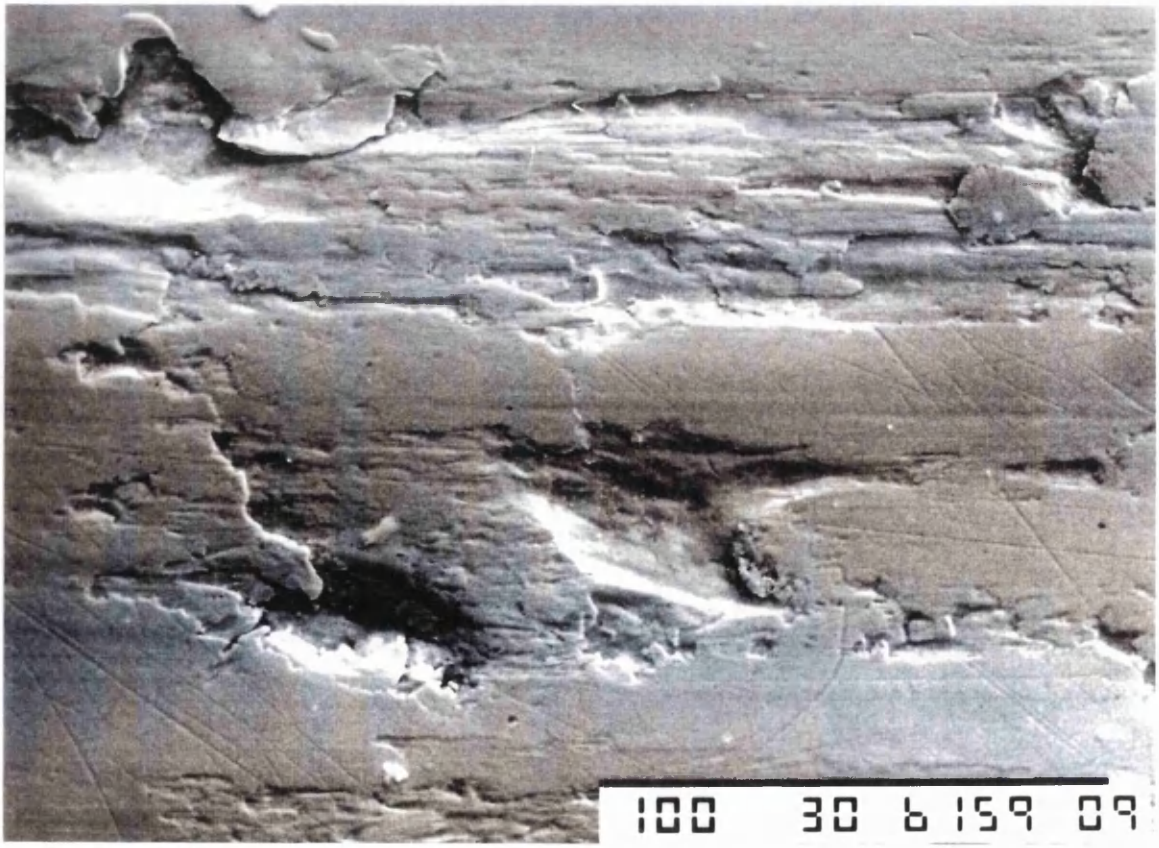


Fig. 7.13b. SEM of the wear track of a gold specimen tested in water (Original magnification X500; bar = 100μm).

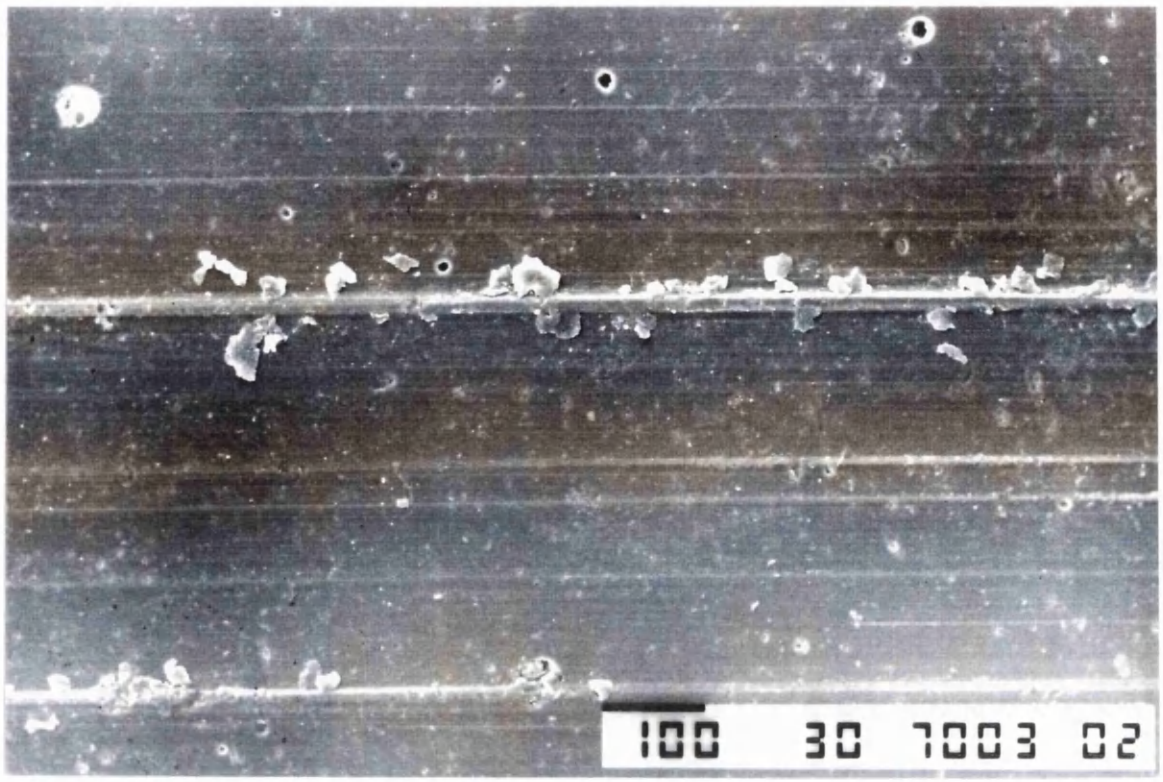


Fig. 7.14a. SEM of the wear track of Alpha porcelain tested with exposure to Coca Cola (Original magnification X100; bar = 100μm).

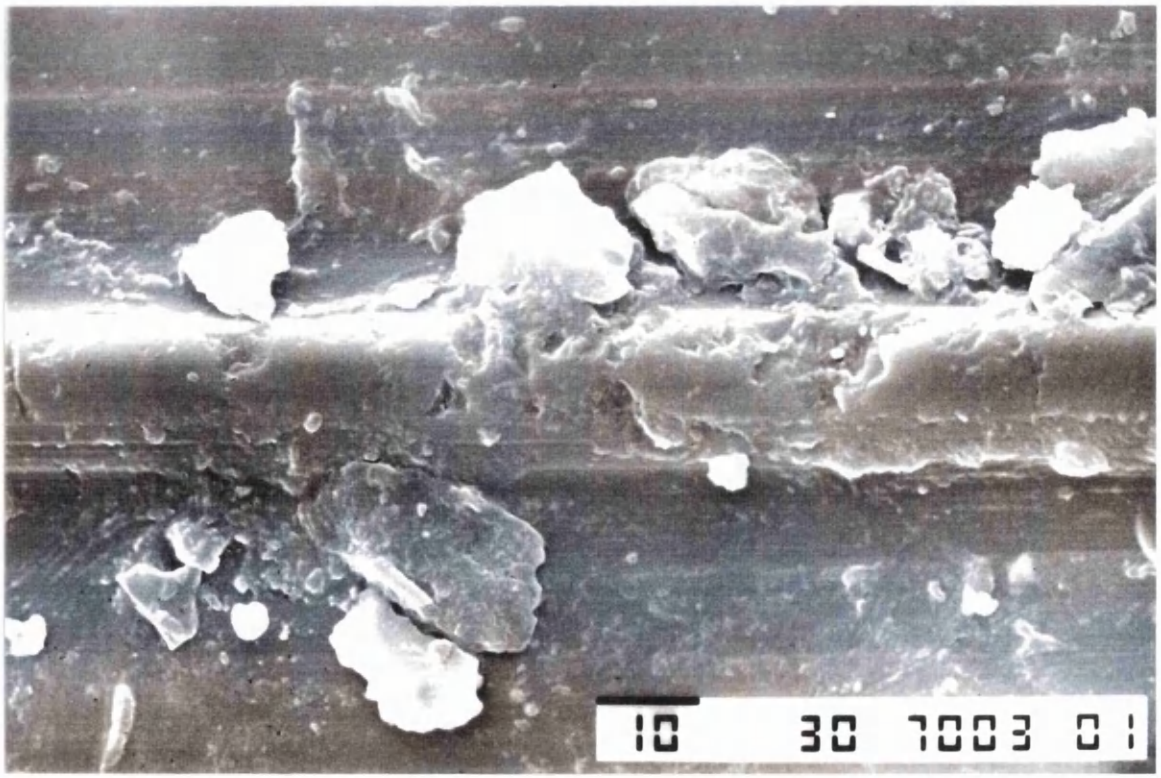


Fig. 7.14b. SEM of the wear track of Alpha porcelain tested with exposure to Coca Cola (Original magnification X1000; bar = 10μm).

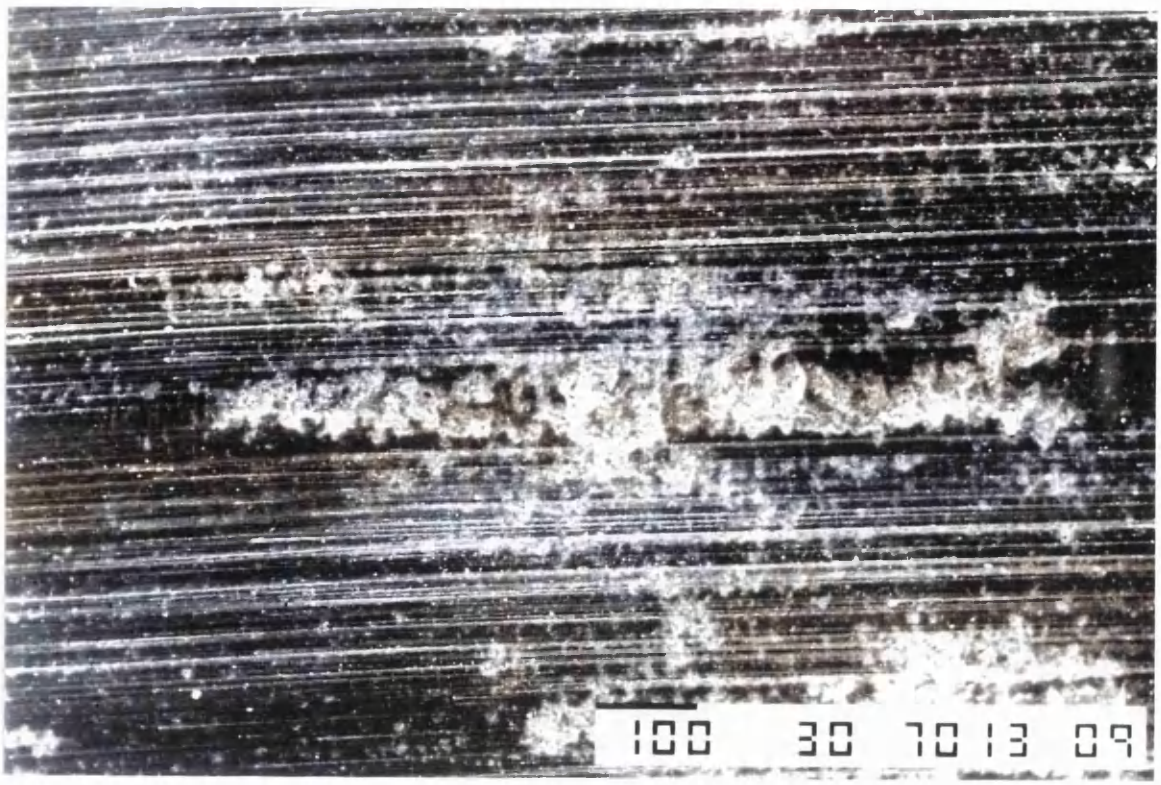


Fig. 7.15a. SEM of the wear track of Vita Mark II tested with exposure to Coca Cola (Original magnification X100; bar = 100μm).

