The Effect of Bracket Material on Fatigue Strength of the Orthodontic Bond

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Abstract

Dental materials placed on the surfaces of teeth are exposed to repetitive occlusal forces. The occlusal forces can cause the propagation of microfractures and the eventual breakdown of the material through the process of fatigue. Structural fatigue of the orthodontic bond may lead to unwanted bonding failures as the orthodontic bracket is subjected to masticatory and parafunctional loading. The purpose of this study was to determine whether bracket material can have a significant effect on fatigue strength of the bond between an orthodontic bracket and tooth. Brackets of three materials were tested under identical conditions; titanium, stainless steel, and ceramic. The sample included 96 mandibular premolar teeth bonded with titanium, stainless steel, or ceramic brackets. Fatigue tests were carried out on 24 samples of each bracket type. The fatigue trials employ a "staircase" methodology where samples were tested sequentially. The samples were subjected to loading on the bracket wings for 5000 cycles. The remaining 24 samples were tested for shear bond strength. Fatigue strengths of the bond of titanium and stainless steel brackets were not significantly different. Ceramic bracket bond fatigue strength was significantly higher than that of titanium or stainless steel brackets. The fatigue strength of the bonds of all three bracket types were significantly different than their shear bond strengths. The bond fatigue strength for stainless steel was 63% of the shear bond strength, 78% for titanium, and 80% for ceramic. Titanium brackets performed at levels comparable to stainless steel and ceramic. Titanium brackets are an acceptable alternative to stainless steel and ceramic brackets.

Introduction

Bond failure in orthodontics has been a problem complicating treatment and progress since the introduction of bonding orthodontic brackets. Various bonding methods have been developed and protocols established to minimize bonding failures, yet clinicians and researchers still find a significant rate of bonding failures during treatment. Failure rates of brackets in clinical trials have ranged from 5 percent for upper incisors to 11 percent for premolars (Millet & Gordon, 1994). Additionally, bonding failures increase over time at a steady rate up to approximately 24 months, implying that structural fatigue of the bond may be an important factor in the survival of the bond over the length of treatment (Linklater & Gordon, 2003).

The recent introduction of titanium as a bracket material has brought speculation that this material may improve the overall survival time of the orthodontic bond by dampening occlusal forces, acting somewhat as a stress absorber between the occlusal forces and the bond. Anecdotal evidence distributed by Sybron Dental Specialties-Ormco, the manufacturer of titanium brackets, suggest lower rates of clinical bond failures when comparing titanium to stainless steel brackets (Bennet, 2002). However no published research in peer reviewed journals supports this claim to date.

Fatigue strength and fatigue limit studies using cyclic stress to simulate forces applied in the oral environment have been well documented for restorative dental materials, yet no fatigue strength testing has been published for orthodontic materials (McCabe et al., 1990; Draughn, 1979; Aquilino et al., 1991;

Braem et al., 1994; Braem et al., 1995). Fatigue testing of the orthodontic bond has been suggested by critics of shear strength testing of orthodontic brackets as a way to more closely approximate clinical performance in the lab (Eliades & Brantley, 2000). Fatigue limit testing uses cyclic loading well below the ultimate tensile or shear strengths with the purpose of investigating the material's ability to survive over an infinite number of stress cycles. Fatigue strength tests evaluate the maximum stress a material can be subjected to when exposed to that stress over a specific number of cycles. Materials with properties better able to withstand cyclic stress will have higher fatigue limits and strengths than those that break down more rapidly under cyclic loading. If titanium brackets do in fact "cushion" the bond interface when placed under stress, the fatigue strengths of the titanium bracket bonds should be higher than those of stainless steel or ceramic brackets.

Literature Review

A fundamental requirement in all fixed appliance orthodontics is that the brackets remain attached to the teeth during treatment. Durability of the bracket and tooth interface depends on the bonding cement staying intact throughout the course of treatment. The bracket and cement together must endure many cycles of occlusal forces. During treatment, it is occlusal forces that likely cause unwanted bonding failures when standard bonding technique has been followed. Loading due to occlusion occurs directly by tooth or food bolus contact with the bracket or via the archwire. The loading of the bracket and cement is repetitive but difficult to assess since it is likely that occlusal forces related to mastication vary in magnitude, frequency, duration, and direction. When the bracket and cement are subjected to repetitive masticatory loads, structural breakdown of the cement or the bonded interface can result. This phenomenon is known as fatigue and can eventually lead to bond failure (Wiskott et al., 1995). It has been suggested that titanium brackets may help prevent bonding failures by reducing the occlusal stress that is transmitted through the bracket to the bond interface. Titanium has a lower modulus of elasticity, which may serve to “cushion” the adhesive bond by absorbing some of the energy of occlusal impacts, and possibly reducing the gradual loss of structural integrity of the bond that can occur due to cyclic loading (Anusavice, 1996).

This study will investigate and compare fatigue strength of the orthodontic bond of titanium, stainless steel and ceramic brackets. Stainless steel and ceramic brackets have a proven track record in clinical practice, each with its own advantages and disadvantages. Both materials are fairly inflexible, ceramic being notably brittle. Titanium brackets have had significantly less time in orthodontic practices, yet they do have promising characteristics. Titanium is known for its biocompatibility and has been found to have similar mechanical strength characteristics to stainless steel. Titanium has a significantly lower elastic modulus than stainless steel or ceramics. The elastic modulus for titanium is 107-122 GPa, for stainless steel 196 GPa, and for ceramics 416 ± 30 GPa (Anusavice, 1996; Munroe, 1997). Whether the difference in elastic modulus of these orthodontic bracket materials is significant experimentally or clinically is unknown.

Stainless steel brackets

Stainless steel orthodontic brackets represent the standard of the profession and have been the primary type of bracket used in orthodontics. Stainless steel has been the bracket material of choice for many years because of its many desirable qualities, including: low cost, adequate bonding properties and resistance to deformation (Kusy, 2002; Kapur et al., 1999; Flores et al., 1994; Powers et al., 1997). Stainless steel does have factors that, at times, make its use undesirable. Primarily esthetics and secondarily nickel allergy present challenges to stainless steel as the material of choice for orthodontics. Five different types of stainless steel are now being used in the manufacture of orthodontic brackets: 303SS, 313SE, 316L, 303S, 17-4PH (Flores et al., 1994). Nominal compositions are listed in Table 1. In this study, the bracket composition is 17-4PH, a martensitic precipitation hardened stainless steel, which offers high strength and hardness and excellent corrosion resistance (Flores et al., 1994).

Table 1

Chemical composition of stainless steel brackets by percent*

Raw material	Cr	Ni	Mn	C	P	S	Si	Mo	Se
310SS	24.0	19.0 26.0	2.0 22.0	.08	.04	.03	1.5	.75	
313SE	17.0	8.0 19.0	2.0 10.0	.15	.20	.06 .17	1.0		.15 .35
316L	16.0 18.0	10.0 14.0	2.0	.03	.04	.03	1.0	2.0 3.0	
303S	17.0 19.0	8.0 10.0	2.0	.15	.04	.18 .40			
17-4PH	15.5 17.5	3.0 5.0	1.0	.07	.04	.03	1.0		

* residual is iron (Fe)

Ceramic brackets

Ceramic brackets are now regularly used where esthetics is a concern. Ceramics have been refined since their introduction in the 1980's, however they still have disadvantages compared to stainless steel. Damage to enamel can occur when debonding ceramic brackets or when the opposing tooth contacts the ceramic bracket in occlusion. Increased abrasion and wear of antagonist teeth due to the hardness of ceramic material was documented by Douglas (1989) and others in clinical investigations (Viazis et al., 1990). Risk of enamel fracture has been a problem found when debonding ceramic brackets (Oggard & Segner, 1988). Enamel damage is more likely to take place during debonding of ceramic than metallic brackets (Joseph and Rossouw, 1990; Ghafari, 1992). Breakage of ceramic brackets is a problem related to low fracture toughness of the material. Fractures of the tiewings of ceramic brackets are a relatively common clinical problem. The ability to resist fracture depends on the type, shape and bulk of the bracket (Scott, 1988). Fractures of ceramic brackets have been reported frequently in debonding investigations, while the metallic brackets have had no reported incidents of fracture (Birnie, 1990; Swartz 1988; Viazis et al., 1990). Breakage of ceramic brackets may occur either in function or in the debonding process. Investigations of ceramic bracket bond strength have reported the incidence of unexpected bracket fractures when attempting to debond using torsion, sheer or peel techniques (Winchester, 1991; Viazis et al., 1993). The primary causes of ceramic fracture have been reported by Viazis, et al (1993) as internal defects and machining interference.

Most ceramic brackets are made of high-purity aluminum oxide, Al_2O_3 (alumina). The brackets are available in both single-crystal and polycrystalline forms. Both forms have advantages and disadvantages. Single-crystal alumina brackets have excellent optical clarity, in contrast to polycrystalline brackets with less clarity due to variation in refractive index within grains and scattering processes at the grain boundaries. Polycrystalline brackets have a higher resistance to crack propagation than single-crystal brackets once fracture initiation has occurred (Brantley and Eliades, 2001). All ceramics used for brackets are hypoallergenic and contain no nickel in the ceramic itself (some ceramic brackets do have a stainless steel slot).

Titanium brackets

Titanium as a bracket material was introduced in the mid 1990's, initially as an alternative to stainless steel, primarily to avoid the allergenic potential of the nickel in stainless steel. Biocompatibility of titanium has been proven through its success in dental implants and other medical devices. The titanium bracket is thought to have similar clinical characteristics to stainless steel brackets without the nickel content. Stainless steel brackets have nickel content that ranges from 3% to 26% depending on the type of steel (Flores et al., 1994). Titanium brackets contain no nickel (Anusavice, 1996). Titanium brackets have been manufactured from commercially pure (cp) titanium and titanium 6-4. Commercially pure titanium contains oxygen (0.5% maximum) and minor amounts of impurities. Titanium 6-4 is 90 wt% titanium, 6 wt% aluminum, and 4 wt% vanadium (Anusavice, 1996).

Comparison of bracket materials

The elastic modulus of a material represents the relative stiffness of the material within the elastic range. It is calculated with the ratio of stress to strain, during elastic deformation, as determined from a stress strain curve (O'Brien, 2002). The physical properties of the bracket materials are shown in Table 2.

Table 2

Physical properties of bracket materials

Raw material	Bracket	Tensile strength MPa	0.2% Yield strength MPa	Elastic modulus GPa
Titanium 6-4	Ormco Orthos II	970	900	107-122
Stainless steel 17-4	Ormco Orthos	1310	1170	196
Ceramic, alumina	Unitek Clarity	267	N/A	416

The modulus of elasticity for titanium 6-4 is 107-122 GPa. The modulus for cp titanium is 110 GPa. The cp titanium that composes the bracket base is ductile (17% elongation) and of lower strength than the 6-4 titanium which has an ultimate tensile strength of 970 MPa and 0.2% yield strength of 900 MPa. Stainless steel 17-4 has modulus of elasticity of 196 GPa, an ultimate tensile strength of 1310 MPa and a 0.2% yield strength of 1170 MPa (Anusavice, 1996).

