THE DEVELOPMENT AND TESTING OF RETENTION PINS WHICH METALLURGICALLY BOND WITH DENTAL AMALGAM

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To my parents and my brother,
I dedicate this thesis as a
small repayment for a great debt.

A B S T R A C T

Up to the present time, stainless-steel has been used for retentive purposes in large amalgam restorations. Its inability to bond with amalgam contributes to the formation of high stress concentrations around the top of the pin. This problem is especially important in the case of very large amalgam restorations because of the possibility of producing fracture or microleakage at the amalgam-dentin interface. It has been demonstrated that a pin capable of forming a strong metallurgical bond with amalgam would overcome these two problems. Several investigators have shown that silver forms a bond with dental amalgam. The purpose of this investigation was to develop pins that would possess improved bonding properties in amalgam restorations.

Two types of smooth pins, considered to be capable of bonding with amalgam, were used in this study. They were, nickel-silver plated stainless-steel pins and sterling-silver pins. Plain stainless-steel smooth pins were included for comparison in this study because they are known to be incapable of bonding with amalgam. Amalgam specimens containing the different types of pins were subjected to axial load-deflection tests, torsion tests and push-through tests. A total of 152 specimens were made for this portion of the investigation. Fifteen specimens were made for microscopic and X-ray microprobe examinations

of the metallurgical bonds at the pin-amalgam interface. In the case of plated stainless-steel pins, the interfaces between nickel, silver and stainless-steel were similarly observed.

Results indicated that an effective bond could be obtained between sterling-silver pins or nickel-silver plated stainless-steel pins and amalgam. Mechanical properties of nickel-silver plated stainless-steel pins were superior to those of sterling-silver pins. The shear stress value of the pin-amalgam bond, in the case of the plated stainless-steel pins, was higher than that of amalgam alone. The technical difficulty in achieving a good bond between the freshly triturated amalgam and the pin was overcome by the use of a rubbing technique during condensation. It is shown that, in the case of large restorations, correct location of pins together with good pin-amalgam bonding improves the resistance to forces which have a horizontal component.

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INTRODUCTION

The development of a material that would directly bond to enamel and dentin and would resist the compressive, tensile or shear stresses produced by occlusal forces, has been a long sought-after goal in Restorative Dentistry. Although research in the field of adhesion has been extensive, no restorative material capable of adhering completely to enamel and dentin has yet been found. The dentist has to rely mainly on the tooth structure to mechanically support restorations.

In a badly mutilated tooth, there is insufficient tooth structure left to surround and support the restoration. This can be overcome by means of inserting pins in dentin in either of the following ways:

1. By casting gold inlays with pins which fit into drilled holes in the dentin, or
2. Threading or cementing metal pins into the dentin around which amalgam or resin is built to restore the lost tooth structure.

The question arises, however, as to whether the restorative material itself is properly supported by these pins, and whether the mechanical properties of the restorative material are affected by the pins.

Because dental amalgam has been widely used in dentistry for a long period of time, either alone or as a core for gold restorations, attention was concentrated on

this restorative material in the present study. A recent investigation [129] has shown that if no pin-amalgam bond is present and if there is a void at the interface, high stresses develop which increase the possibility of fracture of the restoration. Conversely, if there is a bond, stresses are minimized and retention factors are increased.

A number of pin materials have been tried in order to obtain a satisfactory metallurgical bond with amalgam. Under microscopic examination, pure silver appears to form the most satisfactory bond with amalgam [135]. Pull-out tests were performed using silver-plated pins and they showed an improvement in tensile properties as compared with non-bonded pins [144]. No research, however, has been published on the microscopic appearance and related mechanical properties of pin-amalgam bonds.

LITERATURE REVIEW

For ease of presentation and reading, the literature review has been divided into three sections. They deal with chemical composition of dental amalgam, its physical properties and pins as retentive devices.

CHEMICAL COMPOSITION OF DENTAL AMALGAM

Dental amalgam has been the most widely used restorative material in dentistry for over a hundred years. No other dental material has provided so much controversy and the search for its improvement in composition and technique has been constant.

Attempts to examine the constitution of alloys of silver and tin were made at the end of the nineteenth century by Gauthier [1], Charpy [2], Heycock and Neville [3], Herschkowitsch [4], Joyner [5], and others. Studies by Murphy [6, 7] provided a new insight into the chemistry of amalgam. He made an x-ray examination of the silver-mercury system. The lattice forms of the same system were also studied by Stenbeck [8].

One of the most extensive investigations that has been conducted on the chemistry of amalgam was published by Gayler [9, 10]. Her study still serves as

a source of reference, although some of the concepts have been re-evaluated by more modern and exact methods of research. She studied the gamma, gamma-1 and gamma-2 phases and made an attempt to develop a formula for the chemical reaction of amalgam. In addition, X-ray diffraction studies were performed and dimensional changes associated with different compositions were recorded. The relationship of tin and mercury percentages in amalgam were studied and related to the gamma-1 and gamma-2 phases.

Gayler's findings were corroborated by Troiano [11] and more recently by Taylor [12]. Fairhurst and Ryge [13], some ten years ago, demonstrated that Gayler's and Troiano's delta-2 phase (tin-mercury) was, in fact, the same as the gamma-2 phase.

Chemical reactions of amalgam-alloy and mercury

Basic formulas for the chemical setting reaction between amalgam alloy and mercury have been proposed by several authors in the last few years. They are based on the studies of Gayler and Troiano.

An X-ray analysis by Moffett, Ryge and Barkow [14] showed that the final composition of the amalgam crystals was mainly gamma-1 (Ag_2Hg_3) + gamma-2 (Sn_7Hg) + beta-1 (another Ag-Hg phase). The same authors found that the

reaction of pure Ag_3Sn (gamma phase) with mercury produced crystalline gamma-1 and gamma-2 phases. The rate of formation of these phases was found to depend on the mercury-alloy ratio, the particle size and the trituration time. The gamma phase would slowly disappear while the gamma-1 and gamma-2 phases form independently of each other.

A transformation of gamma-1 into beta-1 was studied and confirmed by Johnson [15, 16, 17] whose formula of the setting reaction of amalgam is basically the same as the one presented by Moffett et al [14]. The transition of gamma-1 into beta-1, although very slow, accounts for internal stresses and porosities present in the set amalgam. Otani [18, 19, 20, 21] presents a formula for the hardened amalgam in which unreacted Ag_3Sn is also present:

initial reaction: $\gamma + Hg \longrightarrow \gamma_1 + \gamma_2 + \gamma$ unreacted

final reaction: $\gamma_1 + \gamma_2 + \gamma \longrightarrow \gamma_1 + \gamma_2 + \beta_1 + \gamma$ unreacted

He suggested that the beta-1 phase, nucleated between gamma-1 and gamma-2 crystals, grows and consumes most of the gamma-1, releasing mercury. A proportionality between the mercury content and the gamma-1, gamma-2 and gamma phases was shown to exist. The volumetric ratio of gamma-1 to gamma-2 was also found to be constant, regardless of the mercury content. Some of the silver-mercury phases

described by Gayler were demonstrated by Ryge [22] to be non-existent.

Formulas for set amalgam which did not include a beta-1 phase were proposed by Schnell and Phillips [23], Bachmann [24], Wing [25, 26], Ryge, Moffett and Barkow [27], Mateer and Reitz [28], Asgar, Allan and Peyton [29] and others.

Matrix of set amalgam

The matrix of set amalgam was demonstrated by several authors to be formed by gamma-1 and gamma-2 phases. Work by Wing [30] has shown that the crystals of these phases are not closely intermingled. The gamma-1 phase was found by Schoenfeld and Greener [31] and by Sutfin and Ogilvie [32] to be predominant in the matrix of a solid amalgam and to nucleate homogeneously. The gamma-2 phase would nucleate heterogeneously, using the Ag_3Sn particles as the foreign substance necessary for this kind of nucleation to take place. However, other authors such as Schnuck [33] for example, have considered the matrix of set amalgam as being composed of gamma-2 in which crystals of gamma-1 and gamma are imbedded.

Fairhurst and Cohen [34] found the major bulk of hardened amalgam, when containing 50% mercury, to be constituted by gamma-1 and gamma-2 phases. Crystal growth of these phases was larger at mouth temperature, as shown

by Ryge [35]. Quantitative metallographic procedures made by Mateer and Reitz [36] confirmed that the phase proportion varies over short distances in a condensed amalgam.

Gamma phase

The composition of the alloy itself, as cast or when cut, has been reported by several authors, notably Acuña [37], Asgar, Allan and Peyton [28], Rasberry, Caul and Yezer [38].

The gamma phase, Ag_3Sn, was established by Schoenfeld and Greener [31] to be a noncongruent melting phase. The unreacted gamma particle was shown by Sutfin and Ogilvie [32] and by Smith, Ferguson and Schoonover [39] to be stronger than the other phases of the system. However, when mixed with mercury, the gamma particle, according to Hegdahl and Silness [40], not only expanded but also underwent a reduction in hardness.

Gamma-1 phase

The solubility of silver in mercury was found by Hudson [41] to be a stable phase with well-defined space lattices. The influence of the gamma-1 phase, Ag_2Hg_3, in the hardening of dental amalgam was analyzed by Frankel and Fankuchen [42]. They arrived at the conclusion that constituents other than silver do not contribute to the

hardening, but rather modify the properties of the set mass. A probable chemical composition of $Ag_{11}Hg_{15}$ for gamma-1 was given by Andersen and Jensen [43], although the majority of authors agree with the composition given earlier. Johnson [17] reported the gamma-1 phase to contain about 5 atoms of tin per unit cell.

Gamma-2 phase

The majority of authors agree on the formula $HgSn_{7-8}$ for the gamma-2 phase. However, the presence of copper atoms occupying some of the places of the gamma-2 unit cells in amalgams with up to 6% content copper, was recorded by Allan, Asgar and Peyton [28, 44].

Destructive corrosion of silver-tin amalgam has been markedly decreased by eliminating the gamma-2 phase. Nagai, Ohashi, Habu and Nemoto [45], Stoner, Lawless and Wawner [46], Johnson [17] and others, have reported the disappearance of this phase in alloys containing from 0.0 to 18.5 atomic per cent tin. Suppression of the gamma-2 phase in dental amalgam was induced by Grenoble and Katz [47] utilizing high pressures. High concentrations of copper resulted in the absence of gamma-2 phase in set amalgam, as reported by Sarkar and Greener [48].

Nagai et al [45] found that the formation of gamma-2 phase could be accelerated by prolonging the trituration

time or by increasing the tin content. This effect tends to be reversed, however, if the mixing is extended for too long a time or if the tin content is excessive. The same authors [49, 50] reported that with longer trituration time, within a given range, gamma-2 crystals became smaller, and gamma-1 and gamma-2 phases appeared almost simultaneously.

Copper phases

Copper-tin phases in dental amalgam have also been studied although they, together with the beta-1 phase described earlier, occupy only a small percentage of the total volume of the set material, as demonstrated by Suprinick [51]. According to Jensen [52], in the unreacted alloy particles, most of the copper is present as Cu_3Sn, Cu_6Sn_5 and small amounts dissolved in the Ag_3Sn particles. After reaction of the alloy with mercury, more Cu_6Sn_5 phase is formed at the expense of both the Cu_3Sn phase and the copper dissolved in the Ag_3Sn.

Mateer and Reitz [28] found copper uniformly distributed in unreacted gamma particles and in the reaction product matrix. Quantitative electron microprobe analysis made by Johnson, Asgar and Peyton [53], proved the existence of an etch resistant phase, Cu_6Sn_5, in both the silver alloy ingot and the set amalgam. Jensen and Andersen [54] found the compound Cu_6Sn_5 to be a stable phase under conditions

normally encountered in dentistry, when alloy-to-mercury ratios were ranging from 1:100 to 120:100 - this would include the commonly used ratio of 1:1. Other authors such as Sarkar and Greener [48] and Crowell [55] also observed copper phases in hardened amalgam.

Mercury content

The mercury content of set dental amalgam has also been analyzed. Residual or uncombined mercury was studied by Mitchell, Schoonover, Dickson and Vacher [56]. They demonstrated, by X-ray diffraction, that this kind of mercury is present in the amalgam after its initial solidification. It possibly combines with the unreacted gamma phase and disappears after about 24 hours. Mitchell, Dickson and Schoonover [57], in another investigation, showed that although uncombined mercury diffuses through hardened amalgam, it also can be released if there is an increase in temperature. The relationship between the mercury and alloy is directly proportional to the silver content, as described by Rantanen [58]. Studies by Jorgensen and Kanai [59], Fusayama and Hayashi [60], Radics, Schwander and Gasser [61] showed that the less residual mercury present, the fewer gamma-1 and gamma-2 phases formed and the more Ag_3Sn remains unreacted.

Ryge and Wing [62] found that silver rich alloys, when combined with mercury, form a surface reaction and

have a limited diffusion into the bulk of the amalgam. On the contrary, tin rich alloys give a reaction throughout the matrix. Also, if the Ag_3Sn content is low, there doesn't seem to be any unreacted alloy left in the set amalgam.

PHYSICAL PROPERTIES OF DENTAL AMALGAM

Studies on the physical properties of dental amalgam were first performed by Black [63], Gray [64], Souder and Peters [65].

Ledley [66] examined the functional forces applied to a restoration during mastication. These forces develop compressive, tensile and shear stresses. The importance of the direction of the forces was demonstrated by Tanner [67].

According to Mahler and Mitchem [68] the importance of measuring the strength of a restorative material is in predicting the structural integrity of the restoration under the influence of forces applied in the mouth.

Compressive strength

The compressive strength of set amalgam was shown by Staheli and Von Fraunhofer [69] to be related to the bond strength between the core (gamma phase) and the matrix (gamma-1 and gamma-2 phases). This confirmed earlier studies by Nakai, Ishizaki and Nihei [70, 71] who added the

fact that the gamma-2 phase is the weakest one and decreases the compressive strength. The compressive strength is also diminished by the existence of imperfectly condensed areas and surface defects. Microscopical internal voids do not significantly influence this kind of strength.

The compressive strength of amalgam is lower at 37°C than at room temperature, as proved by Schoenmakers [72]. Peyton and Liatukas [73] showed that high condensation forces result in a high compressive strength and a low mercury content. Several compressive strength values were found by utilizing different condensation forces and a 2 millimeter diameter condenser. For a three pound force, using a conventional alloy, these values were about 8000 PSI after one hour and about 35,000 PSI after twenty-four hours. The compressive strength values were found by Mahler and Mitchem [68] to be directly proportional to the rate of loading. Less than 53% mercury (Swartz and Phillips [74]) and variations in mercury-alloy ratios (Mahler and Mitchem [75]), did not affect the compressive strength of dental amalgam.

Tensile strength

Wing [25], Turchyn and Youdelis [76], and Mahler [77] stated that although compressive strength is usually the one measured, most forces of mastication produce tensile stresses as well.

Nagai, Ohashi, Habu et al [78] found that the compressive strength of amalgam is about 7.5 times greater than the tensile strength. The same authors, in another study [79], found that the more amalgam increments used, the higher the tensile strength. This value, however, decreases proportionally to the time during which the mix is left exposed to air before condensation. Tensile strength was found to have a final value of about 6500 PSI for conventional amalgam, and was observed to be related to brittleness but not to flow, by Mathewson [80]. Young and Johnson [81] suggested that the tensile strength of amalgam might be improved by reducing the amount of the tin-mercury phase present.

Transverse or shear strength

Mahler and Mitchem [68, 75] proved that the rate of loading does not influence the tensile or the transverse strengths of amalgam. They estimated the transverse strength to be 17,000 PSI for conventional alloy, and pointed out that this value is about twice the tensile strength and one third of the compressive strength. The early transverse strength of an amalgam restoration is governed by the packing force, rate and time, as stated by Basker and Wilson [82]. Bjorndal [83] showed that amalgam has its greatest strength in compression, next in shearing

and least in tension.

Crushing and fatigue strengths

Shelmerdine and Smith [84] found that high silver alloys, containing from 65% to 75% silver, had greater crushing strength values when compared to low silver alloys (from 45% to 50% silver content). Jorgensen, Esbensen and Møller [85], and Staheli and Von Fraunhofer [69], showed that a "wet technique" would provide a considerably higher crushing strength than a conventional or Eames' technique. Holst [86] proved that up to 30 seconds of trituration will provide a greater crushing strength. If an increased condensation pressure is added, less residual mercury content and a better adaptability to the cavity walls is obtained. Fatigue strength was studied by Wilkinson and Haack [87] who found it to be 22% of the maximum crushing strength.

Hardness

Shelmerdine and Smith [84] gave values for Brinell hardness of 30 kg/mm^2 for 50% silver content amalgam, and of 60 kg/mm^2 for 70% silver content amalgam. Utilizing microindentation hardness measurements and microstructural observations, Nakai, Ishizaki and Nihei [88] showed that amalgam restorations lack structural uniformity. Low hardness values would indicate a low gamma phase content.

The same authors, and also Suprinick [51], and Staheli and Von Fraunhofer [69] demonstrated that the center of the specimens was harder than the periphery. An optimal structure for dental amalgam was defined by Jørgensen and Saito [89] as having the lowest possible porosity and the highest possible gamma phase content.

Brittleness was related to tensile strength by Mathewson [80]. The ratio of tensile to compressive strength was found to be that characteristic of a brittle material by Sutfin and Ogilvie [32]. The gamma-1 and gamma-2 phases were proven to be non-ductile by Suprinick [51].

Modulus of elasticity

The Young's moduli of amalgam was found to be 9×10^6 PSI by Dickson and Oglesby [90]. The shear, bulk and Young's modulus were shown by Grenoble and Katz [91, 92, 93] to be considerably lower for the gamma-2 phase, because of weaker interatomic bonds. These properties were also found to be dependent on pressure. The authors concluded that Young's modulus is affected by large irregular voids contained in dental amalgam. Muench [94] demonstrated that the proportional limit and the modulus of elasticity of amalgam increase as a function of the age of the specimen. These properties decrease at mouth temperature as compared to room temperature.

Porosity

Nakai, Ishizaki and Nihei [70], and Lautenschlager and Harcourt [95] showed that even when the best techniques are used, internal microporosities are present in dental amalgam. Nakai et al [71] also stated that porosity seems to result from both an insufficient condensation and a contraction of mercury rich phases during hardening. High condensation pressures significantly diminished porosity, according to Takatsu, Daito and Fusayama [96]. Porosity was measured by Lautenschlager [97] by means of a pichnometric technique. Jørgensen et al [83, 87] showed that the presence of one percent porosity reduced the compressive strength ten times.

Flow

Fuse [98] demonstrated that temperature has a considerable effect on the flow. A 20°C rise in temperature results in a flow 2.5 times larger when a fine-cut amalgam is used. A smaller grain size also results in a larger flow. Flow values of 4% to 5% were found for conventional amalgam using the Eames' technique [99].

Influence of condensation on physical properties

The method and force of condensation proved to be important for the physical properties of amalgam. The

importance of an early high load condensation was stressed in the study made by Ryge, Telford and Fairhurst [100], because it produces higher strength as well as an increase of the gamma phase and a decrease of the gamma-1 and gamma-2 phase constituents.

Although hand condensation is still the most popular method used, the effect of mechanical condensation has been studied. Nakai, Ishizaki and Nihei [88] found that a mechanical vibrating condenser gives a more uniform amalgam microstructure. Ryge, Dickson, Smith and Schoonover [101] showed higher compressive strength values and less expansion when amalgam was condensed mechanically with a vibrating plugger, instead of using hand pressure. However, higher strength values of amalgam were found in hand condensed specimens by Mizera and Skinner [102], Bjorndal [83] and Mahler and Mitchem [103], although the residual mercury content was more than that of mechanically condensed samples. Ryge [104] stated that only the amalgam close to the condenser point is properly condensed.

Influence of mercury-alloy ratio on physical properties

Sweeney and Burns [105] showed that great accuracy in the mercury-alloy ratio was not necessary, provided there is an amount of mercury at least equal to the one recommended by the manufacturer. However, the advantages of a 1:1 ratio

were stressed by Eames [99], Skinner and Mizera [106], and by Hollenback and Villanyi [107], especially when related to low percentages for initial and residual mercury content. Low residual mercury content of amalgam is a goal that can be realized regardless of the original proportioning, provided there is thorough condensation, as stated by Ryge [108] and by Swartz and Phillips [74].

Nadal, Phillips and Swartz [109] ascertained that a high mercury content could account for marginal failure, surface roughness and general degradation of amalgam. Residual mercury content of amalgam restorations vary when prepared and condensed by different operators, under the same conditions, as demonstrated in a study made by Ryge et al [101].

Influence of the alloy on physical properties

Aime and Uribe [110] showed the hardness of cast conventional alloy to be similar to that of dental enamel. Crowell and Phillips [111] stated that the properties of alloy chips of a given thickness varied according to the particular region of the billet from which they had been cut. Hargreaves and Davies [112] demonstrated that the properties of amalgam, prepared from alloys commercially supplied in the form of preweighed tablets, were in no way inferior to the conventionally cut alloy.

PINS AS RETENTIVE DEVICES FOR DENTAL AMALGAM

Pins have been widely used to form amalgam reconstructions on severely broken down teeth. Steel staples, such as the ones used by Hyman [113], and other similar devices, were cut to size with a carborundum disc and placed into a predrilled hole in the dentin. This method became popular 15 years ago among members of the dental profession, and has been further studied and very much improved. Several authors, including Johns [114], Leon [115], Winstanley [116], Watson and Gilmore [117], have described the different types of retention pins that are used in practice.

Studies made by Courtade [118], Zarb [119], Roberts [120], Quattrone [121], Markley [122], Dua, Gill and Joshi [123], Johns [114], Winstanley [116], Watson and Gilmore [117], and others, have described techniques to use pins as retentive devices for dental amalgam restorations, and for building up amalgam foundations for gold crowns or fixed bridges.

Pin retention in dentin

Both aspects of pin retention - in dentin and in amalgam - have been examined. Pins in dentin were studied by Dilts, Welk and Stovall [124]. Retention was found to be greatest with self-threading pins, followed by friction-lock pins and then by cemented pins, and increased as the depths of the holes in dentin increased from one to four millimetres.

Watson and Gilmore [117] concluded that pin depths beyond two millimetres in dentin are not advantageous. Enoch [125] showed that the resistance to displacement afforded by several pins seems to be more a function of pin depth into tooth structure than of length of pin into amalgam.

Stresses produced by pins

Installation stresses were found by Standlee, Collard and Caputo [126, 127, 128] to be absent when cemented pins were utilized. It was proven that there is a lack of standardization of manufactured-pin diameters. However, a variance of 0.001 inch in pin diameter can create considerable differences on installation stresses and retentive capacity. Stress and failure phenomena of pins in dentin were related to manufacturing quality, control, and clinical factors such as channel drilling, pin type, and insertion parameters.

The axial stiffness of pins in dentin was found by Dhuru [129] to be important because it partially affects the stress concentration in the amalgam restoration. The stiffness of the pin in dentin was higher when tightly fitted and therefore produced more stresses. These were diminished when a good bond between pin and amalgam was achieved.

Strength of pin-retained amalgam

The effect of pins on the properties of dental

amalgam has been examined by a great number of investigators. It was believed by several, including Bull [130], Markley [131], Courtade [118] and Sheeny [132], that they reinforced amalgam.

Later studies proved this not to be the case. Some investigators, Collard, Caputo and Standlee [127], Going and Nostrand [133], White [134], Moffa, Going and Gettleman [135], found that the compressive strength of amalgam, containing stainless steel pins as retentive devices, was neither increased nor decreased. Osborne [136] proved that if the length of the pin was the same as that of the test specimen, the compressive strength increased. However, when the pin length was below the amalgam surface, there was no significant difference between these specimens and specimens without pins.

Other researchers observed decreased strength values of amalgam restorations containing pins. Crushing strength was lowered by almost 45% by the presence of plain stainless steel pins in amalgam, as proven by Bapna and Lugassy [137]. Lugassy, Lautenschlager and Harcourt [138] showed that the breaking load of specimens without pins was approximately twice that of those containing pins. The crack originated at the pin, whereas in samples without pins, the cracks began at the load contact area. Moffa, Going and Gettleman [135] demonstrated that the cracks did not initiate from the pin

when pure silver pins were used. The average breaking load for a pin-retained amalgam was found by Smith and Hoover [139] to be diminished by 14.1% when stainless steel pins were used. Transverse strength, under the same conditions, was examined by Welk and Dilts [140], and its value was significantly decreased by the presence of pins.

Cecconi [141] determined that a vertical pin placed directly beneath the loading point weakens the amalgam. Tensile strength was found to be reduced. As stated by Cecconi and Asgar [142] even one vertical pin in the restoration is a potential weakening agent, because one cannot predict with certainty where the load point will be, under clinical conditions.

Cecconi [141], Going [143], Duperon [144], Duperon and Kasloff [145] and Narikawa [146] demonstrated that vertically or diagonally positioned pins lowered the tensile strength of amalgam. If the pins were placed parallel to the direction of the tensile force, the tensile stength of amalgam appeared to increase.

The weakening effect on the compressive strength of dental amalgam because of pins was demonstrated by Watson and Gilmore [117], Cecconi and Asgar [142], Wing [147], Going [148], Duperon and Kasloff [149] and Duperon [144].

Studies on amalgam retained and "reinforced" by metallic laminates have also been done. Bull [130] found that transverse strength of amalgam was greatly increased by using silver plates imbedded in it. Much more recently, Peterson and Freedman [150] concluded that the flexural strength of amalgam specimens was significantly augmented by the application of ductile metal laminates in regions subjected to tensile forces, and perpendicular to the direction of the applied force.

The retentive properties of the different kinds of manufactured-pins have also been investigated. Dhuru [129] and Moffa, Razzano and Doyle [151], among others, showed that the self-threading pins were the most retentive in dentin. Their effectiveness in retaining dental amalgam was established by Moffa et al [151] and Barsh [152]. These authors observed that the optimum embedment depth in silver amalgam was two millimetres for both cemented and self-threading pins. Pins that were too long or too thick tended to fracture the restoration much more rapidly.

Although they do not strengthen the amalgam, stainless steel pins are effective in resisting lateral displacement. This was shown by Smith and Hoover [139] and by Enoch [125]. The latter gave evidence of the greater resistance of the amalgam mass to displacement when increasing the number of pins in a preparation with no lateral walls.

Pins bonded to amalgam

The material from which the pin is constructed has proven to be very important in diminishing the deleterious effects on the strength of amalgam. In 1936, Bull [130] reported the use of 90% silver plates placed in amalgam as a reinforcement. The increase in the strength of amalgam, especially crushing strength, was notable. Although this technique proved to be too difficult to be applied clinically, important conclusions were derived from the experiment. The author stated that the plates of silver had become "chemically welded into the filling" and that the nature and strength of the material used for reinforcing, as well as the strength of the bond formed are vital factors.

Stresses forming in amalgam restorations because of the pins, tended to be minimized if a metallurgical bond between the pin and the amalgam was present, as concluded by Dhuru [129]. This effect was more pronounced than that of axial stiffness of the pin. These findings confirm the early study of Bull [130].

The strength of dental amalgam when using pure silver or silver plated pins, which are expected to form a metallurgical bond with amalgam, was also found to be decreased. However, this effect was much less pronounced

than that of amalgam containing non-bonded pins. Several investigators have shown this to be true, among them Dhuru [129], Bull [130], Moffa, Going and Gettleman [135], Cecconi [141], Cecconi and Asgar [142], Duperon [144], Duperon and Kasloff [145, 149] and Peterson and Freedman [150].

Peterson and Freedman [150], who worked with different kinds of laminates, concluded that gold forms a weak bond with amalgam. Ghassan and Taylor [153] determined that gold would firmly attach to amalgam provided an excess of mercury is present. This was confirmed by Bapna and Lugassy [137], who used gold-plated pins wetted with mercury and found that a good pin to amalgam bond was formed.

The chemical compatibility between several metals and amalgam was studied by Amarante, Galan and Chiodi [154] who concluded that silver and the gamma phase of amalgam, Ag_3Sn, were chemically compatible. A possible chemical union between silver and stainless steel pins has been examined by many authors. Henns [155] saw a complete compatibility between silver solder and stainless steel orthodontic wires. Metallographic evidence of grain penetration of the one into the other was found.

Electroplating has been used to silver-coat different kinds of pins which would not otherwise form a chemical bond with amalgam. Duperon [144] and Duperon and Kasloff [145, 149], used platinum-gold-palladium, silver-plated pins, with satisfactory results. These authors,

however, could not obtain a good silver to stainless steel bond. Freedman [156] obtained optimum results in coating stainless steel by electroplating nickel-silver on a stainless steel laminate.