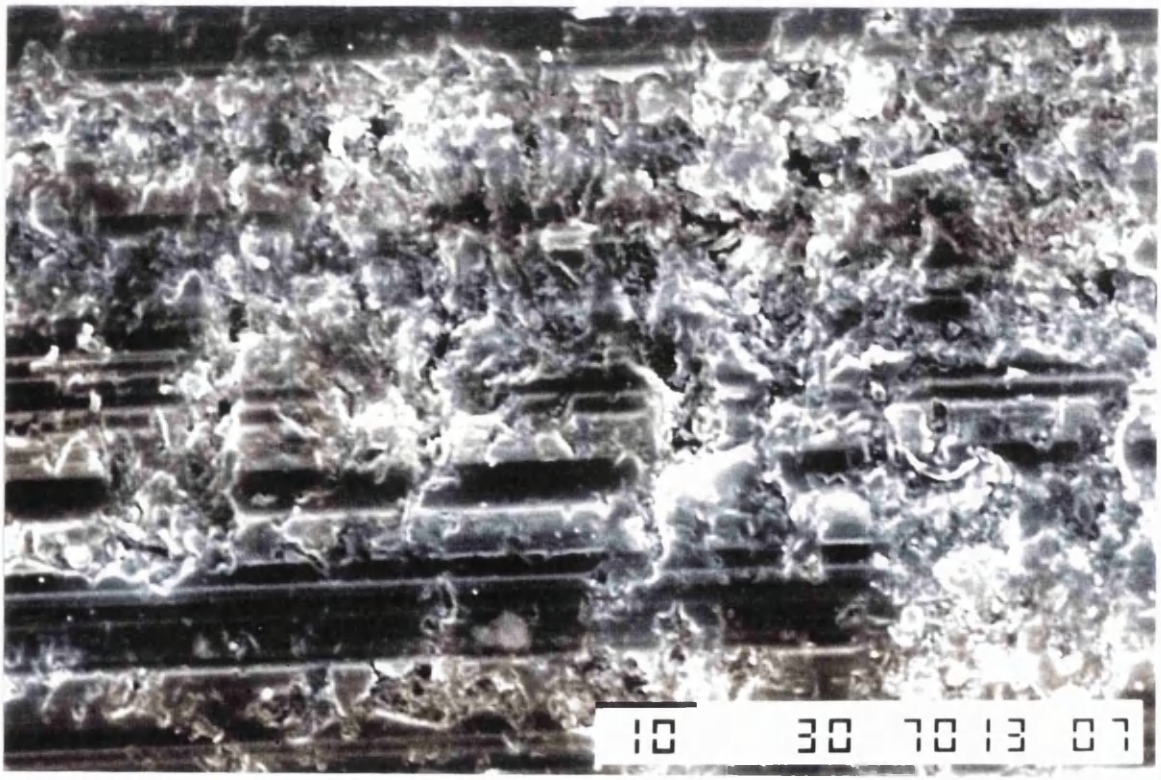


Fig. 7.15b. SEM of the wear track of Vita Mark II tested with exposure to Coca Cola (Original magnification X1000; bar = 10μm).

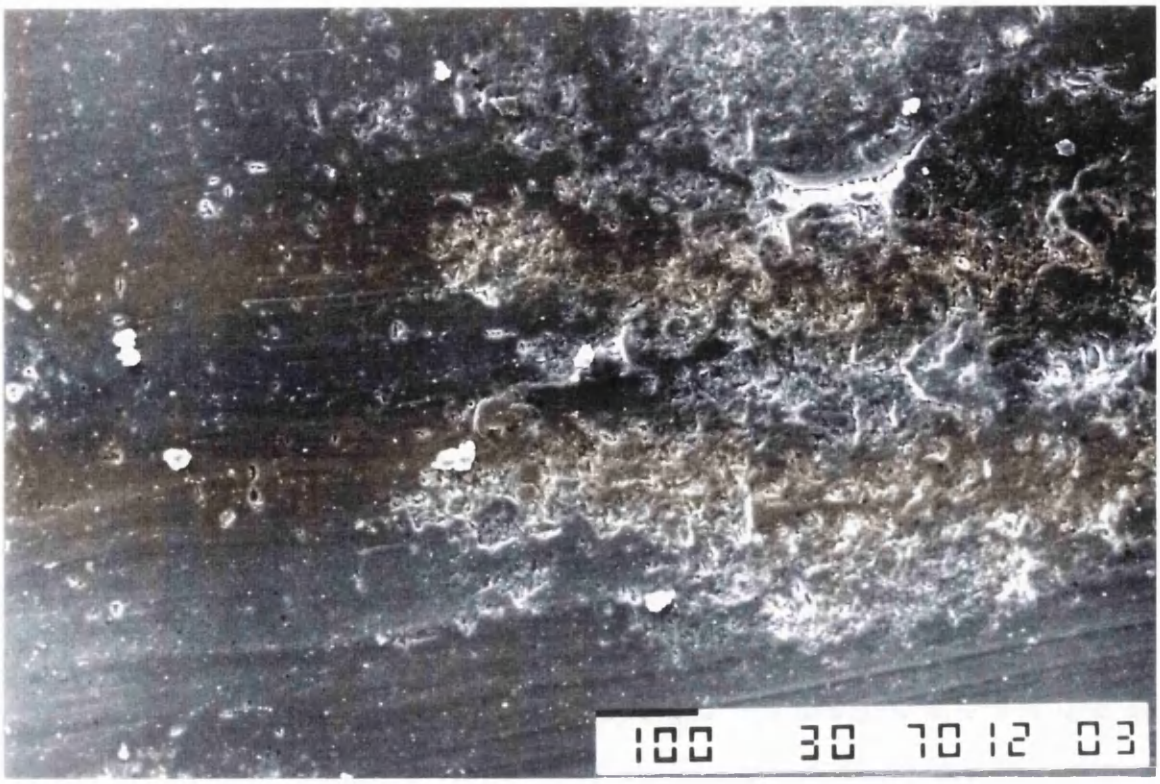


Fig. 7.16a. SEM of the wear track of Duceram-LFC tested with exposure to Coca Cola (Original magnification X100; bar = 100μm).

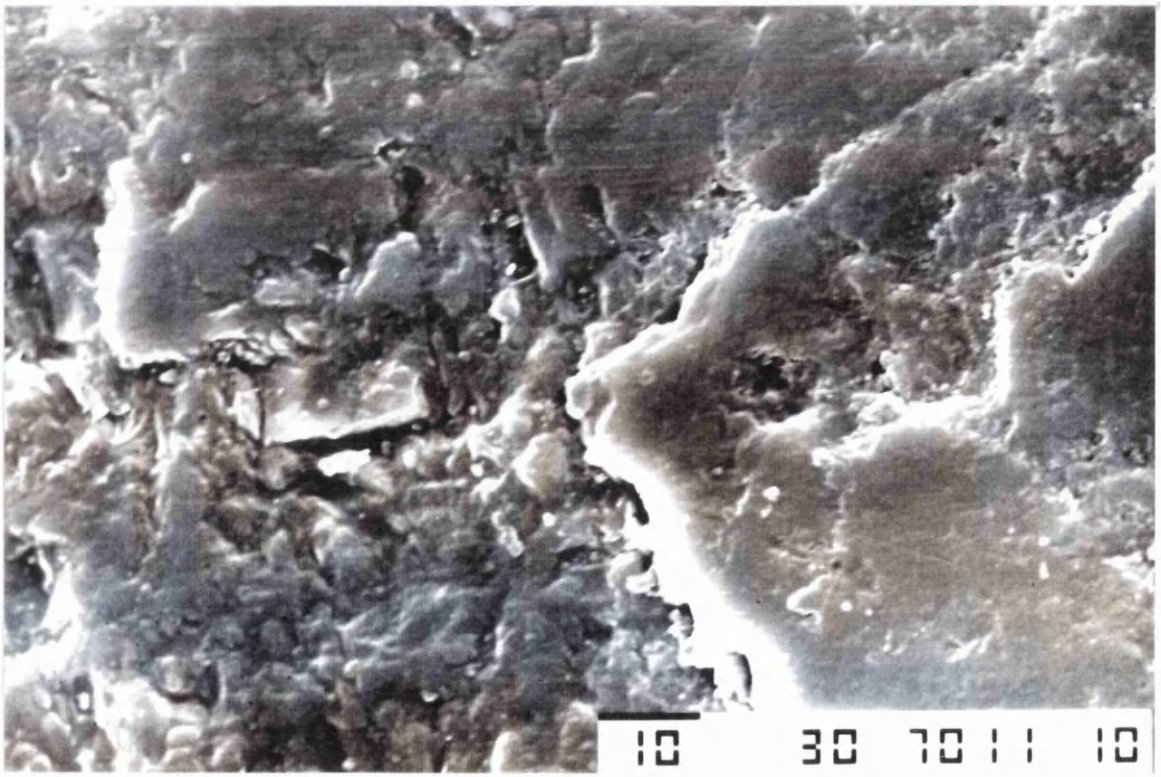


Fig. 7.16b. SEM of the wear track of Duceram-LFC tested with exposure to Coca Cola (Original magnification X1000; bar = 10μm).

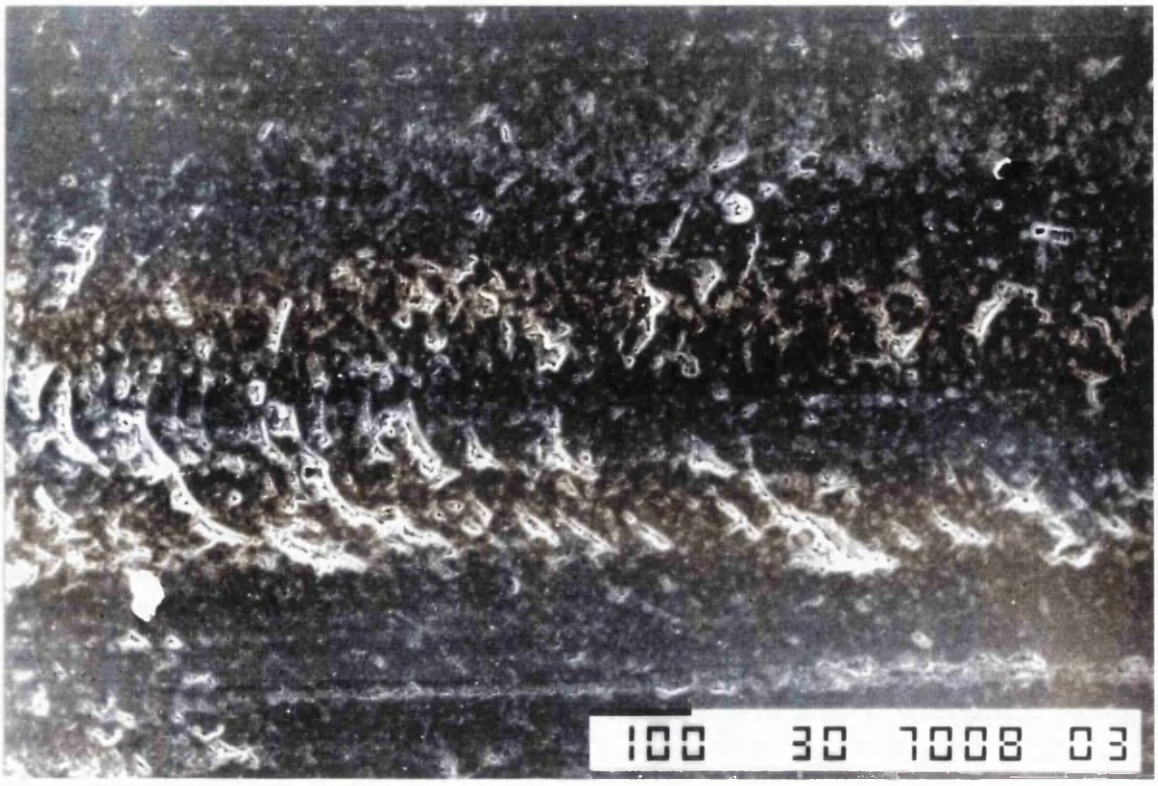


Fig. 7.17a. SEM of the wear track of Alpha porcelain tested in food slurry (Original magnification X100; bar = 100μm).

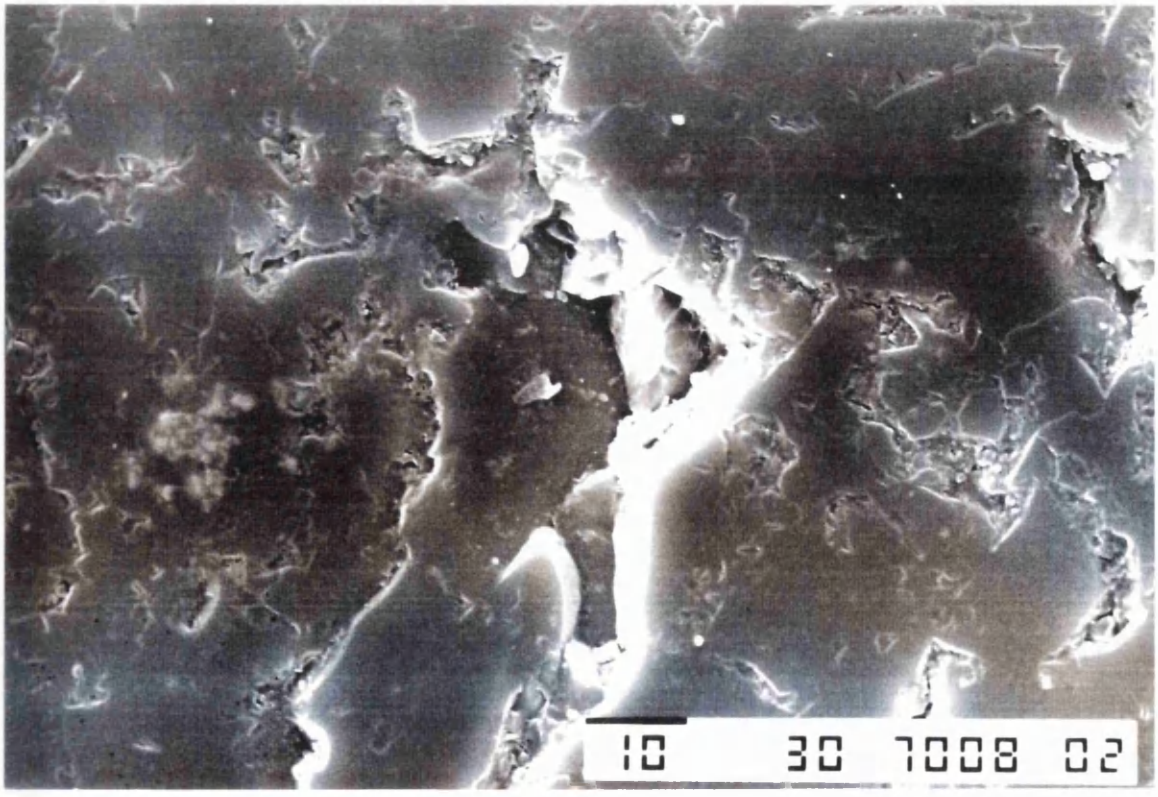


Fig. 7.17b. SEM of the wear track of Alpha porcelain tested in food slurry (Original magnification X1000; bar = 10μm).