Crystalline ceramic materials have a combination of covalent and ionic bonding in their atomic structure, which allow minimal dislocation movement when placed under stress at room temperature. Orthodontic ceramic materials are completely brittle; with the stress-strain plot being a straight line up to the point of fracture (O'Brien, 2002). Polycrystalline brackets will fracture at approximately 35% of the yield strength of the stainless steel brackets regardless of whether or not the ceramic bracket has been scratched. Monocrystalline brackets however fractured at 150% of the stainless steel yield strength when unscratched, but when scratched, fracture at 50% of the stainless steel yield strength (Flores et al., 1989). The ceramic brackets are made from polycrystalline alumina with a density of 3.98 g/cm^3 and have a modulus of elasticity of 416 ± 30 GPa (Munroe, 1997).

Nickel allergy

Stainless steel brackets have been used successfully for many years. However concerns about nickel sensitivity or allergy have led orthodontists to consider using other bracket materials, such as ceramic and titanium. The incidence of allergy to nickel has been reported to range from 9% to 28.5% in the general population, with females approximately 10 times more likely to be nickel sensitive compared to males (Dunlap et al., 1989; Staerkjaer and Menne, 1990). With increasing public awareness of nickel sensitivity there has been an effort by the dental community to limit the nickel content of dental materials. Ceramic brackets, as discussed above, are a problematic alternative to stainless steel, particularly as a full arch appliance. Titanium brackets likely offer a satisfactory alternative to both stainless steel and ceramic when nickel allergy is a concern.

Titanium vs stainless steel bracket friction studies

Since the introduction of titanium as a bracket material, researchers have investigated the characteristics of titanium versus stainless steel brackets. They have found similar or improved characteristics in several areas. Kusy and

O'Grady (2000) found that the static and kinetic coefficients of friction of stainless steel and titanium brackets are comparable. In passive configurations (non-angulated brackets), the kinetic frictional coefficient has been shown to be 0.11±0.01 for a stainless steel bracket when a stainless steel wire was drawn through it. A comparable frictional coefficient of 0.12±0.01 was found for a titanium bracket when a stainless steel wire drawn through it (Kusy and O'Grady, 2000). In active configurations, where the bracket is angulated from 0° to 11° and drawing forces are measured, the investigators also found that the kinetic frictional coefficients of the titanium and stainless steel brackets were not significantly different. When compared to ceramic brackets in the active configuration with stainless steel wire drawn through, the titanium brackets coefficient was 3 to 4 times lower than the ceramic (Kusy and O'Grady, 2000). Kapur and colleagues (1999) also found similar results in comparisons of frictional resistance in titanium and stainless steel brackets. Stainless steel brackets demonstrated higher static and kinetic frictional force values as the wire size increased. In contrast, frictional force decreased as wire size increased for titanium brackets.

Titanium vs stainless steel bracket load transmission studies

Kapur and colleagues (1999) investigated comparison of load transmission and bracket deformation between titanium and stainless steel brackets. Torque was applied to the bracket slots at 15°, 30°and 45°. It was found that titanium brackets transmitted higher loads than the stainless steel at 15° and 30° torque and lower load at 45° torque. One possible explanation is that at lower torque values the titanium brackets offered higher torsional forces by a more complete transmission of the torsion through the brackets. However, at 45° torque the titanium has reached the limit of elastic deformation and therefore gave a lower torsional force as compared to stainless steel brackets. The stainless steel generated more torsional force at 45° due to the rigidity of the bracket material (Kapur et al., 1999).

Titanium vs stainless steel bracket distortion studies

Kapur and colleagues (1999) also investigated distortion of the brackets following the application of torsional force, and found that the titanium brackets showed significantly less bracket deformation than the stainless steel brackets. The author concluded that the titanium brackets were more reactive at 45° torque and produced lower load values as they release the stored energy over a longer period of time as a result of a rebound phenomenon (Kapur et al., 1999). Titanium brackets may have an advantage over stainless steel for fewer bonding failures if they are able to transmit less torsional force through the bracket to the bonding interface. The titanium may act to cushion forces that are applied to it by mastication and occlusion, particularly those forces that may be high enough to cause bond weakening or failure.

Fatigue testing in dentistry

Fatigue testing of dental materials has been well established in research literature with investigations of restorative materials (McCabe et al., 1990, Draughn, 1979; Aquilino et al., 1991; Braem et al., 1994; Braem et al., 1995). However, fatigue testing of orthodontic materials has not been investigated as thoroughly (Moseley et al., 1995) In Eliades and Brantleys (2000) critique of conventional orthodontic bond strength testing, they propose studies of fatigue tests for orthodontic bonding. Fatigue testing the adhesive-bracket system to determine the tolerance of the system to a low-magnitude, cyclic mechanical stress may be more applicable to the clinical situation than the typical debond testing protocol of measuring bond strength to a single, static application of force (Eliades and Brantley 2000). Past bond strength studies have frequently used the universal testing machine, such as an Instron, which shears the bracket from the bonded surface with the application of consistent, increasing force until the bond fails. The crosshead speed is often set at approximately 0.5 mm/min. This methodology has been noted as lacking correspondence to clinical conditions since in vivo debonding incidents are expected to occur at higher velocity (Eliades and Brantley 2000). Important to consider, is the cyclic masticatory forces that may lead to propagation of cracks in the bonding material and interfaces and thus leading to a weakened bond, and possible bond failure.

Fatigue testing for dental materials has been performed as a way to simulate the cyclic application of forces that occur during mastication. Draughn (1979) introduced a method to compare precisely the relative levels of stress which different materials can survive for a pre-set number of stress cycles. This method (the staircase method) is used to determine fatigue strength (Draughn 1979). Fatigue life of a material is defined as the number of stress cycles it can withstand before failing. At high stresses, failure will occur after a minimum number of cycles. As the stress is reduced, the number of cycles the material can withstand increases. Below a certain value of stress, called the fatigue limit (or endurance limit), the material can be subjected to an infinite or very large number of stress cycles without failing. Values of fatigue limit depend on the type of material, the nature of the applied stress, the testing environment and frequency of cyclic loading. Polymeric materials, such as resin composite used for bonding orthodontic brackets, do not exhibit well defined fatigue limits below which the material can be subjected to an infinite number of stress cycles. However it is possible to define a stress level for this material below which thousands of stress cycles are required to cause failure (Draughn 1979). In this study, fatigue strength is defined as the stress below which failure will not occur in 5,000 cycles.

Fatigue testing in orthodontics

Moseley and colleagues (1995) introduced fatigue testing to orthodontic bond strength testing. In that investigation, stainless steel brackets bonded to natural teeth with composite resin were cyclically loaded at 0.5, 1.0 and 1.5 kg at a rate of 1 cycle per 2 seconds over 5,000 cycles. The brackets were then tested for bond strength tested in an Instron universal testing machine. For comparison, bond strength testing was also done for brackets not subjected to cyclic loading. Percent reduction of mean bond strength was reported for the samples of each loading group. For the samples cyclically loaded at 0.5 kg, a 28% bond strength reduction was found, at 1.0 kg a bond strength reduction of 37%, and at 1.5 kg a bond strength reduction of 50%. The author's conclusion was that fatigue produced by cyclic loading resulted in a decrease in mean bond strength, and that durability of bond strength in vivo cannot necessarily be accurately predicted from usual bond strength testing protocol (Moseley et al., 1995).

Purpose of the Study

The study is designed to investigate the differences that bracket material may have upon the fatigue strength of the bond between tooth and bracket. It has been reported, but not confirmed, that titanium brackets may have the potential to preserve the bond while subjected to occlusal forces over time. Preliminary studies have shown that titanium brackets flex more than stainless steel when subjected to higher degrees of torque (Kusy and O'Grady 2000). Stainless steel brackets have been shown to undergo slightly greater permanent deformation than titanium at the high torque values. Additionally, when subjected to high torque values (45°), the titanium brackets are shown to transmit less torque to the tooth when compared to the stainless steel brackets. This indicates that some of the force placed upon the titanium bracket by high torque produces elastic deformation of the bracket (Kusy & O'Grady, 2000). The elastic deformation may play a role in the titanium bracket's ability to withstand repeated stress of masticatory and occlusal loading. Stainless steel and ceramics have less potential for elastic deformation in comparison to titanium and therefore it is predicted that occlusal forces would be more directly transmitted through the stainless steel and ceramic brackets to the bond interface (Anusavice, 1996; Munroe, 1997). Repeated stress of mastication cycles may over time cause stress fatigue of the composite bond. Depending on bracket material characteristics, the bond may develop adhesive or cohesive failure as a result of fatigue stress. Crack propagation within the orthodontic bond is related to stresses placed upon the bond interface. Both magnitude of occlusal force and number of cycles can play a role in crack propagation in the bonding material that holds the bracket to the tooth. The purpose of this study is to determine whether bracket material can have a significant effect on fatigue strength of the bond between orthodontic bracket and tooth. The specific aim of the study is to determine and compare the fatigue strengths and bond strengths of orthodontic bonding between natural teeth and titanium, stainless steel, and ceramic brackets.

Hypothesis

1. The fatigue strength of bonds between titanium brackets and enamel will be greater than that between stainless steel or ceramic brackets and enamel.

Null Hypothesis: There is no difference between the fatigue strengths of the bond between tooth and titanium, stainless steel or ceramic brackets.

2. The ratio of fatigue strength to bond strength of the titanium brackets will be greater than the ratios of the stainless steel or ceramic brackets.

Null Hypothesis: There is no difference between the ratios of fatigue to bond strength for the three bracket types.

Materials and Methods

Sample groups of 24 of each type of bracket, bonded to mandibular premolar teeth were fatigued tested. The sample size was based on the analysis by Draughn (1979) which found that a minimum of 17 samples were necessary for statistically significant results. The samples were tested in the fatigue testing machine (Figures 1-4). The initial load was set at 50% of shear debonding loads estimated in pilot testing. Draughn (1979) reported that composites tested had average compressive fatigue strengths of 64% of the materials compressive strength. The samples were fatigue tested sequentially, with the applied load in each succeeding test being increased or decreased by a fixed increment, according to whether the previous test resulted in failure or not. This fixed increment represents 5% of the fatigue strength found in the pilot tests. If a sample failed to survive the fixed number of loading cycles, the applied load was reduced by 5% and a new sample tested. If the sample survived the cycles, then the applied load was increased by 5% and a new sample tested. The number of cycles was set at 5,000 with a frequency of 1.5 Hertz. The samples were fixed into the fatigue testing machine so that the load was applied vertically, along the long axis of the tooth, directly placing the load upon the bracket tie wings (Figures 5, 6). After each sample was tested, survival or failure of the bond was recorded and the following sample was tested either at a 5% increase or 5% decrease of applied load (the "staircase" method). A follow up study was conducted to determine shear bond strengths of the titanium, stainless steel and ceramic brackets. Eight brackets of each type were prepared and bonded identically to the fatigue samples. Debonding tests were carried out in an Instron universal testing machine using the same method for engaging the bracket wings as was used in the fatigue tests. The Instron machine operated with a cross-head speed of 0.05 inches/min (Figures 7, 8).

Materials tested

Three bracket materials were tested; titanium, stainless steel and ceramic. The titanium brackets are distributed by Ormco. The pad is fabricated from commercially pure titanium (cpTi). The body of the bracket is fabricated from titanium 6-4, a titanium alloy containing 6% Al and 4% V. The bracket base dimension is 14.0 mm^2. The stainless steel brackets, distributed by Ormco, are fabricated from 17-4 precipitation hardened stainless steel. The bracket base dimension is 14.0 mm^2. The ceramic brackets, composed of polycrystalline alumina, are distributed by 3M Unitek. The bracket base dimension is 12.8 mm^2. The titanium and stainless steel brackets were chosen for their identical shape and size, therefore minimizing variables. All brackets have 0.022 x 0.025 inch slot size.