STATEMENT OF THE PROBLEM

It has been demonstrated that resistance to displacement of amalgam from pins used for retention, is increased considerably when a metallurgical bond capable of withstanding masticatory loads exists. Such a condition has been shown to reduce the development of stresses compared to restorations where unbonded pins are used.

Silver is capable of forming a good metallurgical bond with amalgam. It was, therefore, considered desirable to investigate the possibility of using silver-plated stainless-steel or sterling-silver pins for providing optimum mechanical and physical properties to amalgam restorations using pins for retention purposes.

MATERIALS AND METHODS

PREPARATION OF SPECIMENS

PINS

Nickel-silver plated stainless-steel pins

A thin layer of nickel was plated on 18-8 stainless steel wire commonly used for orthodontic procedures*. A layer of silver was then plated onto the nickel. The diameter of wire chosen was 0.022 inch (0. 570 mm), since it was thought to be representative of the most commonly used diameter of stainless-steel pins in the mouth. Stainless-steel pins used in teeth generally have diameters ranging from 0.021 inch (0.533 mm) to 0.027 inch (0. 690 mm). This assumption was based on personal observations and not on any statistical study.

The stainless-steel to nickel to silver bond was obtained using the following technique of plating the stainless-steel wire [150, 156, 171]. Methods of improving electrolytic deposition were found in a publication by Sand [157].

Oil, greases, organic contamination, etc., were removed with a suitable solvent. In this case clean acetone, i.e. of a non-redistilled grade, was used. The

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* Tru-chrome (pink) - Rocky Mountain, Willowdale, Ont., Canada

18-8 stainless-steel wire was rinsed in the solvent at room temperature for 40 seconds.

The cleaning of the wire was continued with a mild alkaline solution in order to remove non-organic surface contaminants. A commercial preparation, "Pennsalt 45" *, was used for this purpose (8.5 grams per 200 cc distilled water). The chemical composition of "Pennsalt 45" is not given by the manufacturer, but it is known to contain phosphates, silicates and carbonates [171]. The 18-8 stainless-steel wire was left in a boiling solution of "Pennsalt 45" for 3 minutes. It was then immediately rinsed in running water at room temperature for 1 minute. The wire was not allowed to dry before the water rinse.

To finish removing organic impurities and any oxide present on the surface of the wire, a hydrochloric acid solution was used (74.24 cc of 37.4% HCl solution ** and 125.76 cc distilled water). The wire was pickled at room temperature for 90 seconds. Following this procedure, it was rinsed in running water at room temperature for 1 minute.

The wire was then transferred immediately to an acid nickel-chloride solution at room temperature (47.55 grams nickel chloride **, 59.5 cc of 37.4% HCl solution **

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* Pennsalt Chemicals Incorporated, Oakville, Ont., Canada

** J.T. Baker Chemical Co., Phillipsburg, N.J., U.S.A.

and 200 cc distilled water). A pure nickel anode had been previously immersed in the solution. After 15 minutes without current, a current flow of 11.5 milliamperes at a potential of 0.5 volts was then passed throught it for 12 minutes. In this way, once the 18-8 stainless-steel wire was activated, it was immediately covered with a very thin layer of nickel (flash) without having any contact with air, thus avoiding any formation of the passive chromium oxide layer on the surface. This step was followed by a 3 minute running water rinse at room temperature.

The wire was then immersed in a potassium cyanide solution at room temperature (3.17 grams of potassium cyanide * and 200 cc of distilled water). It remained in this solution for 45 seconds. It was immediately transferred to the next bath without any rinse.

The electrolytic bath used in this step consisted of a low concentration silver plating solution (1 part commercial silver plating solution ** and 8 parts distilled water). Although the chemical composition of the commercial solution is not given by the manufacturer, its most important constituent is known to be silver cyanide. Just before the stainless-steel wire was immersed in this bath,

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* J.T. Baker Chemical Co., Phillipsburg, N.J., U.S.A.

** Concentrated silver plating solution - Canadian Hanson and Van Winkle Co. Ltd., Montreal, P.Q., Canada

a potential of 1.5 volts was applied between the wire and the anode. As soon as the wire was immersed in the plating solution, a current flow of 4 milliamperes was established. This was done in order to avoid any deposition of the silver onto the wire as a result solely of a chemical reaction. This would result in a weak chemical bond, instead of the much stronger and consistent bond obtained by electrochemical deposition. The anode used was an 18-8 stainless-steel strip. The wire was plated in this solution for 90 seconds. A flash layer of silver was thus obtained. No water rinsing followed this step.

Immediately following the deposition of the flash layer of silver, the wire was immersed in a highly concentrated silver plating solution *. The same technique as described for the low concentration silver electrolyte was used. The current flow was 34 milliamperes and the potential was 0.65 volts. The anode was pure silver. The wire was plated for 10 minutes.

Once silver-plated, the wires were thoroughly rinsed in cold running water for 1 minute and then in hot running water for 3 minutes. This was done to remove the solution from the surface of the wire.

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* Concentrated silver plating solution - Canadian Hanson and Van Winkle Co. Ltd., Montreal, P.Q., Canada

FIGURE 1 - BOILING ALKALINE SOLUTION

a- Wire

FIGURE 2 - CONSTANT CURRENT ELECTROPLATING APPARATUS ASSEMBLY

a- Acid nickel chloride solution

b- Low concentration silver plating solution (flashing solution)

c- Concentrated silver plating solution

d- Cardboard separating acid and cyanide solutions

e- Milliammeter, individual circuit controls and station selector

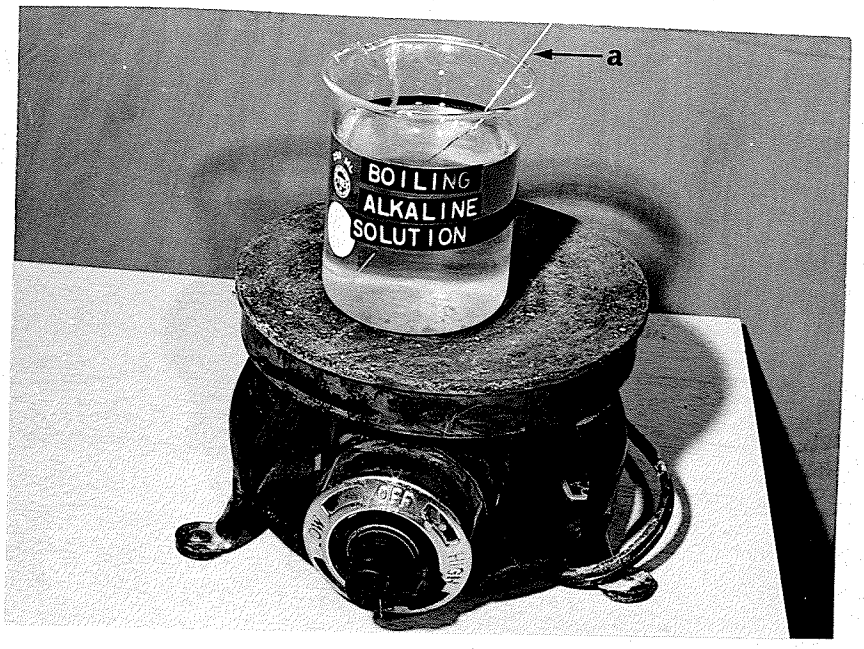

FIGURE 1

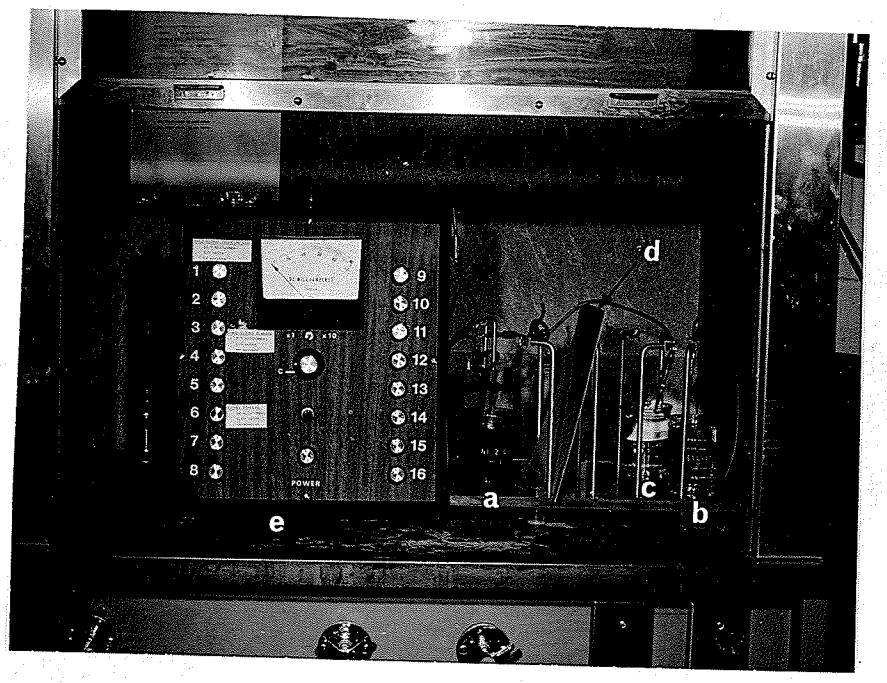

FIGURE 2

In every step care was taken to prevent any acid coming into contact with cyanide solutions in order to avoid the formation of poisonous gas. The reason for using a low concentration silver plating solution before the regular silver plating solution is to assure a good electrochemical bonding of the silver to the nickel layer. If the first layer of silver deposited is too thick, the quality of the bond is decreased [171]. The apparatus used for the electroplating of the stainless-steel wire is shown in Figures 1 and 2.

Once the 18-8 stainless-steel wire was plated with nickel and silver, it was dried and then hand polished. If a wire that has been silver plated is examined under the microscope at a low magnification (4 X), it presents a rough and irregular surface. If good condensation and metallurgical bonding of the amalgam around the wire are to be achieved, the surface should be much smoother than that formed by electroplating. Because the thickness of the silver deposited on the wire is approximately 0.015 inch (0.380 mm) and because pure silver is a soft material, the wires were hand polished in order to remove as little silver as possible. A 14 micron cloth, then a 1 micron cloth without nap and finally a 1/2 micron cloth with nap were used in the polishing process. Though appearing to be completely smooth and polished when viewed by the naked eye, the surface of the

wire presented some microscratches when viewed under a 4 X magnification.

Nickel plated stainless-steel wires

To facilitate a microscopical study of the nickel to stainless-steel bond, some of the stainless-steel wires were plated with nickel only. This was accomplished by carrying out the electroplating procedure previously described up to and including the nickel plating step. During the plating of the nickel onto the stainless-steel wire, however, the current was allowed to flow for 25 minutes rather than 12 minutes so that a thicker layer of nickel was deposited. Following this procedure, the nickel plated wire was thoroughly rinsed under cold and then hot running water. Nickel plated wires were not polished because they were not being used for placement in amalgam specimens.

Sterling-silver pins

Sterling-silver pins with a round cross-section were used in this study. Their diameter was approximately 0.021 inch (0.533 mm). They were constructed using the procedure described below.

18-8 stainless-steel orthodontic wires * with

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* Tru-chrome (pink) - Rocky Mountain, Willowdale, Ont., Canada

the dimensions required were mounted vertically on a sprue base with molten pink base plate wax. Care was taken to leave about 0.4 inch (1.0 mm) of each wire inside the wax, in order to facilitate their removal from the investment. A wetting solution was painted over the wires, the wax and the upper part of the sprue base. A casting ring without asbestos liner was secured to the base. It was found that the diameter of the cast wires varied to a greater degree if an asbestos liner was used. "Luster Cast" * thermal investment was used. The ratio was 50 grams of powder to 15 cc of distilled water. Mixing and investing were completed under vacuum ** and the investment was allowed to set for one hour. The sprue base was removed, the wires were withdrawn from the investment and the ring was placed in an oven at room temperature. The temperature was raised to 1200°F (648.8°C) in 40 minutes and then held constant for about 15 minutes.

Sterling-silver *** with an approximate composition of 92.5% silver and 7.5% copper was used as the casting metal. The sterling-silver was placed in the casting machine **** at

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* Kerr Mfg. Co., Detroit, Mich., U.S.A.

** Vac-U-Vestor - Whip-Mix Co. Inc., Louisville, Ky., U.S.A.

*** Williams Co., Ft. Erie, Ont., Canada

**** Thermotrol Junior electric casting machine - J.F. Jelenko Co. Inc., New York, N.Y., U.S.A.

a temperature of 1600°F (871°C). The pins were centrifugally cast when the alloy had reached 1740°F (948.8°C) and quenched when it had reached about 1400°F (760°C). At this temperature a solid solution of copper in silver is formed [175]. This was important because the sterling-silver pins required heat treatment to improve their physical properties, especially strength and stiffness. The pins were heat treated by placing them in an oven at 575°F (301.6°C) for one hour. As cast, quenched sterling-silver material has a tensile strength of 37,400 lb/in^2, a yield strength of 19,700 lb/in^2 and a 42% elongation. After heat treatment the tensile strength becomes 43,400 lb/in^2, the yield strength 30,000 lb/in^2 and the percentage elongation 25% [175].

The pins were separated from the sprue button and polished after the heat treatment had been completed. Any nodules present were carefully hand removed with a fine grit sand paper disc. The pins were then hand polished following the same technique used for polishing the stainless-steel plated wires.

PIN-RETAINED AMALGAM SPECIMENS

Specimens consisting of pins embedded in amalgam

cylinders were prepared. The volume of amalgam used in the specimen was similar to that required to restore a cusp. Specimens were used both for microscopic studies and mechanical tests. In both cases three types of pins were utilized. They were, nickel-silver plated stainless-steel, sterling-silver and stainless-steel pins (Figure 3). Except for the length of the pins, the technique used to prepare both kinds of specimens was exactly the same.

Description of the mould

The mould used to prepare the specimens was the same one described by Duperon [144] and similar to the mould for dental amalgam specimens described by the American Dental Association specification No. 1. It consisted of a steel mould, a base and two plungers, as shown in Figure 4.

The mould was cylindrical in shape and measured 0.75 inch (19.0 mm) in height. Both the top and bottom surfaces were flat and perpendicular to the long axis. A hole, parallel to the long axis of the mould and having a diameter of 0.20 inch (5.0 mm) was drilled through the center of this cylinder.

The base for the mould was also cylindrical, with a rim on the top surface to secure the mould in place. The diameter of the base was 1.20 inch (31.0 mm). The

FIGURE 3 - TYPES OF PINS USED IN THE INVESTIGATION

a- Smooth stainless steel pin

b- Smooth nickel-silver plated stainless steel pin

c- Smooth sterling silver pin

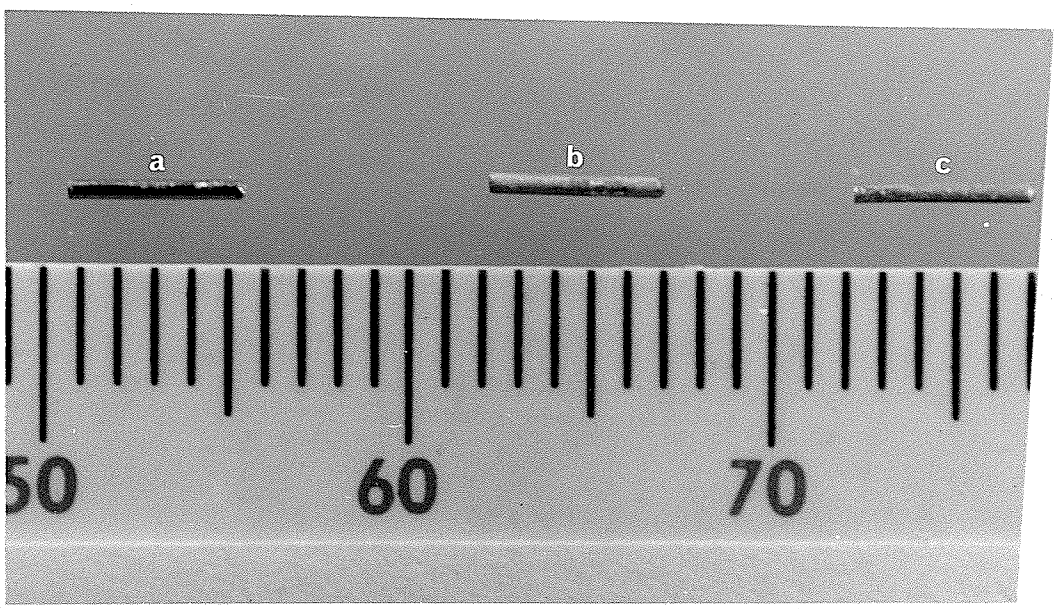

FIGURE 3

FIGURE 4 - MOULD FOR PREPARATION OF AMALGAM SPECIMENS

a- Stainless steel mould

b- Plungers

c- Base for the mould

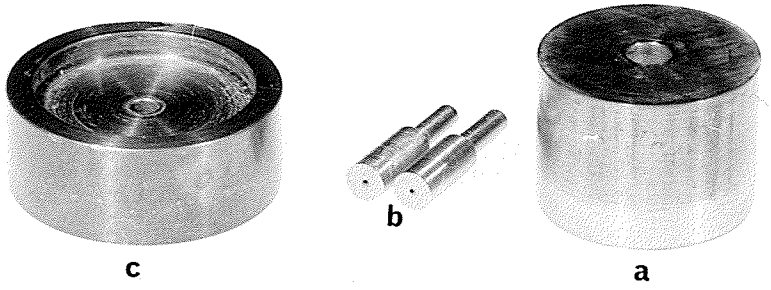

FIGURE 4

upper and lower surfaces were both flat and perpendicular to the long axis. The rim had a height of 0.12 inch (3.0 mm). The diameter of the recess left inside the rim was the same as the diameter of the mould. A hole was drilled through the base parallel to its long axis and with a diameter of 0.12 inch (3.0 mm).

The two plungers were also cylindrical. The diameter of one end of the plunger was such that a snug, but free fit was obtained between it and the mould in order to permit its easy removal and reinsertion. The height of this end of the plunger was made so that an amalgam sample measuring 0.31 inch (8.0 mm) in height and 0.20 inch (5.0 mm) in diameter would be obtained. For especially designed push-through test specimens, a steel piece 0.12 inch (3.0 mm) long was placed inside the hole of the base. In this way, the height of the amalgam specimen could be reduced to 0.2 inch (5.0 mm).

The other end of the plunger was made to fit the hole in the base. The end that could be adapted to the base had two functions: to hold the plunger vertically in place, and to facilitate the removal of the amalgam specimen by pushing it through the top of the mould. Both end surfaces of the plungers were flat. Each plunger had an axial hole placed in the flat surface of the end facing into the mould. For the first plunger, this hole had a depth of 0.12 inch (3.0 mm), and a diameter of 0.022 inch (0.570 mm), to hold

the stainless-steel pins or the sterling-silver pins in place. A second plunger with a hole also having a depth of 0.12 inch (3.0 mm) but a diameter of 0.024 inch (0.61 mm) was built to hold the nickel-silver plated stainless-steel pins.

Finishing of pins for their insertion in amalgam

The wires, utilized for microscopic studies, were cut to arbitrary lengths. They were inserted into the appropriate plunger for constructing the specimens. Once the amalgam specimen was completed, the protruding portion of wire was cut back flush with the amalgam surface.

The wires used for the axial load-deflection tests were flattened on one end by means of holding them against a carborundum disc revolving at a low speed. This was done to produce a surface as perpendicular as possible to the long axis of the pin. The other end of the pin was polished by hand with a carborundum disc to obtain a slightly curved surface (Figure 3). The pins thus obtained were measured with a micrometer and trimmed until they were 0.20 inch (5.0 mm) in length. Any chips of material present around the edges were carefully removed by hand, using a fine grit paper disc. The wires were then inserted into the appropriate plunger. The specimens were made so that the domed end of the wire protruded about 0.12 inch (3.0 mm)

from the surface of the completed amalgam specimen, while 0.79 inch (2.0 mm) was imbedded in the amalgam. The domed end of the protruding pin would assure axial loading and eliminate the error that would result from elastic binding.

The wires utilized for torsion tests were cut to a length of 0.24 inch (6.0 mm) and both ends were prepared so that they would be as perpendicular as possible to the long axis of the pin. The edges were smoothed as before. The completed amalgam specimen consisted of two identical sections joined by a pin placed so that one half of its length (i.e. 0.12 inch = 3.0 mm) was imbedded in each section.

The wires utilized for push-through tests were 0.30 inch (7.5 mm) long. The pin ran through the amalgam so that about 0.04 inch (1.0 mm) protruded on one side and about 0.06 inch (1.5 mm) protruded on the other side. Both ends of the wire were made perpendicular to the long axis of the pin.

Condensation of the amalgam

In order to make pin-amalgam specimens, the mould, base and plunger, with the appropriate wire inserted in it, were assembled (Figures 5 and 6). The specimens were made with a conventional fine cut silver amalgam alloy

FIGURE 5 - BASE - PLUNGER ASSEMBLY

a- Pin

b- Plunger

c- Base

FIGURE 6 - COMPLETE MOULD ASSEMBLY

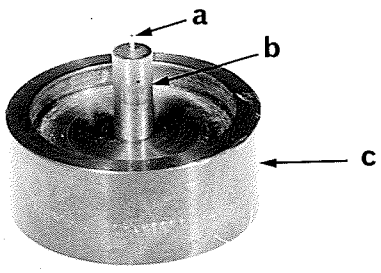

FIGURE 5

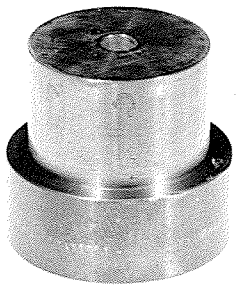

FIGURE 6

containing zinc in preweighed pellet form *. Pellets were preferred, as dispensers were found to display a great deal of variation in their degree of accuracy [160]. Accurate proportioning is of significance for the strength and dimensional behaviour of amalgam. Pure mercury **, as recommended by the American Dental Association specification No. 6, was mixed with the alloy. The mercury was measured using a Caulk dispenser with an "E" plunger. According to the manufacturer, one drop of mercury thus obtained would give a 1:1 ratio by weight when mixed with one of the pre-weighed pellets. A mechanical amalgamator *** was used to triturate the mix for a period of 18 seconds. The pestle was then removed from the capsule and the amalgam mulled for 5 seconds. The mixed amalgam was placed on a rubber dam for ease of handling. No mercury was squeezed out prior to condensation. The advantages of a low mercury content mix were demonstrated by Eames [99], Skinner and Mizera [158], and Swartz and Phillips [159].

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* Fine cut alloy - Pellets: 6 grains each - Caulk Co., Toronto, Ont., Canada

** Red label triple distilled mercury - Denco, Winnipeg, Man., Canada

*** Wig-L-Bug amalgamator - Crescent Dental Mfg. Co., Chicago, Ill., U.S.A.

Hand condensation was selected, in order to simulate clinical condensing conditions so that values for pin-amalgam bond performance would have more practical significance. The hand condensation technique proved to be additionally valuable, particularly when packing amalgam around the pin, as will be explained at the end of this section. One mix containing two alloy pellets was required for the push-through test specimens. All other specimens required two mixes of two alloy pellets each. Each mix was divided into three portions and each portion was carried to the cavity in the mould with a pair of cotton pliers. Condensation was initially attempted with the technique commonly used in clinical practice, in order to obtain specimens which were as consistent as possible.

Based on the recommendations of previous investigators [69, 82, 99, 103, 144], a force of three pounds was applied during condensation. A constant pressure condensing apparatus, designed by Hollenback [172] and modified by Duperon [144], was used (Figure 7). It consists of a lever with a weight on one side and a holder for the base of the mould on the other side. It includes a hand rest as well. The apparatus was adjusted so that three pounds were necessary to activate the lever.

FIGURE 7 - CONSTANT PRESSURE CONDENSING APPARATUS WITH STAINLESS-STEEL MOULD IN PLACE

a- Stainless steel mould in place

b- Hand rest

c- Fulcrum

d- Weight

e- Small balance weights

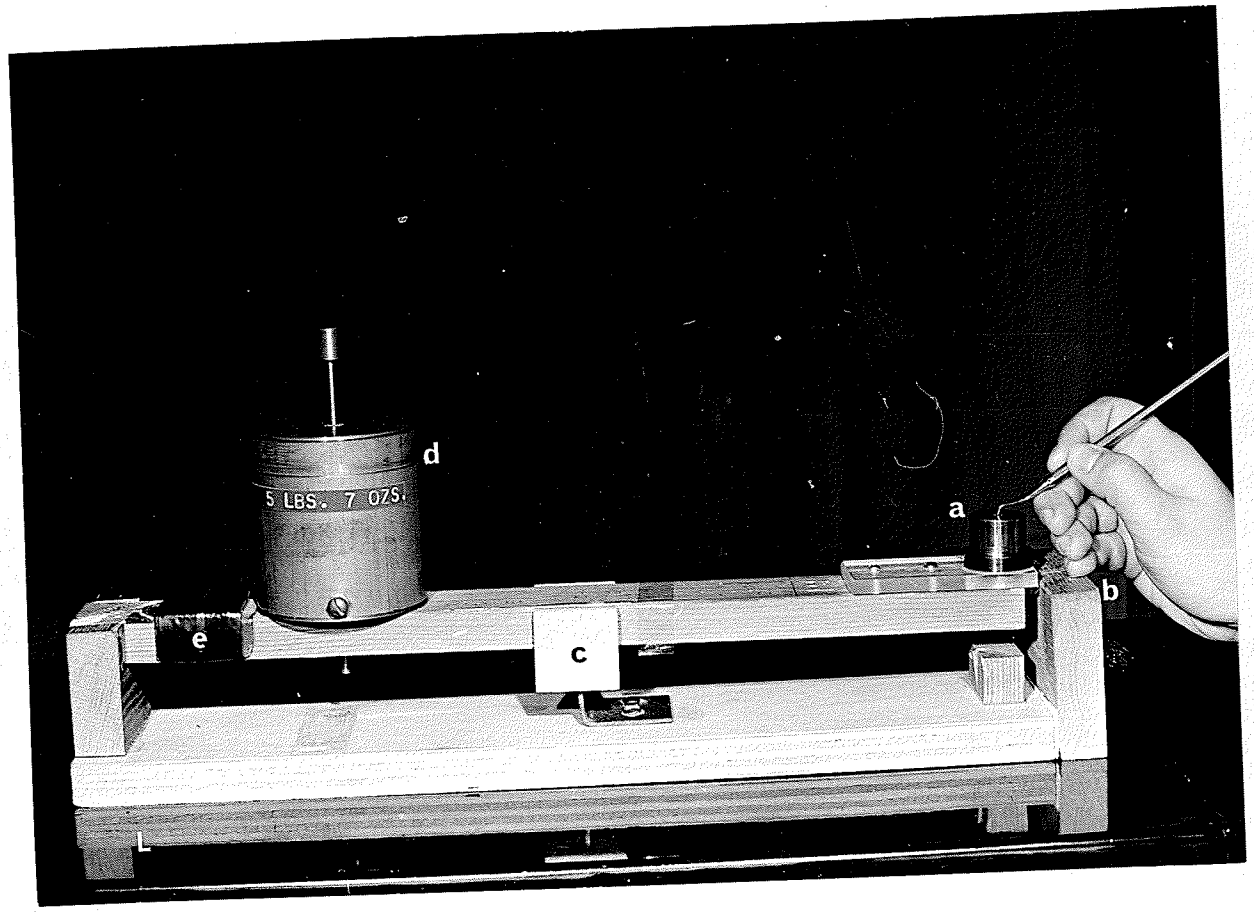

FIGURE 7

After preliminary tests, in order to reduce the formation of voids between pin and amalgam, the first portion of the initial mix was rubbed against the surface of the pin with the flat end of a plastic instrument *, prior to condensation with a 0.04 inch (1.09 mm) diameter smooth condenser **. This rubbing technique was found to be essential. The two remaining portions of the first mix and the two first portions of the second mix were condensed with a 0.07 inch (1.74 mm) diameter smooth condenser ***. The last portion was condensed using a 0.10 inch (2.56 mm) diameter smooth condenser ***.

The force per unit area developed by each condenser, using a force of three pounds, was calculated to be 18.91 PSI for the largest condenser, 826.00 PSI for the next size and 2066.11 PSI for the smallest condenser. Thirty strokes were used to condense each portion of amalgam [144]. The plashy amalgam was removed after condensing each portion. Once the final increment was placed, the excess amalgam was trimmed back flush with the mould surface. After removing the base,

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* Instrument No. 9A - American Dental Mfg. Co., Missoula, Mont., U.S.A.