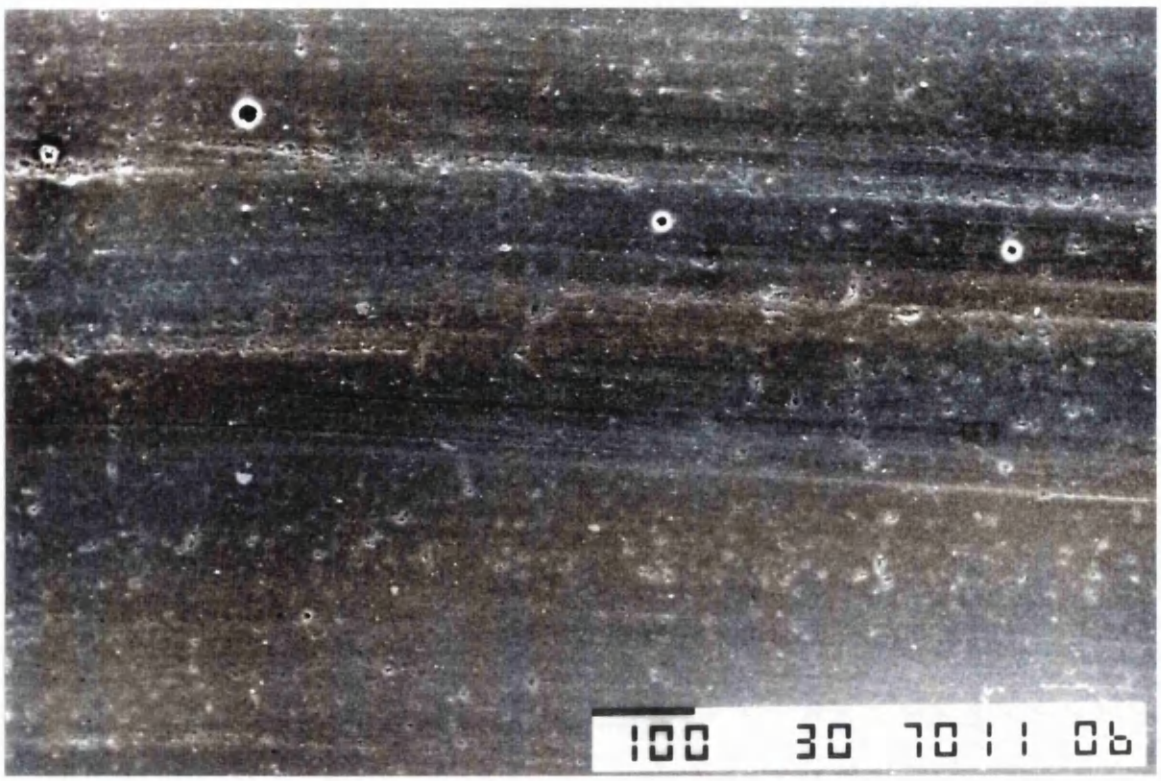


Fig. 7.18a. SEM of the wear track of Vita Mark II tested in food slurry (Original magnification X100; bar = 100μm).

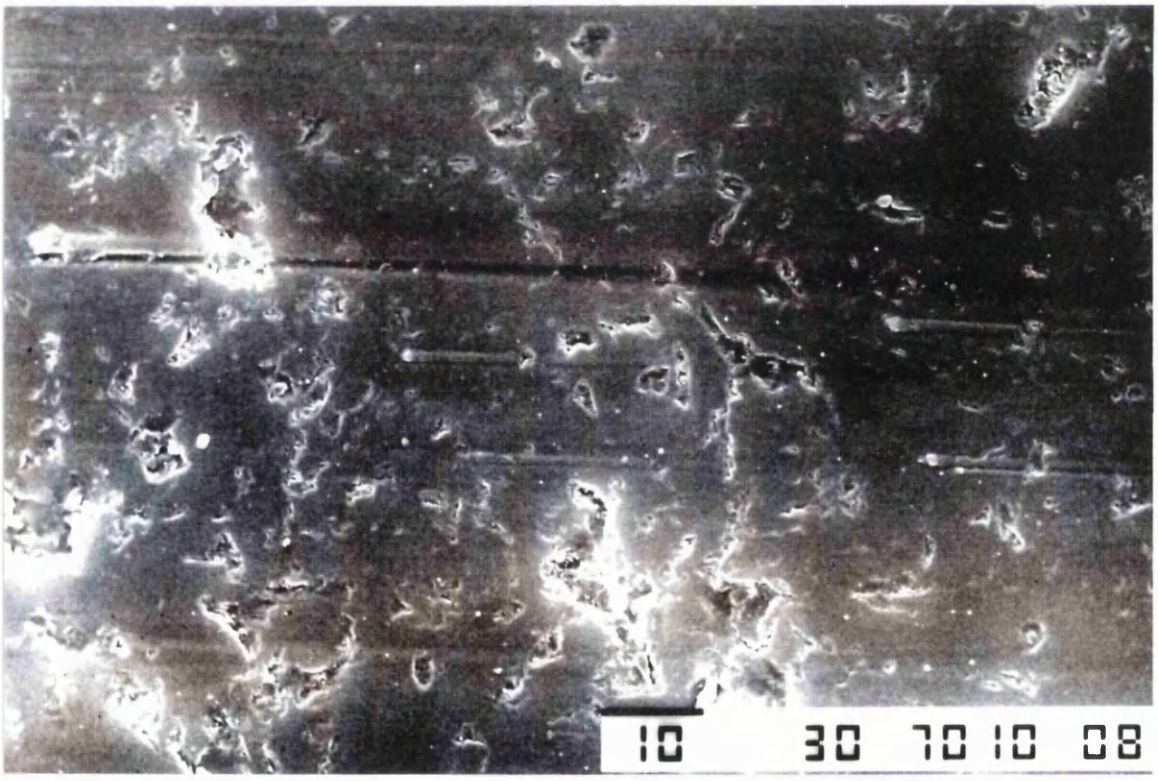


Fig. 7.18b. SEM of the wear track of Vita Mark II tested in food slurry (Original magnification X1000; bar = 10μm).

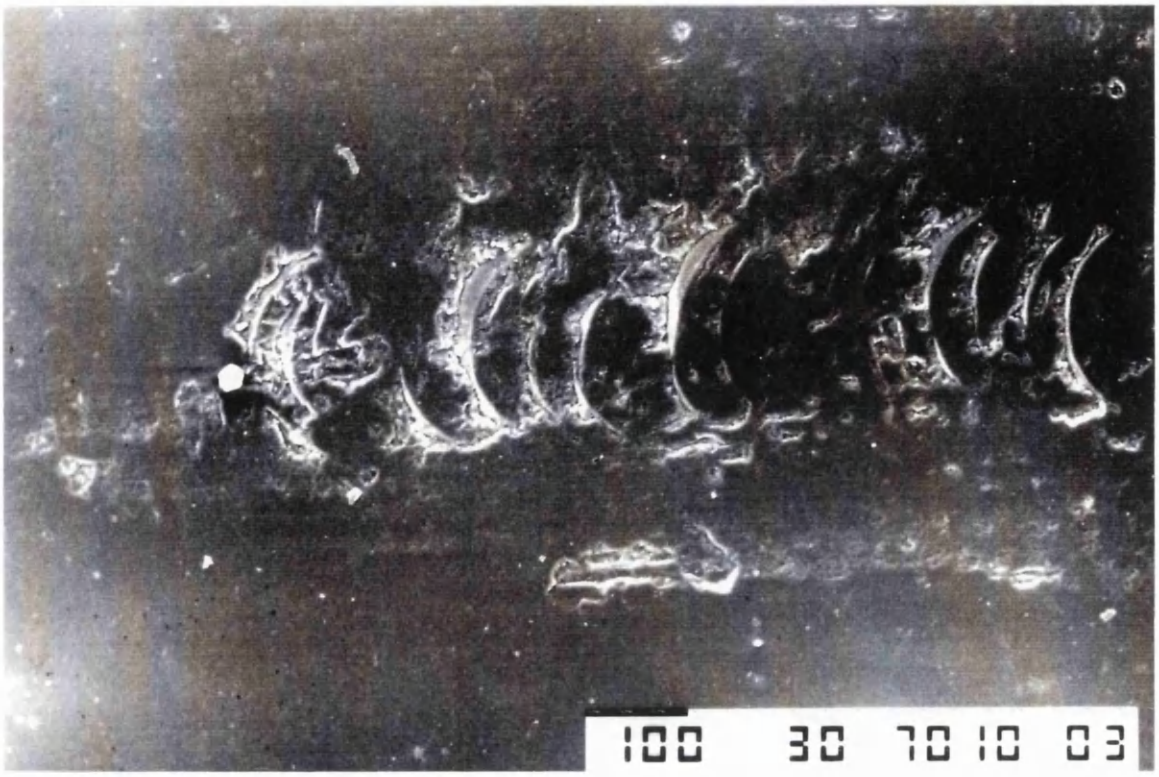


Fig. 7.19a. SEM of the wear track of Duceram-LFC tested in food slurry (Original magnification X100; bar = 100μm).

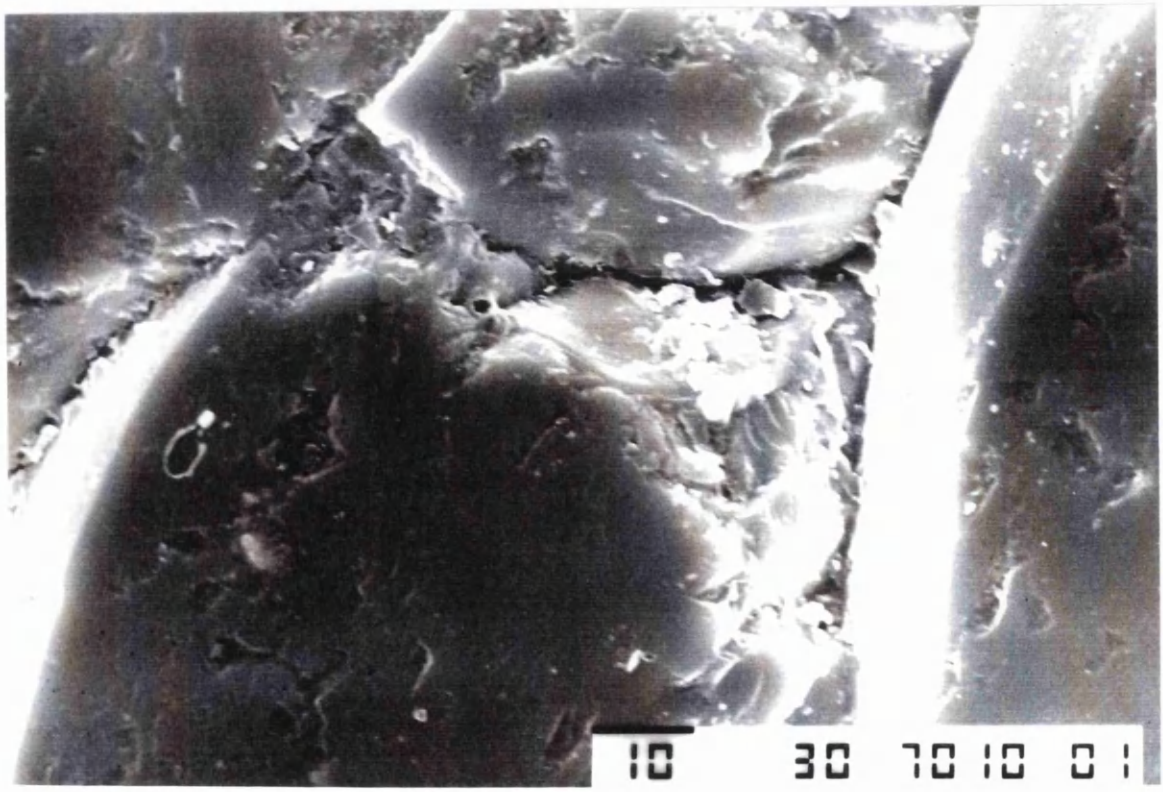


Fig. 7.19b. SEM of the wear track of Duceram-LFC tested in food slurry (Original magnification X1000; bar = 10μm).