The composite resin for bonding brackets is distributed by 3M Unitek under the name Transbond XT light cure adhesive. It is a highly filled (80%) light cured composite resin made specifically for orthodontic bonding of all bracket types. The resin adhesive primer used in the study is also distributed by 3M Unitek, under the name Transbond XT. 35% phosphoric acid etchant (Ultradent) was used for bonding procedures (Figure 9).

Recently extracted first and second mandibular premolars, stored in distilled water, were used for this study. Each premolar was used once for the bonding of a test bracket. None of the premolars were reused.

Preparation of samples

The extracted mandibular premolars were embedded upright in acrylic to the approximate level of the cemento-enamel junction (Figure 10). The bonding surface of the teeth were cleaned with a pumice slurry, rinsed 15 seconds, etched with 35% phosphoric acid for 30 seconds, rinsed for 5 seconds, dried with warm air for 15 seconds, and a thin coat of 3M Unitek adhesive resin primer was brushed on the enamel. 3M Unitek Transbond XT composite was pushed into the mesh of the bracket pad. The mesh surface had no other prepartion. The brackets were seated with approximately 200 gms of force for 10 seconds using a force gauge (Ormco Richmond gauge, Figure 11). The load to seat the brackets was reported as the average load value used to place brackets in simulated clinical situations (Itoh et al., 1999). Excess bonding material was removed with the tip of an explorer. The brackets were adjusted on the tooth prior to light curing using the jig that delivered the applied loads during the trials. The adjustment jig assured equal loading of the bracket wings during the fatigue and shear testing. Brackets were cured for 20 seconds from the mesial and 20 seconds from the distal with a quartz-tungsten-halogen curing light operating at 600 mW/cm^2 (VIP, Bisco). The bonded teeth were stored in distilled water for 24 hours prior to testing. The bracket pads were reduced in area based on pilot study findings. The pads were reduced to a uniform size of 7.0 mm^2 for all three types of brackets (Figure 12). It was found in the pilot study that debonding loads for the original brackets would exceed the fatigue machine capacity. Thus, metal bracket pads were reduced from the edges with an aluminum oxide disk, and the ceramic brackets were divided into halves by snapping them at the score line manufactured into the brackets. The brackets with pad reduction can be compared to full size brackets by converting the units to megapascals (MPa). The megaPascal, equivalent to one Newton per square millimeter, is one of the most commonly used units in bond strength studies (Eliades and Brantley, 2000).

Pilot Study

Two pilot studies were performed to determine the applied load necessary to debond the three different bracket types. Fatigue strength testing was to begin at 50% of the value of the debonding stress.

For each pilot study, four brackets of each type were bonded per protocol noted in Materials and Methods. The Instron universal testing machine was used to debond the brackets. The Instron machine cross-head speed was 0.05 inches/min, and a jig was used that was designed to engage the bracket tie wings and debond in a shear direction. The brackets were carefully evaluated for fracture or permanent deformation occurring prior to bond failure during the pilot study. No deformation or fracture was found in the sample.

The pilot study results found average load applied to debond brackets with the full sized pad ranged from 38 lbs for stainless steel to 44 lbs for ceramic brackets. Okeson (2003) noted that maximum biting forces ranged from 79lbs to 99lbs for females and from 118lbs to 142lbs for males. Forces during normal mastication were found to be 36% of the maximum bite force. Debonding forces in the pilot study were well below maximum bite forces reported, however they were similar to the forces reported for mastication. One possible explanation for clinical bond failures is that forces of mastication can be similar or greater than the force required for shear debonding. An important factor is the direction of occlusal force during mastication. Orthodontic brackets, due to their position on the buccal surfaces of teeth, are unlikely to bear the full force of mastication. Lesser forces placed upon the brackets and archwires by food bolus or tooth contact are a probable source of bond degradation due to fatigue.

The fatigue machine's loading capacity is approximately 20 lbs, therefore making the fatigue strength tests likely to exceed the machine's capacity. The experimental design was modified based on these results by reducing the stainless steel and titanium bracket pad size by 50% from 14.0 mm^2 to 7.0 mm^2. The ceramic brackets were reduced from 12.8 mm^2 to 7.0 mm^2, an area reduction of 45%. A second pilot study with the reduced brackets found the average load to debond was 17 lbs to 24 lbs, which was equivalent to 45% to 55% of the loads to debond full size bracket pads. The reduction of applied force necessary to debond the modified brackets was proportional to the amount of pad reduction performed. The comparable bond strengths, calculated in megaPascals, verify that the modifications to the bracket pads did not significantly effect outcome of further tests. The bond strengths found in the pilot studies are presented in Table 3. The fatigue testing was initiated at stress levels of 50% of the shear bond strength of the reduced brackets.

An additional pilot study was performed using the fatigue machine. Five bonded brackets of each group were tested at 5000 cycles of stress at 1.5 Hz, gradually increasing the load at each trial. The fatigue strength pilot study established the fixed increment that the applied load was adjusted between the sequential tests. The applied load causing the initial fatigue failure of the bonded bracket was determined and 5% of that load used as the increment to be added or subtracted from the fatigue load tested in the sequential "staircase" pattern.

Table 3

Shear bond strength pilot test results

Bracket type	Full size bracket pad Shear bond strength			Reduced bracket pad Shear bond strength		
	n	MPa	SD	n	MPa	SD
Titanium bracket	4	9.85	1.35	4	9.30	1.97
Stainless steel bracket	4	10.31	0.62	4	10.39	1.61
Ceramic bracket	4	12.95	4.43	4	13.35	1.31

Statistical analysis

The analysis of the fatigue strength data was based on the least frequent event (non-failures). To determine the mean fatigue strength and the standard deviation the following equations were used:

Mean fatigue limit $\overline{x} = X_0 + d(\Sigma i n_i / N \pm ½)$

Standard deviation $S = 1.62 d(N \cdot \Sigma i^2 \cdot n_i - (\Sigma i n_i)^2 / N + .029)$

X_0 equals the lowest stress levels considered in the analysis (i.e. the lowest stress where either failure or non-failure occurred, and non-failure was used in this study based on the results) and d equals the stress increment used in the experiments. In determining the mean fatigue strength, the positive sign is used when the analysis is based on non-failures and the negative sign is used when failures are considered. The number of events for the least frequent event (failure or non-failure) is N. The lowest level at which failure or non-failure occurred is designated as i=0, the next as i=1 and so on; n_i is the number of events at the given stress level; Σn_i is the sum of n_i; Σin_i is the sum of in_i; and $\Sigma i^2 n_i$ is the sum of $i^2 n_i$. Fatigue strength of each group of brackets, (based on the bracket material), was calculated separately and compared as groups, using ANOVA and Tukey multiple comparisons with 0.05 level of significance. The analysis of the shear bond strength of each group of brackets was calculated separately for means and standard deviations. Then comparisons of the groups using ANOVA and Tukey multiple comparisons at 0.05 level of significance were made. Comparison of fatigue strength to sheer bond strength was done, where fatigue strength is calculated as a percentage of bond strength.

The difference between shear bond strength and fatigue strength means of each bracket type were compared for statistical significance ($P < 0.05$) using the Independent-Samples t-test. An adhesive remnant index based on the format of Årtun and Bergland (1984) was established with brackets and teeth visually examined for site of failure. The site of failure was classified into three categories to confirm patterns of bond failures for both fatigue and bond strength testing. The categories were; failure at the adhesive-bracket interface where the bracket separated cleanly from the adhesive, failure at the adhesive-tooth interface where the adhesive remained on the bracket and no adhesive remained on the tooth, and mixed site of failure where some adhesive remained on the tooth and some on the bracket.

Results

Fatigue testing

The figures graphically represent the sequential experimental data. When the fatigue testing was performed, at the end of each test consisting of 5000 cycles of stress, the bracket had either separated from the tooth or remained bonded. The event of bracket separation is labeled as a bond failure (denoted by 'x' in the graphs). In the case of the bracket remaining bonded to the tooth, that event is labeled as a non-failure (denoted by 'o' in the graphs). When the bond failed, the following trial with a new bracket and tooth was run with the load reduced by 5% as determined in the pilot testing. When the bond did not fail, the following trial with a new bracket and tooth was run with the load increased by 5%. Figure 4 graphically shows the 3 brackets fatigue tests for comparison.

Figure 13-15 graphically shows the results of the fatigue tests of titanium, stainless steel and ceramic brackets. **Figure 13**