** Instrument No. 5A - American Dental Mfg. Co., Missoula, Mont., U.S.A.

*** Double end instrument No. 1A - American Dental Mfg. Co., Missoula, Mont., U.S.A.

the specimen was ejected from the mould by means of the plunger. The specimen, illustrated in Figure 8, was then stored for approximately 30 hours.

SPECIMENS FOR MODULUS OF ELASTICITY DETERMINATION

Sterling-silver

Sterling-silver pins were constructed as described previously but modified for this test. Three pins were cast at one time. They were left on the sprue-button after heat treatment was completed. No fine polishing was necessary. The base of the sprue-button was ground flat on a 240 grit sand paper. Mounted specimens are shown in Figure 9.

Dental amalgam

Cylindrical amalgam specimens with a diameter of 0.06 inch (1.50 mm) and a length of 0.31 inch (8.0 mm) were constructed. Each specimen had a conical base with a diameter of 0.16 inch (4.0 mm). Mounted specimens are shown in Figure 10. To construct this type of specimen, a split mould was made from two plastic sheets. The two sheets were firmly secured by means of three bolts and nuts (Figure 11).

For each specimen, only one pellet of alloy was used for a mix. Small portions of the mix were transferred

FIGURE 8 - PIN-AMALGAM SPECIMEN

a- Pin, partially embedded in amalgam

b- Amalgam specimen

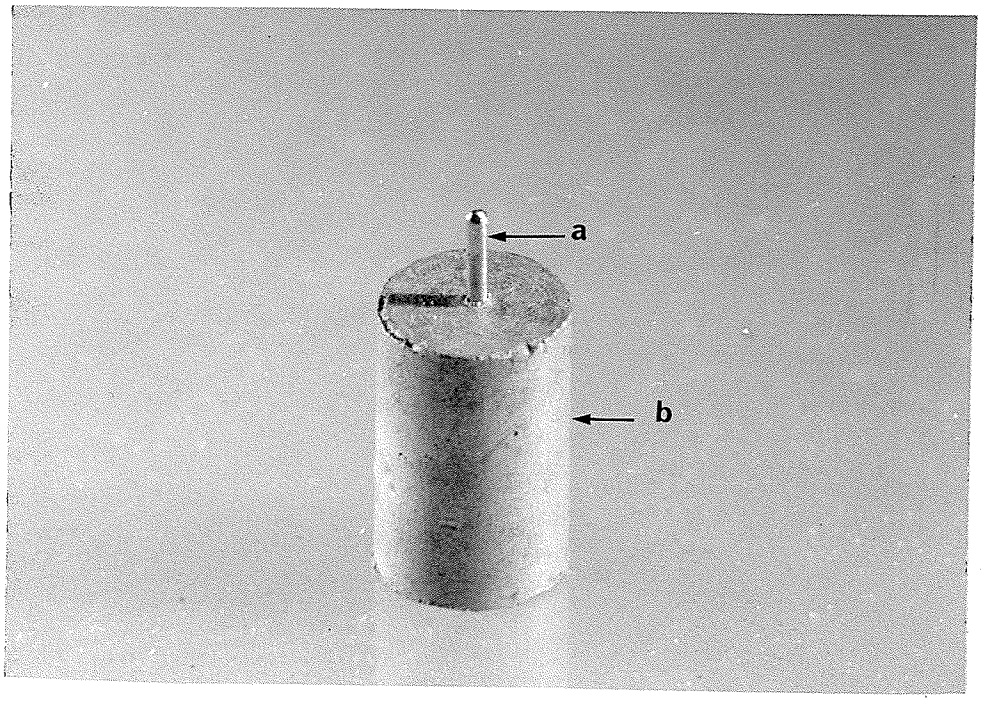

FIGURE 8

FIGURE 9 - STERLING-SILVER SPECIMENS MOUNTED FOR MODULUS OF ELASTICITY EXPERIMENT (Diagram)

a- Sterling-silver pin

b- Sprue button in epoxy glue

c- Metallic L-shaped plate

FIGURE 10 - DENTAL AMALGAM SPECIMENS MOUNTED FOR MODULUS OF ELASTICITY EXPERIMENT (Diagram)

a- Dental amalgam pin

b- Hard rubber ring from which scale-pan is hung with a thread (see figure 14)

c- Base of amalgam pin in epoxy glue

d- Metallic L-shaped plate

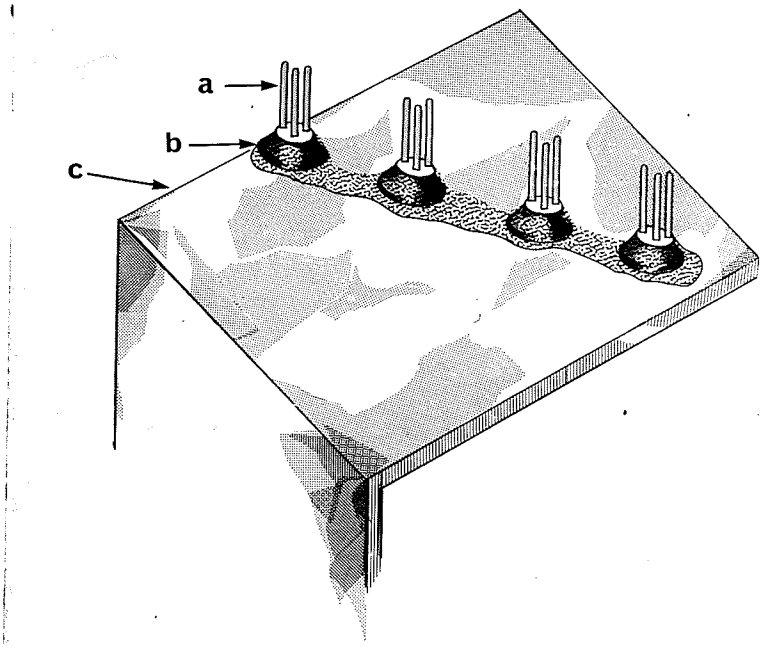

FIGURE 9

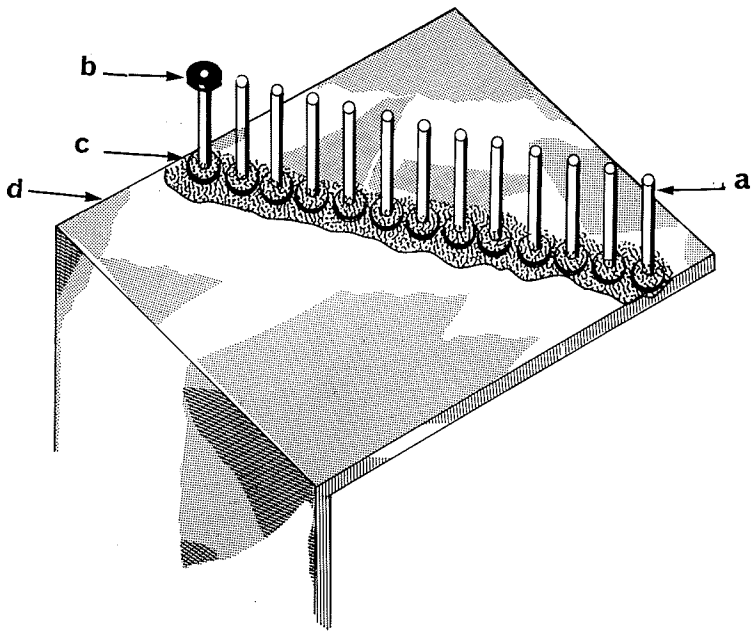

FIGURE 10

FIGURE 11 - MOULD FOR DENTAL AMALGAM PINS USED IN MODULUS OF ELASTICITY EXPERIMENTS

a- Hollow mould

b- Removable piece to facilitate withdrawal of the finished specimen

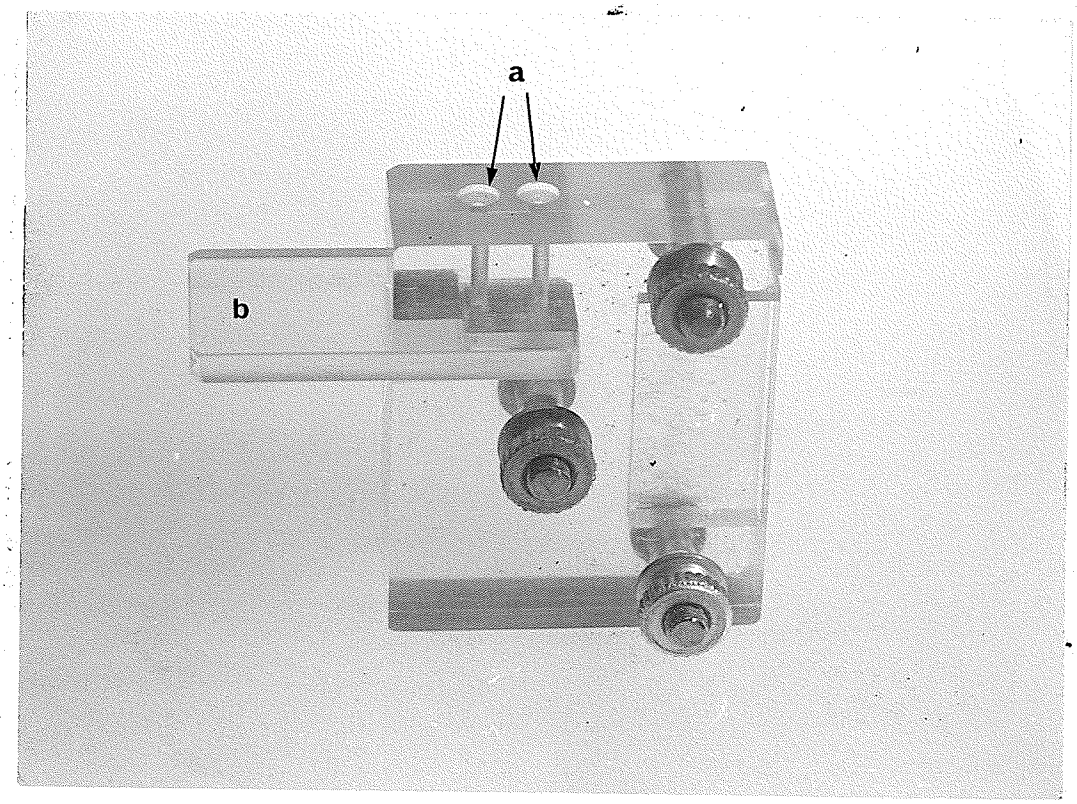

FIGURE 11

to the mould with an amalgam carrier *. A stainless-steel orthodontic wire having a diameter of 0.032 inch (0.813 mm) and flattened and smoothed at one end, was used for hand condensing the amalgam into the cylindrical portion of the mould. The top of the mould was filled with a condenser ** measuring 0.068 inch (1.74 mm) in diameter. The excess amalgam was carved flush with the mould.

The amalgam was allowed to harden for 30 minutes before removing the specimens from the mould. After 24 hours, the base was ground flat.

MICROSCOPIC EXAMINATION

MOUNTING AND POLISHING OF SPECIMENS

Specimens for low and high power light microscopes

Pins: Nickel plated and nickel-silver plated stainless-steel pins were studied. Aribtrary lengths of the wires were cut, mounted in Bakelite ***, and polished metallurgically

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* Ash 5X - England

** Double end instrument No. 1A - American Dental Mfg. Co., Missoula, Mont., U.S.A.

*** 1380 AB black Bakelite mounting powder - Buehler Ltd., Evanston, Ill., U.S.A.

(Figure 12 b). Firstly, a grinder * fitted with successively finer abrasive sand paper (240, 320, 400 and 600 grits) was used. The surface of the specimen was then cleaned by rubbing it with cotton under running water. The final polishing was done on a polishing wheel using 0.30 micron alumina powder followed by 0.05 micron alumina powder. Both polishing agents were prepared as suspensions in soapy water. Appropriate microcloths, moistened with distilled water, were used in each case. A cloth with a nap was used for the 0.05 micron alumina. The specimen was cleaned with running water and then with alcohol, and dried with warm air. After polishing, specimens were stored in a desiccator.

Before viewing under the high power light microscope, nickel plated wires were etched in order to be able to detect a difference in structure between the stainless-steel and the pure nickel layer which had been deposited onto its outer surface. The etch was composed of 10 parts of nitric acid, 15 parts of hydrochloric acid and 10 parts of acetic acid.

Pin-retained amalgam specimens: Amalgam specimens containing one of three types of pins, nickel-silver

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* Handimet grinder - Buehler Ltd., Evanston, Ill., U.S.A.

FIGURE 12 - MOUNTED SPECIMENS FOR LIGHT MICROSCOPE AND X-RAY MICROPROBE STUDIES

a- Pin-amalgam specimen mounted in bakelite

b- Pin specimens mounted in bakelite

FIGURE 13 - MOUNTED SPECIMEN FOR SCANNING ELECTRON MICROSCOPE STUDY

a- Pin-amalgam specimen

b- Silver dag

c- Mounting stub

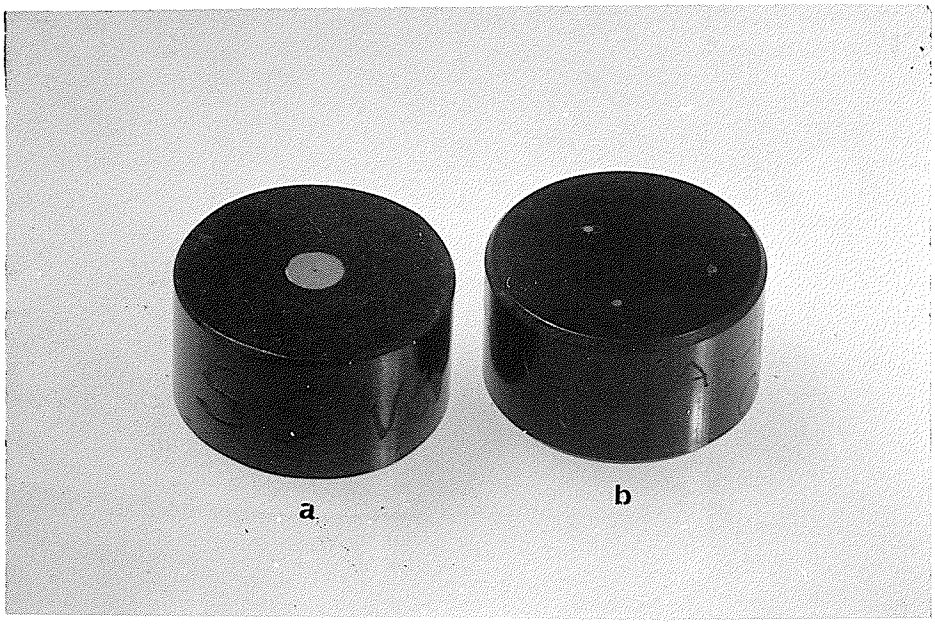

FIGURE 12

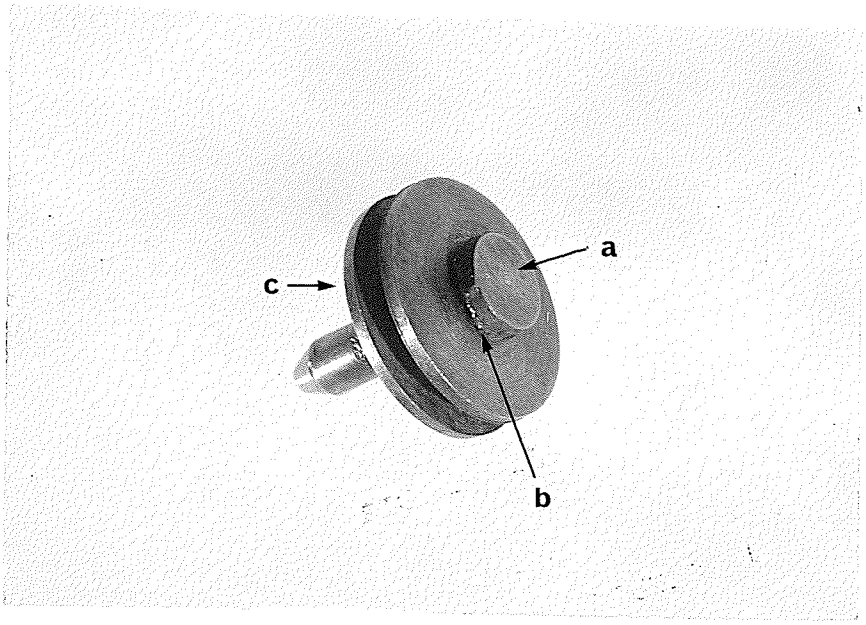

FIGURE 13

plated stainless-steel, sterling-silver or stainless-steel were observed under the low power light microscope. For mounting, the usual procedure of embedding in bakelite was modifided to avoid undesirable effects of heat rise on the amalgam. Techniques on how to mount and polish amalgam specimens for microscopic studies have been described by several authors [44, 161, 162]. A hole, parallel to the long axis and 0.205 inch (5.20 mm) in diameter was drilled through the base. The pin-retained amalgam specimen was "cemented" in the hole with auto-polymerizing polymethylmethacrylate resin, as shown in Figure 12 a. The heat evolved from the small amount of acrylic required to cement the specimen caused a negligible rise in temperature of the amalgam. Once the acrylic had hardened, polishing was undertaken. The method utilized for polishing was the same as described for the wires, with two modifications. The polishing cloths were moistened with benzene rather than water and the specimen was wetted with benzene instead of alcohol before the final drying. Benzene was utilized to avoid oxide formation on the surface of the amalgam [173]. The specimens were stored in the desiccator.

Specimens for scanning electron microscope (SEM)

SEM specimens were not mounted in Bakelite. They were polished to a course finish only, utilizing the

procedure described for the light microscopic samples. They were not polished to a fine degree because a highly polished surface would create difficulty in visualizing details with the SEM. The amalgam specimen height was reduced to 0.078 inch (2.0 mm) to facilitate viewing with the SEM. The specimens were mounted on special mounting stubs (Figure 13) and held in place with Silver Dag *. As the sample was naturally conductive, no further treatment was required to provide a low resistance path between the sample surface and the stub.

The specimens studied under the SEM were, nickel plated stainless-steel wires, nickel-silver plated stainless-steel wires and amalgam containing pins of either nickel-silver plated stainless-steel or sterling-silver.

APPARATUS

Light microscopes

Three types of light microscopes were utilized in this study. One was a common low-power microscope with a magnification range between 1.6 X and 4 X. The second was an inverted type metallographic microscope equipped with camera and an incident light source, and having a magnification range between 10 X and 250 X. The third type was a high-power light microscope ** which was used to view

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* Acheson Colloids Canada Ltd., Brantford, Ont., Canada

** Metallograph - M55 Vickers

specimens in greater detail. The final magnification obtainable ranged up to 3000 X. This microscope was equipped with a polaroid camera.

Scanning electron microscope (SEM)

Light optical microscopy is normally restricted to a middle range of magnification and the depth of focus is too poor to study details on undulating surfaces. Because of this, the specimens were also viewed under a scanning electron microscope (SEM). The specimen needs little or no preparation prior to its study with this microscope. The SEM has a magnification ranging between 50 X and 30,000 X. The primary reasons for utilizing the SEM for this study was its capability of producing great surface detail and an image with depth of field which varies inversely with magnification (1000μ at 100 X to 10μ at 10,000 X) [166]. The method of analysis of amalgam samples using SEM has been described by several authors [33, 164, 165, 166, 167].

COMPOSITION DETERMINATION

MOUNTING AND POLISHING OF SPECIMENS FOR X-RAY MICROPROBE ANALYSIS

The specimens for X-ray microprobe analysis were

mounted in Bakelite in the same manner as the samples for microscopic examination. The metallurgical polishing method was altered in order to obtain the extremely flat surfaces necessary for analysis by the X-ray microprobe. Methods of polishing to obtain especially flat specimens have been described [38, 163]. If the polishing procedure as described before is used, the softer amalgam is polished away more rapidly than the pin. As a result, the pin protrudes above the amalgam.

The specimen to be viewed under the X-ray microprobe was course-polished on a grinder as for optical observation and then polished with 6 micron and 3 micron diamond pastes on polishing wheels with no microcloth. Final polishing was completed in an automatic polisher using a suspension of 0.3 micron alumina powder in water. Specimens were cleaned with cotton under running water, then with alcohol or benzene, and dried with warm air. A much flatter surface was obtained by using this method. Following this procedure, the surface of the specimens was carbon-coated under vacuum. The carbon coat was applied in order to prevent the build up of heat and electrical charge during the microprobe analysis, and also to increase electrical conductivity. Specimens were stored in a desiccator.

APPARATUS

The X-ray microprobe analyzer utilizes electron optics and gives qualitative and quantitative analyses by X-ray spectrometry. When the area to be studied is bombarded by electrons, the atoms of each element emit characteristic X-rays and each element can be determined from its characteristic wave length. By comparison with standards, the percentage of each component can be determined [29]. The ratio of intensities of characteristic radiation (i.e. back-scattered or peak) to continuous radiation (i.e. backround) is essentially constant [168]. However, the importance of the X-ray microprobe is not in its sensitivity, which is lower than that of other probes, but rather in its ability to analyze very small volumes of material. Techniques to analyze dental amalgam specimens with the X-ray microprobe have been described in the literature [30, 42, 53, 168, 169, 170].

DETERMINATION OF MECHANICAL PROPERTIES

MODULUS OF ELASTICITY

Tests for an approximate determination of the modulus of elasticity were performed in order to assure that correct methods of preparation of amalgam and of heat treatment of sterling-silver were being used. Also, values given in the

literature for Young's modulus of amalgam differ from 10^6 to 4 X 10^6 PSI when condensed with low loads [90]. Therefore, it was necessary to find a value of modulus of elasticity for amalgam under the conditions of the present study.

The value for sterling-silver was utilized as one of the correction factors for the elastic deformation of the pin during the axial load-deflection tests. The value for amalgam was useful in calculating the theoretically limiting cases for the axial deflection of the pin, as demonstrated by Dhuru [129].

Mounting of specimens

Both sterling-silver and dental amalgam specimens were mounted in the same way. Their base was fixed to a metallic L-shaped plate, utilizing an epoxy resin glue *. They were positioned in a diagonal line, so that they could all be seen when viewed from the side (Figures 9 and 10). Four sterling-silver specimens with three pins each, and twelve dental amalgam specimens were tested.

Apparatus and method

A travelling microscope ** was utilized to measure the deflection of each specimen when loaded with weights of

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* "5 Minute Epoxy" - Devcon Corp., Danvers, Mass., U.S.A.

** The Gaertner Scientific Corp., Chicago, Ill., U.S.A.

FIGURE 14 - EXPERIMENT FOR MODULUS OF ELASTICITY DETERMINATION

a- Travelling microscope

b- Metallic plate with specimens mounted

c- Thread for supporting pan and weights (Arrow shows the direction of the force)

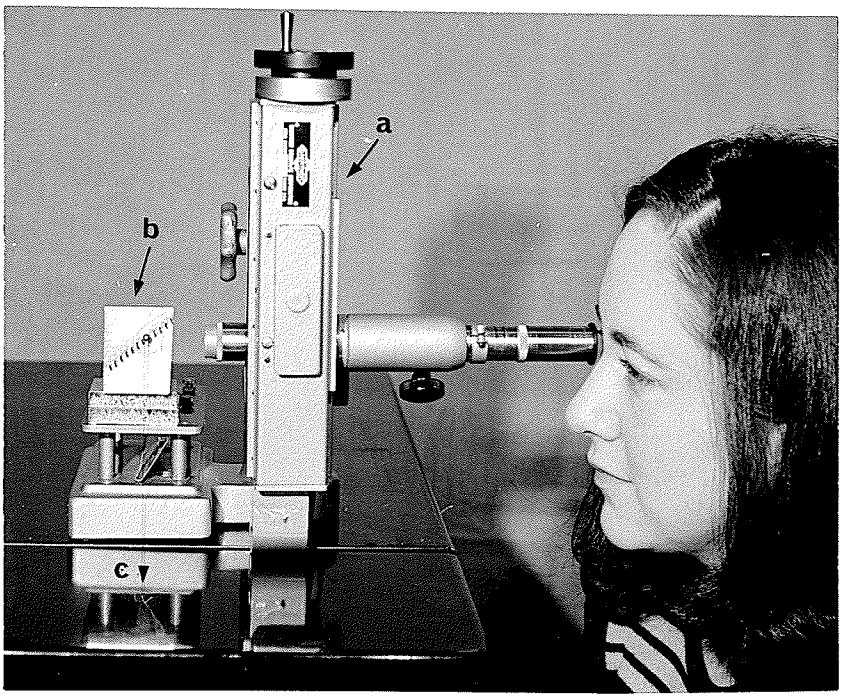

FIGURE 14

15, 50, 100 and 120 grams. The pan for the weights was supported by a loop of thread suspended from the tip of each pin (Figure 14). The modulus of elasticity of each material was found by applying the formula:

$$E = \frac{Wl^3}{3} \cdot \frac{65}{\pi d^4} \cdot \frac{1}{\sigma}$$

where "E" is the Young's modulus, in Nw/m^2

"W" is the load, in Newtons

"l" is the distance from the root of the cantilever to the point of loading, in meters

"d" is the diameter of the cantilever, in meters

"σ" is the deflection at the point of loading, in microns

It is recognized that with such high powers of length and diameter involved in this formula, a very accurate determination of Young's modulus is not possible. In this study, only an approximate value of Young's modulus was required. Thus, the accuracy of this method was adequate.

EFFECTIVENESS OF THE PIN-AMALGAM BOND

Axial load-deflection tests

Mounting and polishing of specimens: The technique utilized to mount pin-amalgam specimens for axial load-deflection tests was similar to that described for light

microscope specimens. The bases were built from transparent acrylic, measuring 1.0 inch x 1.0 inch x 0.31 inch (25.4 mm x 25.4 mm x 8.0 mm). The bottom surface of the specimen was hand polished in a grinder * so that it would be completely even and flat. On the upper surface of the base, four lines were drawn parallel to each one of the sides of the base and touching the edge of the amalgam specimen. The intersection of these lines provided four equidistant points from the pin. A finished specimen is shown in Figure 15. Thirty-five specimens were constructed for each one of the three types of wires utilized in this research. All the specimens were between thirty and forty hours old at the time of testing.

Apparatus and method: The apparatus used for axial-load deflection measurements was the same one used by Dhuru [129]. It consists of a linear-voltage differential transformer with a device for zero adjustment and a probe capable of moving with vertical axial deflections. All of these devices are contained in a cylindrical brass housing (Figure 16). The housing was held in position so that spurious movements were minimized [129].

The specimen to be tested was placed under the housing. The probe was successively placed over each one of the four intersections of the lines drawn on the top surface of the specimens (Figure 17). The axial deflection of the

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* Handimet grinder - Buehler Ltd., Evanston, Ill., U.S.A.