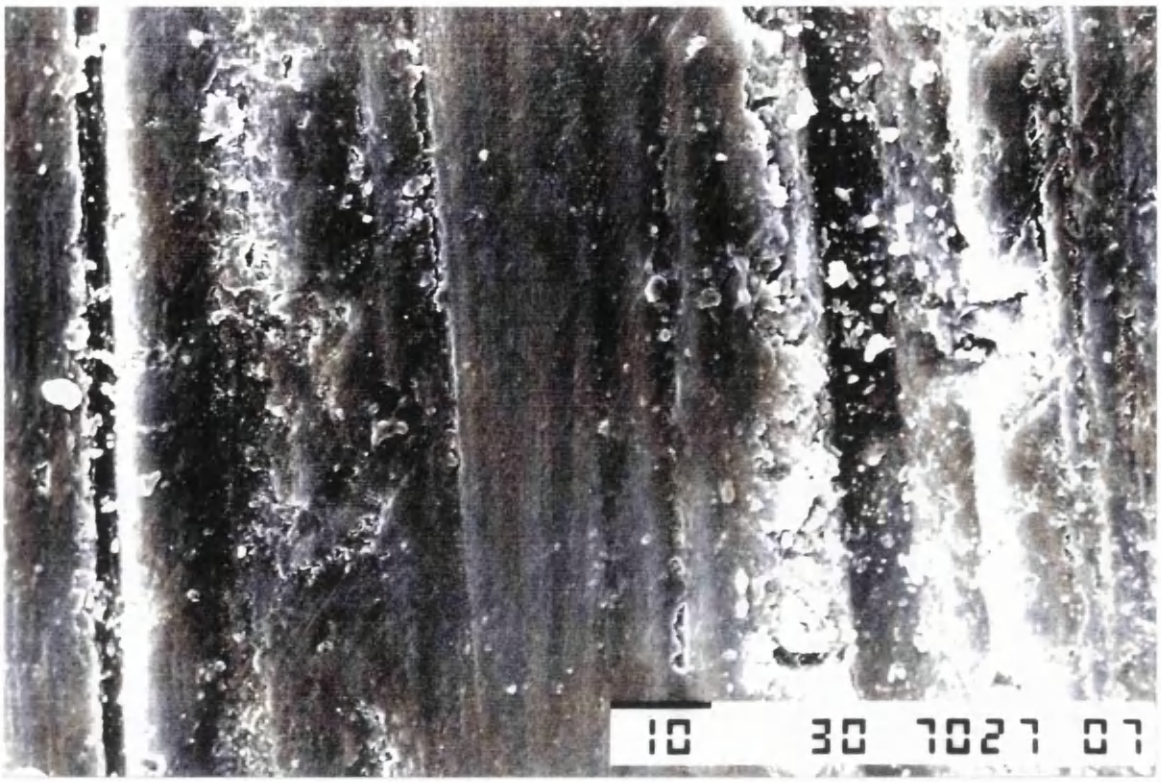


Fig. 7.20. SEM of the wear facet of tooth enamel tested against glazed Alpha porcelain in water (Original magnification X1000; bar = 10μm).

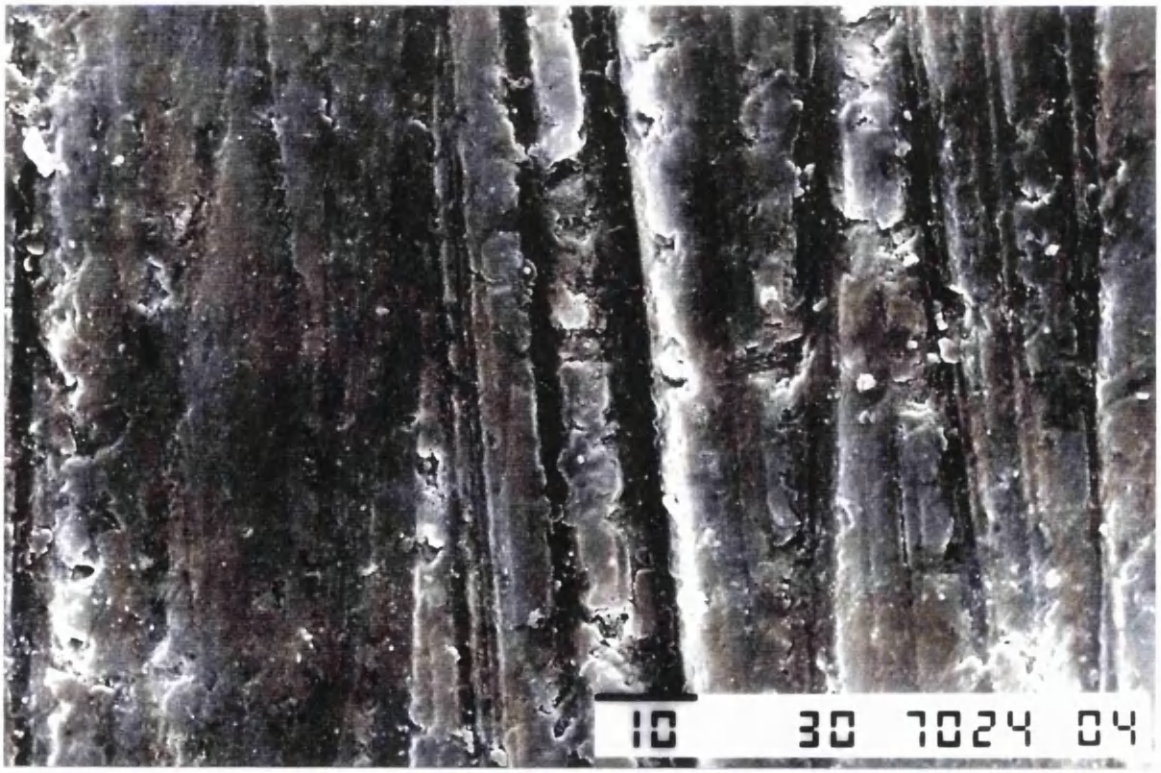


Fig. 7.21. SEM of the wear facet of tooth enamel tested against glazed Alpha porcelain with exposure to Coca Cola (Original magnification X1000; bar = 10μm).

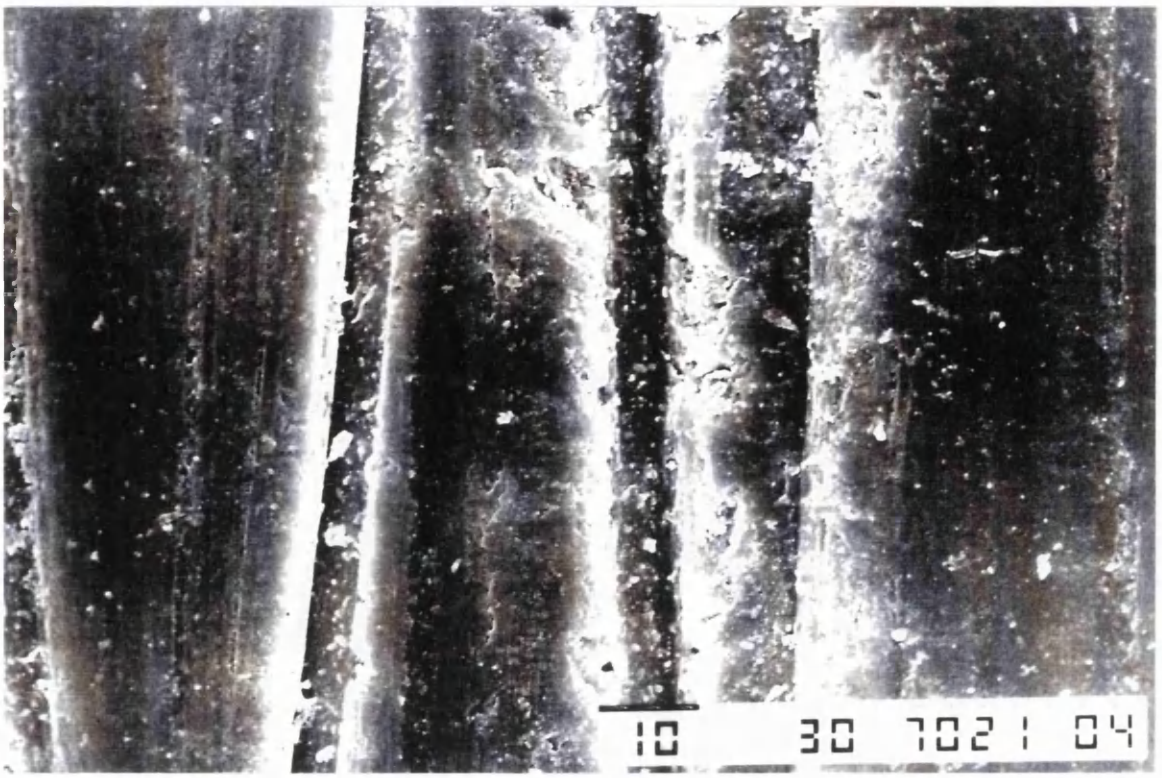


Fig. 7.22. SEM of the wear facet of tooth enamel tested against unglazed Alpha porcelain in water (Original magnification X1000; bar = 10μm).

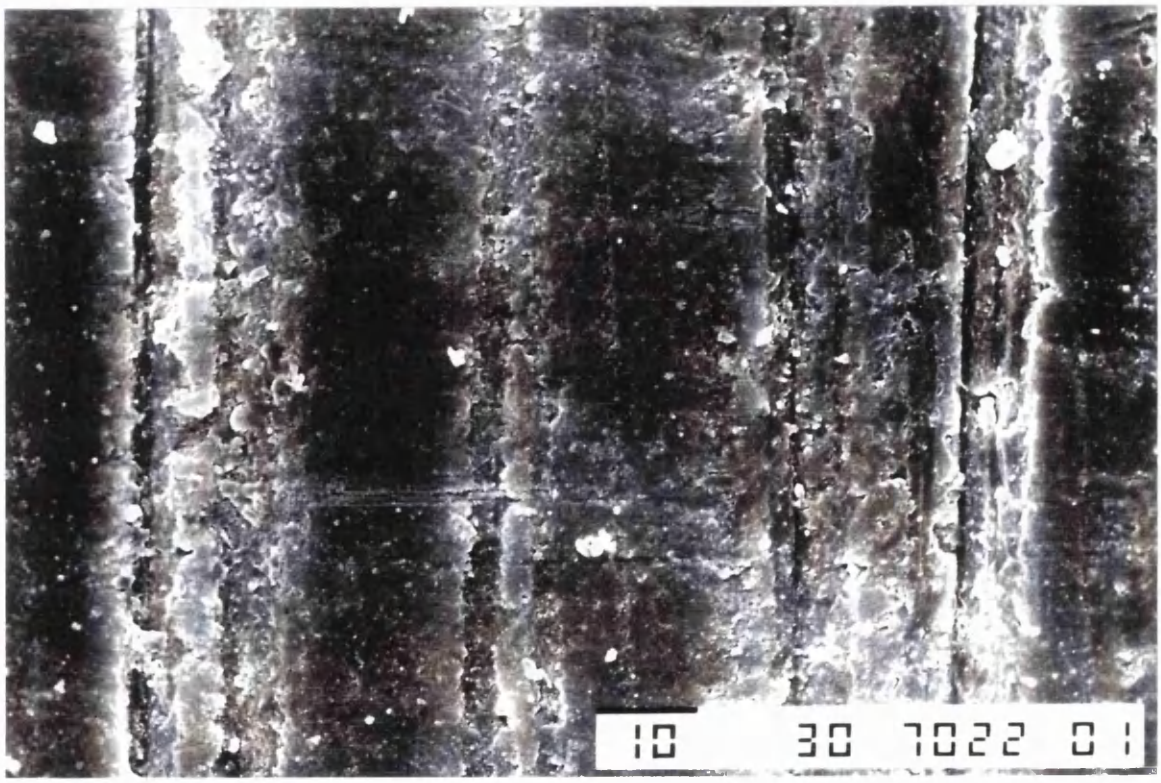


Fig. 7.23. SEM of the wear facet of tooth enamel tested against unglazed Alpha porcelain with exposure to Coca Cola (Original magnification X1000; bar = 10μm).