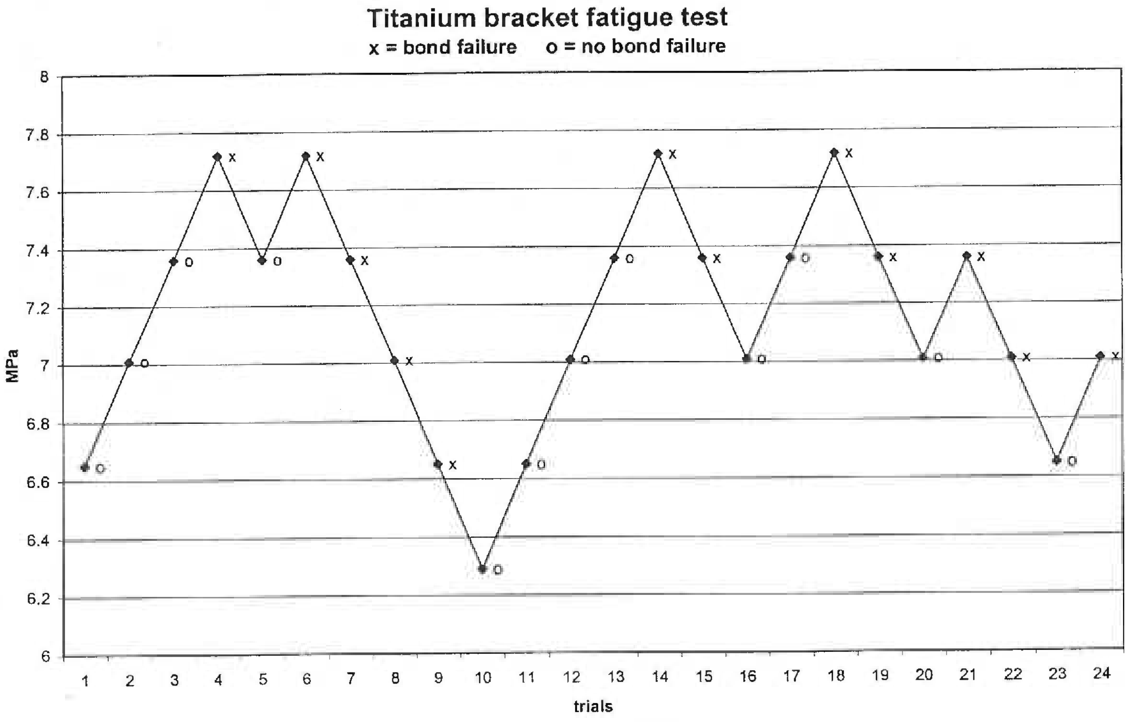


Figure 14

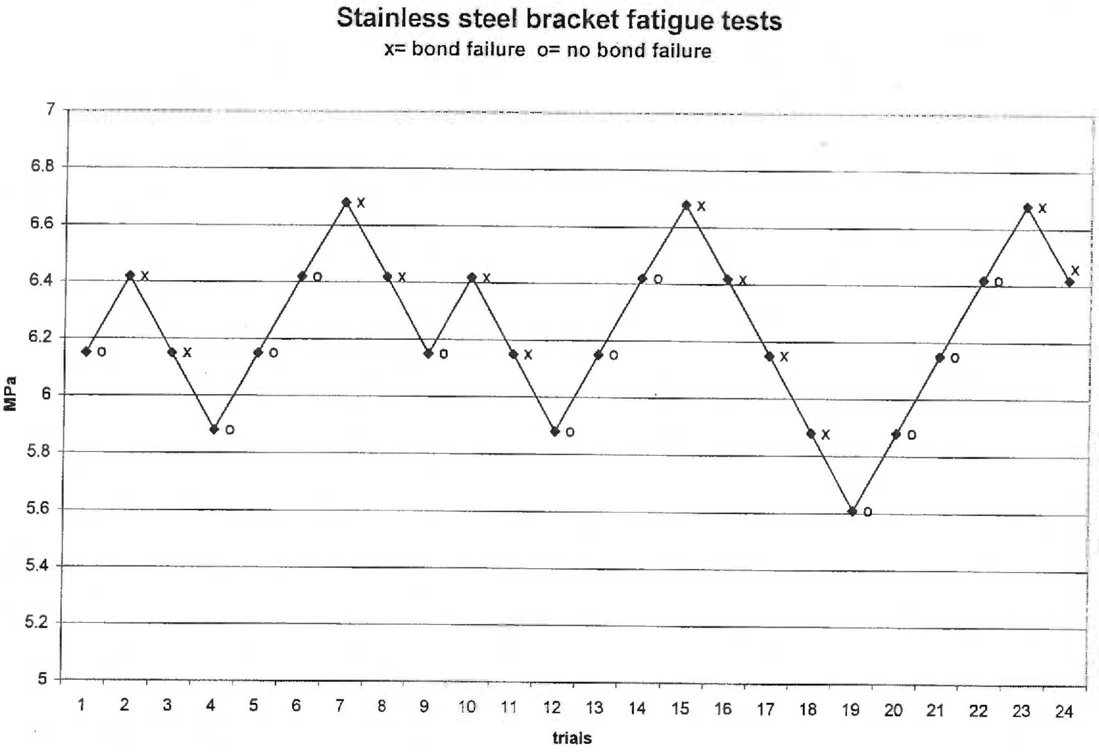
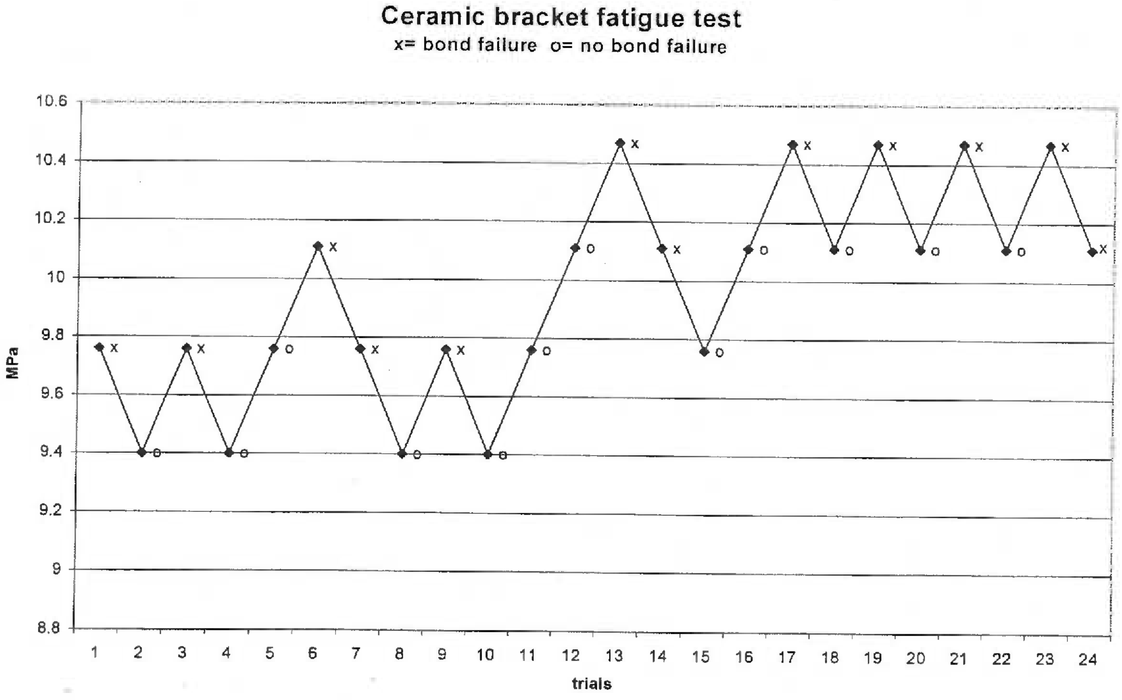


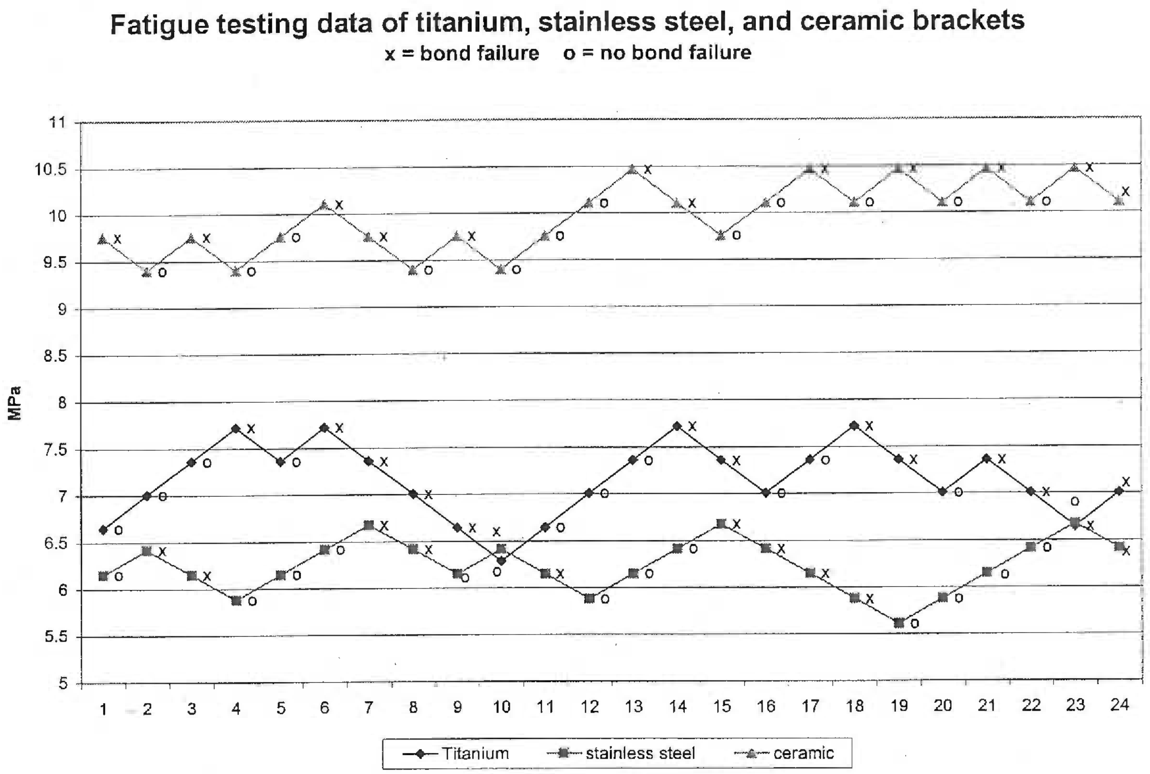
Figure 15



The three graphs of each bracket type demonstrate the range of the fatigue data and the variable nature of the effects of fatigue on the orthodontic bond. Fatigued bond failures ranged from 6.8 MPa to 7.7 MPa for titanium brackets, 5.9 MPa to 6.7 MPa for stainless steel brackets, and 9.7 MPa to 10.4 MPa for ceramic brackets.

Figure 16 demonstrates the difference in fatigue strength of the bonds among the three bracket types. The ceramic brackets consistently performed at greater stress levels than the metal brackets, and had a smaller standard deviation than either metal bracket. The titanium and stainless steel brackets performed more similarly, with overlapping data points. The statistical analysis of the data collected in the fatigue strength trials clarifies the observed trends of the graphical data.

Figure 16



Fatigue testing statistical analysis

The results of statistical analysis of the fatigue strength tests are given in Table 3. The analysis is based on non-failure events. Analysis of variance (ANOVA) among the 3 bracket types for the fatigue strength data indicates a significant difference between the means of the groups at a significance level of 0.05. Tukeys multiple comparisons reveal a significant difference ($P < 0.05$) between the means of the ceramic versus titanium and ceramic versus stainless steel brackets, and no significant difference ($P > 0.05$) between the mean fatigue strength of titanium and stainless steel brackets.

Table 4

Fatigue strengths of orthodontic bonding based on bracket material

Bracket material	N (non-failures)	Mean fatigue strength (MPa)	Standard deviation (MPa)	Significance* ($P<0.05$)
Titanium	12	6.78	0.532	A
Stainless steel	12	5.97	0.366	A
Ceramic	12	9.60	0.438	B

* At the 0.05 significance level, the means of two groups with the same letter are not significantly different

Shear bond strength testing statistical analysis

The results of statistical analysis of the shear bond strength tests are given in Table 4. Analysis of variance (ANOVA) of the shear bond strength data indicates a significant difference at a significance level of 0.05 between the means of the groups. Tukeys multiple comparisons indicate significant differences ($P < 0.05$) between the means of ceramic and titanium and the means of ceramic and stainless steel brackets. No significant difference ($P > 0.05$) was found between the means of titanium and stainless steel brackets. A load versus time curve was plotted for the initial shear bond strength tests. The plots tended to be linear to failure with no evidence of plastic deformation found.

Table 5

Shear bond strength: mean, standard deviation, statistical significance

Bracket material	N	Mean shear bond strength (MPa)	SD (MPa)	Significance* ($P<0.05$)
Titanium	8	8.66	1.37	A
Stainless steel	8	9.43	1.55	A
Ceramic	8	12.06	2.17	B

* At the 0.05 significance level, the means of two groups with the same letter are not significantly different

Comparison of fatigue and shear bond strength

The means of bond fatigue strength and shear bond strength are compared in figure 17 and 18. In each case the mean fatigue strength is significantly less than the shear bond strength ($P<0.02$). Titanium fatigue strength is 78% of its shear bond strength. Stainless steel fatigue strength is 63% of its shear bond strength. Ceramic fatigue strength is 80% of its shear bond strength.