FIGURE 15 - SPECIMEN FOR AXIAL LOAD-DEFLECTION TEST

a- Transparent acrylic base with lines drawn on the top surface

b- Pin

c- Amalgam

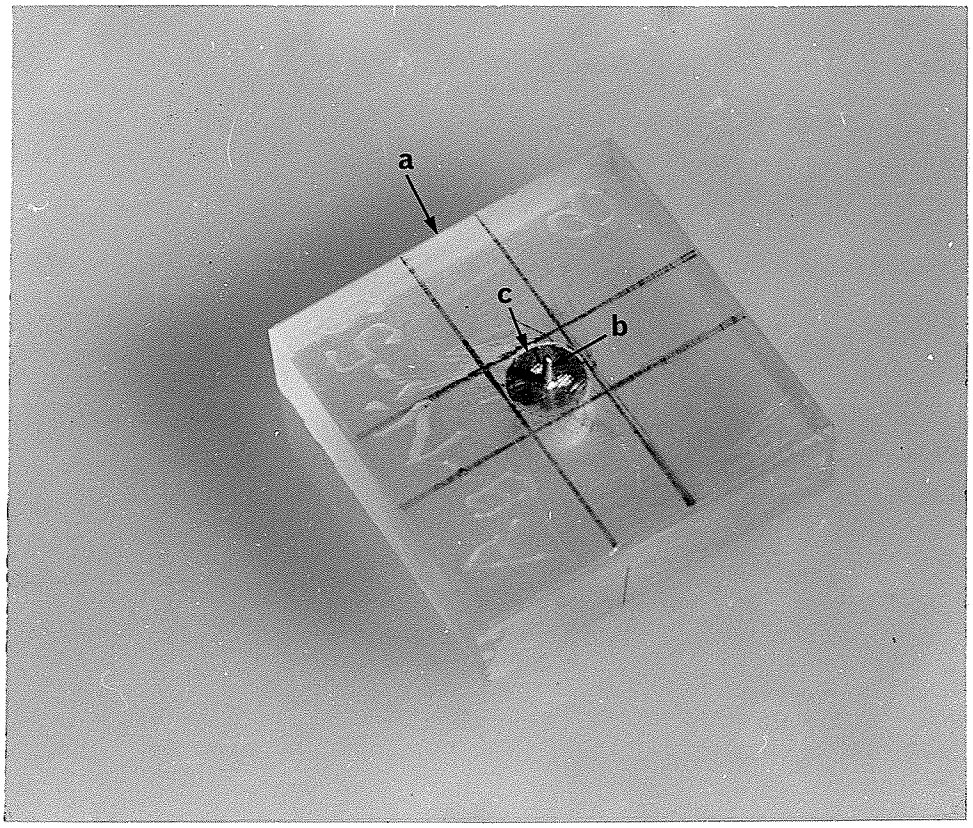

FIGURE 15

FIGURE 16 - APPARATUS FOR AXIAL LOAD-DEFLECTION MEASUREMENTS

a- Brass housing

b- Device for zero adjustment

c- Cord connecting the linear voltage differential transformer contained in the housing, with a meter

d- Specimen in place

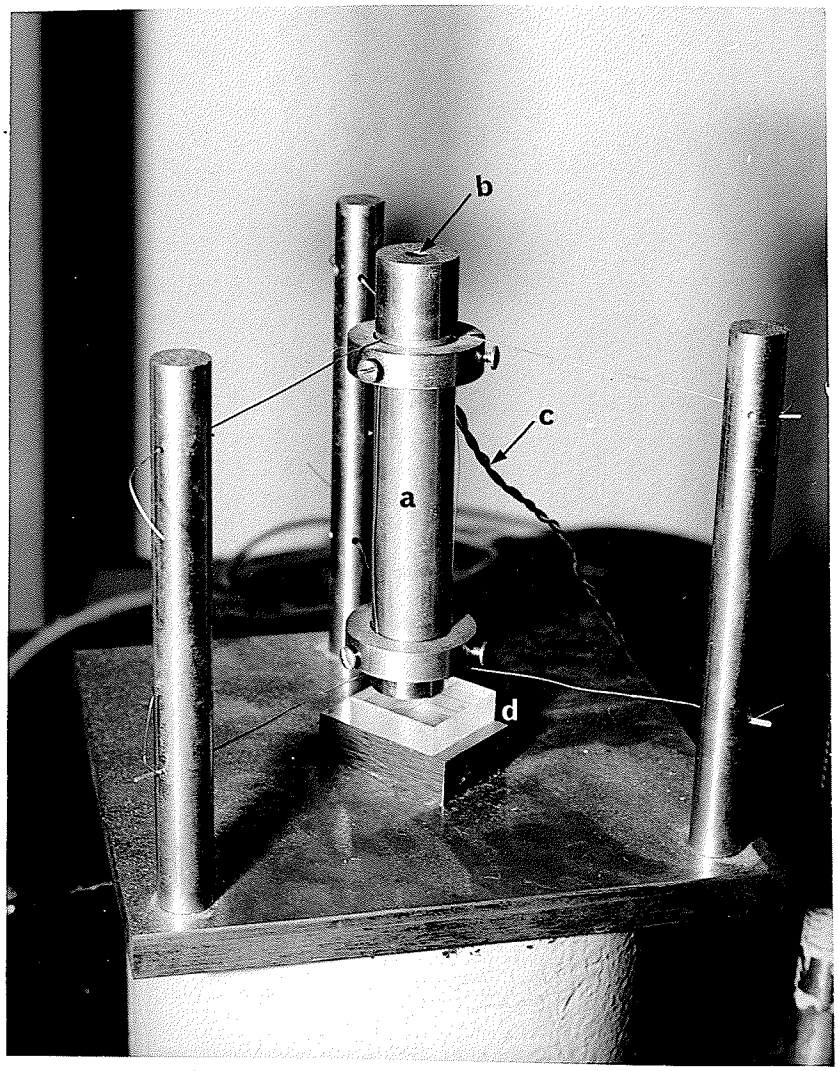

FIGURE 16

FIGURE 17 - APPARATUS FOR AXIAL LOAD-DEFLECTION MEASUREMENTS

a- Steel platten

b- Probe capable of moving with vertical axial deflections

c- Pin

FIGURE 18 - APPARATUS FOR AXIAL LOAD-DEFLECTION MEASUREMENTS

a- Brass housing

b- Specimen in place

c- Weights

d- Bar holding weights so they can be gently applied and removed

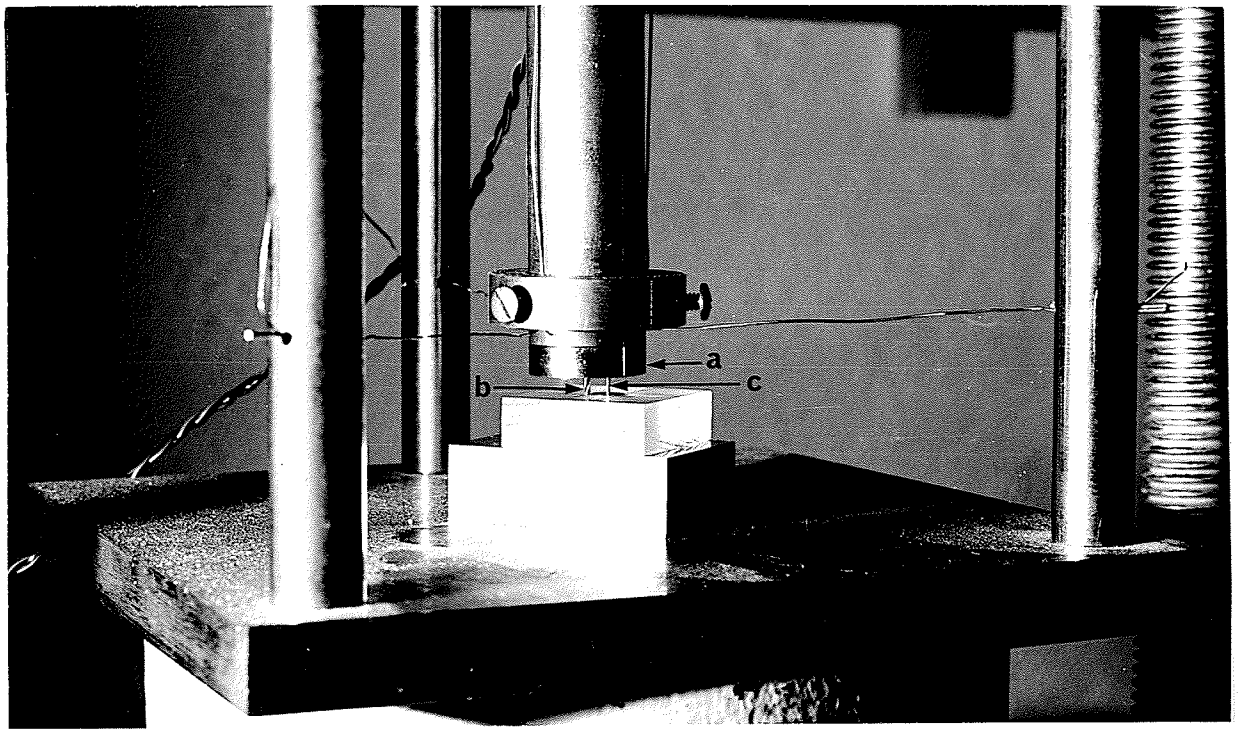

FIGURE 17

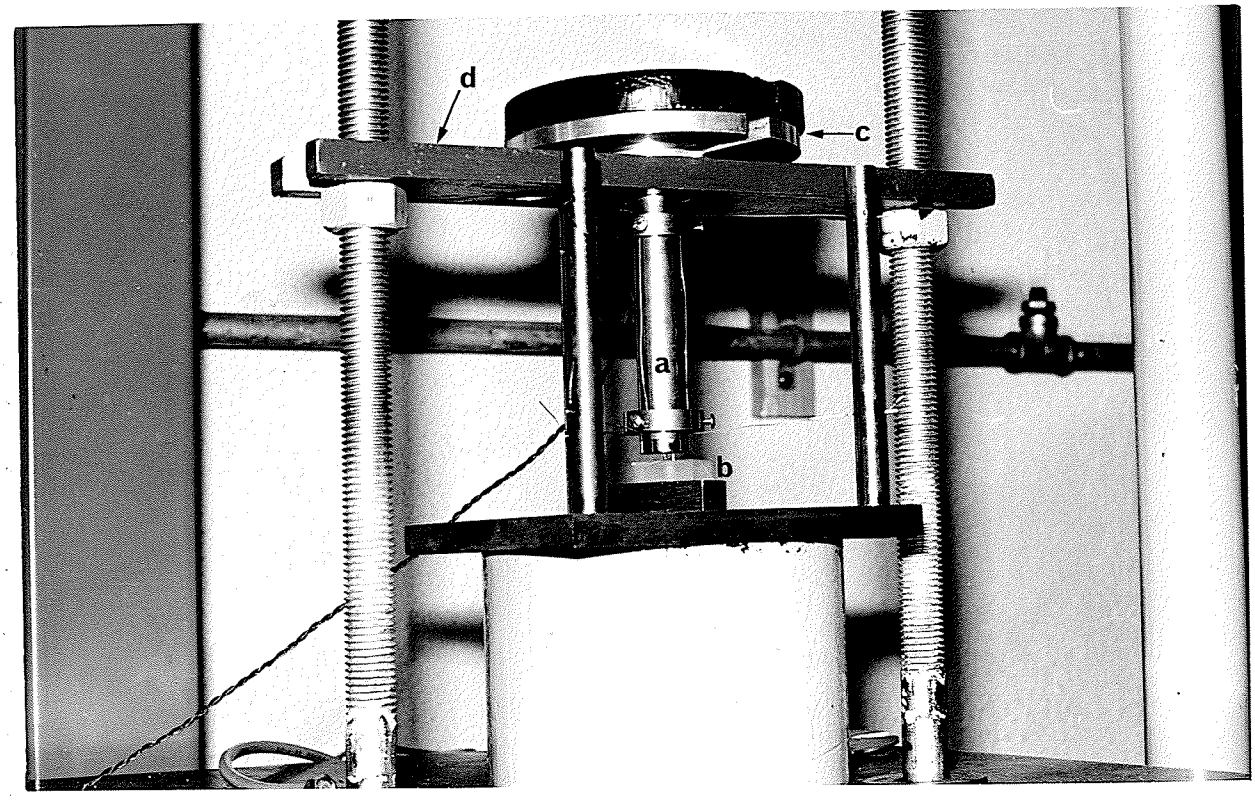

FIGURE 18

FIGURE 19 - APPARATUS FOR AXIAL LOAD-DEFLECTION MEASUREMENTS

a- Meter for recording deflection in microns

b- Experiment set-up as shown in detail in figures 16, 17 and 18

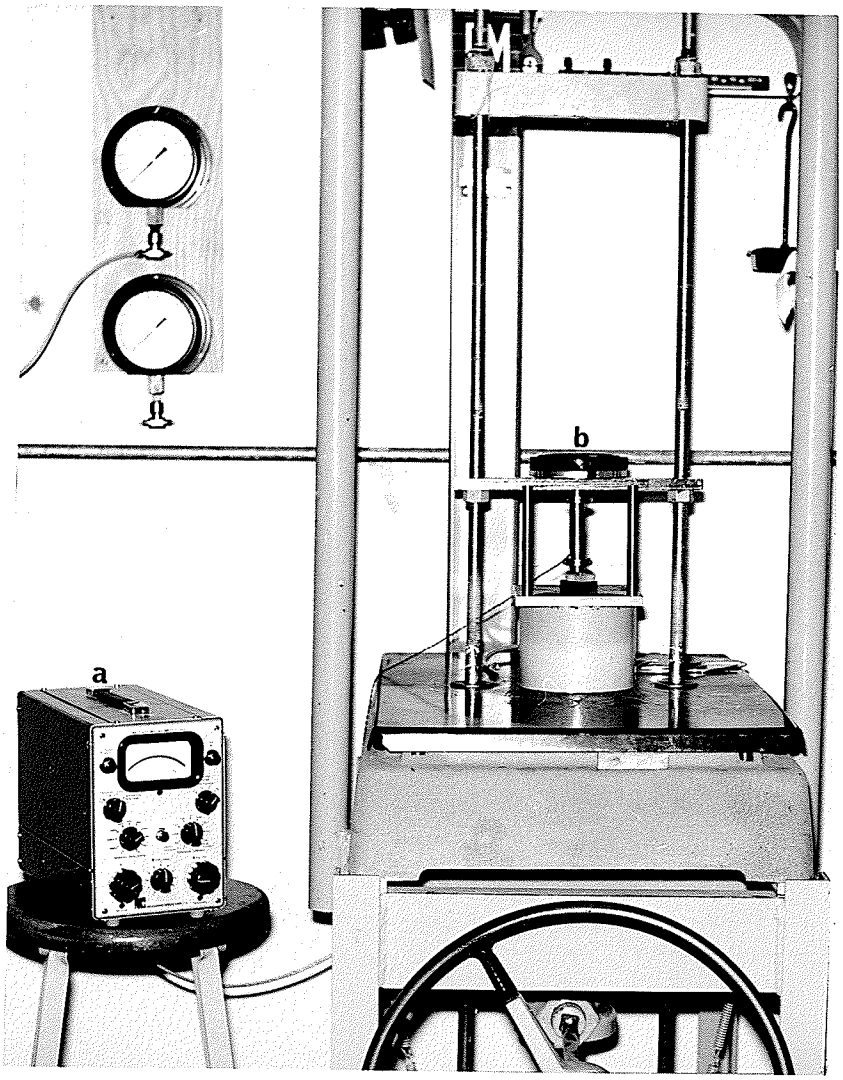

FIGURE 19

pin due to different dead weights applied to the top of the housing was then recorded by the probe (Figure 18). The four readings taken on the same specimen for each load were averaged. This eliminated the possibility of any error due to the canting of the specimen when loaded. The load-deflection relationships were recorded by a meter * with a sensitivity of 0.05 microns (Figure 19). The pin was gently loaded and unloaded by applying dead weights to the top of the transducer housing. In order to obtain consistent and reliable measurements, each load was applied three times before any results were recorded. This allowed any plastic deformation at the top of the pin to take place.

For the first ten specimens of each kind, load values using one pound increments and varying from 0.5 to 5.5 pounds (0.2 to 25.4 Newton) were utilized at each one of the four stations. Because the results obtained were consistent and linear, the remaining specimens were similarly tested with a series of only 1.5, 4.5 and 5.5 pound (6.7, 20.1 and 24.5 Newton) loads.

Correction factors: The measured values obtained with the technique described had to be corrected taking into account several factors:

Probe-pin distance: When the load is applied, the amalgam immediately surrounding the pin suffers a

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* Model KWS/T-5 - Hottinger-Baldwin, West Germany

deformation. If the probe had been placed against the pin, the amalgam deformation would have been added to the deflection of the pin. On the other hand, the pin and the probe cannot be placed too far from one another. The effect of any movement of the transducer housing in any other direction than the vertical, is increased in direct proportion to the square of the probe-pin distance. A distance of 3 mm between the pin and the probe was judged acceptable in keeping the correction factors small.

Canting of the specimen: Because there is a distance existing between the pin and the probe, any canting of the specimen due to the application of the load introduces an error in the final value of the deflection. In two diametrically positioned points, the readings are likely to have errors that are equal in magnitude but opposite in sign. As a result of this fact the four points chosen give an average value which would eliminate the error.

Canting of transducer housing: As already stated, the magnitude of the error due to slight canting of the housing when loaded is related to the square of the probe-pin distance. Experimentally, a formula has been given to find its influence on the final value of the deflection of the pin [129]:

$$e = 0.041\ d^2$$

where "e" is the error due to the canting of the housing

"d" is the distance in millimeters between the pin and the probe.

Deflection of the transducer housing: Dhuru [129] calculated the deflection of the housing due to its elastic deformation under the applied load. He found it to be equal to 0.008 microns per Newton.

End effect: As already explained, the specimens were first loaded in order to complete a plastic deformation at the domed end of the pin. Once this happens, an elastic deformation of the microscopic irregularities present at the top of the pin takes place. This elastic deformation is called "end effect". It is only important experimentally because the deflection of the pin can only be measured at the same point at which the load is applied. In the mouth, the pin receives the load indirectly through the amalgam. As stated by Dhuru [129] the end effect is a constant function of the load and is independent of the dimensions of the pin.

The end effect is found experimentally by making a larger size replica of the situation encountered between the top of the pin and the platten of the transducer housing

when a dead weight is applied. It was found to be 1.6 micron for 4.5 pound (20 Newton) loading force for stainless-steel pins [129].

Although three types of pins were utilized for the present study, no distinction was made between stainless-steel and nickel-silver plated stainless-steel pins, as far as the end effect is concerned. It was believed that the material from which the pin had been constructed would not significantly change the value of the end effect. Nevertheless, an experimental verification of this hypothesis was deemed necessary and experiments similar to those made by Dhuru [129] were performed for sterling-silver. The requirement in this case was that of measuring the end effect between a sterling-silver pin and the steel platten of the transducer housing. Consequently, it was necessary when increasing the number of connections that they always be between steel and sterling-silver. To achieve this, alternate sections of stainless-steel and sterling-silver were used to form the long pin in a measuring block.

A steel measuring block with a hole 0.040 inch (1.016 mm) in diameter and 0.74 inch (19.0 mm) in depth was utilized (Figure 20). A sterling-silver wire (0.040 inch (1.016 mm) in diameter and 0.86 inch (22.0 mm) in length would have presented a similar situation to that encountered with the pin-amalgam specimens, but with two end effects. The overall length of the pin was kept

FIGURE 20 - EXPERIMENTS FOR " END EFFECT"

EXPERIMENTS FOR "END EFFECT"
(DIAGRAM)
(NOT TO SCALE)

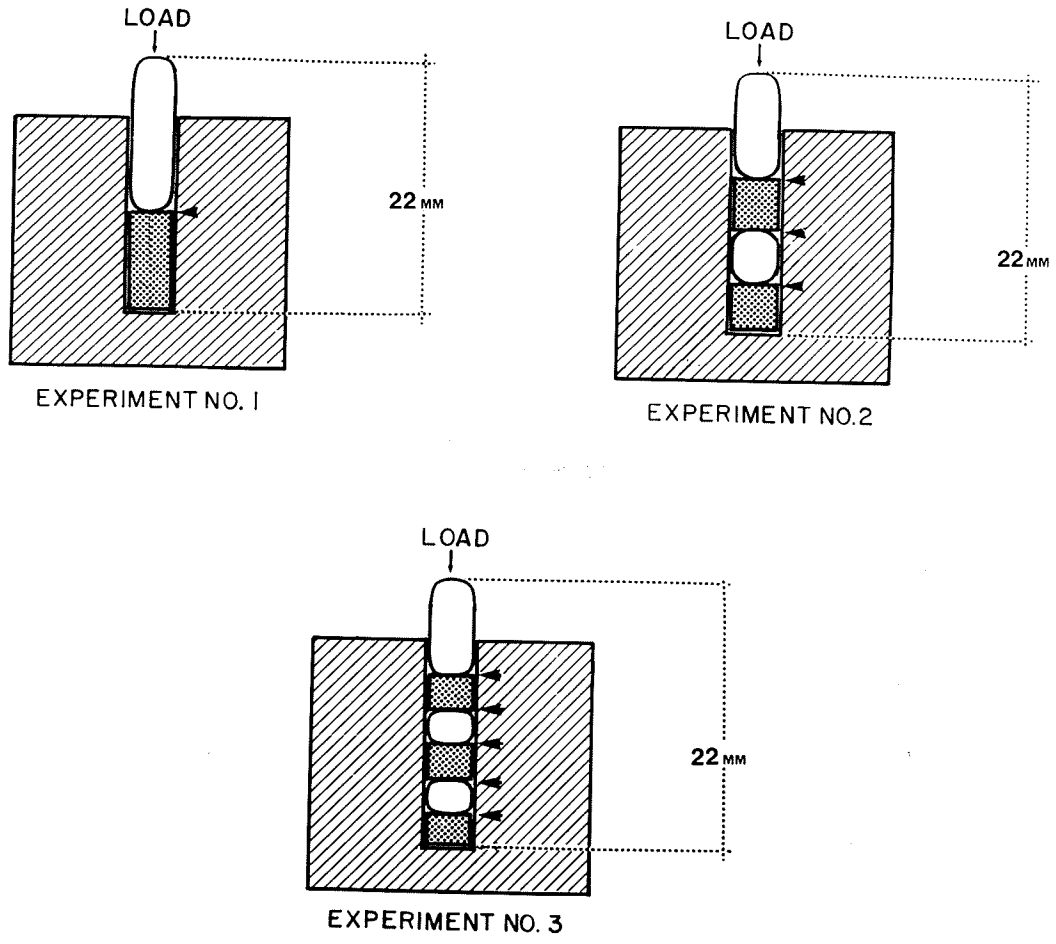

FIGURE 20

constant throughout and three "pins" were used divided into two, four and six pieces respectively. The pieces of each "pin" were arranged as shown in Figure 20. Both ends of the sterling-silver pieces were domed, whereas the ends of the stainless-steel pieces were flat and perpendicular to the long axis of the pin. Thus, each end effect of the sterling-silver would take place against a flat stainless-steel surface. In this way, the situation encountered by the specimen when the sterling-silver pin was deflected by the steel platten of the housing, was exactly duplicated. The number of interfaces was plotted against the deflections and the deflection caused by the end effects could be determined.

The end effect for one sterling-silver/stainless-steel interface was 1.6 micron for a 4.5 pound (20 Newton) loading force. Thus, the assumption made that the end effect was not a function of the material of the pin was confirmed.

Elastic deformation of the pin outside amalgam: Since it is the deflection of the pin at the surface of the amalgam that is important in this case, the elastic deformation of the free standing part of the pin must be subtracted from the measured deflections. This correction can be calculated from the formula:

$$\Delta = \frac{\sigma \, l}{E}$$

where "σ" is axial stress in pin

"l" is the length of pin above amalgam

"E" is Young's modulus of pin material.

Thus, by subtracting Δ from the measured pin deflection the appropriate correction can be made.

Torsion tests

Mounting of specimens: The specimens for the torsion tests were composed of two halves. The first half was the same as the specimens used for load-deflection tests, except for the length of the pin. The second half consisted of amalgam condensed around the protruding pin of the first half. The way the second half of the specimen was done is described below.

Two small pieces of cellophane paper * were placed over the surface of the amalgam on the first half of the specimen. A small hole in the centre of the papers allowed the pin to pass through them. This is shown in Figure 21. The cellophane paper was used in order to slightly separate the two halves of the specimen, so that they could rotate freely one against the other while tested. The amalgam for the second half of the specimen was condensed into an

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* Film foil - Denco, Winnipeg, Man., Canada

FIGURE 21 - FIRST HALF OF A SPECIMEN FOR TORSION TEST

a- Transparent acrylic base

b- Sheets of cellophane paper

c- Pin embedded in amalgam

FIGURE 22 - SPECIMEN FOR TORSION TEST

a- First half of the specimen

b- Second half of the specimen

c- Amalgam

d- Retention for amalgam

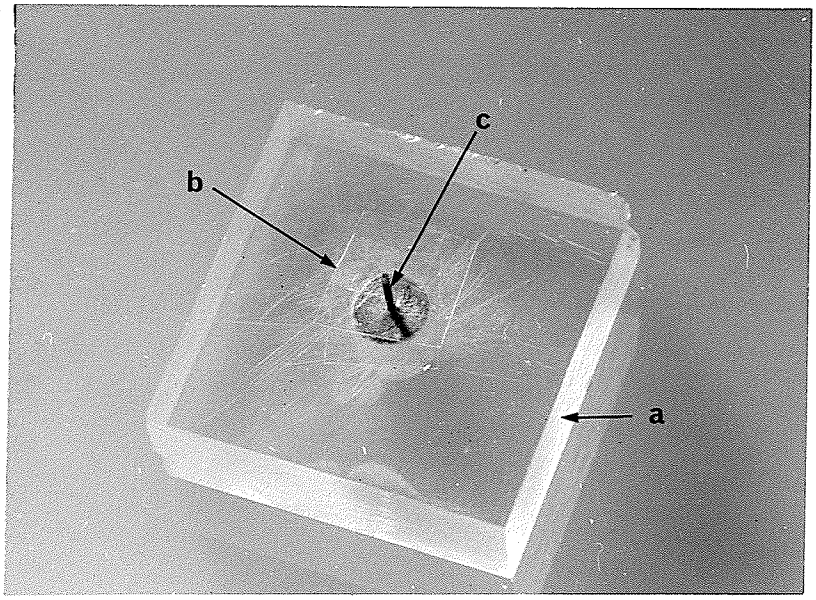

FIGURE 21

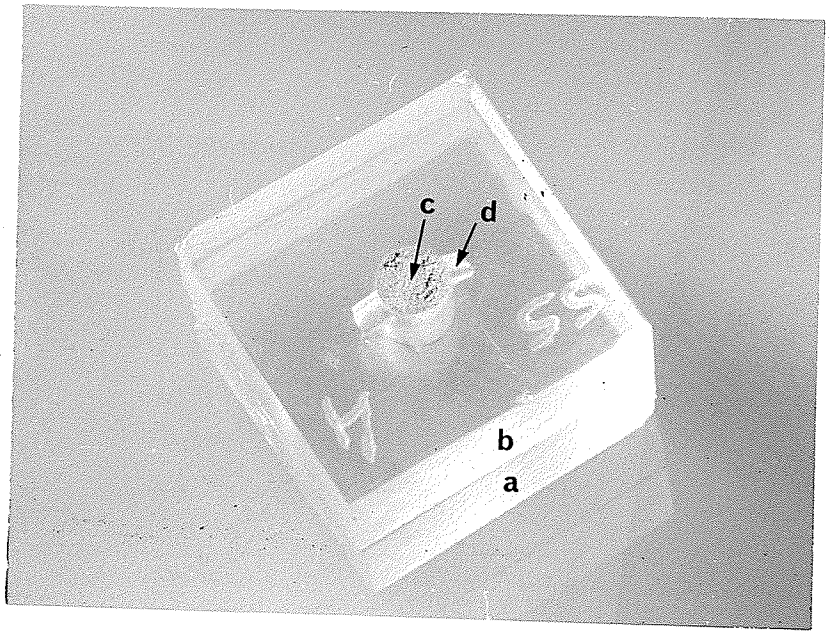

FIGURE 22

acrylic base. This base had the same characteristics as the one described for load-deflection specimens. It had a hole through its centre, measuring 0.20 inch (5.20 mm) in diameter and 0.31 inch (8.0 mm) in depth. Two retentive cavities were cut on the side wall of the central hole, utilizing a 702 steel bur. They served to avoid any displacement of the bulk of set amalgam during testing (Figure 22). The base thus prepared was placed over the first half of the specimen. A specially constructed device tightly held together both bases while condensing the amalgam. It was placed on the constant pressure condensation apparatus, as shown in Figure 23. The same technique described for preparing and condensing the amalgam was used. The amalgam was condensed into the lateral retention cavities with a smaller diameter condenser. The specimens were carefully handled to avoid even slight damage to the pin-amalgam bond before testing.

A total of thirty-two specimens were constructed. Six of them contained stainless-steel pins. Ten were made with sterling-silver pins. Sixteen were constructed using nickel-silver plated stainless-steel pins. When tested, the first half of the specimen was approximately three days old, and the second half approximately forty hours old.