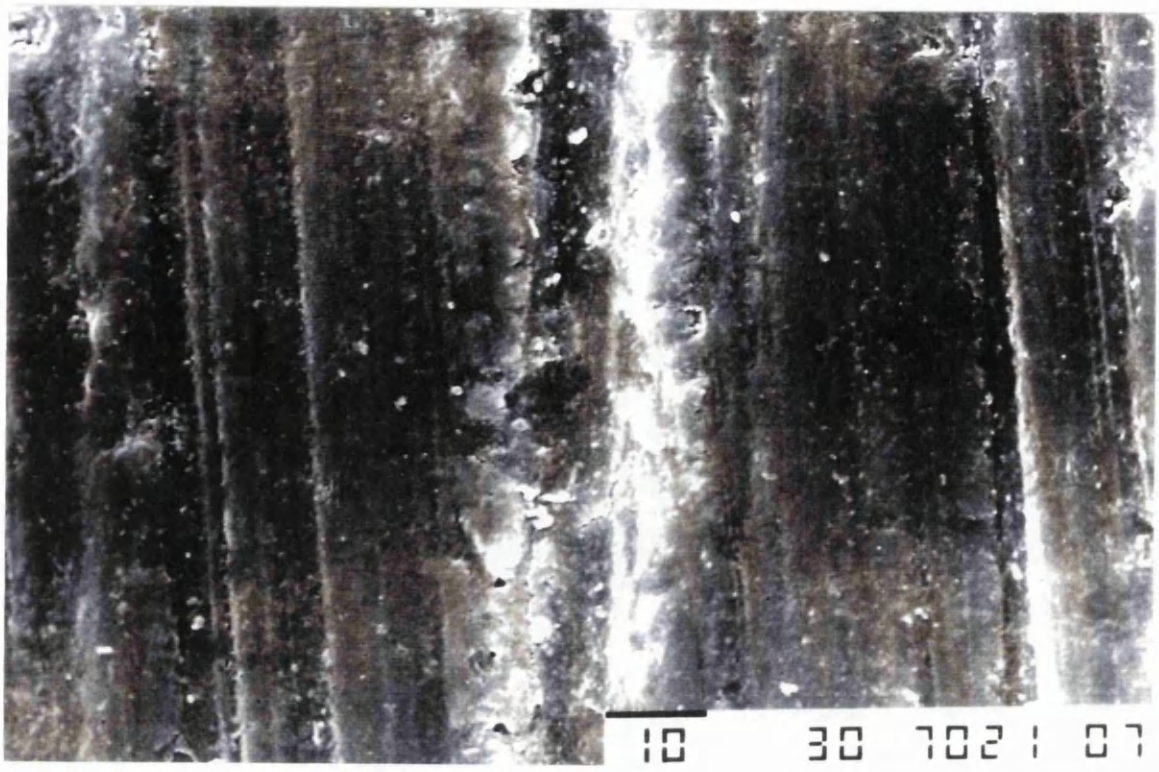


Fig. 7.24. SEM of the wear facet of tooth enamel tested against polished Alpha porcelain in water (Original magnification X1000; bar = 10μm).

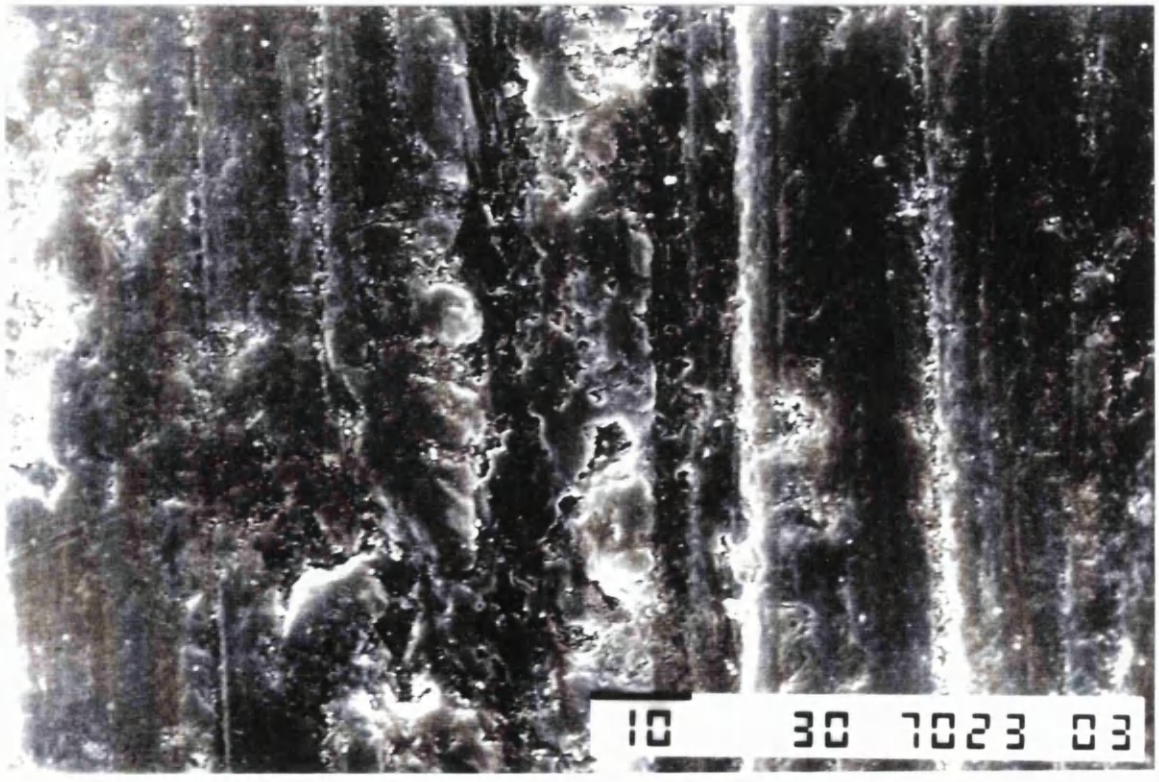


Fig. 7.25. SEM of the wear facet of tooth enamel tested against polished Alpha porcelain with exposure to Coca Cola (Original magnification X1000; bar = 10μm).

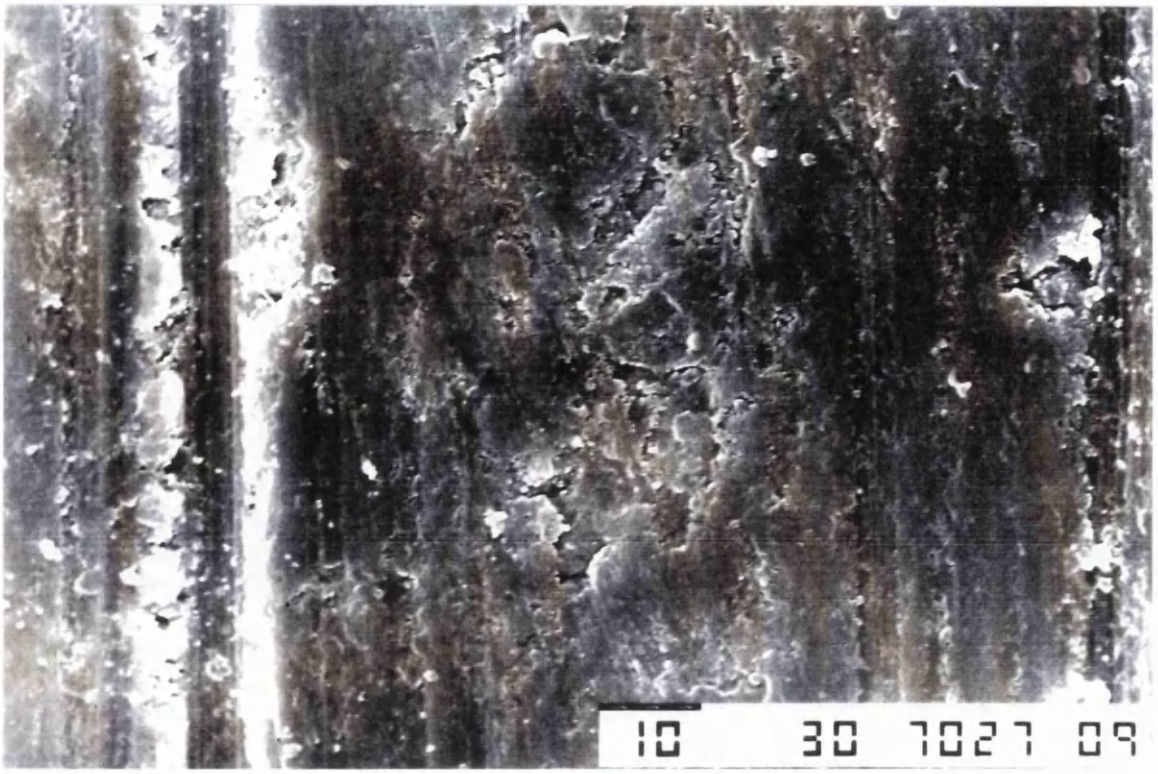


Fig. 7.26. SEM of the wear facet of tooth enamel tested against glazed Omega porcelain in water (Original magnification X1000; bar = 10μm).

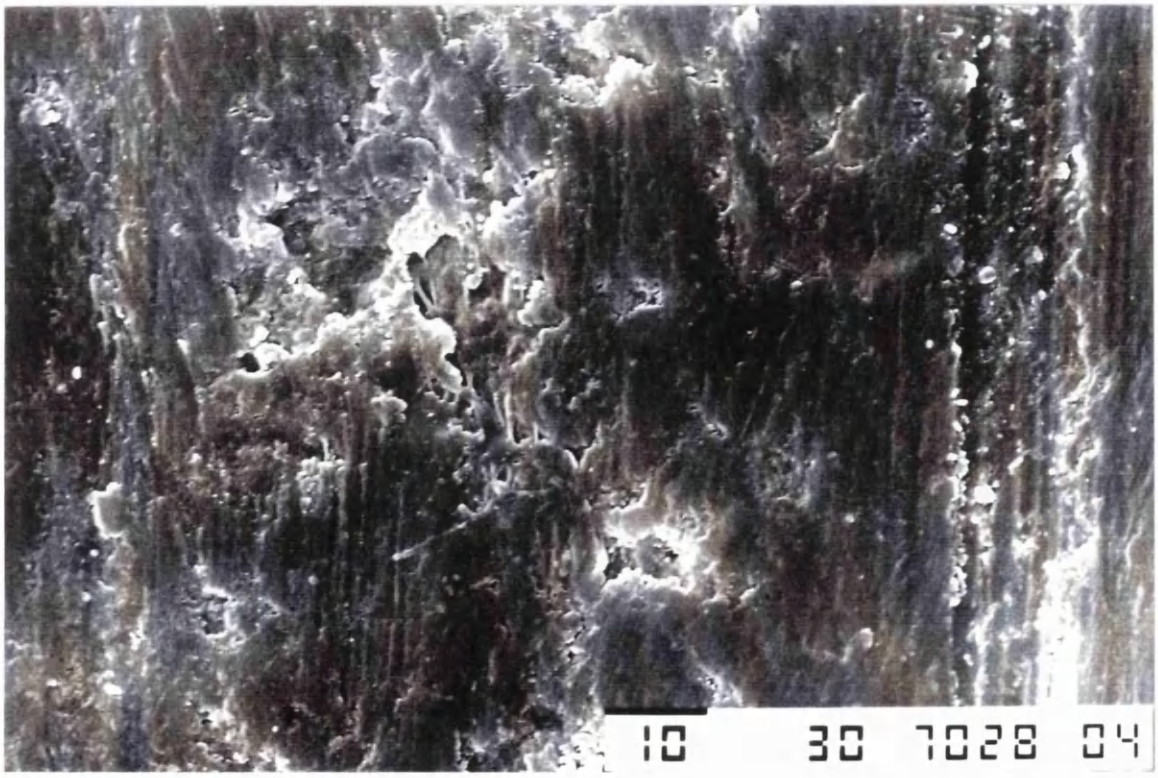


Fig. 7.27. SEM of the wear facet of tooth enamel tested against polished Vita Mark II in water (Original magnification X1000; bar = 10μm).

Fig. 7.28. SEM of the wear facet of tooth enamel tested against glazed Duceram-LFC in water (Original magnification X1000; bar = 10μm).

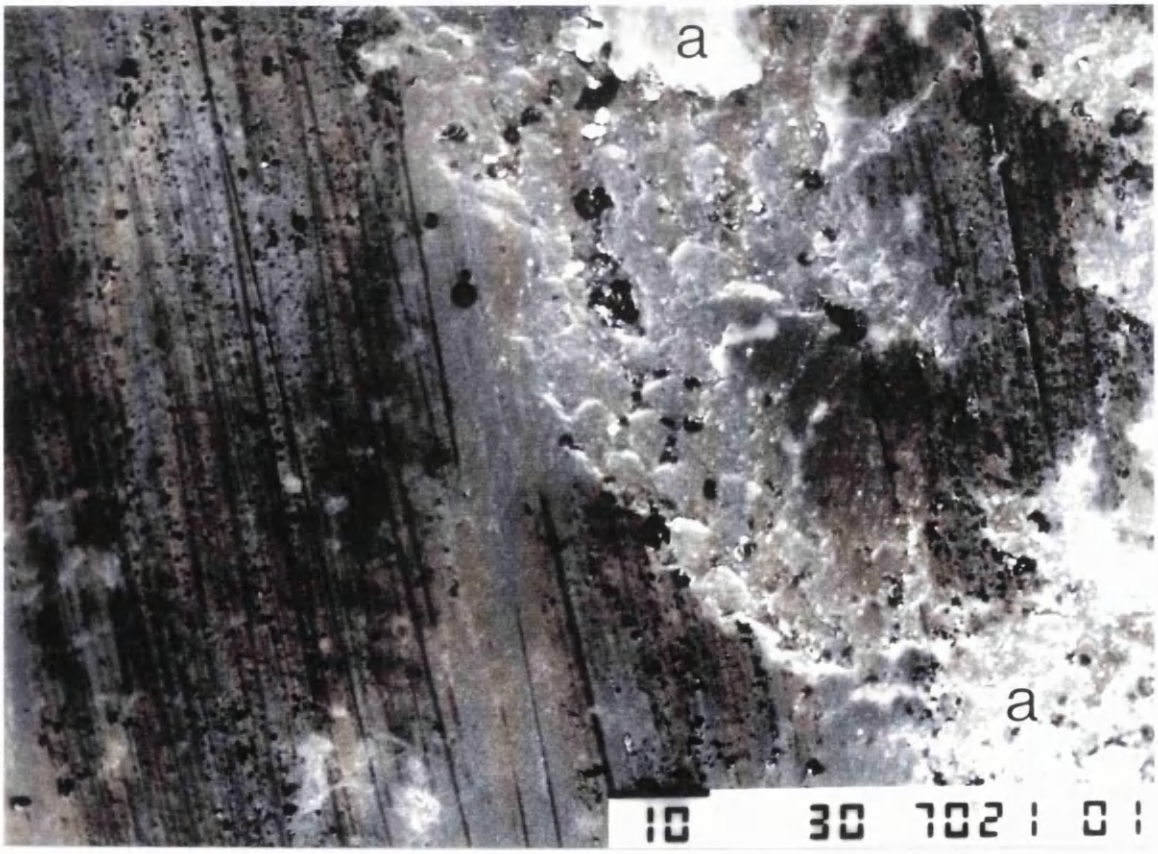


Fig. 7.29. SEM of the wear facet of tooth enamel tested against gold in water (Original magnification X1000; bar = 10μm). The light patches are probably gold deposited as a result of adhesive wear mechanisms (a).