Figure 17

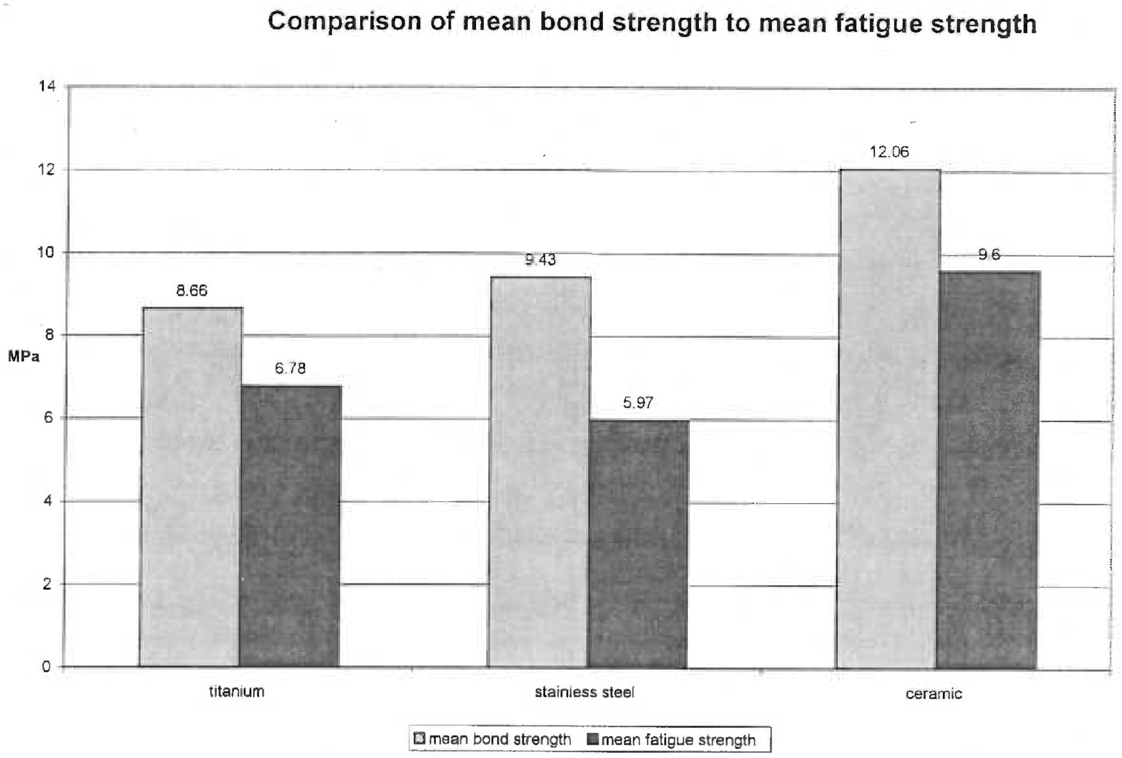
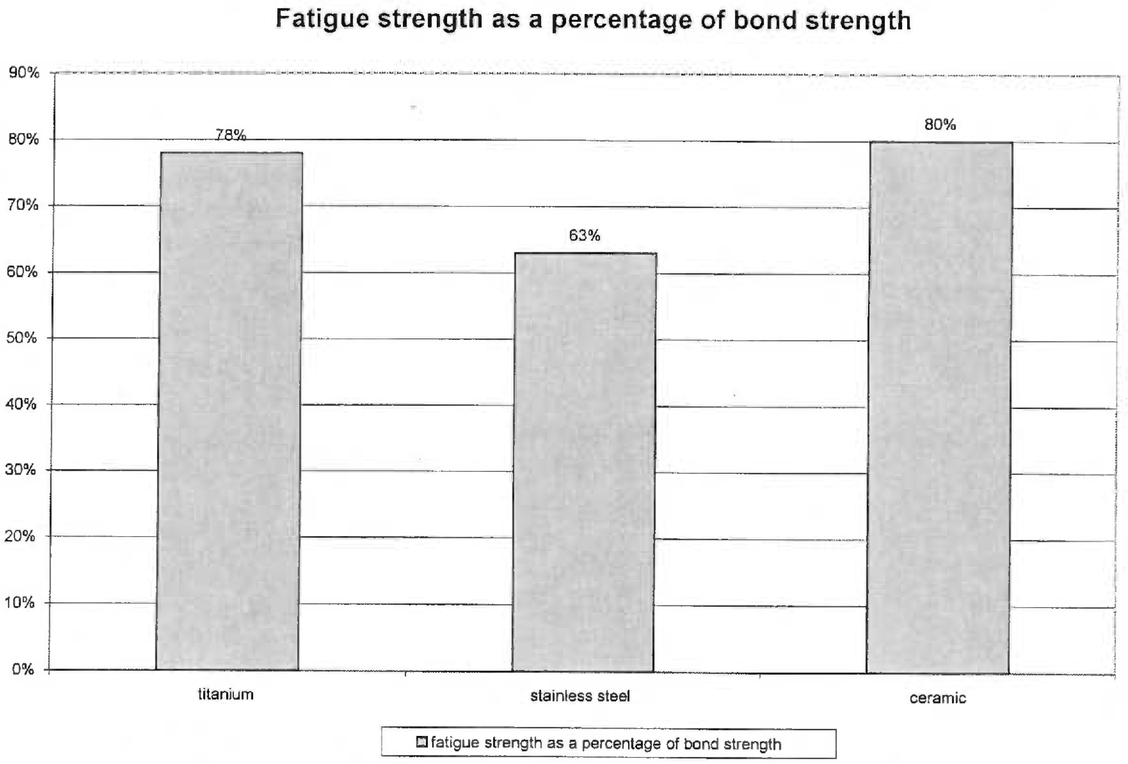


Figure 18



Site of failure index

The site of failure index was developed by Årtun and Bergland (1984) to record where brackets were separating from the teeth to which they were bonded. When an orthodontic bracket bond failed, the site of failure was recorded. The categories for site of failure were: failure at the adhesive-bracket interface where no visible adhesive remained on the bracket pad, failure at the adhesive-tooth interface where no visible adhesive remained on the tooth, and a mixed failure site where some adhesive remained on the bracket pad and some remained on the tooth.

The site of failure index data for fatigue strength trials and for bond strength trials for this study is outlined in Figures 19 and 20. Failure primarily occurred at the adhesive-bracket interface in both fatigue and bond strength trials. For the fatigue tests, the site of failure at the adhesive-bracket interface occurred for; 83% of the titanium brackets, 75% of the stainless steel brackets, and 67% of the ceramic brackets. Mixed site of failure in the fatigue tests occurred in; 17% of the titanium brackets, 25% of stainless steel, and 16.5% for ceramic brackets. Adhesive-tooth interface failure occurred in 16.5% of the ceramic brackets. The total combined percentages for the site of failure in the fatigue tests were; 75% for adhesive-bracket failure, 19.5% for mixed failure, and 5.5% for adhesive-tooth failure. In bond strength tests, 100% of the brackets failed at the adhesive-bracket interface.

Figure 19

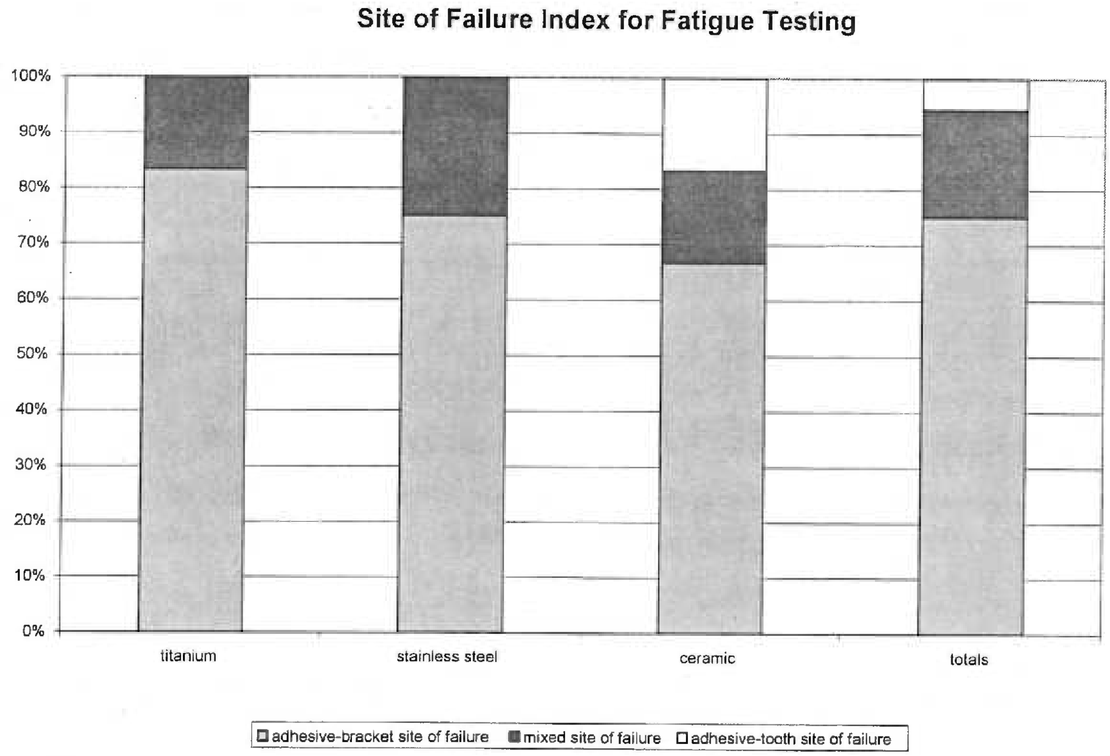
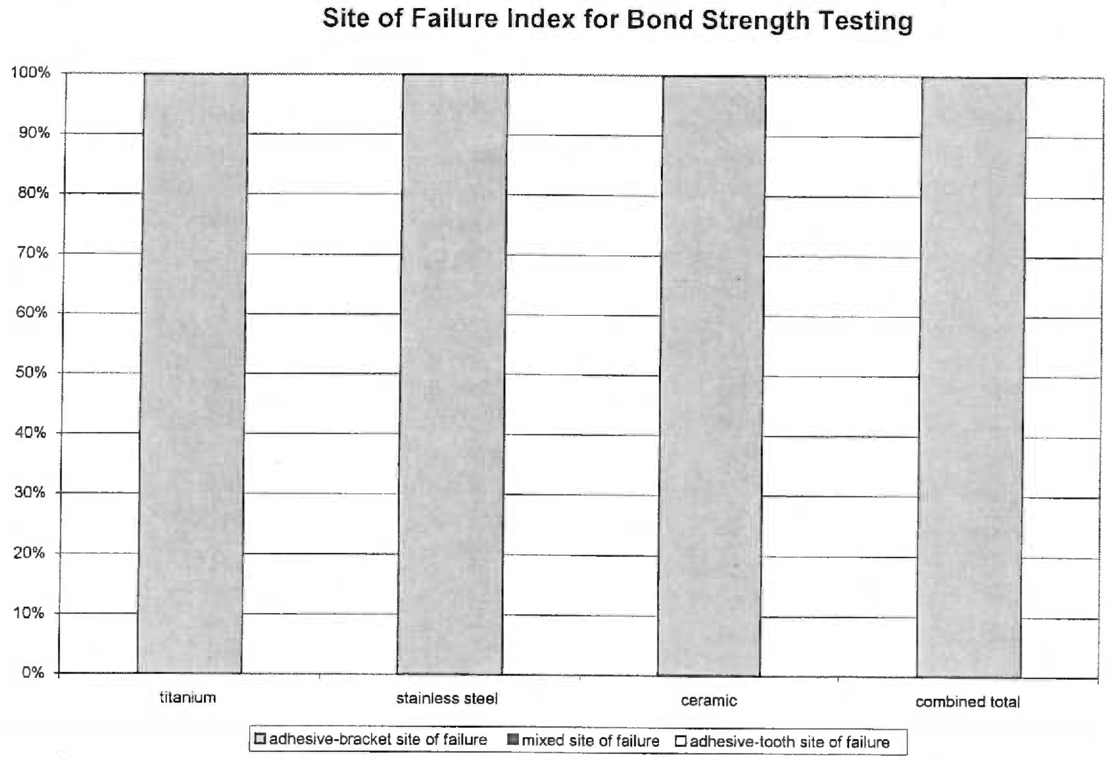


Figure 20



Discussion

The staircase method for determining fatigue strength finds the limit of fatigue strength for a given material over a predetermined number of cycles. The orthodontic bond in these experiments was subjected to an applied load over 5000 cycles. The number of cycles that the actual bracket, in vivo, is subjected to is likely quite variable depending on: the bracket's position in the arch, where the bracket is placed incisal-gingivally, how long the bracket is bonded to the tooth, eating habits and chewing patterns. For an orthodontic bond similar to those in this experiment to survive greater than 5000 cycles, the applied stress must be less than the mean values of fatigue strength found here.