Apparatus and method: An indexing and dividing table *

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* Emco, Austria

FIGURE 23 - CONSTANT PRESSURE CONDENSING APPARATUS WITH TORSION TEST SPECIMEN IN PLACE (Details of apparatus are explained in figure 7)

a- Torsion test specimen in place for condensing amalgam in the second half of the specimen

b- Device to hold the specimen while condensing amalgam

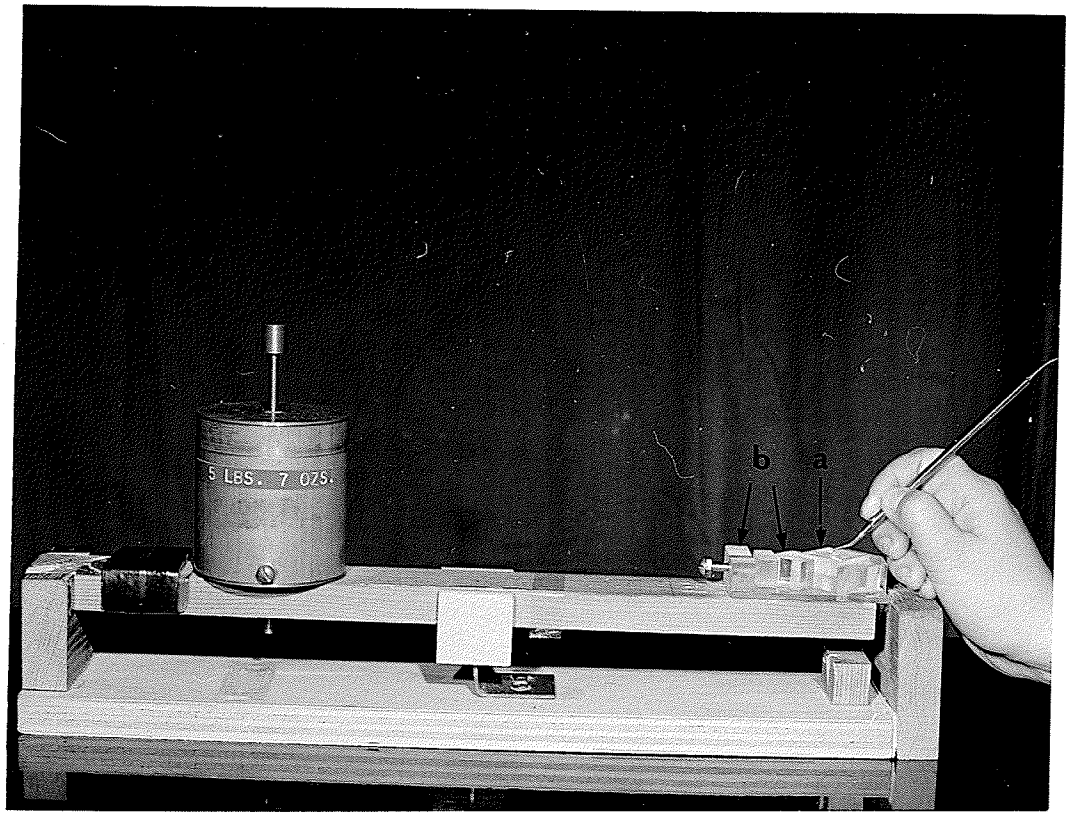

FIGURE 23

FIGURE 24 - INDEXING AND DIVIDING TABLE USED FOR TORSION TESTS

a- Device for measuring rotation in quarters of a degree

b- Torsion test specimen in place

c- Thread acting as a couple on the outer half of the specimen (Arrows show direction of forces)

d- Pulley

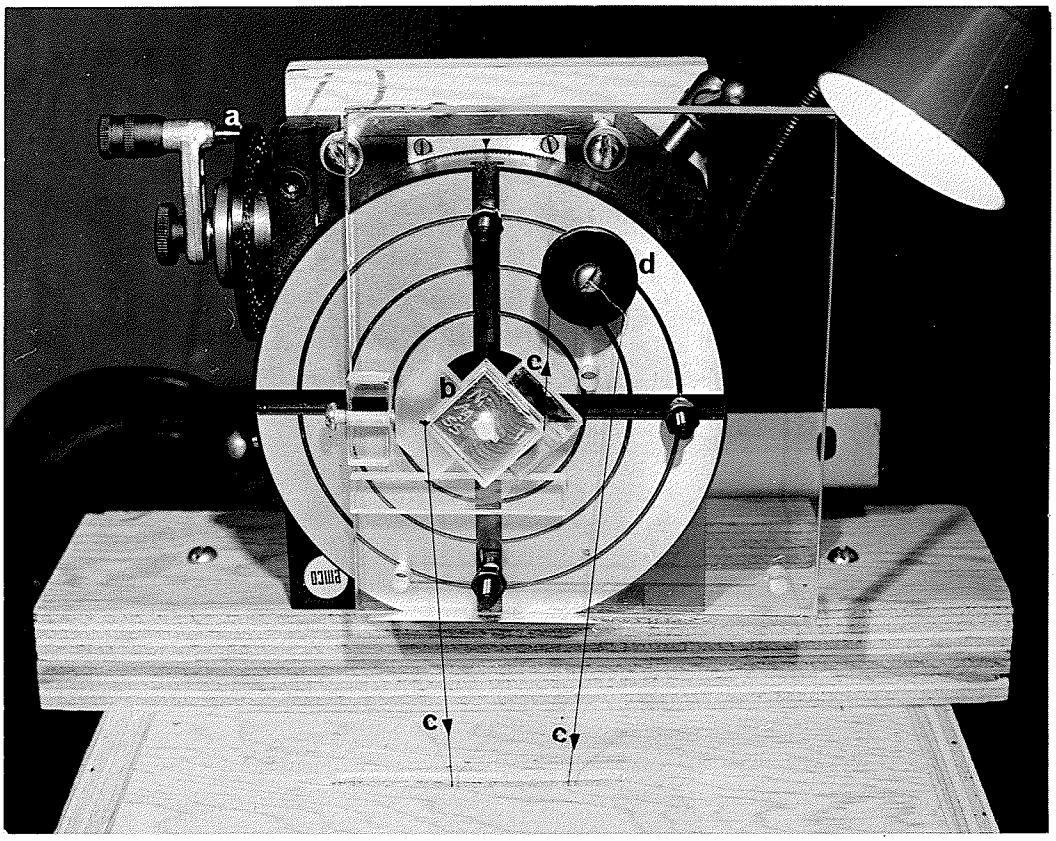

FIGURE 24

was used to measure the deflection of the pins under a given torsional load. The method of fixing the specimen to the indexing table and applying the torsional load is shown in Figure 24. The two threads have a common load applied as indicated by the arrows. The small pulley serves to reverse the direction of one of the forces resulting from the load on the thread. Assuming the pulley to be frictionless, this arrangement results in a pure couple on the specimen. A couple is defined in terms of two forces of equal magnitude with parallel lines of action but opposite signs. Since the sum of these forces is zero, the specimen is subjected to pure torsion only and no bending or other effects can be present. In practice the pulley must have some friction, but this was checked and found to be negligibly small.

As shown in Figure 24, the inner half of the specimen is secured to the dividing table whilst the outer half has the couple applied via the threads. Application of the couple then results in angular deflection of the outer half from its original position. Rotation of the dividing table and, hence, the inner half of the specimen, can then be made to restore the outer half to its original position. Thus, the amount of movement of the dividing table required to make this restoration is a direct measure of the angular deflection caused by the applied couple. Detection of the position of the outer half

was easily performed by means of a microscope * (Figure 25). The cross-wires of the microscope were aligned with one corner of the outer half of the specimen under zero-couple conditions. When a couple of given magnitude was applied, the dividing table was gently rotated until this corner of the specimen was again aligned with the microscope cross-wires.

Once the load had been removed, the zero position was checked. Any variation as compared to the initial location of the zero, gave an indication of plastic deformation or of initiation of the failure of the pin-amalgam bond. Increments of load of 20 grams up to the point of failure were utilized for sterling-silver and nickel-silver plated stainless-steel pins. Plain stainless-steel pins failed at a load of less than 10 grams. Longitudinal sections through the pin of the tested specimens were polished for microscopical examination, using the low power light microscopes.

Push-through tests

Specimens: The pin-amalgam specimen constructed for this kind of test was similar to the specimen used for load-deflection tests. It differed in the height of the amalgam (0.20 inch - 5.0 mm) and in that the pin protruded from both sides of the specimen, as shown in Figure 26. The push-through specimens were not mounted in bases. Five specimens

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* Travelling microscope - The Gaertner Scientific Corp., Chicago, Ill., U.S.A.

of each kind were built. They were tested when between thirty and forty hours old.

Apparatus and method: A universal screw type testing machine * adapted for tests in compression was used. The specimen was first placed on the top of the steel block that had been used for end effect experiments. One of the protruding ends of the pin was placed so that it would coincide with the hole in the block. In this manner, the flat surface of the amalgam could rest against the surface of the block. The whole assemby was placed between the jaws of the testing machine (Figure 27). A loading rate of 0.010 inch per minute (0.29 mm per minute) was used and the apparatus traced a load-deflection curve. The test was stopped in either one of three cases: (i) when the pin had been pushed through the amalgam, (ii) when it had completely deformed under the load, or (iii) when the amalgam was beginning to crack.

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* Riehle Testing Machine, Inc., East Moline, Ill., U.S.A.

FIGURE 25 - APPARATUS FOR TORSION TESTS

a- Travelling microscope

b- Experiment set-up as shown in figure 24

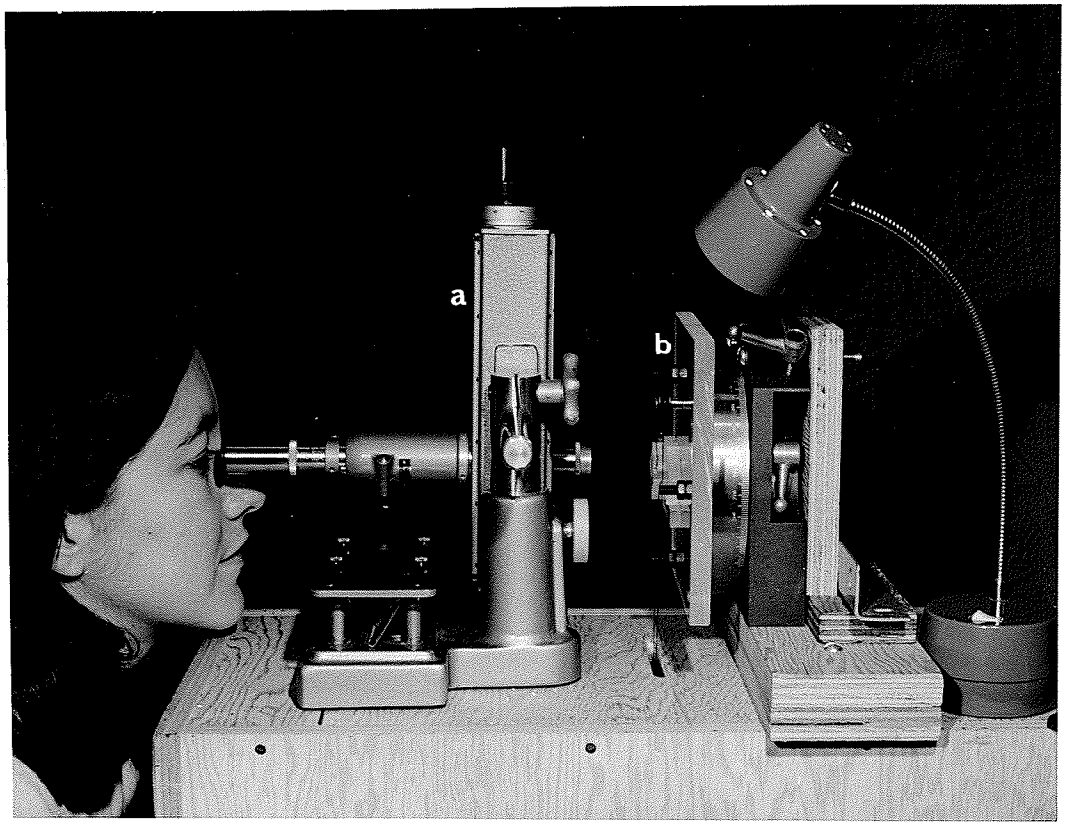


FIGURE 25

FIGURE 26 - SPECIMEN FOR PUSH-THROUGH TEST

a- Pin

b- Amalgam

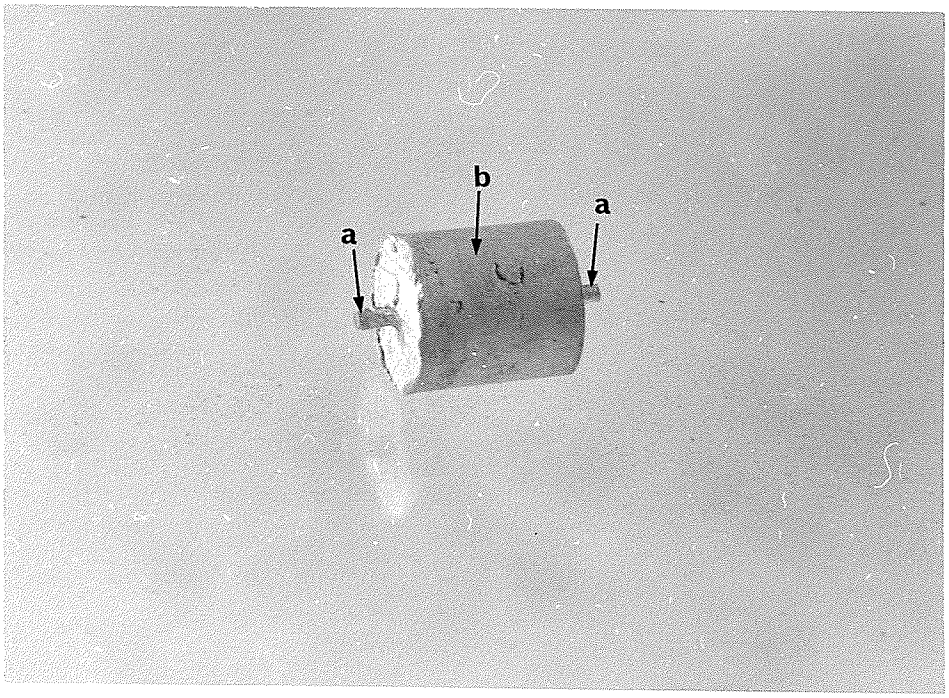


FIGURE 26

FIGURE 27 - PUSH-THROUGH TEST

a- Jaws of universal screw type testing machine

b- Steel block

c- Push-through specimen

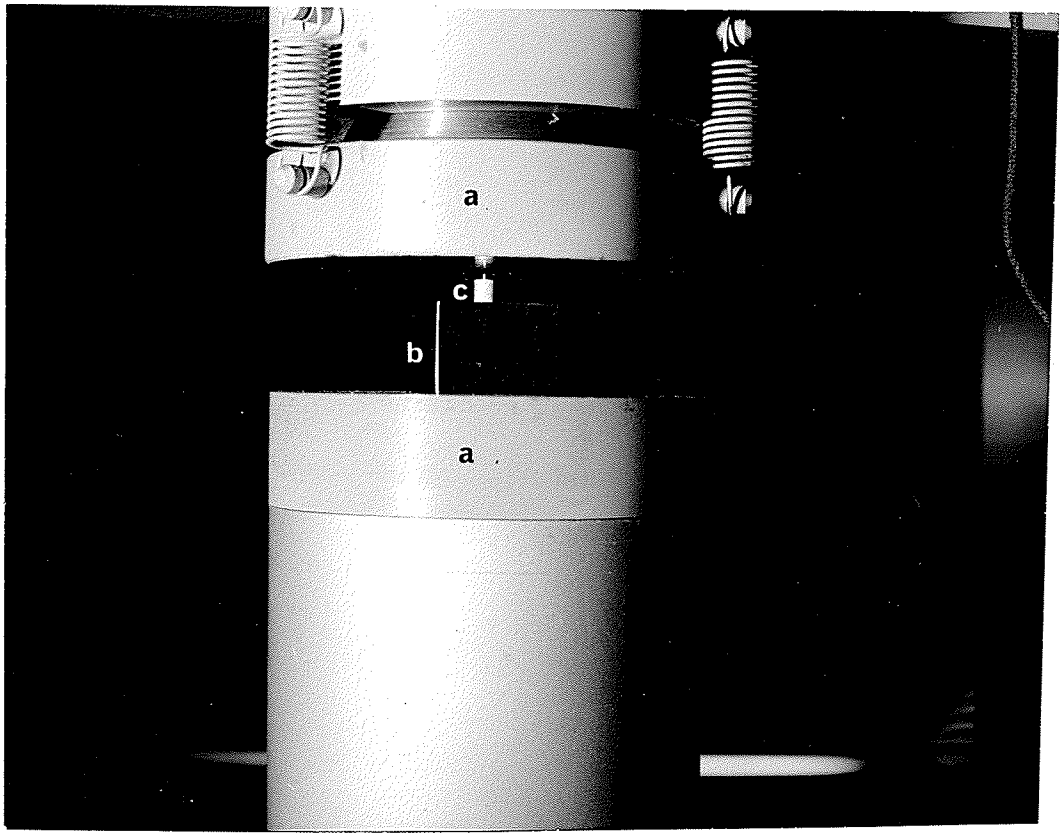


FIGURE 27

RESULTS

NICKEL-PLATED STAINLESS-STEEL WIRES

The interface between the nickel plate and the stainless-steel wire is shown in Figures 28 to 30. The continuity of the layer of nickel and the absence of voids between it and the stainless-steel surface is apparent in all the photomicrographs. This indicates a potential for good bonding.

An X-ray microprobe scan for nickel of a stainless-steel wire plated with nickel can be seen in Figure 31. The nickel layer applied on the surface of the wire was thicker than that used for microscopic examinations so that it could be clearly distinguished from the nickel present in the 18-8 stainless-steel. It can be observed that there appears to be a complete continuity between the nickel contained in the wire and the outside nickel layer. This fact is again stressed in the corresponding graph (Figure 32). The peaks representing the outside layer of nickel and the nickel present in the stainless-steel are indicated. No discontinuity was detected by the electron beam. However, as the beam had a diameter of the order of one micron, the possibility of a discontinuity measuring less than one micron could not be completely ruled out.

NICKEL-SILVER PLATED STAINLESS-STEEL WIRE

The metallographic microscopic examination indicated a complete continuity of the nickel-silver layer and the surface

of the stainless-steel, as shown in Figures 33 and 34. In this case, the extremely thin nickel layer is barely distinguishable from the silver layer or the stainless-steel wire. When examined with the SEM at different magnifications (Figures 35 to 40), the excellent adaptation of the plating to the wire is again shown. The outer surface of the plated wire had not been hand polished when this study was done.

A section of the same wire was analyzed with the X-ray microprobe (Figures 41 to 44). The three main components of stainless-steel (iron, chromium and nickel) as well as the silver layer, were scanned to find their distribution. The nickel layer applied to the surface of the wire is not distinguishable because it is extremely thin. In all photographs, there is a diffuse and ill-defined pattern corresponding to backscattered radiation. When superimposed, the images show that the silver has apparently diffused into the stainless-steel surface. The graph in Figure 45 shows the close relationship existing between the silver and the nickel layers. All these findings, however, were not considered to be sufficient proof of the presence of a bond between the plated layers and the stainless-steel. They merely displayed an excellent adaptation of the plated layers to the wire. Mechanical tests would give the assurance of bonding being present.

FIGURE 28 - NICKEL-PLATED STAINLESS STEEL WIRE
(HIGH POWER LIGHT MICROSCOPE)
2700 X original magnification, incident illumination, oil immersion, cross section
a- Etched stainless steel wire
b- Layer of nickel plate

FIGURE 29 - NICKEL-PLATED STAINLESS STEEL WIRE
(SCANNING ELECTRON MICROSCOPE)
100 X original magnification, cross section
a- Stainless steel wire
b- Layer of nickel plate

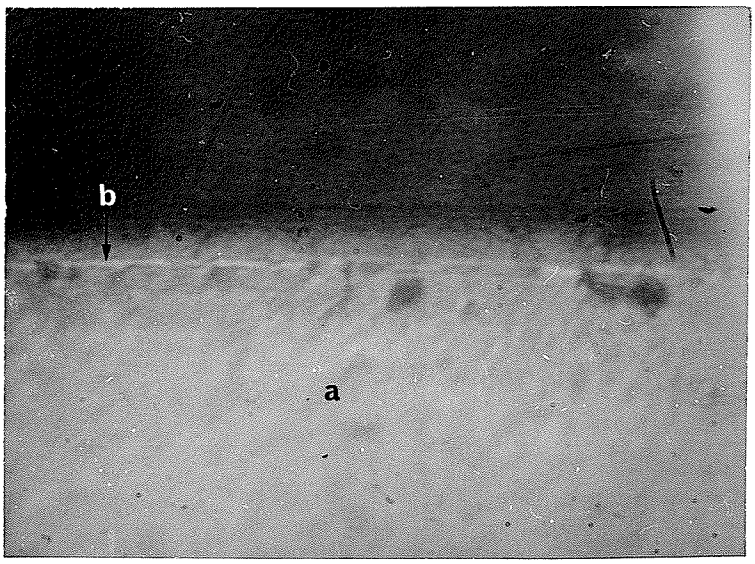


FIGURE 28

FIGURE 29

FIGURE 30 - NICKEL-PLATED STAINLESS STEEL WIRE
(SCANNING ELECTRON MICROSCOPE)
2000 X original magnification, cross section
a- Stainless steel wire
b- Layer of nickel plate
c- Bakelite mounting base

FIGURE 31 - NICKEL-PLATED STAINLESS STEEL WIRE
(X-RAY MICROPROBE, SCANNING FOR NICKEL)
a- Nickel contained in stainless steel wire
b- Nickel contained in layer of nickel-plate

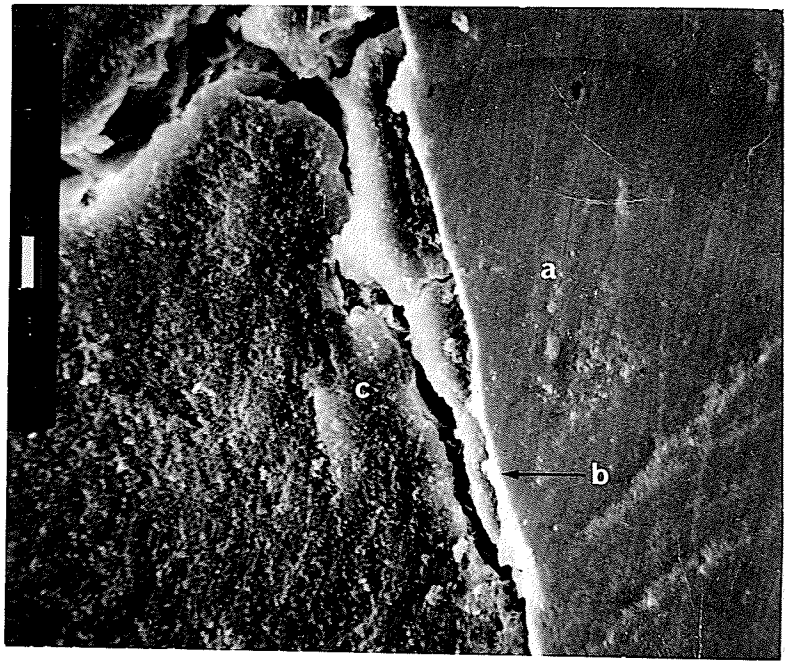


FIGURE 30

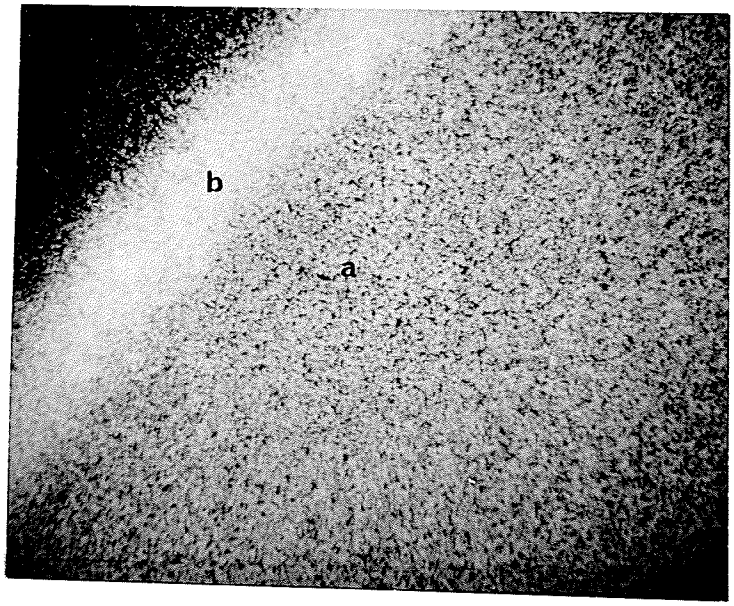


FIGURE 31

FIGURE 32 - GRAPH CORRESPONDING TO FIGURE 31

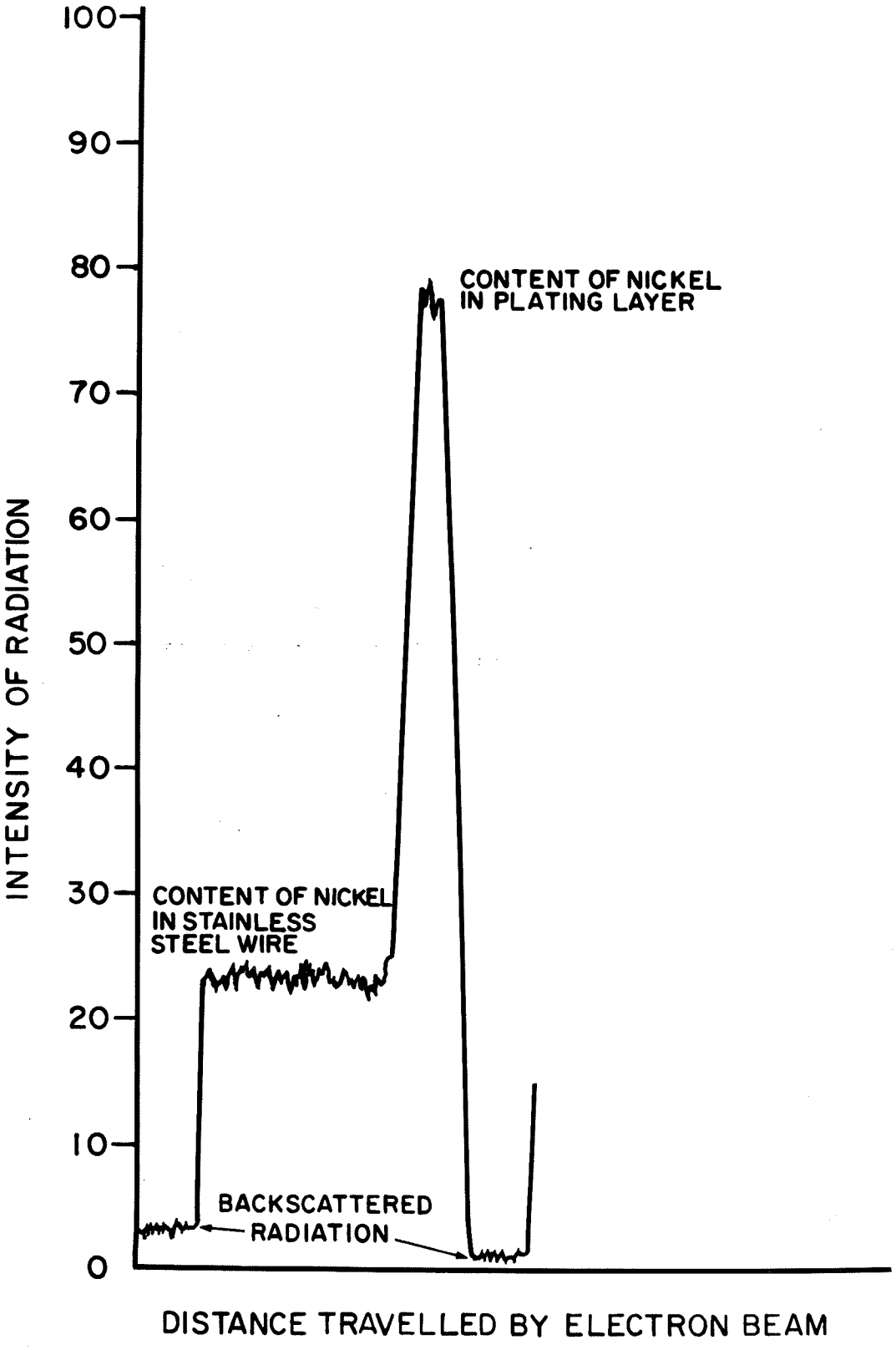

100
90
80
70
60
50
40
30
20
10
0
INTENSITY OF RADIATION
CONTENT OF NICKEL
IN PLATING LAYER
CONTENT OF NICKEL
IN STAINLESS
STEEL WIRE
BACKSCATTERED
RADIATION
DISTANCE TRAVELLED BY ELECTRON BEAM

FIGURE 32

FIGURE 33 - NICKEL-SILVER PLATED STAINLESS STEEL WIRE (METALLOGRAPHIC MICROSCOPE)

80 X original magnification, cross section

a- Stainless steel wire

b- Layer of nickel plate

c- Layer of silver plate

FIGURE 34 - NICKEL-SILVER PLATED STAINLESS STEEL WIRE (METALLOGRAPHIC MICROSCOPE)