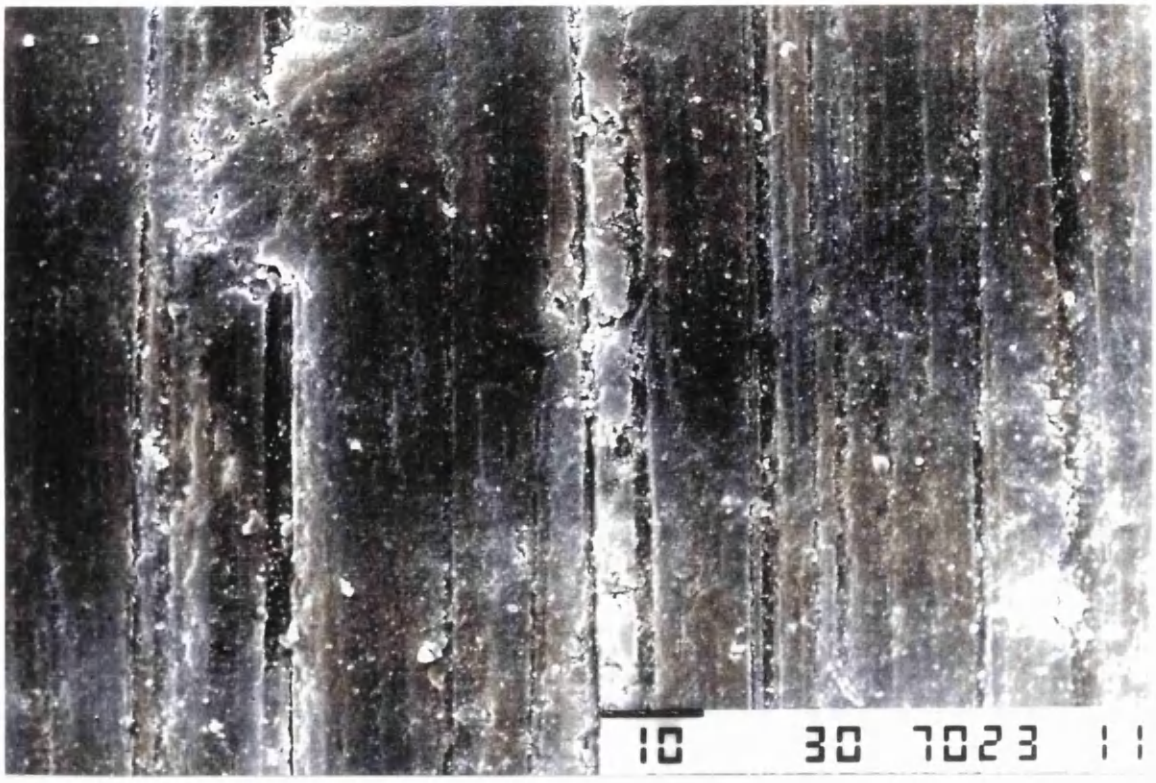


Fig. 7.30. SEM of the wear facet of tooth enamel tested against polished Vita Mark II with exposure to Coca Cola (Original magnification X1000; bar = 10μm).

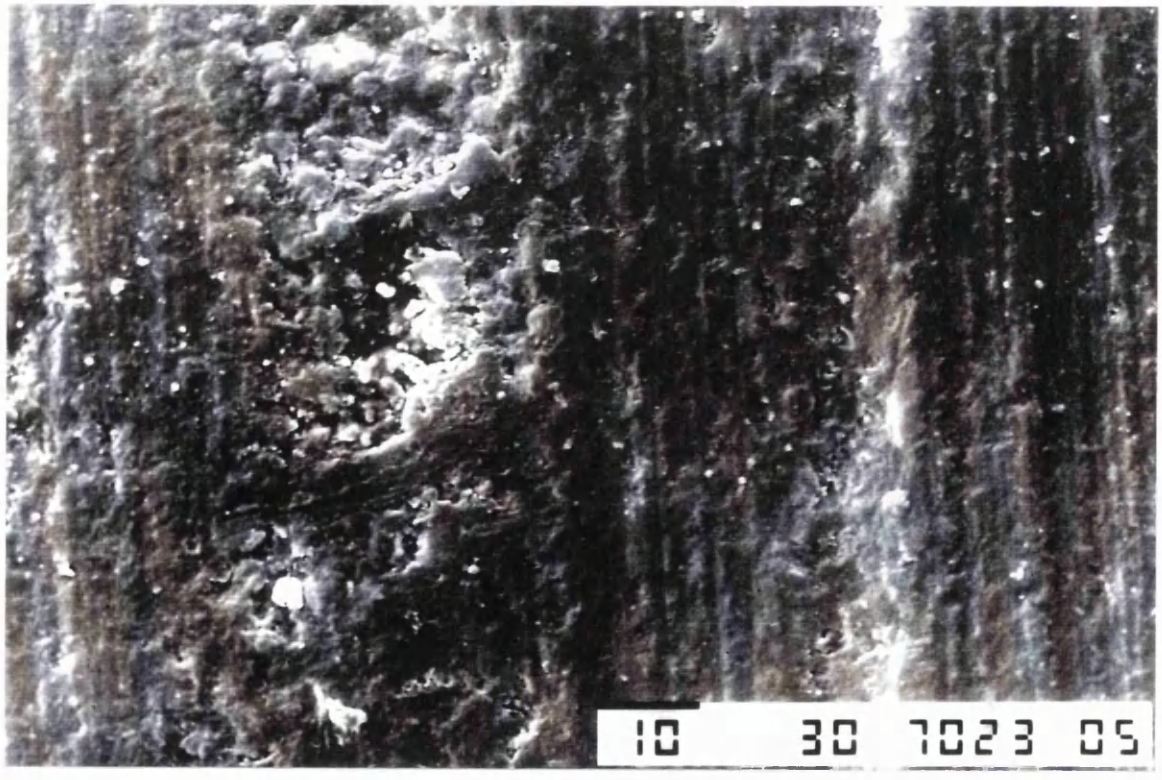


Fig. 7.31. SEM of the wear facet of tooth enamel tested against glazed Duceram-LFC with exposure to Coca Cola (Original magnification X1000; bar = 10μm).

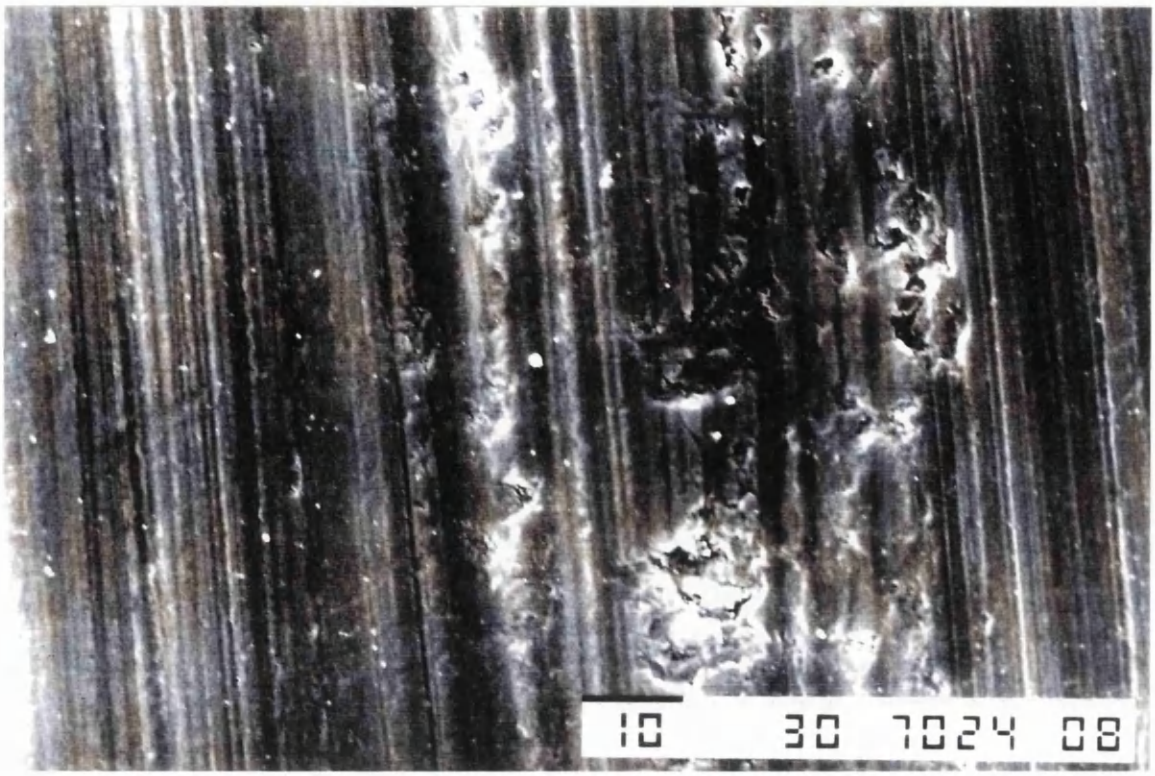


Fig. 7.32. SEM of the wear facet of tooth enamel tested against glazed Alpha porcelain in food slurry (Original magnification X1000; bar = 10μm).

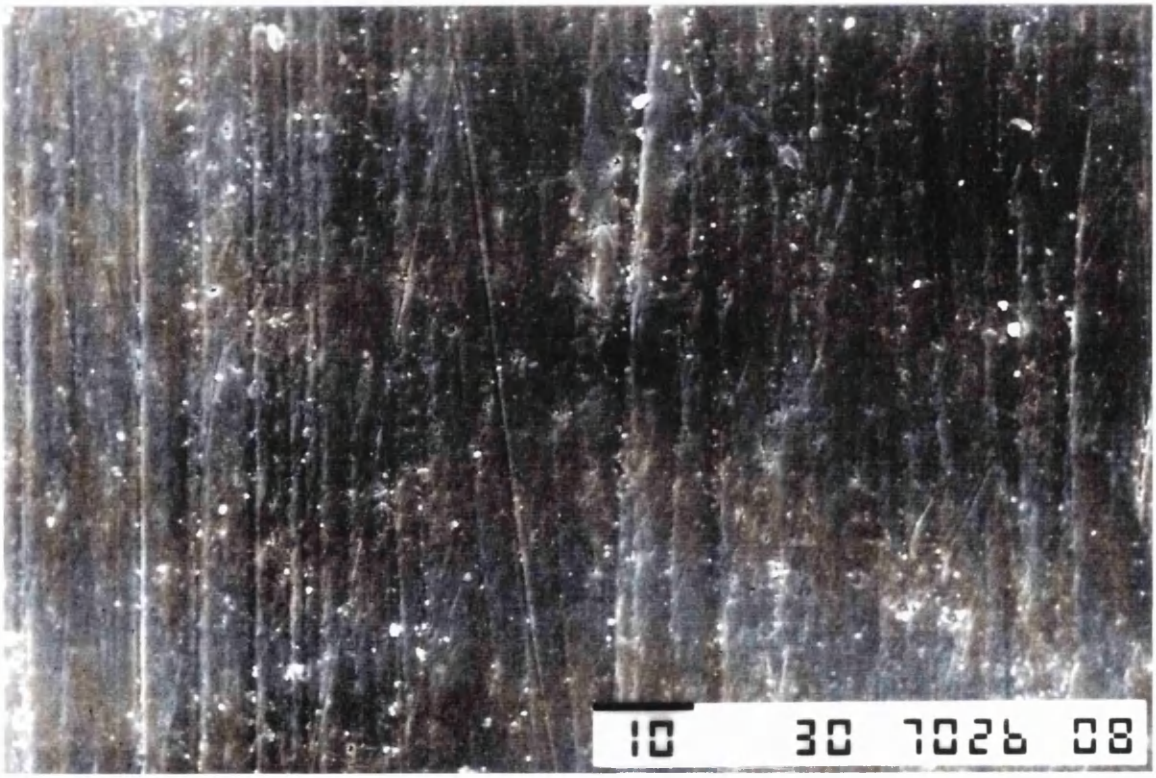


Fig. 7.33. SEM of the wear facet of tooth enamel tested against polished Vita Mark II in food slurry (Original magnification X1000; bar = 10μm).