The bonds of titanium, stainless steel and ceramic brackets were fatigue tested under identical conditions, other than bracket composition, to determine fatigue strengths of the orthodontic bond. The experimental design was undertaken to determine if there are significant differences in fatigue strength due to bracket composition. The bracket bases were modified, by reducing the area of each bracket to 7.0 mm^2. All brackets had the same surface area for bonding. The fatigue and shear testing used the same devices engaging the bracket wings and directed the force along the long axis of the bonded tooth.

This study found bond fatigue strength was significantly different between the metal brackets and the ceramic brackets. The stainless steel bracket mean bond fatigue strength was 62% of the mean ceramic bond fatigue strength and the titanium bracket mean bond fatigue strength was 70% of the mean ceramic bond fatigue strength. The difference between titanium and stainless steel mean bond fatigue strengths were not found to be significant. The ceramic brackets also had the greatest shear bond strength. The statistical significance of shear bond strength mirrored that of fatigue strength. Comparing titanium brackets to stainless steel, the trends in the data suggest that titanium may protect the bond during cyclic stressing somewhat better than the stainless steel. The titanium bond fatigue strength was 78% of the shear bond strength, while stainless steel bond fatigue strength was 63% of the shear bond strength. The orthodontic bond of the stainless steel brackets tolerated less cyclic stress imposed upon it during the fatigue testing when compared to the titanium or ceramic brackets. However, the difference was not statistically significant in the comparison of stainless steel to titanium brackets. There was significant difference when comparing the bond fatigue strengths of stainless steel and titanium to ceramic brackets. Since the differences between stainless steel and titanium bond fatigue test means were not found to be statistically significant in our results, titanium cannot definitively be shown to cushion or protect the orthodontic bond.

The fatigue strength to shear bond strength ratios ranged from 63% for stainless steel to 80% for ceramic brackets. This result is in good agreement with other literature for composites, adhesives and cements. Draughn (1979) found a mean ratio of 64% for fatigue strength to compressive strength for composite restorative materials, with a range of 58% to 68%. Aquilino (1991) found the ratio of fatigue strength to ultimate tensile strength of prosthodontic adhesives ranged from 38% to 69%. Moseley (1995) tested cyclic loading of orthodontic bonds and examined the reduction of bond strength as a result of the fatigue. He found fatigued bonds were 50% to 94% of the original bond strength.

Site of bond failure provides useful information about where fatigue stress is most likely to lead to bonding failures in orthodontics. The bond failures for the fatigue and shear bond strength tests were predominantly at the adhesive resin-bracket interface. This suggests that the interface is the weakest link between orthodontic brackets and the tooth, when the bracket is subjected to conditions such as repeated stress on the bracket wings. The results here are comparable to other bond strength studies that have used similar bonding techniques. Lee and associates (2003) found that 90% of bond failures were located at the adhesive resin-bracket interface. Buyukyilmaz et al (2003), found 85% of the acid etched samples in his study failed at the adhesive resin-bracket interface. However others have found failures in the mixed category more common. Toledano et al (2003) found 65% of samples in shear debonding tests with some adhesive remaining on the bracket, while 23% of the sample had debonded cleanly at the adhesive resin-bracket interface. It has been suggested that debonding occurs primarily at the bracket-adhesive interface because of incomplete polymerization of the resin just below the metal base of the bracket. The lack of a complete cure of the adhesive may occur since light cannot directly polymerize the material behind the bracket pad mesh, particularly toward the center of the pad. This likely weakens the bond strength and may be responsible for failure at the adhesive resin-bracket interface. Other possible explanations have suggested that air pockets in the area of the mesh exclude adhesive and reduce the mechanical interlocking of adhesive and mesh (Toledano et al., 2003). It is also likely that differences in testing geometry and load application among studies affect the site of failure.

Shear bond strengths found in this study are consistent within ranges found in other studies. Bond strengths found in recent studies have been reported between 6.6 MPa and 16.0 MPa (Lee et al., 2003; Buyukyilmaz et al., 2003; Toledano et al., 2003; Yi et al., 2003; Dorminey et al., 2003). Dorminey (2003) found bond strengths that were similar to this study when testing various orthodontic brackets on human teeth in vitro. Mean bond strength were reported between 8.2 MPa and 11.9 MPa. In this study, the shear bond strengths were obtained for comparison to fatigue strengths. The shear bond strengths could be expected to represent the strength of the bond under ideal conditions, prior to exposure to stresses of mastication and occlusal contacts. Our fatigue strengths give a value that represents the level of stress that the bond can withstand when exposed to that stress for 5000 cycles. Comparison of bond strength to fatigue strength for each type of bracket reveals the loss of bond strength when exposed to cyclic stresses. The comparison of shear bond strength to fatigue strength in this study found significant differences for each bracket type, showing that cyclic stress reduces the strength of the bond for the brackets studied.

The elastic modulus of a material is a measure of its stiffness. The elastic modulus can help predict the extent to which a material resists bending or changes in shape when under stress. The elastic moduli of the bracket materials used in this study have been reported as: 107-122 GPa for titanium, 196 GPa for stainless steel and 416 GPa for ceramic. (Anusavice, 1996; Munroe, 1997). Titanium is least able to resist bending under stress, while ceramic is most able to resist bending and shape changes when under stress. Of the three bracket materials, titanium 6-4 has the lowest elastic modulus and therefore most likely to bend or change shape when placed under stress. The question remains that if a bracket is placed under stress does the material's stiffness make a difference in the fatigue strength of the bond? If bracket material stiffness (modulus of elasticity) had been a strongly influential factor in this experimental design, then it would seem likely that the ratios of fatigue strength to shear bond strength for the three bracket types would follow the pattern of the moduli of elasticity. The bracket with the lowest modulus, titanium, could be reasoned to be most elastically deformed under the stresses delivered by the fatigue device and possibly less likely to transmit the full magnitude of stress to the bonding interface as much of the energy of the stress is dissipated in bracket deformation. If this were the case, the difference between fatigue and bond strength would have been less than the other brackets with higher moduli, and the ratio closer to one. In contrast, the ceramic bracket with the highest modulus of elasticity is least likely to elastically deform under the stresses delivered by the fatigue device and possibly most likely to transmit the full magnitude of stress to the bonding interface. If that were the case, the ratio of fatigue to bond strength for ceramic brackets would have been less than the metal brackets.

The results of fatigue testing show that under the conditions set up in the experimental design, the bracket material modulus of elasticity may not have played a significant role in differentiation of fatigue strengths. The stiffest material, ceramic, had the highest fatigue strength and was found to be significantly stronger than titanium or stainless steel ($P<0.05$). Conversely, stainless steel, with an elastic modulus that is greater than titanium, was found to have a fatigue strength that was not significantly different ($P>0.05$) than titanium.

The fatigue strength to shear bond strength ratio could also be expected to reflect bracket material stiffness. The stiffer bracket material would be more likely to transmit stresses to the bonding surfaces and therefore exhibit a greater reduction in strength when comparing the shear bond strength to fatigue strength. This however, is not the case in this experimental design. The ceramic brackets experienced the least difference between fatigue and shear bond strengths and the stainless steel brackets showed the greatest difference between fatigue and shear bond strength. These points are illustrated in Table 6

Table 6

Comparison of fatigue strength and fatigue to bond strength ratios to modulus of elasticity

Bracket Material	Fatigue strength (MPa)	Standard deviation (MPa)	Fatigue/bond	Modulus (GPa)
Titanium	6.78	.53	78%	107-122
Stainless steel	5.97	1.39	63%	196
Ceramic	9.60	.44	80%	416

The ratio of fatigue and bond strength of the ceramic brackets (80%) was similar to the ratio of the titanium brackets (78%). This suggests that the bond of titanium and ceramic brackets may have similar fatigue degradation patterns. When comparing the fatigue to bond strength ratio of stainless steel (63%) to titanium and ceramic, titanium and ceramic demonstrate more bond fatigue resistance. Clinical trials could determine if the difference found here in bond degradation due to fatigue between titanium and stainless steel is a significant factor in the longevity of an orthodontic bracket bond.

The titanium and stainless steel brackets had bond strengths similar to each other without a significant difference between them (P=0.30). Bond strength data for the ceramic brackets was significantly greater than either metal bracket (P=0.02). This is consistent with studies comparing the shear bond strength of ceramic and metal brackets where significant differences were found between the bracket groups (Oggard & Segner, 1988; Joseph & Rossouw, 1990; Viazis, 1990). Differences between bond strength of ceramic and metal brackets can be attributed to the ability of ceramics to chemically as well as mechanically bond to composites through silanation and under cuts manufactured into ceramic bracket pads. Metallic brackets rely on mechanical bonding only and have lower shear bond strengths as shown in the above studies.

Wiskott (1995) noted that fatigue failure is initiated by microscopic cracks that develop in areas of stress concentration at or near the surface of the material. Most common stress raisers are grain boundaries, inclusions, local intrusions and sudden changes in the geometric configuration of the surface. The interface of the bracket pad and the orthodontic adhesive composite creates an area of stress concentration. The composite is forced into the mesh of the pad when it is seated on the tooth. As a result, irregular geometric configurations occur in the adhesive composite. These irregularities are apparent under scanning electron microscope (SEM) examination. Maijer and Smith (1981) documented with SEM the irregular surface of the polymerized adhesive composite and identified the sites of bond failure as being predominantly at the bracket-adhesive interface. The bonding surfaces appear to represent the weak point in fatigue testing of orthodontic brackets with the predominance of failures occurring at the bracket-adhesive interface.

Titanium and stainless steel brackets performed similarly in this experimental design, where no statistically significant differences were found between the bracket materials. Other studies comparing titanium and stainless steel brackets have investigated friction, load transmission with torque applications and deformation of the brackets following torque applications. Kusy and O'Grady (2000), studying friction characteristics, found no significant differences between titanium and stainless steel brackets when drawing stainless steel or beta-titanium wires through the brackets. Kapur and associates (1999) investigated friction and found no significant differences between titanium and stainless steel brackets except when drawing 0.021 x 0.025 inch stainless steel wire through the brackets. In that case, titanium was found to have significantly lower frictional force than stainless steel brackets. Kapur and associates (1999) also investigated load transmission through stainless steel and titanium brackets by applying increasing degrees of torque at the bracket slot. The study used both .018 inch and .022 inch slot size brackets of both materials. The results of the study show that at lower torque intervals (15° and 30°) the .022 titanium brackets transmitted higher forces compared to stainless steel brackets. At 45° torque, the titanium brackets (.022 and .018 inch slots) transmitted lower forces. At 15° and 30° torque, the brackets with .018 inch slots showed no significant differences. The author interpreted their results to mean that at lower torque intervals, the titanium brackets offered higher torsion resistance. Conversely, at the 45° torque interval, titanium had reached the point of elastic deformation and gave a lower load value compared to the stainless steel brackets. The latter generated higher load values because of the rigidity of the bracket material. The author suggested that titanium brackets might be more effective in transmitting forces for lower range torque applications (Kapur et al., 1999).