120 X original magnification, cross section

a- Stainless steel wire

b- Layer of nickel plate

c- Layer of silver plate

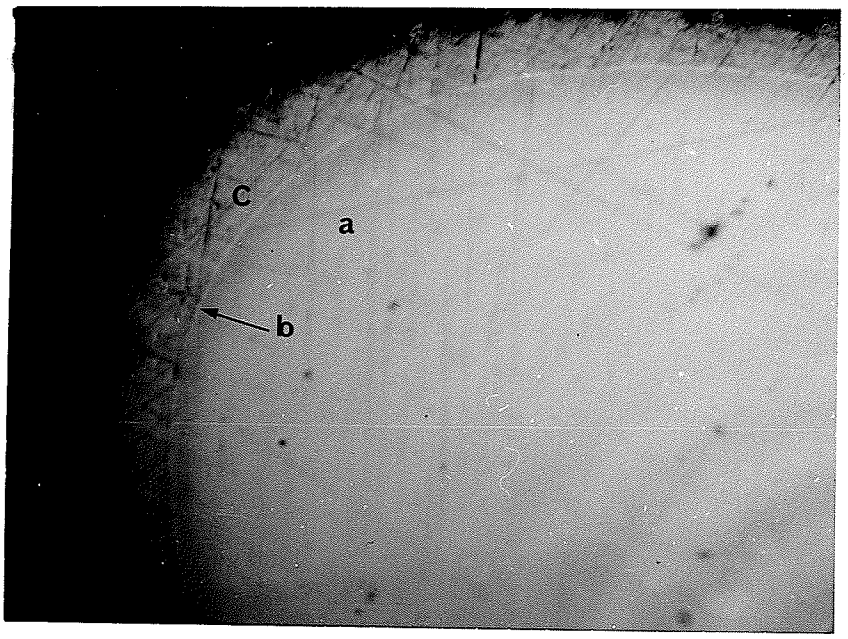


FIGURE 33

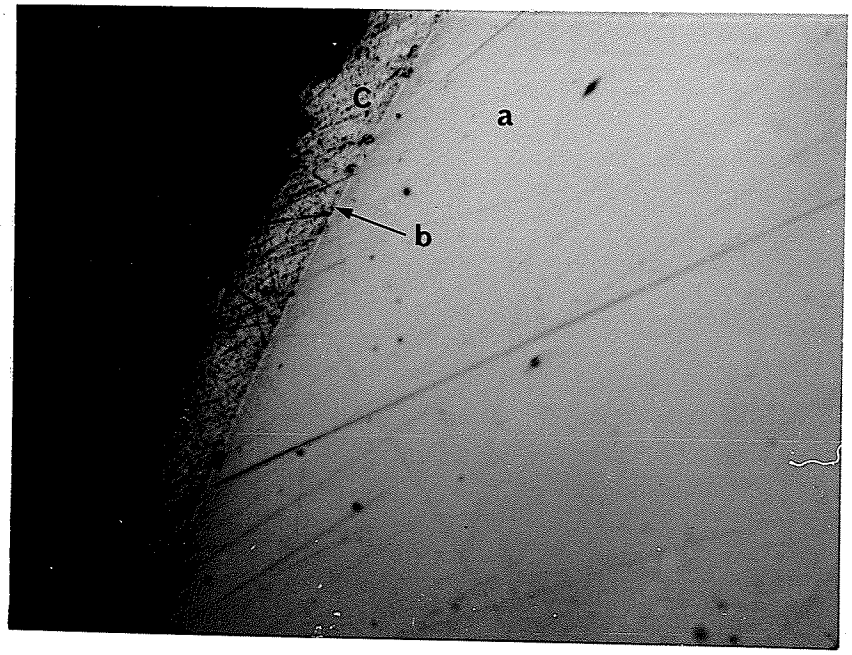


FIGURE 34

FIGURE 35 - NICKEL-SILVER PLATED STAINLESS STEEL WIRE (SCANNING ELECTRON MICROSCOPE)
100 X original magnification, cross section
a- Nickel and silver plate layers
b- Stainless steel wire

FIGURE 36 - NICKEL-SILVER PLATED STAINLESS STEEL WIRE (SCANNING ELECTRON MICROSCOPE)
200 X original magnification, cross section
a- Nickel and silver plate layers
b- Stainless steel wire

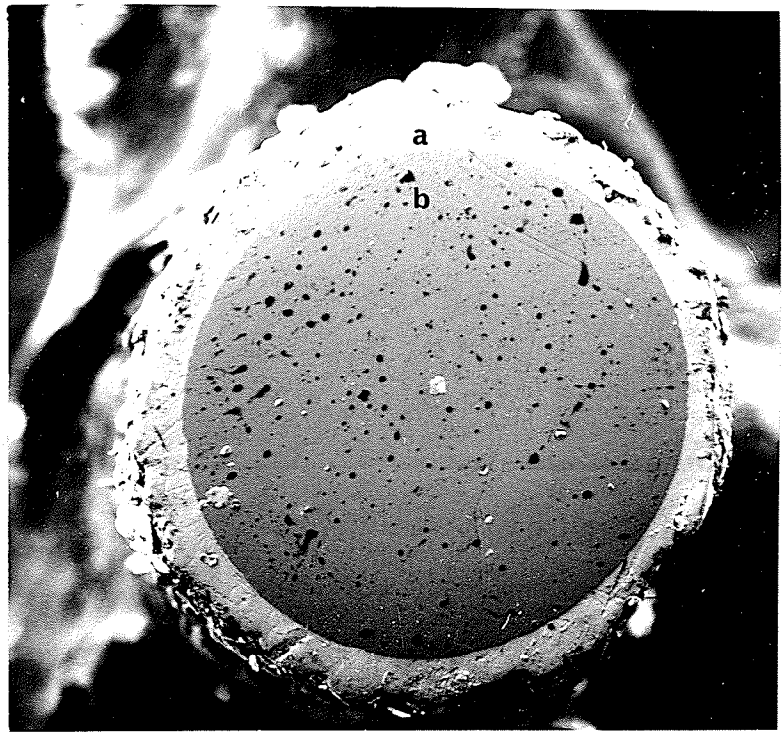


FIGURE 35

FIGURE 36

FIGURE 37 - NICKEL-SILVER PLATED STAINLESS STEEL WIRE (SCANNING ELECTRON MICROSCOPE)
230 X original magnification, cross section
a- Nickel and silver plate layers
b- Stainless steel wire

FIGURE 38 - NICKEL-SILVER PLATED STAINLESS STEEL WIRE (SCANNING ELECTRON MICROSCOPE)
1100 X original magnification, cross section
a- Nickel and silver plate layers
b- Stainless steel wire

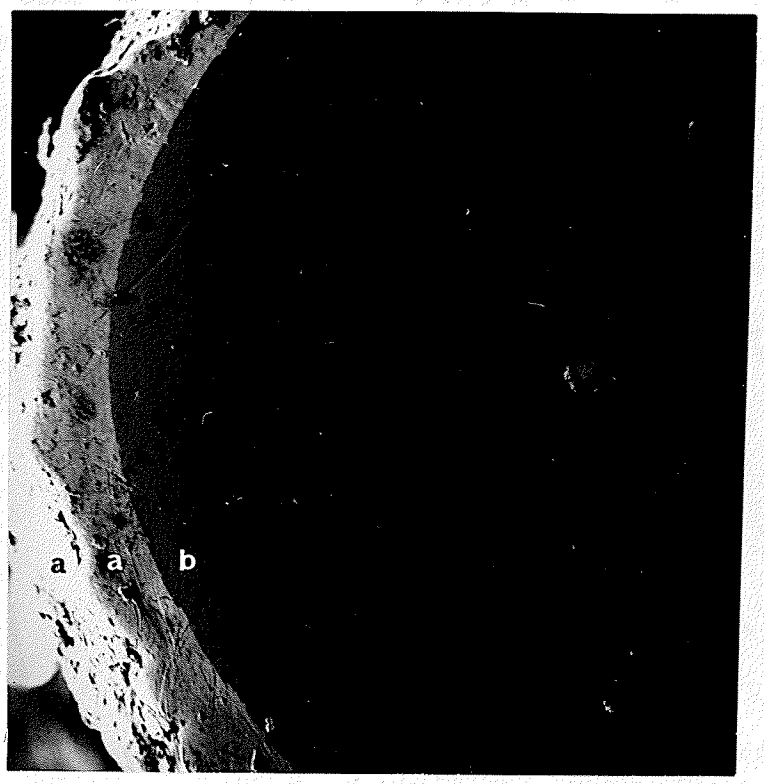


FIGURE 37

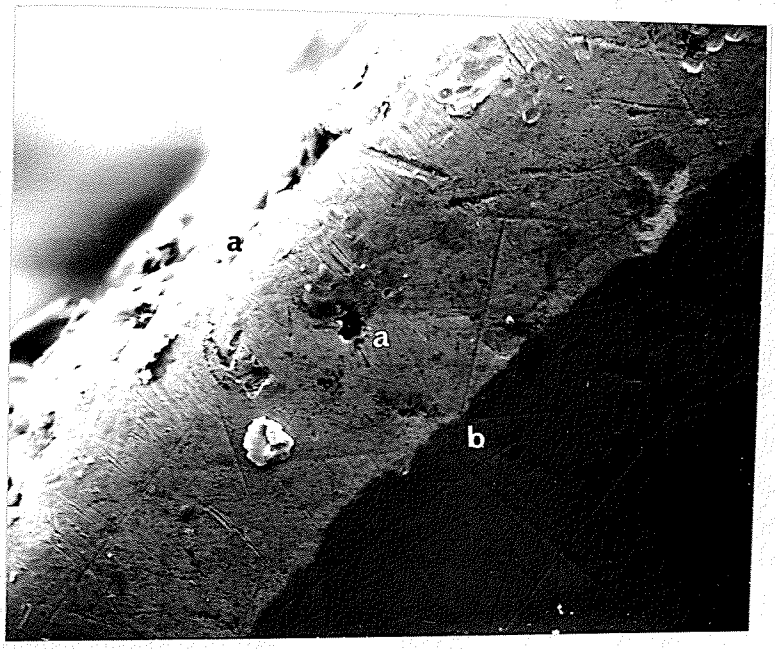


FIGURE 38

FIGURE 39 - NICKEL-SILVER PLATED STAINLESS STEEL WIRE (SCANNING ELECTRON MICROSCOPE) 2200 X original magnification, cross section

a- Nickel and silver plate layers

b- Stainless steel wire

FIGURE 40 - NICKEL-SILVER PLATED STAINLESS STEEL WIRE (SCANNING ELECTRON MICROSCOPE) 5500 X original magnification, cross section

a- Nickel and silver plate layers

b- Stainless steel wire

FIGURE 39

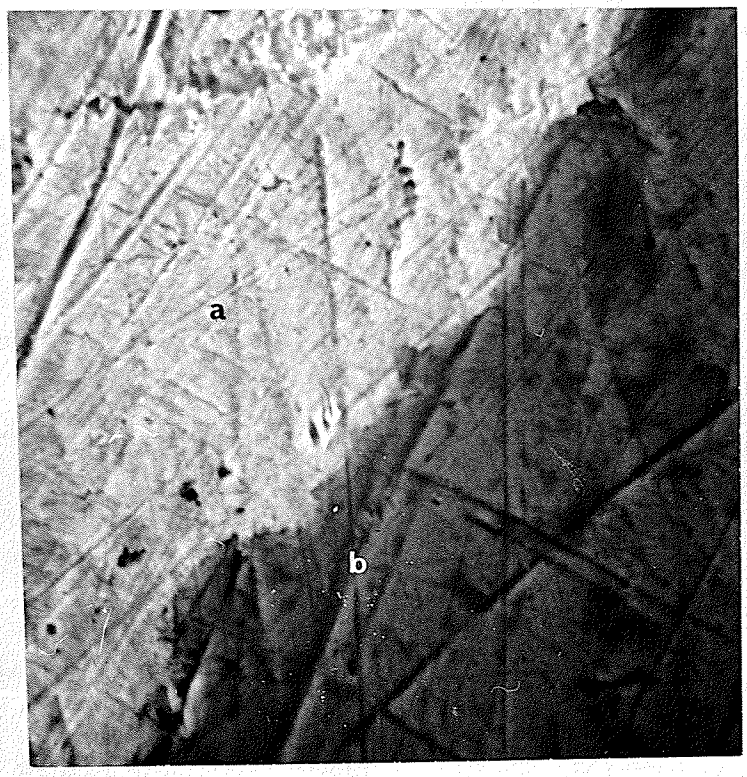


FIGURE 40

FIGURE 41 - NICKEL-SILVER PLATED STAINLESS STEEL WIRE (X-RAY MICROPROBE, SCANNING FOR SILVER)

FIGURE 42 - NICKEL-SILVER PLATED STAINLESS STEEL WIRE (X-RAY MICROPROBE, SCANNING FOR NICKEL)

FIGURE 43 - NICKEL-SILVER PLATED STAINLESS STEEL WIRE (X-RAY MICROPROBE, SCANNING FOR IRON)

FIGURE 44 - NICKEL SILVER PLATED STAINLESS STEEL WIRE (X-RAY MICROPROBE, SCANNING FOR CHROMIUM)

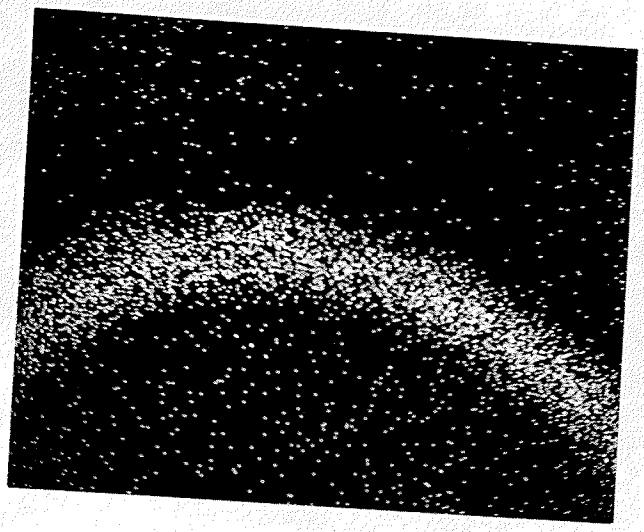


FIGURE 41

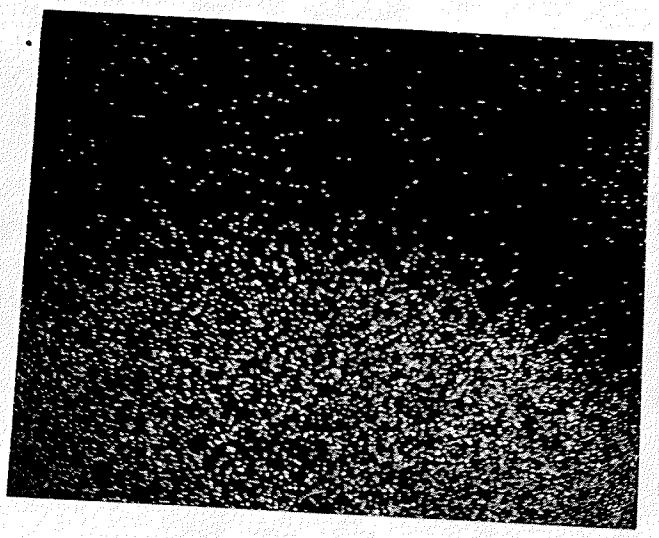


FIGURE 42

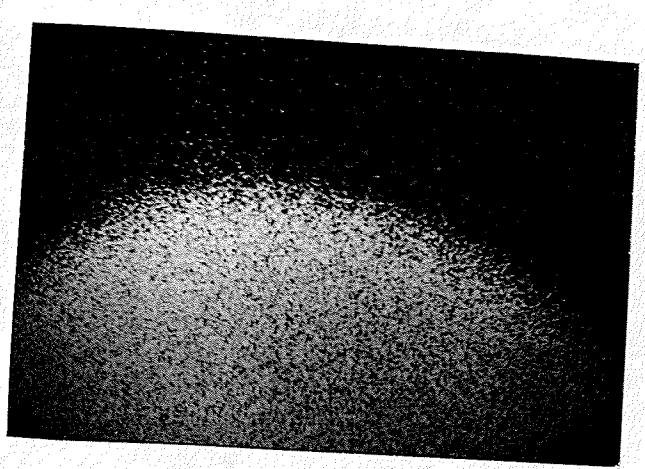


FIGURE 43

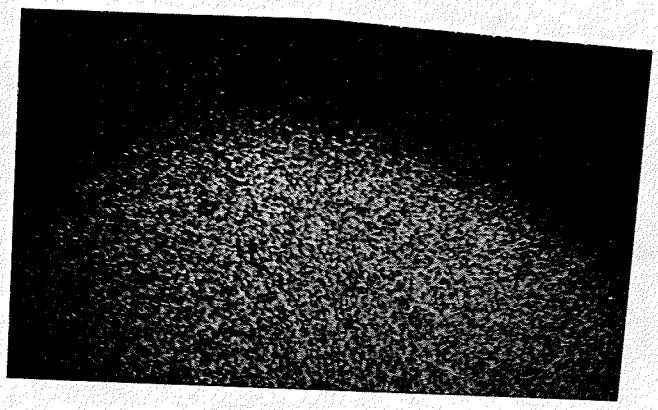
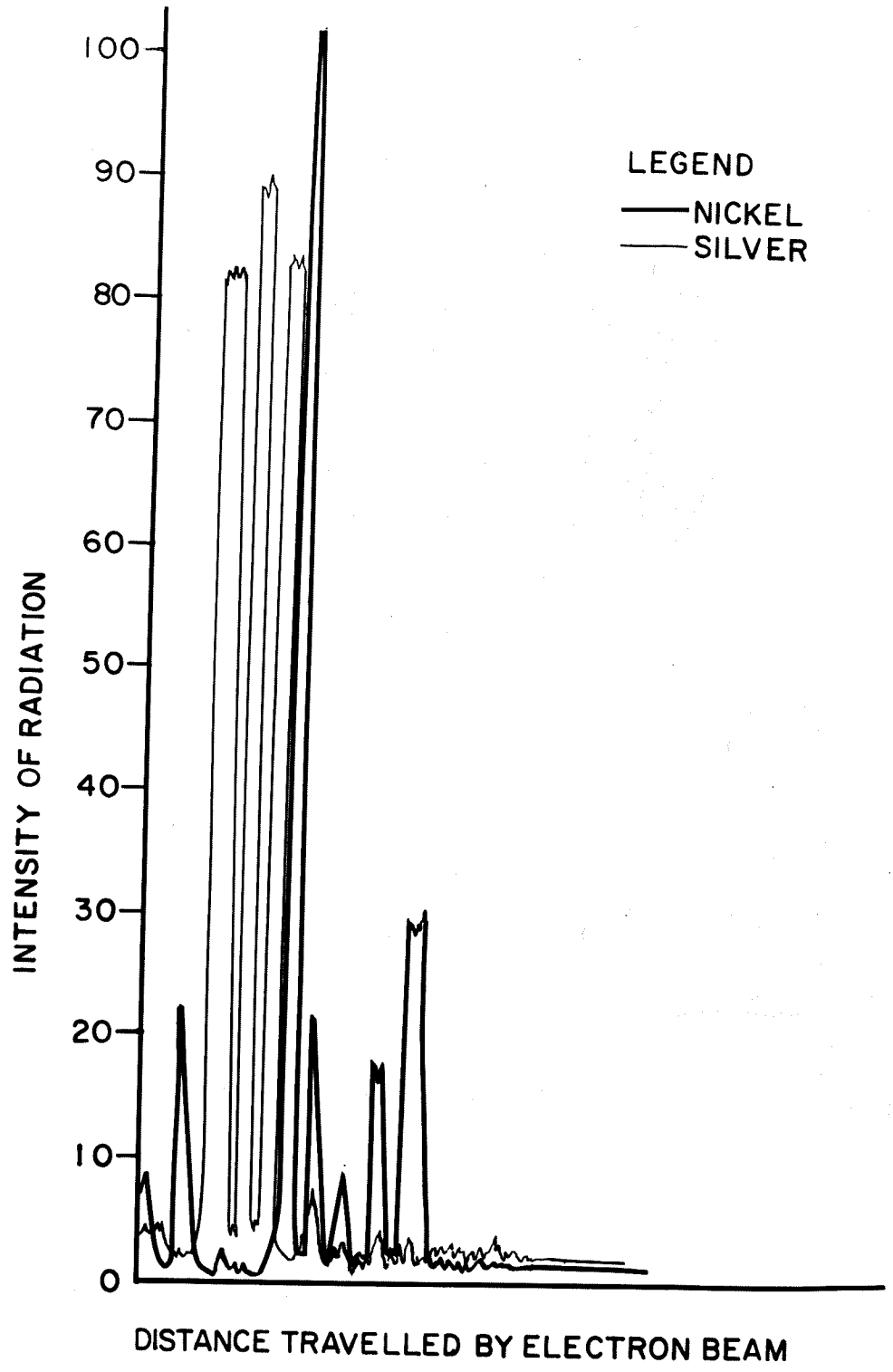


FIGURE 44

FIGURE 45 - NICKEL-SILVER PLATED STAINLESS STEEL WIRE (X-RAY MICROPROBE)
Graph corresponding to scanning for silver and nickel plate layers


100
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0
INTENSITY OF RADIATION
LEGEND
NICKEL
SILVER
DISTANCE TRAVELLED BY ELECTRON BEAM

FIGURE 45

PIN-RETAINED AMALGAM

The method of condensing amalgam around pins proved to be very important. If not condensed as suggested in this thesis, the amalgam does not come into proper contact with the entire surface of the pin resulting in the formation of large voids between the pin and the amalgam. Mechanical retention, the only kind afforded by a stainless-steel pin, is not as effective if voids are present at the pin-amalgam interface. The nickel-silver plated stainless-steel and sterling-silver pins cannot produce a metallurgical bond with amalgam if they are not in proper contact with it.

The complete lack of bonding between ordinary stainless-steel and amalgam was confirmed by the experiments performed in the present research. These pins, when embedded in amalgam, were viewed under a low power microscope. As shown in Figure 46, large voids are present around the pin when conventional condensing methods are used. When the freshly mixed amalgam was carefully rubbed against the surface of the pin before condensation, the adaptation of amalgam to the pin greatly improved. A continuous space is present around the stainless-steel pin because of the lack of metallurgical union between the amalgam and the pin. Large voids are absent (Figure 47).

Low-power light-microscope photomicrographs showing results of both methods of amalgam condensation around sterling-silver and nickel-silver plated stainless-steel pins,

can be seen in Figures 48 to 52. Pins, in which a chemical bond with the amalgam was anticipated, were examined with the scanning electron microscope. Figures 53 to 56 show the excellent adaptation of the amalgam to the silver layer plated on the stainless-steel pins. Also, Figures 57, 58 and 59 show that the adaptation of the sterling-silver pin to the amalgam is of such a high order that the pin-amalgam interface can hardly be recognized. Both results confirm findings by other authors [135] about the superior metallurgical compatibility between silver and dental amalgam.

The X-ray microprobe study of bonded pins in amalgam was done in two parts. The first involved scanning of the pin and surrounding amalgam in order to see the relationship of the different kinds of metals in the pin and the amalgam. The second consisted of an analysis of the composition at the pin-amalgam interface.

The silver contained in the sterling-silver pin diffused at the pin-amalgam interface (Figure 60). A scan for silver of the plated stainless-steel pin and the surrounding amalgam, showed, as expected, a reaction between the layer of silver and the amalgam (Figure 63). This was later confirmed by the results obtained from the mechanical tests performed to determine the effectiveness of the pin-amalgam bond. A scan for tin showed an even distribution of this element around both types of pins studied (Figures 61 and 64). The scan for mercury did not give clear results

(Figures 62 and 65).

In the second part of the X-ray microprobe study it was not possible to analyze the sterling-silver pin-amalgam interface. This was due to the fact that the diameter of the electron beam was larger than the reaction layer thickness. In the case of plated stainless-steel pins in amalgam, only a limited analysis was possible. Because of the many phases of different compositions present in amalgam, no exact standards for silver, tin or mercury could be set. For this reason, it was not possible to give exact percentages of these elements at the plated pin-amalgam interface. A much more complex analysis, related to the reactions of the silver layer with each one of the different neighbouring amalgam phases, is beyond the scope of this investigation. The results indicate that silver, tin and mercury are all present at the plated pin-amalgam interface. Silver at the interface is present in a higher proportion than either tin or mercury. This aspect of the research requires further investigation to find the exact composition of the reaction layers present at the bonded pin-amalgam interfaces.