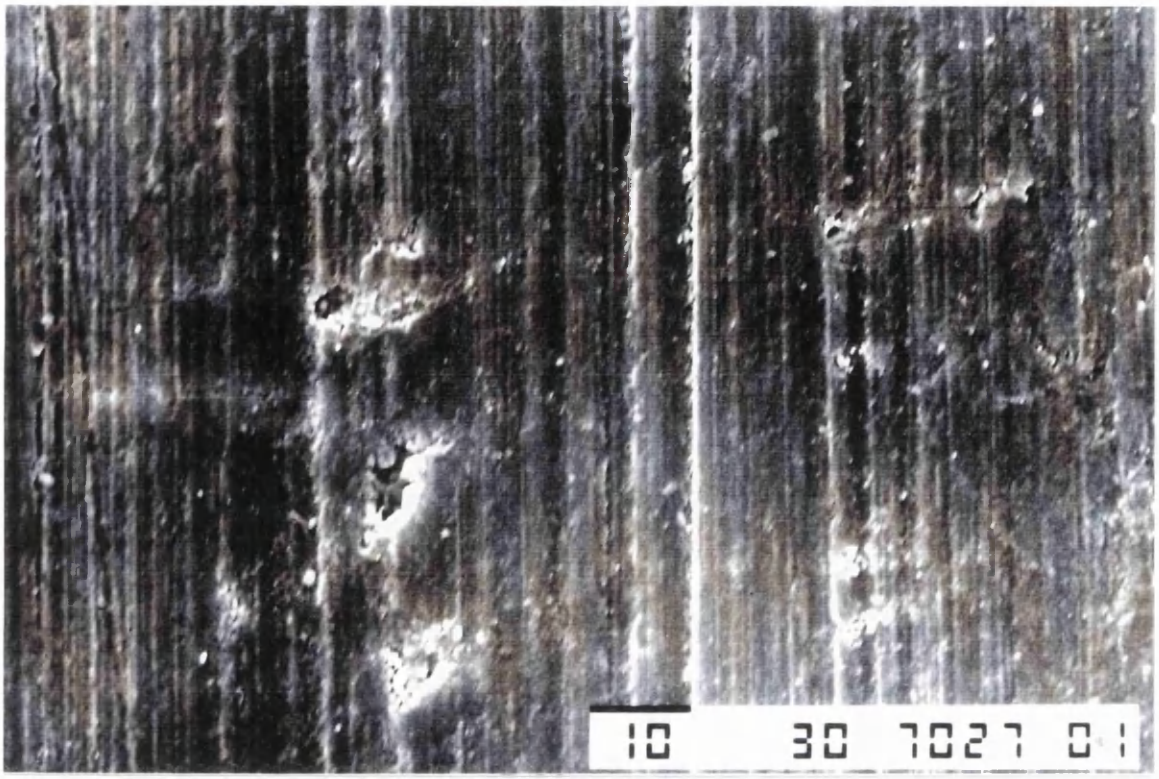


Fig. 7.34. SEM of the wear facet of tooth enamel tested against glazed Duceram-LFC in food slurry (Original magnification X1000; bar = 10μm).

7.4. Discussion

7.4.1. Surface finishing of restorative materials

The SEM observations were found to support the surface roughness data for the Alpha porcelain specimens (glazed, unglazed, polished) tested in study I (Chapter 3). Fig. 7.2 clearly demonstrates that by grinding a porcelain surface with diamond bur the glazed surface is removed completely, and extensive disruption of the surface is clearly evident showing a maze of ridges with sharp edges which can be quite abrasive compared with the smooth glazed surface. These ridges have been removed by polishing the surface with a porcelain finishing wheels and diamond polishing paste (Fig. 7.3). However, some microporosity was still present in the polished surface. These porosities most probably are voids that already existed under the glazed surface during specimen preparation and have been exposed when the surface was ground by the diamond bur. The polishing procedure has managed to remove the irregularities and the edge from the surface. However, it was not possible to remove the porosities from the surface. Such findings have already been observed by other authors (Sulik and Plekavisch, 1981; Patterson *et al.*, 1991; Fuzzi *et al.*, 1996).

Similarities were found between the glazed surfaces of Alpha porcelain, Omega porcelain, and the Duceram-LFC. Difficulties were encountered during focusing for the photomicrographs in these cases which may be attributed to the relatively smooth surface and absence of morphological facets for focusing. The Omega porcelain surface, in particular, had shown some granularity that interrupted the smooth surface appearance. Patterson and co-workers (1991) also reported the same observation in a bonded porcelain glazed surface (VMK bonded porcelain) and suggested that these

granularities would be expected and these contributed to the life-like visual characteristics of the final restoration. The fact that these granularities were most evident in the Omega porcelain (bonded porcelain) might be because of the high alkali content in its chemical structure which might make the porcelain more susceptible to devitrification (McLean, 1979; Anusavice, 1996). This also might explain why the surface roughness (Ra) values for the Omega porcelain was slightly higher than the Alpha porcelain and Duceram-LFC, although the difference was not statistically significant. Ward *et al.* (1995) also found that the glazed surface of a bonded porcelain, Ceramco II, was slightly rougher than the glazed Duceram-LFC.

Existence of multiple voids or porosities found on the polished Vita Mark II surface was a surprise. It was thought that a manufacturer-made ceramic would have superior quality to a laboratory hand-condensed porcelain (Kelly *et al.*, 1996). The voids indicate that even under the jurisdiction of the manufacturer's control, their complete elimination cannot be achieved. However, another possibility is that the polishing procedure was unable to smoothen completely the ceramic surface that had been adjusted previously by the diamond burs, thus leaving small grooves or pits where the finishing wheels were not able to reach. The size of the microporosities was quite small since the surface roughness measurement of the polished Vita Mark II was slightly less than the other glazed surface ceramics tested. Perhaps, due to the small size of these porosities, the stylus of the Dektak machine with a tip diameter of 5μm was unable to detect them.

Although the surface roughness value of the polished gold specimens was significantly lower and hence smoother than all the ceramic materials tested, the scanning electron micrographs revealed a relatively smooth surface interrupted with scratches in different directions. The latter were most probably created during the surface polishing with the abrasive rubber wheels.

7.4.2. Wear track / facet evaluation

Generally the wear tracks showed grooves and ridges running along the wear track which is indicative of an abrasive wear mechanism. In addition, surface pitting was observed creating what can be called lacunae. Such observations have been reported by DeLong *et al.* (1986) in an *in vitro* study, as well as in *in vivo* studies by Ekfeldt and Øilo (1988, 1989, 1990). These lacunae were seen to be surrounded by multiple microcracks indicating that the latter was formed as a result of a fatigue process. As a result of cyclic loading of the tooth onto the ceramic surface, further cracks will be formed and propagated. This causes a fatigue fracture, thereby loosening some more particles from the ceramic material leaving behind a rough surface. This type of fatigue wear occurring in the ceramic material has been termed by Rabinowicz (1965) as brittle fracture wear.

Wear test in water

For Alpha porcelain used in the first study (Chapter 1) the wear track demonstrated the same characteristics despite the finishing condition of the porcelain surface. This consisted of grooves and ridges as a result of abrasive wear and in addition lacunae as a fatigue wear (brittle fracture). The antagonist tooth enamel surfaces, overall,

showed groove formation in the direction of their sliding path which further proves that the nature of the wear between Alpha porcelain and the tooth enamel surface was of an abrasive wear mechanism.

Omega and Vita Mark II specimens showed similar characteristics as Alpha porcelain in their wear track as well as the wear facets on the opposing tooth enamel. However, the grooves for Vita Mark II were less distinct when compared with the Alpha and Omega porcelains. This could be because the latter was made from porcelain of small particle size (4μm, Vita product information).

Duceram-LFC showed a substantially smooth surface for both the wear track and the tooth enamel wear facet. This can be attributed to the structure of the material which is leucite-free with a dense homogeneous structure, in addition to the silicon-hydroxyl layer which may play a role in protecting the ceramic from damage (Komma, 1993). Thus, the number of lacunae was much less compared with that for the other ceramic materials tested and also the lacunae were much reduced in size. This can also be deduced from the relatively smooth wear facet of the opposing antagonist tooth enamel which showed scratches rather than grooves, reflecting a less abrasive material surface.

The wear of ceramics has been categorised as mild and severe. Mild wear is associated with a low wear rate, smooth surface and relatively constant friction. The mechanism of wear is dominated by plastic flow or surface reaction. Severe wear is associated with rough surfaces, fluctuating friction and the wear mechanism is

dominated by brittle fracture (Mair *et al.*, 1996). From the above description, it appears from the results of this study that the hydrothermal ceramic Duceram-LFC may have what is called mild wear, although lacunae (brittle fracture wear) was observed. The wear of conventional Alpha and Omega porcelains exhibited what is called severe wear. The wear of Vita Mark II appeared to lie in between these two types of wear. The wear track of the Vita Mark II was rougher than that seen with Duceram-LFC and showed an obvious brittle fracture wear (fatigue). This may make it similar to the conventional porcelain. However, its wear rate was significantly lower than that of the conventional porcelain (Alpha and Omega) and even slightly lower than the wear of Duceram-LFC. This, again, could be because the material is made from small particle sized feldspathic porcelain.

Despite the above classification, the four ceramic materials tested in water showed common wear characteristics suggesting that ceramic wear occurs by a combination of a fatigue and an abrasive wear mechanism.

Gold showed a wear track with pits, the appearance of which suggest that that the material was spalled. This means that some particles of the gold had been plucked away. This is usually a result of subsurface crack formation that propagates towards the surface, thus weakening or loosening that particle. The scanning electron micrograph of the wear track also suggested that the wear of gold had occurred in layers. Most probably, the delamination theory of the wear mechanism can be applied to the type of wear that occurred with gold. The scanning electron micrograph of the gold wear track also showed that some of the worn gold particles were reattached to

the surface. Some gold particles were also seen to be attached to the antagonist tooth enamel surface indicating an adhesive wear mechanism, supporting observations and suggestions made by Hacker *et al.* (1996).

Wear test in cola/water

When the three ceramic materials, Alpha porcelain, Vita Mark II and Duceram-LFC, were tested with an intermittent exposure to Coca Cola, Duceram-LFC and Vita Mark II showed an increase in the number and size of lacunae as well as showing a rough surface compared with that seen in water. This may indicate that both of the materials have been affected by the exposure to Coca Cola. The resulting rough surface was more abrasive and subsequently affected the opposing tooth enamel surface. Therefore, the increase in the enamel wear against Vita Mark II and Duceram-LFC, in particular, was higher than the increase against Alpha porcelain, after exposure to Coca Cola. Thus, the SEM observations support the quantitative measurement obtained in Chapter 5. The Alpha porcelain wear track showed a substantial decrease in the number of lacunae, which were almost absent. This could because of the softening effect of the Coca Cola on the tooth enamel (Eccles, 1982; Lussi *et al.*, 1993), resulting in less stress being imposed onto the porcelain surface. Another possibility is that the Coca Cola may not have the same effect on Alpha porcelain as it had on Duceram-LFC and Vita Mark II. Prominent ridge formation was present on the wear track of the porcelain and their indentation was obvious on the opposing tooth enamel as deep, sharp grooves, indicating that these ridges were ploughing into the softened tooth enamel structure.

Wear test in food slurry

The special pattern of cracks observed on the wear track of Duceram-LFC coincides with a type of wear that has been described by Powers and Craig (1972c) for fluorapatite crystals. They observed that in all instances the cracks or chevrons formed pointing towards the origin of their formation, which was opposite to the direction of the relative motion of the slider. Chevron formation is an indication of a brittle mode of failure (Powers and Craig, 1972c). Such cracks/chevrons that were noticed in Duceram-LFC tested in the presence of food particles, could be because of the possible absence of the silicon-hydroxyl layer that supposedly protects the surface and provides it with some flexibility (Komma, 1993). The absence or removal of the silicon-hydroxyl layer could be because of the mechanical action of the food slurry or a chemical reaction. The wear of the ceramic and opposing tooth was affected by the presence of food particles (slurry), resulting in an increased wear rate.

However, the food slurry had affected the wear of Alpha porcelain and Vita Mark II in a totally opposite way. This, perhaps, is because of the different structure of the Duceram-LFC from the Alpha porcelain and Vita Mark II. The substantial reduction in the size and number of the lacunae from the Alpha porcelain and Vita Mark II wear tracks could be explained by the fact that the food particles had acted as a cushion, thus absorbing some of the cyclic stress between the tooth and the ceramic surface. Thus, the food slurry had formed an intermediate layer which had protected both surfaces and thus reduced their wear.

So far, SEM examination was of a great help in elucidating the surface characteristics of the wear tracks of the ceramic materials and tooth enamel. This qualitative wear evaluation not only supported the results of the quantitative wear evaluation, but also enabled a better understanding of the wear mechanism. The change in the wear track surface characteristics was found to affect the wear of opposing enamel both qualitatively and quantitatively. Thus, the results of this study are in agreement with the fact that the "size and shape of abrasive features that develop on a dental ceramic surface during contact appeared critical for determining enamel wear" (Kelly *et* al., 1996).

Finally, it must be admitted that the SEM technique was unable to give any information about the subsurface of the wear track. Perhaps confocal microscopy would be of help in this regard, enabling a better understanding of the wear mechanisms operating on the ceramics under these different conditions.

7.5. Conclusion

Based on the scanning electron micrographs in this study the following were concluded:

1. Adjusting a porcelain surface with diamond burs (fine and superfine) produced an extensive surface disturbance with a maze of sharp ridges and grooves.