Results of deformation studies of stainless steel and titanium brackets, after 45° of torque application, found that both types of brackets had deformed slightly, and found significant differences in the degree of deformation between stainless steel and titanium brackets. The stainless steel bracket permanent deformation measured approximately 0.01 mm, while titanium bracket deformation measured approximately 0.002 mm (Kapur et al., 1999). In general, the results of previous studies comparing titanium and stainless steel have found mixed results. When significant differences have been found, titanium has shown superior performance compared to stainless steel. However, the finding of no significant difference has been the most common result in studies comparing stainless steel and titanium brackets, as was the case in this study. If the results of previous studies as well as the current study can be extrapolated to clinical performance, titanium and stainless steel will likely perform equally well, without one clearly superior to the other.

This study found small differences between stainless steel and titanium brackets. While the differences were not statistically significant, the stainless steel brackets had slightly greater shear bond strength and slightly lesser bond fatigue strength when compared to titanium brackets. Titanium brackets have less fatigue of the bond compared to stainless steel, demonstrated by the differing ratios of fatigue to bond strength. The superiority of titanium or stainless steel as a bracket material cannot be proven with the data from current or previous studies; however data shows that titanium brackets are comparable to stainless steel brackets and therefore, clinically the two can be expected to perform similarly. Costs are somewhat similar with titanium brackets costing approximately 20% more than stainless steel. Titanium offers an adequate alternative to stainless steel when there is a potential problem with the nickel content of the stainless steel brackets.

Stainless steel brackets have been the standard by which other types of orthodontic appliances are judged due to their long history of clinical success. Titanium has recently been studied as an alternative bracket material and has performed at levels comparable to stainless steel with bond fatigue properties possibly superior to stainless steel. Titanium provides orthodontists a metal bracket alternative to stainless steel brackets.

Conclusions

1. The mean bond fatigue strength of ceramic brackets was significantly higher than titanium or stainless steel brackets.
2. The mean bond fatigue strengths of titanium and stainless steel brackets were not statistically different.
3. The mean bond fatigue strength for all three types of brackets was significantly less than their mean bond strength.
4. Fatigue strength to bond strength ratios of ceramic and titanium brackets were similar and greater than that of stainless steel brackets.
5. The majority of bond failures occurred at the interface of the orthodontic bracket and the adhesive for all three types of brackets.
6. In this study, titanium brackets performed at levels comparable to stainless steel brackets and had less fatigue degradation of the bond.
7. Results from this and other studies show that titanium brackets are an acceptable or superior alternative to stainless steel brackets.

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Figures

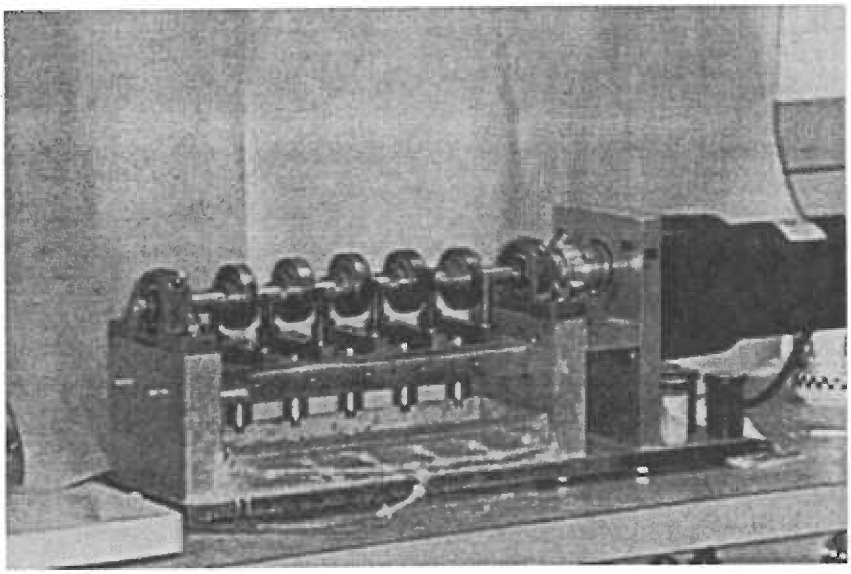

Figure 1.

Fatigue machine used for fatigue strength testing. Samples are placed in the well at the machine base.

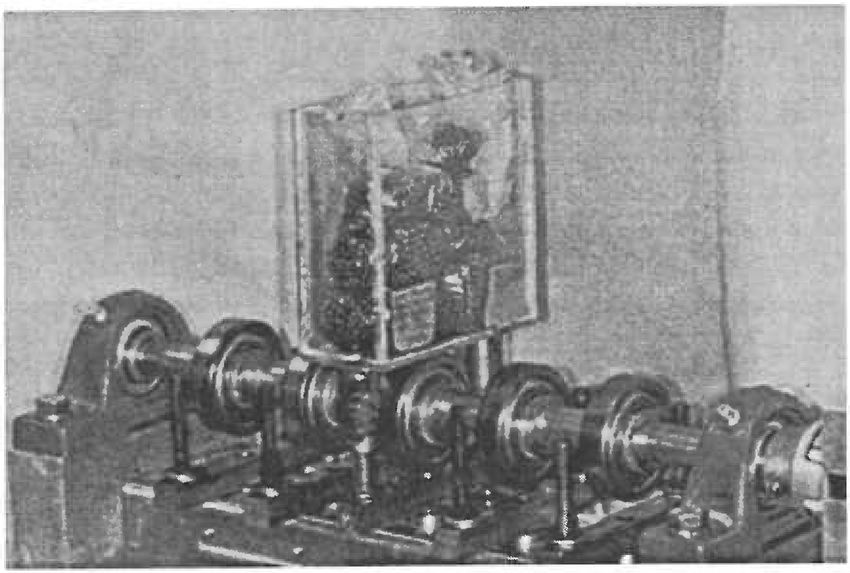

Figure 2.

Fatigue machine delivering load to sample, spring is compressed. Weight can be added or removed from box to increase or decrease stress load.

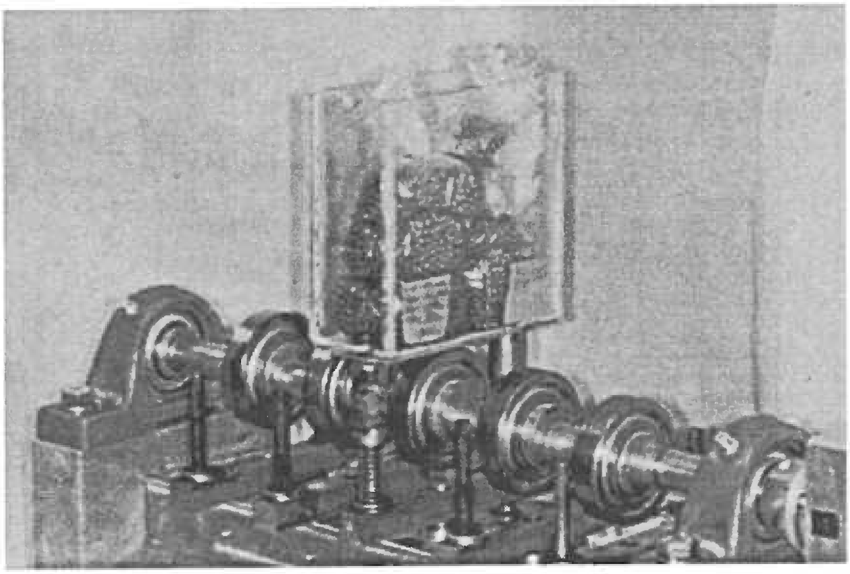

Figure 3.

Eccentric wheel has lifted loaded box, unweighting the sample. The fatigue machine smoothly applies the load cyclically.

Figures

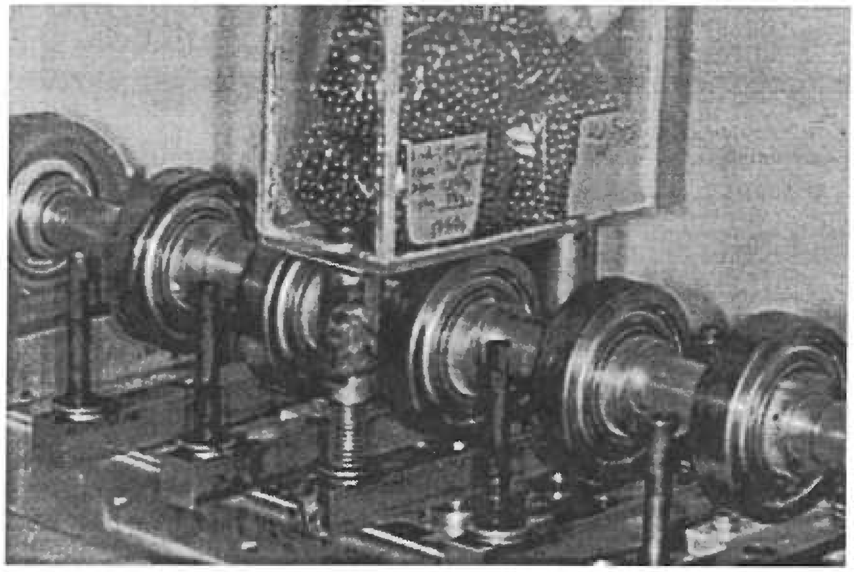

Figure 4.

Detail of fatigue machine delivering load to sample.

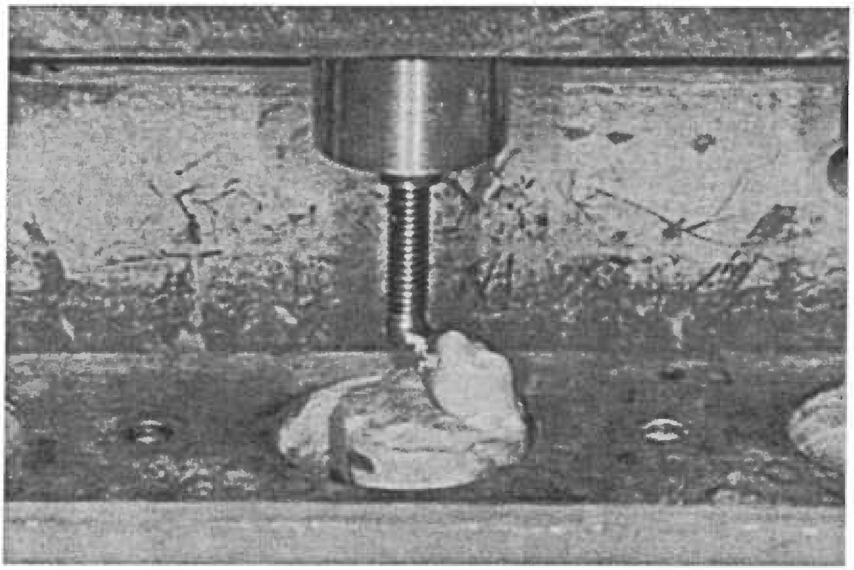

Figure 5.

Sample placed in fatigue machine. Bracket engaged.