All of these results were not considered to be sufficient proof of the formation of a metallurgical bond. The possibility of burnishing the silver onto the stainless-steel surface when the sample was prepared for microscopic study could produce close adaptation of the silver to the

FIGURE 46 - STAINLESS STEEL PIN IN AMALGAM - CONVENTIONAL METHOD OF AMALGAM CONDENSATION (METALLOGRAPHIC MICROSCOPE)
80 X original magnification, longitudinal section
a- Stainless steel pin
b- Void
c- Amalgam

FIGURE 47 - STAINLESS STEEL PIN IN AMALGAM - RUBBING METHOD OF AMALGAM CONDENSATION (METALLOGRAPHIC MICROSCOPE)
40 X original magnification, longitudinal section
a- Stainless steel pin
b- Space
c- Amalgam

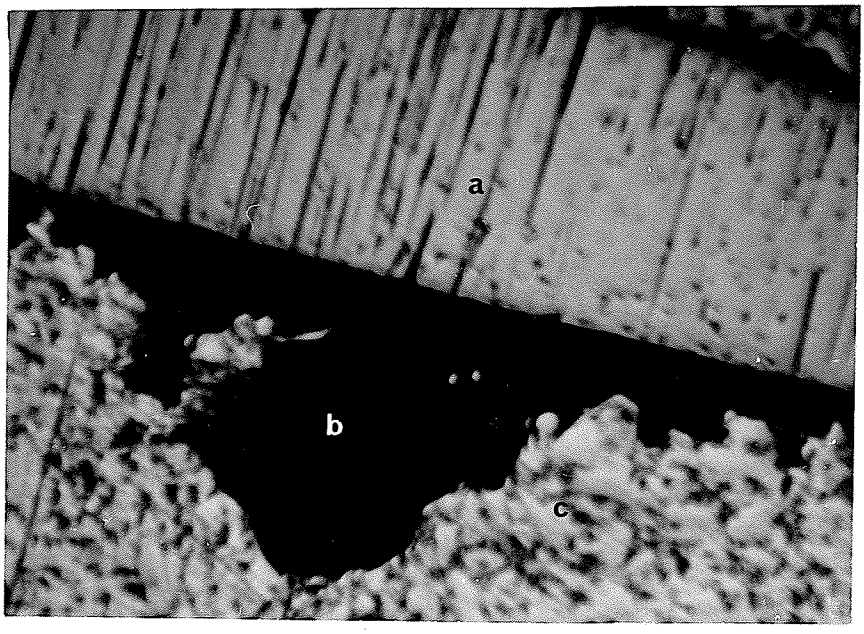


FIGURE 46

FIGURE 47

FIGURE 48 - STERLING-SILVER PIN IN AMALGAM - CONVENTIONAL METHOD OF AMALGAM CONDENSATION (METALLOGRAPHIC MICROSCOPE)
160 X original magnification, cross section
a- Sterling-silver pin
b- Space
c- Amalgam

FIGURE 49 - STERLING-SILVER PIN IN AMALGAM - RUBBING METHOD OF AMALGAM CONDENSATION (METALLOGRAPHIC MICROSCOPE)
160 X original magnification, cross section
a- Sterling-silver pin
b- Pin-amalgam reaction layer
c- Amalgam

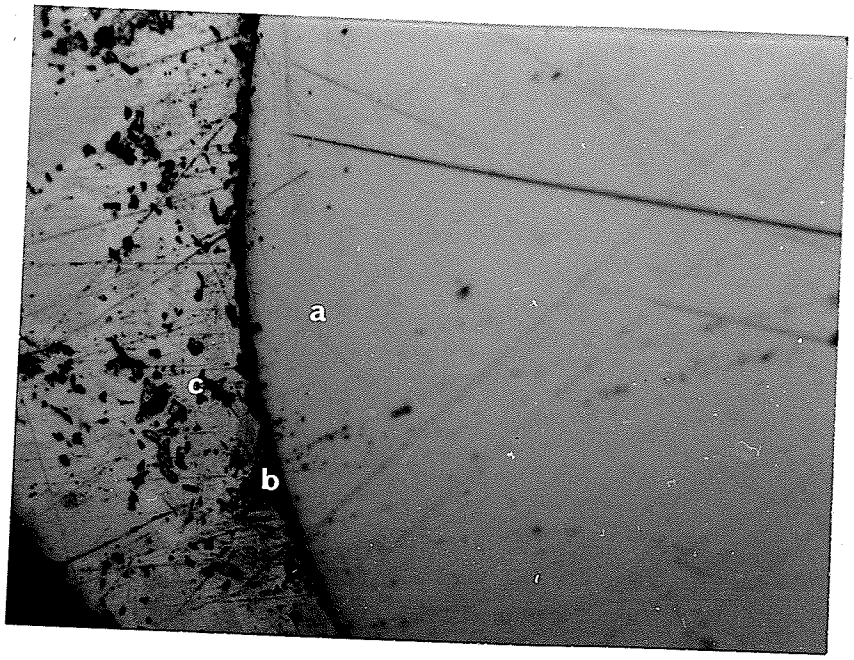


FIGURE 48

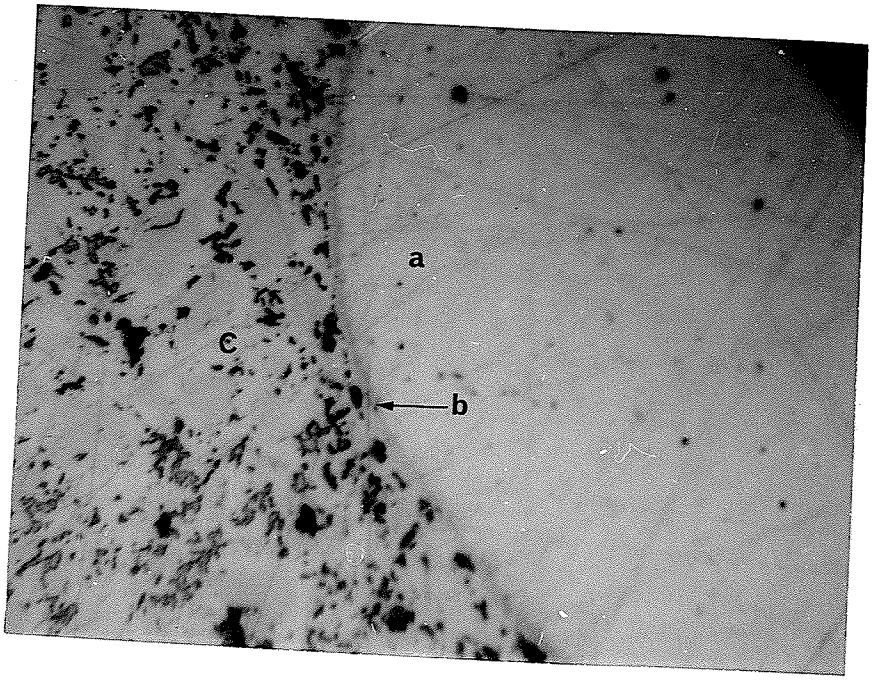


FIGURE 49

FIGURE 50 - STERLING-SILVER PIN IN AMALGAM - RUBBING METHOD OF AMALGAM CONDENSATION (METALLOGRAPHIC MICROSCOPE)

30 X original magnification, cross section

a- Sterling-silver pin

b- Reaction layer between pin and amalgam

c- Amalgam

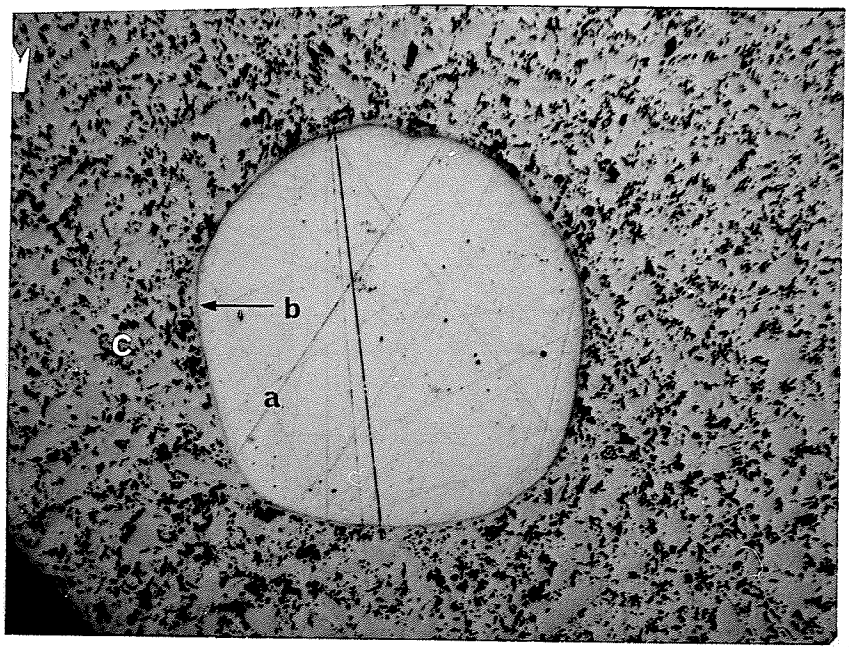


FIGURE 50

FIGURE 51 - NICKEL-SILVER PLATED STAINLESS STEEL PIN IN AMALGAM - CONVENTIONAL METHOD OF AMALGAM CONDENSATION (METALLOGRAPHIC MICROSCOPE)

80 X original magnification, cross section

a- Stainless steel pin

b- Nickel and silver plate layers

c- Space

d- Amalgam

FIGURE 52 - NICKEL-SILVER PLATED STAINLESS STEEL PIN IN AMALGAM - RUBBING METHOD OF AMALGAM CONDENSATION (METALLOGRAPHIC MICROSCOPE)

80 X original magnification, cross section

a- Stainless steel pin

b- Nickel and silver plate layers

c- Amalgam

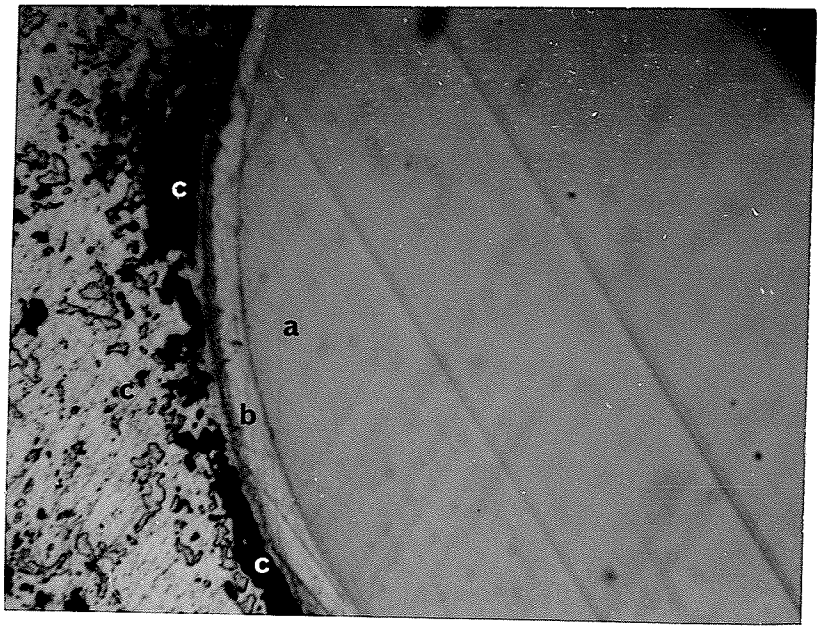


FIGURE 51

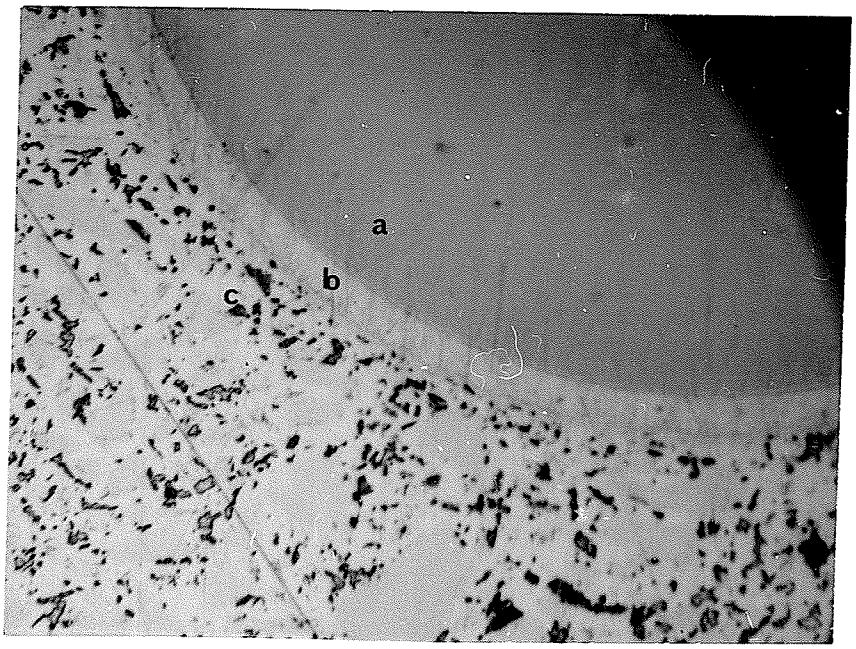


FIGURE 52

FIGURE 53 - NICKEL-SILVER PLATED STAINLESS STEEL PIN IN AMALGAM - RUBBING METHOD OF AMALGAM CONDENSATION (SCANNING ELECTRON MICROSCOPE)

110 X original magnification, cross section

a- Stainless steel pin

b- Nickel and silver plate layers

c- Amalgam

FIGURE 54 - NICKEL-SILVER PLATED STAINLESS STEEL PIN IN AMALGAM - RUBBING METHOD OF AMALGAM CONDENSATION (SCANNING ELECTRON MICROSCOPE)

1100 X original magnification, cross section

a- Stainless steel pin

b- Nickel and silver plate layers

c- Amalgam

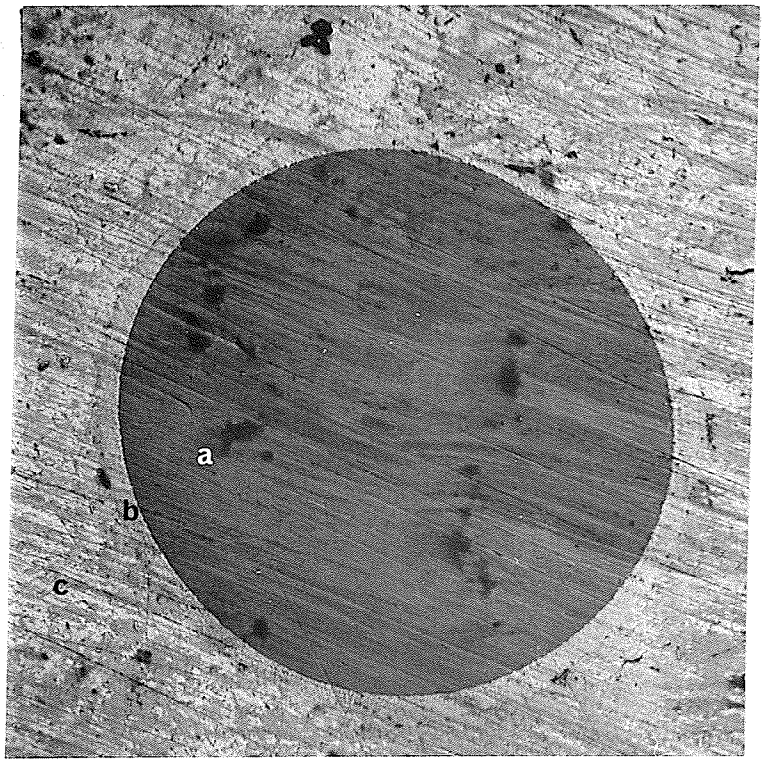


FIGURE 53

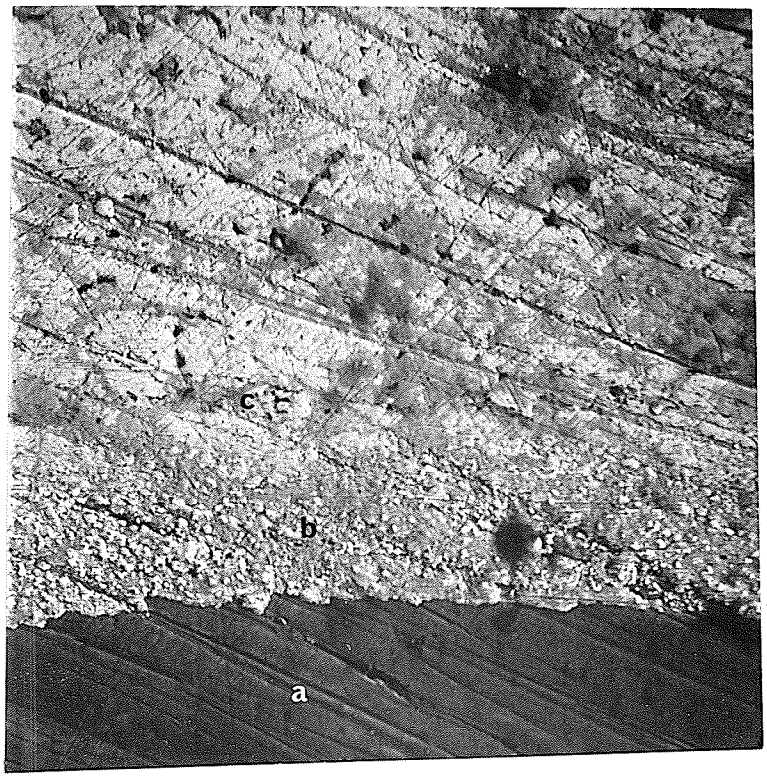


FIGURE 54

FIGURE 55 - NICKEL-SILVER PLATED STAINLESS STEEL PIN IN AMALGAM - RUBBING METHOD OF AMALGAM CONDENSATION (SCANNING ELECTRON MICROSCOPE)

1600 X original magnification, cross section

a- Stainless steel pin

b- Nickel and silver plate layers

c- Amalgam

FIGURE 56 - NICKEL-SILVER PLATED STAINLESS STEEL PIN IN AMALGAM - RUBBING METHOD OF AMALGAM CONDENSATION (SCANNING ELECTRON MICROSCOPE)

5600 X original magnification, cross section

a- Amalgam

b- Nickel and silver plate layers

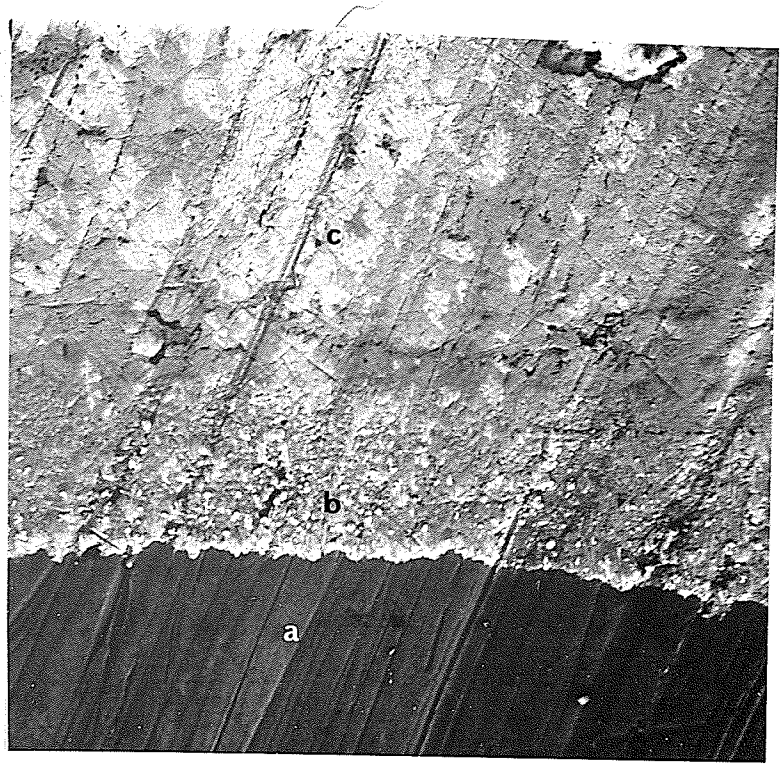


FIGURE 55

FIGURE 56

FIGURE 57 - STERLING-SILVER PIN IN AMALGAM -
RUBBING METHOD OF AMALGAM CONDENSATION
(SCANNING ELECTRON MICROSCOPE)
55 X original magnification, cross section
a- Sterling-silver pin
b- Amalgam

FIGURE 58 - STERLING-SILVER PIN IN AMALGAM -
RUBBING METHOD OF AMALGAM CONDENSATION
(SCANNING ELECTRON MICROSCOPE)
110 X original magnification, cross section
a- Sterling-silver pin
b- Amalgam

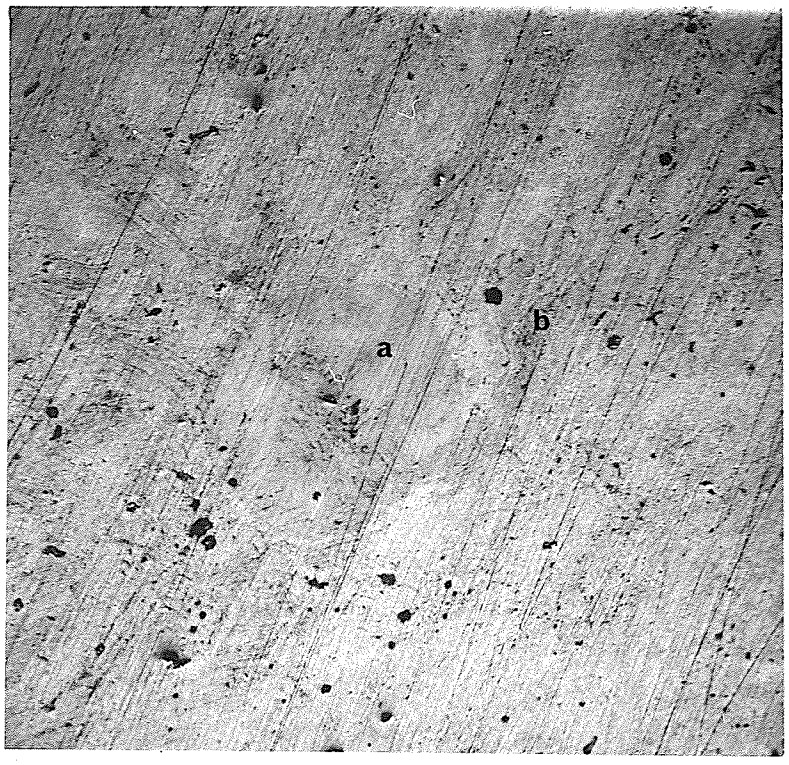


FIGURE 57

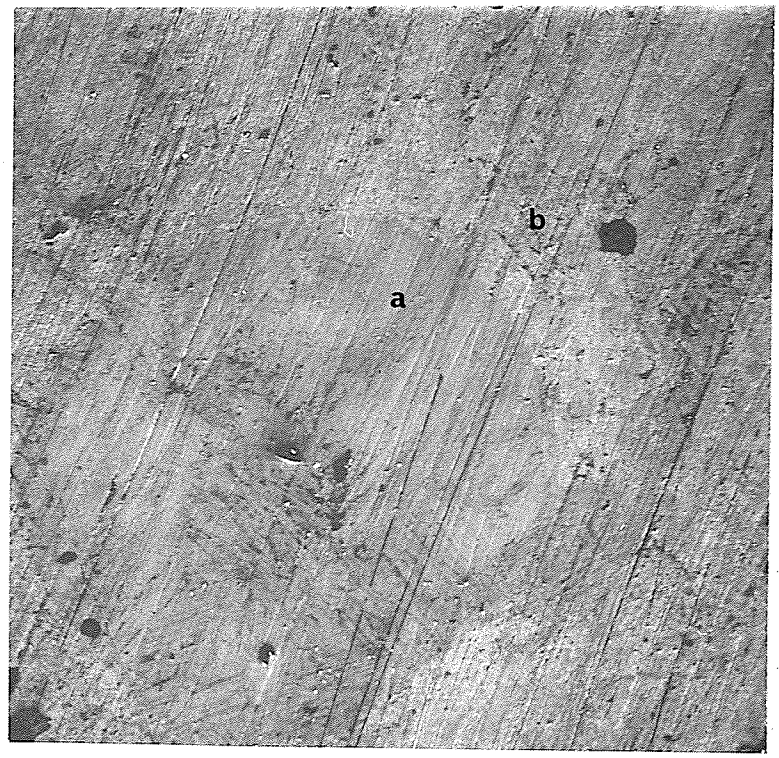


FIGURE 58

FIGURE 59 - STERLING-SILVER PIN IN AMALGAM -
RUBBING METHOD OF AMALGAM CONDENSATION
(SCANNING ELECTRON MICROSCOPE)
220 X original magnification, cross section
a- Sterling-silver pin
b- Amalgam

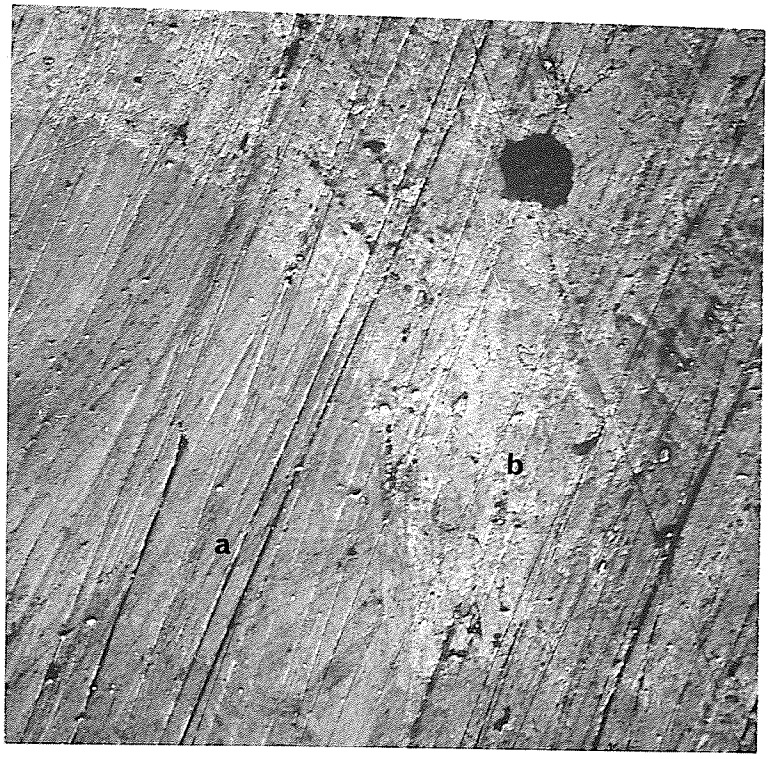


FIGURE 59

FIGURE 60 - STERLING-SILVER PIN IN AMALGAM
(X-RAY MICROPROBE, SCANNING FOR SILVER)

FIGURE 61 - STERLING-SILVER PIN IN AMALGAM
(X-RAY MICROPROBE, SCANNING FOR TIN)

FIGURE 62 - STERLING-SILVER PIN IN AMALGAM
(X-RAY MICROPROBE, SCANNING FOR MERCURY)

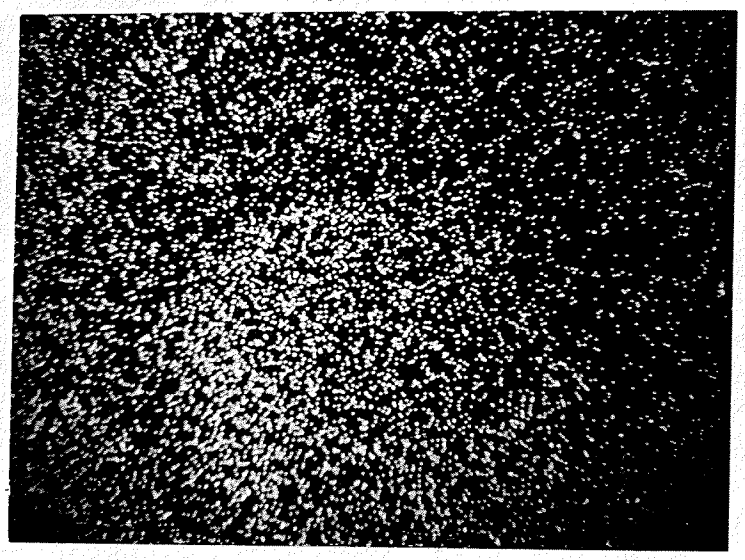


FIGURE 60

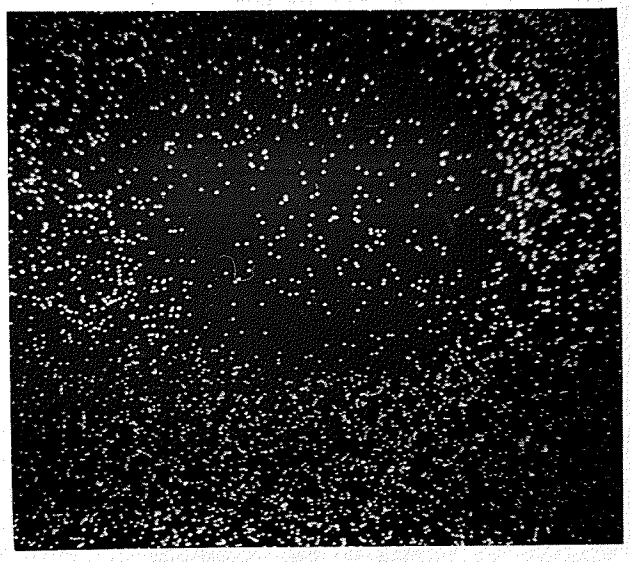


FIGURE 61

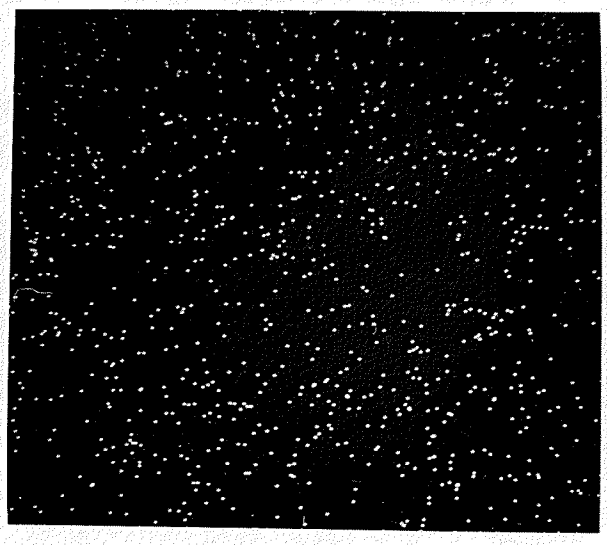


FIGURE 62

FIGURE 63 - NICKEL-SILVER PLATED STAINLESS STEEL PIN IN AMALGAM (X-RAY MICROPROBE, SCANNING FOR SILVER)

FIGURE 64 - NICKEL-SILVER PLATED STAINLESS STEEL PIN IN AMALGAM (X-RAY MICROPROBE, SCANNING FOR TIN)

FIGURE 65 - NICKEL-SILVER PLATED STAINLESS STEEL PIN IN AMALGAM (X-RAY MICROPROBE, SCANNING FOR MERCURY)

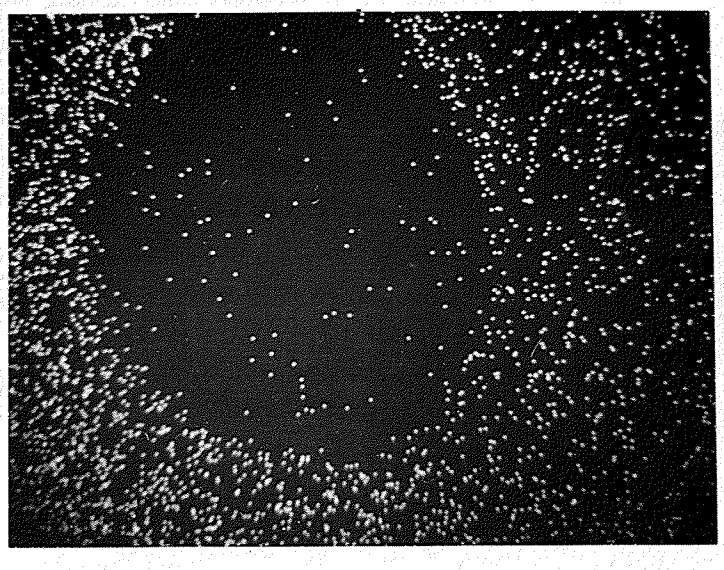


FIGURE 63

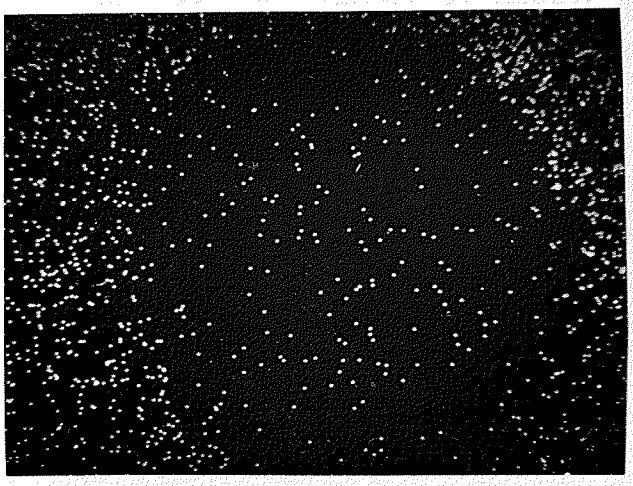


FIGURE 64

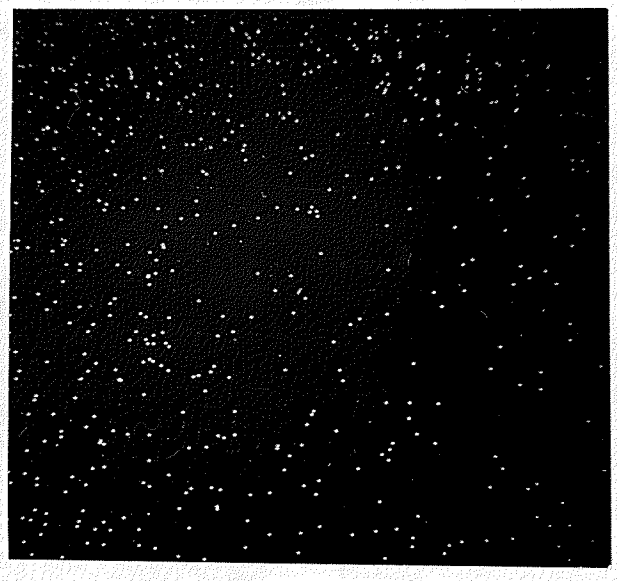


FIGURE 65

pin. Also, an excellent adaptation of the amalgam to the pin surface could give the impression of a good bond being present. However, metallurgical studies conducted so far, strongly indicated that it is possible to obtain a good pin-amalgam bond. To confirm this fact, mechanical tests were subsequently performed.