2. Polishing treatment using ceramic polishing wheels and diamond paste managed to remove all the sharp ridges found on the adjusted porcelain, yet some porosities still existed in the surface because of voids or incomplete condensation of the porcelain.

3. The machinable ceramic Vita Mark II showed the presence of porosity on the surface after polishing.

4. The smooth appearance of the glazed surface of Alpha porcelain, Omega porcelain and Duceram-LFC were similar. However, some granularity in the glazed surface of Omega porcelain was obvious.

5. The wear of dental ceramics appeared to be caused by fatigue and abrasive wear mechanisms and the wear of antagonist enamel was mainly by an abrasive wear mechanism.

6. The wear mechanism of gold against enamel was mainly a combination of fatigue and adhesive wear mechanisms.

7. Duceram-LFC was seen to be the most affected by the acidic media and food particles in the wear test.

CHAPTER 8

GENERAL DISCUSSION AND CONCLUSION

Chapter 8: General Discussion and Conclusion

8.1. Specimen Preparation

8.1.1. Restorative material specimens

The construction of the restorative material specimens was according to recommended clinical laboratory procedures. However, the method advocated for Duceram-LFC is different from that used in the present study. For full-ceramic inlays, onlays and veneers the Duceram-LFC (low fusing ceramic) is built onto a thin base of Duceram metal ceramic (conventional porcelain), which is first built and fired onto a refractory die (Fiechter, Duceram-LFC working instructions). However, a pilot study showed that construction of the refractory die-method was difficult to achieve without cracks forming in the porcelain. This might be because of the large size and shape of the specimens used in the present study. Therefore, the Duceram-LFC specimens were built directly onto platinum foil. This difference should not have affected subsequent surface characteristics. The Vita Mark II specimens were ground and polished to simulate the clinical condition of the Cerec restorations, where the establishment of occlusal morphology is achieved at the chairside using rotating diamond instruments followed by polishing procedures (Krejci *et al.*, 1994; Heymann *et al.*, 1996).

8.1.2. Tooth specimens

The tooth specimens were prepared from caries-free mandibular premolars. This was because of their suitable morphology where the buccal cusp alone can be easily used after grinding the lingual cusp(s), if necessary, without risk of weakening the tooth

structure. Although, obtaining a large number of sound mandibular premolars was not easy, great effort was applied to select those teeth that were similar in size and also free of any cracks, observable by eye. Inevitably, complete standardisation of the tooth specimens cannot be achieved. This is because the sources are different as they are collected from different patients, and thus the size and the history of these teeth could be different. By sectioning each tooth in half (in its bucco-lingual direction, described in chapter 2) and thus obtaining two specimens from each tooth, the number of teeth required was reduced and therefore the variation between the specimens. However, there were relatively low standard deviations of the enamel wear data throughout the study. In addition, the cut surface of the tooth specimen was useful in two ways. Firstly, enamel thickness over the dentino-enamel junction was clearly seen, thus ensuring that all the specimens had sufficient thickness of enamel before the wear test. Secondly, measuring the cusp height reduction with the reflex microscope was much easier to perform from a flat surface rather than a convex surface. Therefore, after focusing, the measurement was controlled by X and Y axis (the coordinates in the horizontal plane) of the microscope only and did not employ any vertical adjustment through the Z axis. Values obtained through the Z axis have been reported to be more susceptible to variation (Adams *et al.* 1989; Sharkey, 1993).

8.2. Wear Test Procedure

The wear machine used in the present study was similar to the machine described by Monasky and Taylor (1971). However in the present study the tooth specimens were cusps (half cusp) of mandibular premolars, while in the study by Monasky and Taylor the specimens were flat plates of enamel prepared from the labial surface of upper

central incisors. It was felt that the use of a cusp shape was more relevant clinically. Phillips (1982) stated that the properties of enamel vary with its position on the tooth. Cuspal enamel is stronger than the enamel found on the side of a tooth and is stronger under compression in a direction parallel to the enamel rods than in a direction perpendicular to the rods (Sulong and Aziz, 1990; Jagger and Harrison, 1995a).

The wear machine provided a combined action of impact followed by sliding which matches the inherent action of closure during mastication of the mandibular teeth onto the maxillary teeth (Sulong and Aziz, 1990). The rate of cycling was based on a review by Bates *et al.* (1975b) where 80 cycles per minute was reported to be a reasonable estimation for the chewing cycle rate. The load and the number of cycles used in this study was similar to that used in previous *in vitro* investigations (Jacobi *et al.*, 1991; Ratledge *et al.*, 1994). Therefore, the regime for wear testing used in the present study was based on previous reports from the literature, namely a rate of 80 cycles per minute for a total of 25000 cycles under a load of 40N.

Distilled water was used as a medium to simulate the lubricating action of saliva in the mouth and it was renewed after each 5000 cycles in order to avoid the accumulation of wear particles that might be produced during the test. Thus, a two-body wear test could be simulated. The alternate exposure to Coca Cola was to investigate the effect of the latter on the wear of enamel and dental ceramics, since many carbonated beverages are consumed extensively in the modern society. Admittedly, it is important to note that in the present *in vitro* study, no account was taken of the natural

buffering capacity of saliva present *in vivo* which may partially compensate for the acidic effect of the carbonated beverage. Nevertheless, the results of this study give further insight into the harmful effect of the carbonated beverage on tooth enamel by accelerating wear rates and also the results highlight the different behaviour of various ceramics in an acidic environment during wear testing.

Further attempts were made to simulate the three-body wear that occurs in the mouth with the presence of food particles. The use of cornmeal grit with wholemeal flour was an attempt to simulate the texture and the consistency of the natural food consumed. The cornmeal grit simulated the relatively hard particles that could exist in food and flour was added to give the mixture viscosity so that it would be chewed and trapped between the tooth and ceramic specimens easily. In a preliminary study, various types of seeds and different slurry mixtures in water were tried. Millet and poppy seeds proved difficult to trap between the tooth and material specimen because of their rounded shape and smooth surface. Thus, when the tooth touched the seed, the seed easily escaped from underneath the tooth specimen. Since only one cusp (half cusp) was used in this study against a flat surface of the ceramic specimens, the trapping of seed particles was even more difficult. Rice was also tried but was not easily trapped due to the large size and the elongated shape, especially at the early stage of the test when the contact area of the cusp was small (pointed). Ground rice proved difficult since when mixed in water it became soft too quickly and there was no gritty feel to the mixture. The latter problem was also observed with semolina, which produced a very soft texture after being soaked in water for a relatively short time. Cornmeal grit was thus found to be the most suitable, since the grit particles

were small enough to be trapped, the surface was rough enough to prevent them from sliding away and the hard texture appeared to be retained even after 1 hour (approximately enough for 5000 cycles) of being immersed in water, although not to the same extent as the original unsoaked grit. However, this mixture closely simulated the effect of the saliva on any solid natural food product. As stated earlier, the wholemeal flour was added to give some viscosity to the mixture in addition to its high content of fibre which was considered as an additional advantage in simulating normal food.

Generally, the development of wear machines can be understood as an attempt to simulate the clinical masticatory cycle and oral environment (Mair *et al.* 1996) and perhaps complete simulation by a machine will never be achieved (De Gee and Pallav, 1994). Thus, this fact should always be considered in both interpretation of results and any conclusions drawn from *in vitro* studies. Nevertheless, these *in vitro* studies may help to understand the wear mechanism of restorative materials and help to rank restorative materials and enable comparisons with new materials in a shorter testing time.

8.3. Wear Measurement

The wear assessment was limited to tooth cusp height reduction (height loss) and the wear track depth of the restorative materials, which is vertical assessment only and not volumetric loss assessment. The advantage of the latter method for evaluation of wear lies in its linearity with time. Wear-time linearity cannot be observed by the height loss method because of the conical shape of the tooth cusp. However, the

vertical assessment method could have clinical relevance since it might correlate with a diminished vertical dimension of occlusion (DeLong *et al.*, 1992), if the eruption process was not fast enough to compensate fully the vertical loss in cases of high rates of wear. The cusp height reduction of the tooth was measured using a reflex microscope and the repeatability of measurement of the latter was found to be within 1μm for the X and Y axes (Sharkey, 1993). The material wear track depth was measured from their resin replicas. The reason for using the latter was to avoid any anomalies arising from porcelain fractures during decementation of the specimens from the wear machine specimen holder. Resin replicas also enabled measurement of the wear track depth at different time intervals and their accuracy was found to be within an acceptable level (chapter 3 and 4). Both enamel wear and restorative material wear data were found overall statistically normally distributed. Thus parametric statistical tests were performed using analysis of variance (ANOVA) followed by appropriate multiple comparison methods to reveal any significant differences between the groups.

Overall, the objectives of this study have been achieved, and the wear machine has provided a good *in vitro* model for studying the wear process of natural tooth structure and restorative materials. The rough surface of the porcelain after diamond bur adjustment was found to increase the enamel wear rate significantly, in agreement with previous reports (Monasky and Taylor, 1971). Gold was included in one of the studies as a control since it is known to be ideal for occlusal restoration due to its low abrasivity against the natural dentition. It has been found in many studies to be substantially less abrasive than dental ceramics (Mahalick *et al.*, 1971; Jacobi *et al.*,

1991; DeLong *et al.*, 1992; Jagger and Harrison, 1995a; Hacker *et al.*, 1996) which was also found in the present study. This study also proved that the microstructure of the ceramic has a major influence on its abrasivity and wear properties. This was obvious from the significant reduction in both enamel wear and ceramic wear for the Duceram-LFC and the machinable Vita Mark II compared to the conventional Alpha and Omega porcelains, when tested in water. Duceram-LFC is a leucite free hydrothermal ceramic forming a self-protective silicon-hydroxyl layer on its surface when in contact with water and has proved to be the least abrasive among the four ceramics tested in water. It was also found to be significantly more resistant to wear than conventional porcelains. Vita Mark II is a machinable ceramic manufactured from fine particle size feldspathic porcelain which may explain its low abrasivity and high resistance to wear which is significantly different from hand made conventional porcelains (Alpha and Omega).

However, the results of this study suggest that the properties of the hydrothermal ceramic Duceram-LFC were affected when the wear test was carried out in an acidic environment and in the presence of food particles (three-body wear). This could be due to possible interactions of the material structure with the surrounding media. Further investigations are needed to elucidate the nature of these interactions. The results of this study suggest that a two-body wear test alone is not sufficient for elucidating the abrasivity and the wear properties of restorative materials.

The SEM was of great help in understanding the mechanism of wear for both restorative materials and tooth enamel. Overall, the wear of dental ceramics was

found to be dominated by fatigue and abrasive wear mechanisms whilst the wear of opposing enamel was mainly of an abrasive nature. The wear observed with gold mainly consisted of fatigue wear mechanism combined with adhesive wear mechanism.

8.4. Conclusion

Overall and under the conditions and parameters employed in this *in vitro* study the following can be concluded:

1. An adjusted porcelain restoration should not be left without polishing if it cannot be reglazed, since the adjusted porcelain surface (unglazed) was found to be significantly more abrasive.

2. Gold remains the least abrasive and the most resistant to wear than all the dental materials tested in this study under the two-body wear test conditions.

3. Carbonated beverages (Coca Cola) significantly increased the rate of enamel wear against dental ceramics.

4. Two-body wear tests carried out in neutral media (eg. water) are insufficient to investigate the wear properties of any dental restorative materials and their abrasivity against natural teeth.

5. The presence of food particles and the acidic environment in the wear test was found to have a definite effect on the wear result. This was found to correlate with the microstructure of the ceramic materials.

6. The hydrothermal low fusing ceramic Duceram-LFC performed extremely well when tested in water compared with the conventional porcelain. However, this was

not the case when the test was carried out in an acidic environment and in the presence of food particles suggesting a tribochemical wear mechanism.

7. Overall, the machinable Vita Mark II was found to be the most acceptable ceramic in regard to its abrasivity against enamel and its resistance to wear under the different conditions incorporated in this study.

8. The wear mechanism of dental ceramics occurred generally via fatigue and abrasive wear and that of the opposing tooth enamel occurred mainly by abrasive wear. The wear of gold occurred mainly by a combination of fatigue and adhesive wear mechanisms.

8.5. Future Research

Possibilities for future research includes the following:

1. Investigation of the ceramic wear track using confocal microscopy for subsurface evaluation.

2. The effect of "add-on" staining and glazing of Vita Mark II on its abrasivity against tooth structure.

3. Investigate the wear of restorative dental materials when opposed to other materials eg. ceramic against ceramic or a flat enamel surface against spherical ceramic specimens.

4. Investigate other types of ceramic materials, including other low fusing porcelains and machinable ceramics.

5. The effect that wear across the tooth-intracoronal restoration junction has a subsequent microleakage.

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Addendum

Page v (line 16): Thanks are also due to Mr William Richardson from the department of Clinical Physics and Bio-Engineering (West of Scotland Health Boards) who kindly calibrated the dental wear machine at the beginning of this study.

Page 126 (line 6): The dental wear machine used in this study was constructed by Mr William Richardson from the department of Clinical Physics and Bio-Engineering (West of Scotland Health Boards), under the supervision of Dr Ronnie Strang and Dr James Alun Scott, Glasgow Dental Hospital and School.

Page 126 (line 19): The tooth specimen was oriented with the flat (cut) surface towards the sliding direction of the tooth over the material specimen.