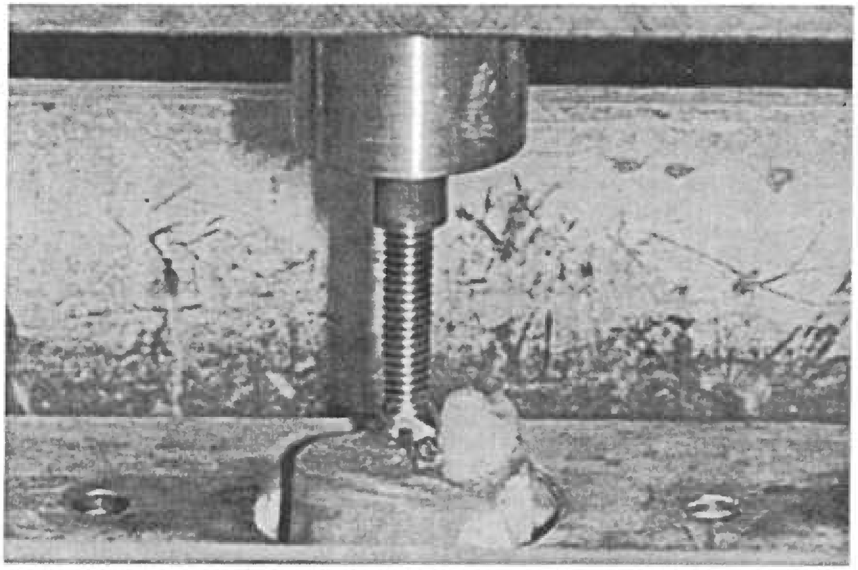

Figure 6.

Example of a bond that failed during fatigue testing.

Figures

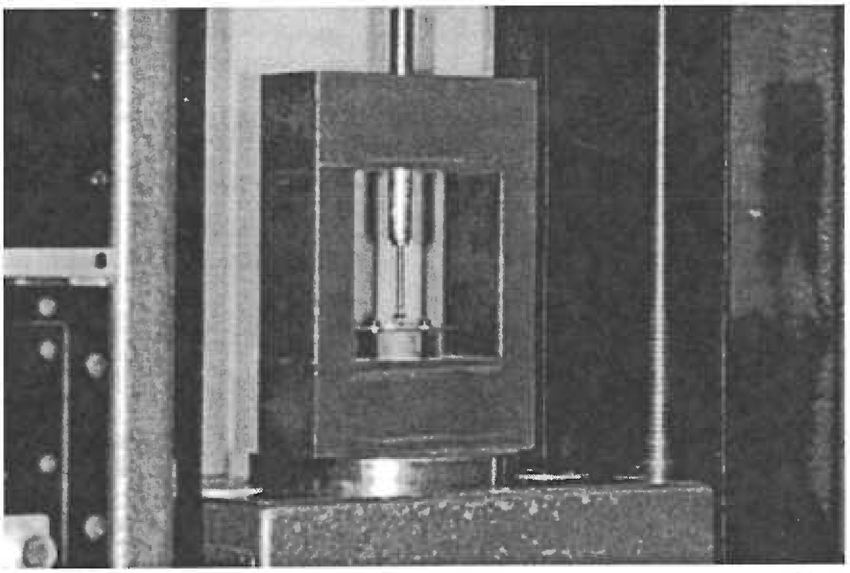

Figure 7.

Shear bond strength testing in an Instron universal testing machine.

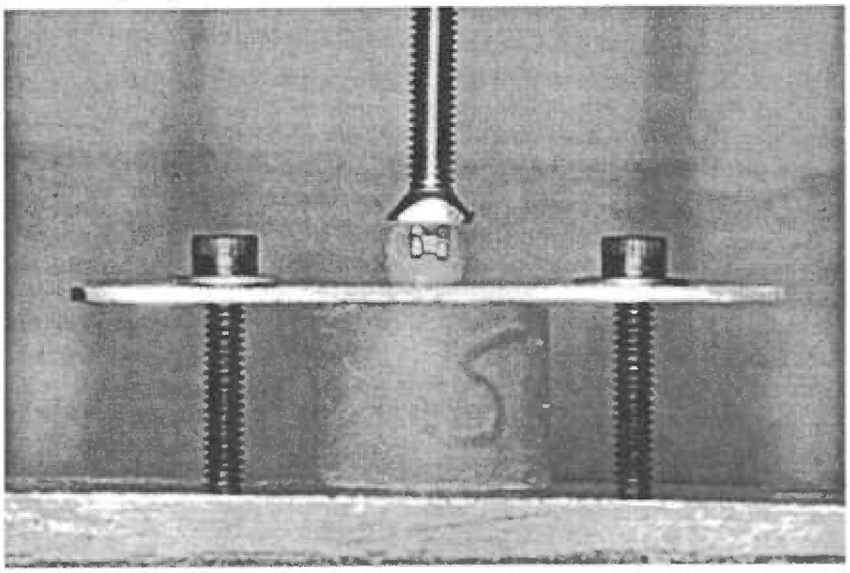

Figure 8.

Detail of shear bond strength testing.

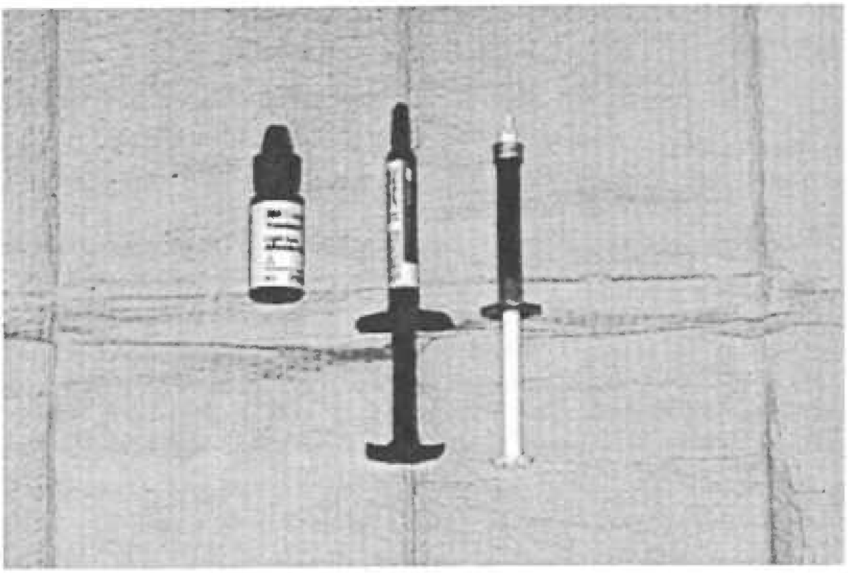

Figure 9.

Primer, bonding composite, etchant.

Figures

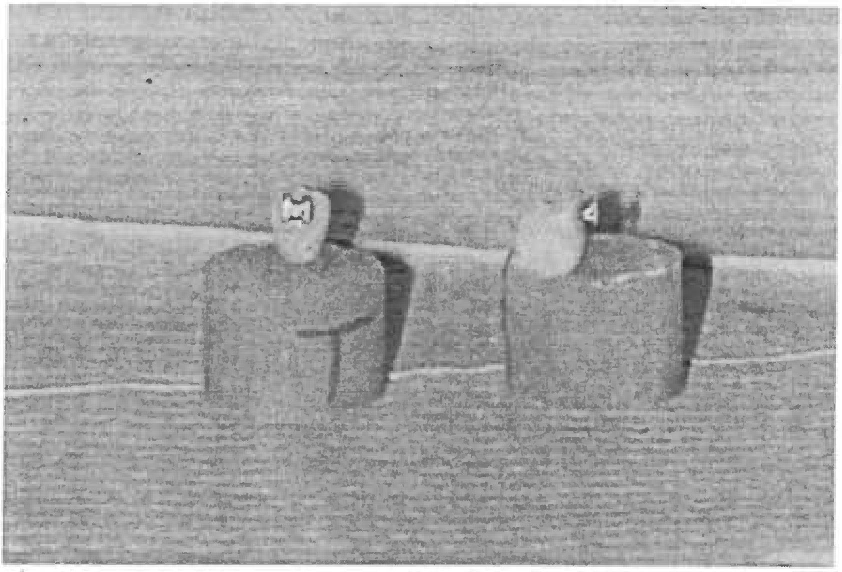

Figure 10.

Extracted teeth embedded into acrylic.

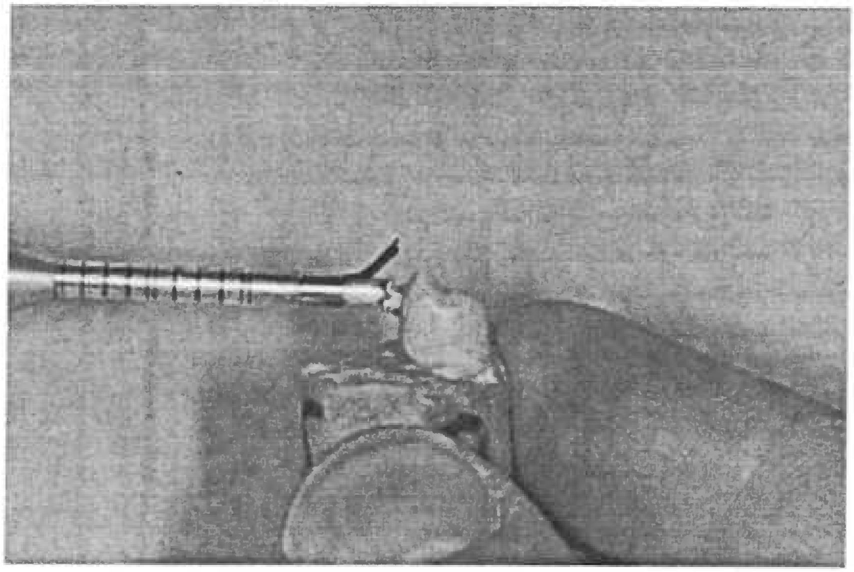

Figure 11.

Force gage used to seat brackets.

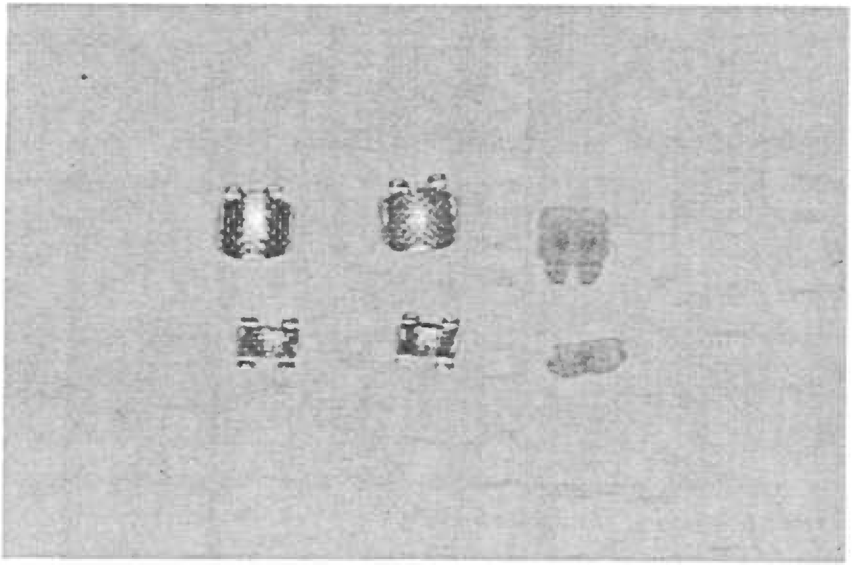

Figure 12.

Stainless steel, titanium, and ceramic brackets. Original pad size and reduced pad size (7.0mm^2).