DETERMINATION OF MECHANICAL PROPERTIES

MODULUS OF ELASTICITY

The mean values found for Young's modulus were about 2×10^6 PSI for dental amalgam and about 10×10^6 PSI for sterling-silver. No further statistical analysis was performed, because only a rough check of the two materials was required. Values were in agreement with previously published data [90].

AXIAL LOAD-DEFLECTION TESTS

Tables I and II give the means, standard deviations, standard errors of the mean and coefficients of variability of the corrected results obtained from axial load-deflection tests. An analysis of variance for mixed factorial designs was performed. The results are presented in Tables III and IV.

TABLE I

AXIAL LOAD - DEFLECTION MEASUREMENTS * FOR A 6.7 Nw (1.5 lb) LOAD

	MEAN	STANDARD DEVIATION	STANDARD ERROR OF THE MEAN	COEFFICIENT OF VARIABILITY
Stainless steel pins	8.286	2.051	0.346	0.246
Sterling silver pins	4.600	3.273	0.553	0.711
Nickel-silver plated stainless steel pins	5.657	3.067	0.518	0.541

* Deflections are given in microns

TABLE II

AXIAL LOAD - DEFLECTION MEASUREMENTS * FOR A 20.1 Nw (4.5 lb) LOAD

	MEAN	STANDARD DEVIATION	STANDARD ERROR OF THE MEAN	COEFFICIENT OF VARIABILITY
Stainless steel pins	24.686	6.003	1.014	0.242
Sterling silver pins	14.686	11.585	1.958	0.788
Nickel-silver plated stainless steel pins	16.714	5.963	1.007	0.356

*Deflections are given in microns

TABLE III

MEAN AXIAL LOAD-DEFLECTION MEASUREMENTS * FOR EACH OF THREE KINDS OF SPECIMENS AT 6.7 Nw (1.5 lb) AND 20.1 Nw (4.5 lb) LOADS

	DEFLECTION UNDER LOAD		DEFLECTION DIFFERENCES BETWEEN THE TWO LOADS	MEAN OF DEFLECTIONS REGARDLESS OF LOAD
	6.7 Nw	20.1 Nw		
Stainless steel pins	8.286	24.686	16.400	16.486
Sterling silver pins	4.600	14.686	10.086	9.643
Nickel-silver plated stainless steel pins	5.657	16.714	11.057	11.186
MEAN OF DEFLECTIONS REGARDLESS OF THE KIND OF SPECIMEN	6.181	18.695	12.514	12.438

* Deflections are given in microns

TABLE IV

ANALYSIS OF VARIANCE FOR MIXED FACTORIAL DESIGNS

SOURCE OF VARIATION	DEGREES OF FREEDOM	MEAN DEFLECTION SQUARE
Among specimens	2	901.7712 **
Error (a)	102	55.1877
Between loads	1	8221.8711 ***
Specimen X load	2	202.2968 **
Error (b)	102	21.5345

** $P < 0.01$

*** $P < 0.001$

The values found for the correction factors for the experimental means were:

Correction factor	Deflection in microns	
	4.5 lb (20.1 Nw)	1.5 lb (6.7 Nw)
end effect	1.60	0.70
canting of transducer	0.53	0.18
deflection of transducer	0.16	0.06
TOTAL	2.29	0.94

The above correction factors were constant for all the specimens and could therefore be subtracted as a total. The deflection of the pin outside the amalgam was calculated for each individual pin. Formulas for correction of the experimental mean were as follows:

For 4.5 pound (20.1 Nw) load :

Corrected mean = (experimental mean) - (2.29) - (deflection of pin)

For 1.5 pound (6.7 Nw) load :

Corrected mean = (experimental mean) - (0.94) - (deflection of pin)

Stainless-steel pins presented the highest deflection values. The deflection values of plated stainless-steel pins

and sterling-silver pins followed in that order and were not appreciably different. The slenderness ratio of the pins was such that with the axially applied loads no buckling of the pins occurred. The slenderness ratio is the ratio of the length of the pin to the radius of gyration of the cross-section.

TORSION TESTS

Typical load-deflection curves in torsion for the three types of pin-amalgam specimens and the zero offset after release of load are plotted in Figure 66.

Typical failure loads for each one of the three kinds of pin-amalgam specimens were as follows:

- stainless-steel pins in amalgam, 10 grams
- sterling-silver pins in amalgam, 100 grams
- plated stainless-steel pins in amalgam, 240 grams

The three types of pins produced typical curves that were very different from one another. For each type of pin used, the results were quite consistent for all of the specimens studied. For these reasons no statistical analysis was considered necessary.

In Figure 67 a specimen is shown while being loaded to the point of failure. Stainless-steel pin-amalgam specimens failed completely and suddenly with the first load used, namely,10 grams. There is the possibility that this

failure might have occurred with less load, but this was not checked. Once the specimen failed, it was removed from the dividing table. It was extremely easy to separate the two halves with the fingers. The pin was easily withdrawn from one half but was retained in the other half of the specimen (Figure 68). Only friction factors and microscratches accounted for this retention. A slight degree of lateral movement of the pin was present when pushed with the fingers. A longitudinal section of the remaining pin in amalgam after failure of the specimen, was viewed under 80 X original magnification as shown in Figure 69. A complete absence of bond and a chipping of the amalgam edges surrounding the pin were evident. The nature of the occurrence of failure of the two other kinds of specimens tested was much less dramatic than that of stainless-steel pin-amalgam specimens. This failure occurred progressively with increasing loads.

Once the test was completed and the bonded pin-amalgam specimens removed from the dividing table, their two halves were separated by hand. Plated stainless-steel pin-amalgam specimens presented some resistance to separation. The plated pin was withdrawn from the tested half and remained tightly fitted on the other half of the specimen (Figure 70). When viewed under 40 X original magnification, the silver plating was still present on the pin. No peeling of the plating was evident but its surface was brilliant and rough.

FIGURE 66 - TORSION TESTS - TYPICAL LOAD-DEFLECTION CURVES UP TO THE POINT OF FAILURE

Curve A = Assumed

Curves B and C = Best fit to experimental points

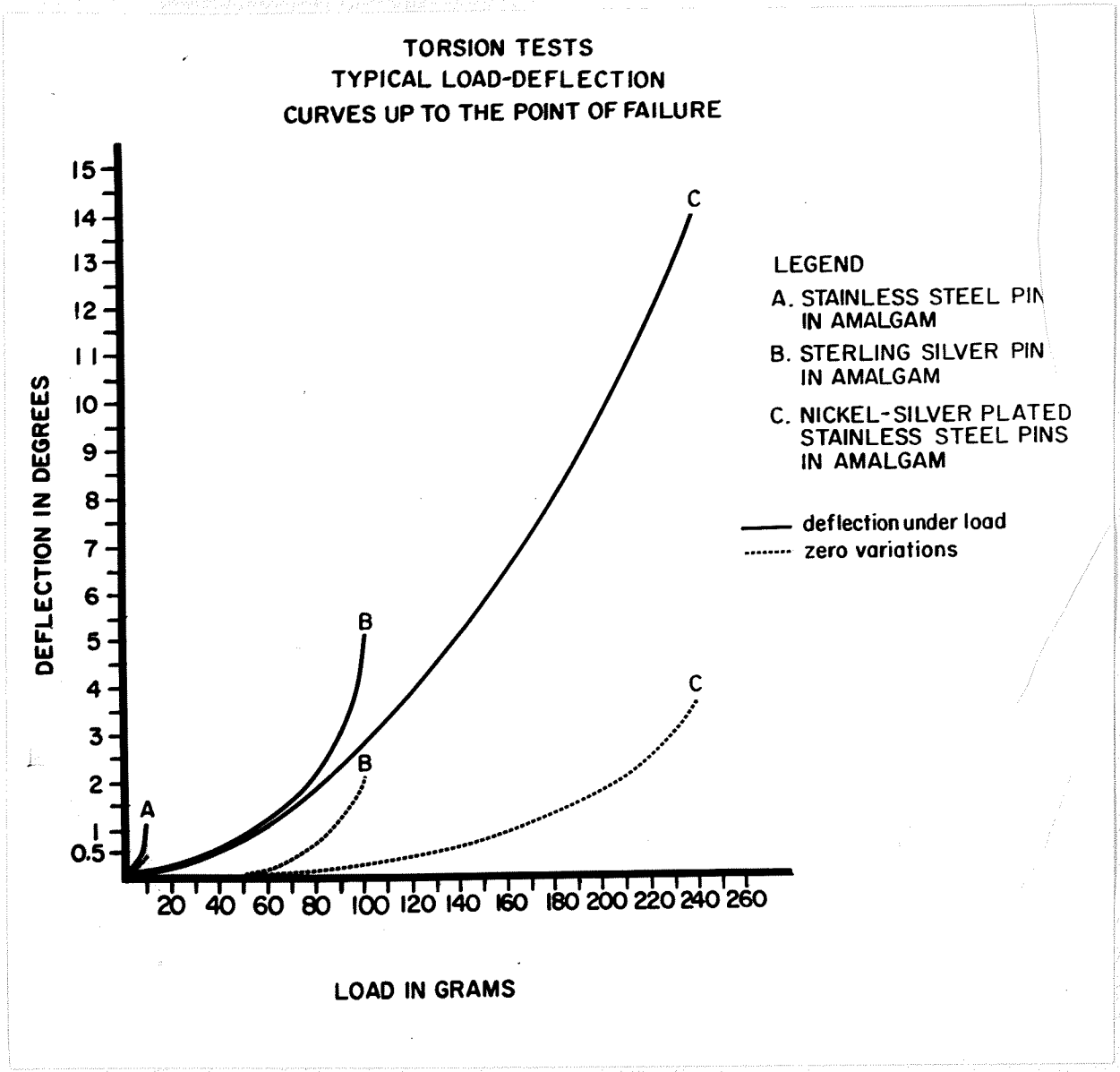

TORSION TESTS
TYPICAL LOAD-DEFLECTION
CURVES UP TO THE POINT OF FAILURE
DEFLECTION IN DEGREES
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0.5
A
B
B
C
C
20 40 60 80 100 120 140 160 180 200 220 240 260
LOAD IN GRAMS
LEGEND
A. STAINLESS STEEL PIN IN AMALGAM
B. STERLING SILVER PIN IN AMALGAM
C. NICKEL-SILVER PLATED STAINLESS STEEL PINS IN AMALGAM
deflection under load
zero variations

FIGURE 66

FIGURE 67 - TORSION SPECIMEN DURING TESTING TO THE POINT OF FAILURE

Arrows show direction of forces

Explanation of the method of testing is shown in figure 24

a- Inner half of the specimen

b- Outer half of the specimen

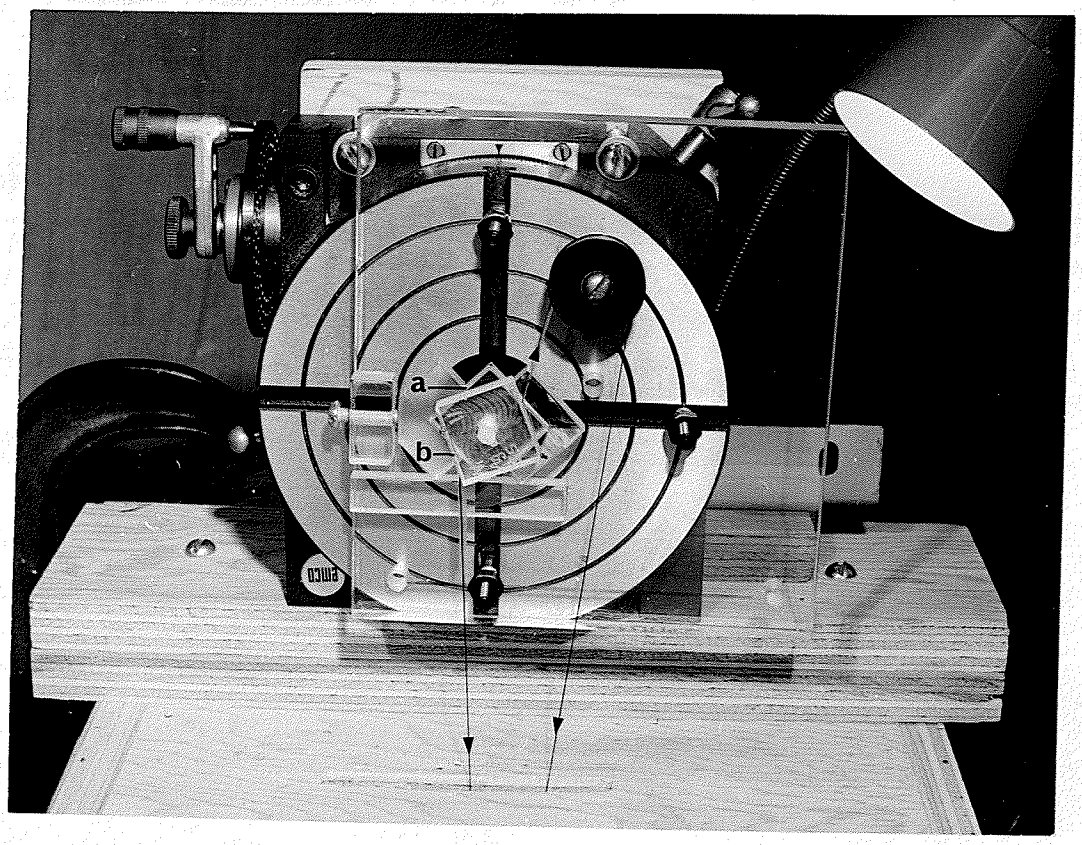


FIGURE 67

FIGURE 68 - STAINLESS STEEL PIN-AMALGAM SPECIMEN FAILED IN TORSION

a- Inner half of the specimen

b- Outer (tested) half of the specimen

c- Pin

d- Hole from which the pin was withdrawn

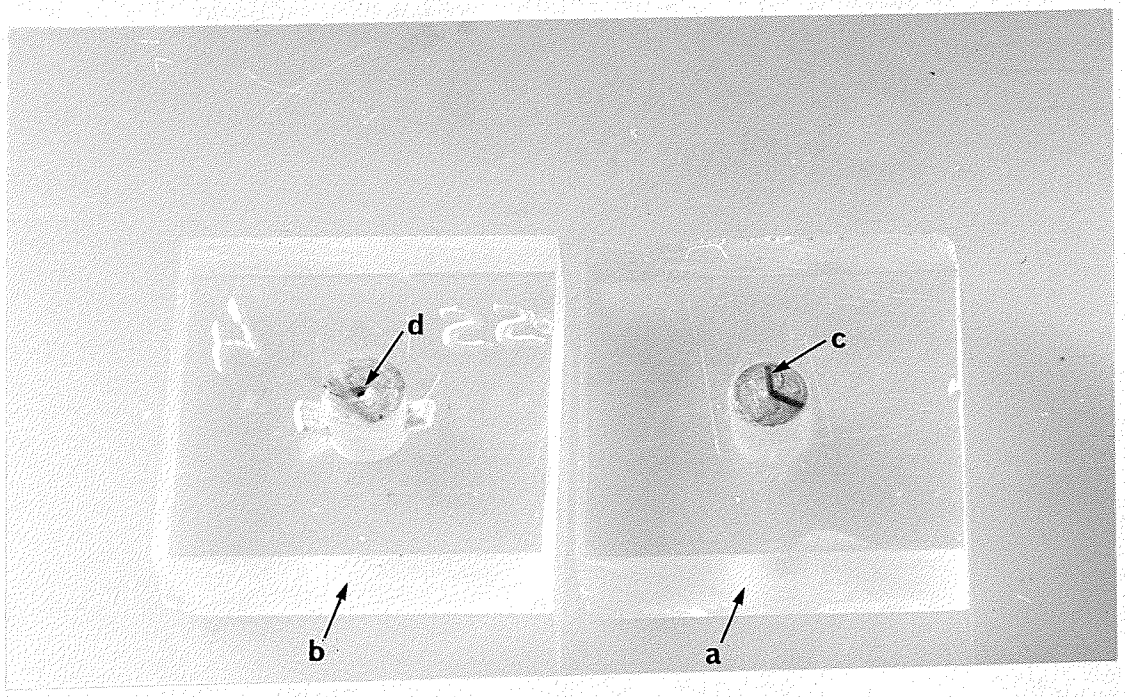


FIGURE 68

FIGURE 69 - STAINLESS STEEL PIN IN AMALGAM AFTER TORSION TEST (METALLOGRAPHIC MICROSCOPE) 80 X original magnification, longitudinal section

a- Stainless steel pin

b- Amalgam

c- Chipping of amalgam edges

FIGURE 69

FIGURE 70 - NICKEL-SILVER PLATED STAINLESS STEEL PIN-AMALGAM SPECIMEN FAILED IN TORSION

a- Inner half of the specimen

b- Outer (tested) half of the specimen

c- Pin with plate layers

d- Hole from which the pin was withdrawn

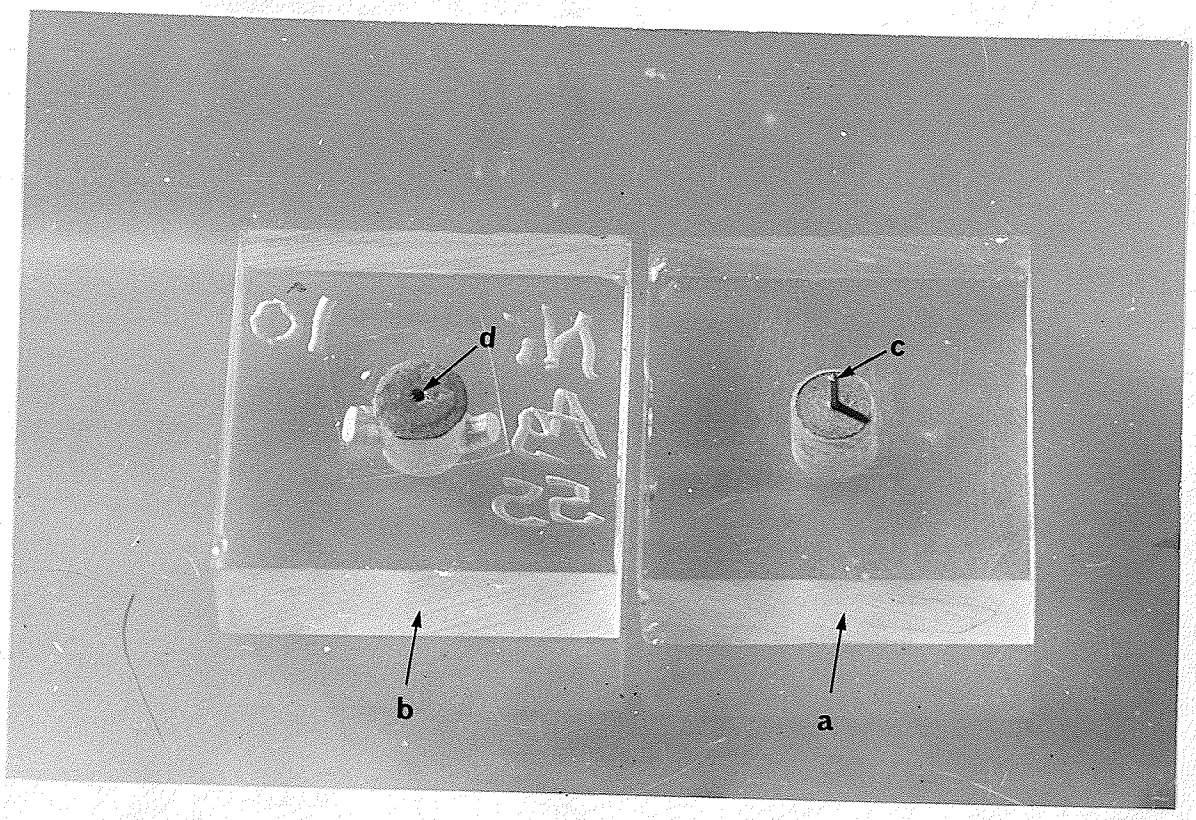


FIGURE 70

This gave the impression that either part of the silver had remained attached to the amalgam or part of the amalgam was attached to the surface of the plating. Both possibilities could have happened simultaneously. On the other hand, the brilliance and roughness of the silver layer could also be due to a change in its chemical composition because of the reaction with amalgam which had taken place.

The hole left in the amalgam after withdrawal of the plated pin was viewed under 120 X magnification. Because it was impossible to completely illuminate its depth, only the edge of its inside wall could be viewed. No evidence of silver plating attached to the amalgam was present. No longitudinal section was examined because the extremely thin silver plating, if any existed, would have been worn away during metallurgical polishing.

Longitudinal sections of the half of the plated pin-amalgam specimen, in which the pin was still imbedded in amalgam, were viewed with 160 X original magnification (Figures 71, 72). An undamaged bond of the plated pin to the amalgam and of the plated layers to the pin was seen. The bond, however, was lost at the point of protrusion of the pin from the surface of the amalgam specimen. This was very likely caused by local fracture of the amalgam at the free surface.

Sterling-silver pin-amalgam specimens presented

the highest resistance to separation of their two halves. It was necessary to further turn the tested half of the specimen to detach it completely. Contrary to what was expected, sterling-silver pins did not withdraw from the amalgam. Instead, the pin itself broke at the only place where it was not imbedded in amalgam, namely the small gap present in between the two halves of the specimen. As a result, each half of the specimen remained with the original part of the pin imbedded in the amalgam. This is shown in Figure 73. Longitudinal sections of each one of the halves of the failed specimen were viewed with 160 X original magnification (Figures 74 and 75). The pin-amalgam bond was shown to have remained exactly the same as before testing, except for a very small failure located at the point of protrusion of the pin from the amalgam specimen. This failure, however, was most likely due to the plastic deformation of the pin material at the point of breakage.

PUSH-THROUGH TESTS

Typical load-displacement curves for each of the three kinds of specimens tested are shown in Figure 76. The curves did not overlap and were very different from one another although always consistent for each specimen of the same kind. No statistical analysis was considered necessary.

Stainless-steel pins were completely pushed through

the amalgam with a negligible load, until they were level with the surface of the amalgam (Figure 77, a). At this point, the corresponding curve shows that the amalgam specimen itself is being subjected to the compressive load (Figure 76).

Nickel-silver plated stainless-steel pins could only be partially pushed through the amalgam at a very slow rate (Figure 77, b). The pin-amalgam bond failed little by little, as clearly shown in the corresponding graph (Figure 76).

Sterling-silver pins could not be pushed through the amalgam specimen. In nearly all cases failure was due to plastic deformation of the pin into the classical barrel shape well known in compression tests on ductile materials, as illustrated at b, in Figure 78. This mode of failure accounts for the initial ascending part of the corresponding load-displacement curve (Figure 76). In a few cases, the pin length was great enough to allow for buckling failure but these were regarded as atypical (Figure 78, a). The corresponding curve for a one millimeter protruding sterling-silver pin is shown in Figure 76 and represents not only the plastic deformation of the pin, but also the failure of the amalgam up to the point at which the specimen was vertically divided. As can be seen in Figure 78 at c, failure of the amalgam occurred partially along the pin and partially away from it.

For initial calculations it was assumed that the shear stress on the bond with the plated pin was uniformly distributed. With this assumption the shear failure stress

was calculated and found to be 6×10^3 lb/in^2. However, it is known that in this type of test the stress is not uniformly distributed but is concentrated in a region just below the free surface of the amalgam. Thus a reasonable estimate of the bond shear failure stress is 20×10^3 lb/in^2.

For sterling-silver pins, compressive failure of the pin material occurred at about 25×10^3 lb/in^2 which is equivalent to a bond shear stress of approximately 10^3 lb/in^2. It should be noted, however, that the bond did not fail at this stress level.

Longitudinal sections of failed sterling-silver pin-amalgam specimens in which the pin showed a barrel-shape failure were studied with the metallographic microscope. The result is shown in Figure 79.

FIGURE 71 - NICKEL-SILVER PLATED STAINLESS STEEL PIN IN AMALGAM AFTER TORSION TEST (METALLOGRAPHIC MICROSCOPE)

160 X original magnification, longitudinal section

a- Stainless steel pin

b- Nickel and silver plate layers

c- Undamaged bond

d- Amalgam

FIGURE 72 - NICKEL-SILVER PLATED STAINLESS STEEL PIN IN AMALGAM AFTER TORSION TEST (METALLOGRAPHIC MICROSCOPE)

160 X original magnification, longitudinal section

a- Stainless steel pin

b- Nickel and silver plate layers

c- Undamaged bond

d- Amalgam

e- Unplated end of the pin

f- Space between unplated part of stainless steel pin and amalgam

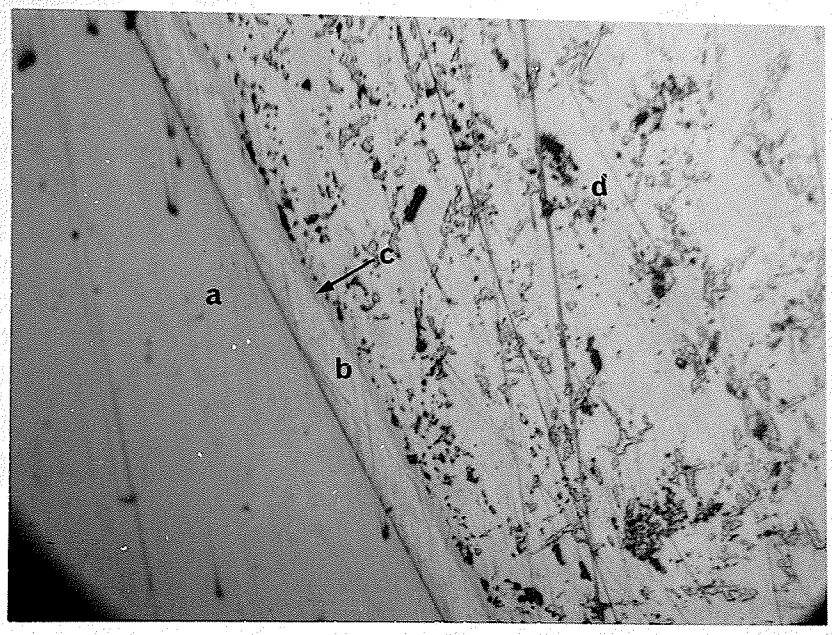


FIGURE 71

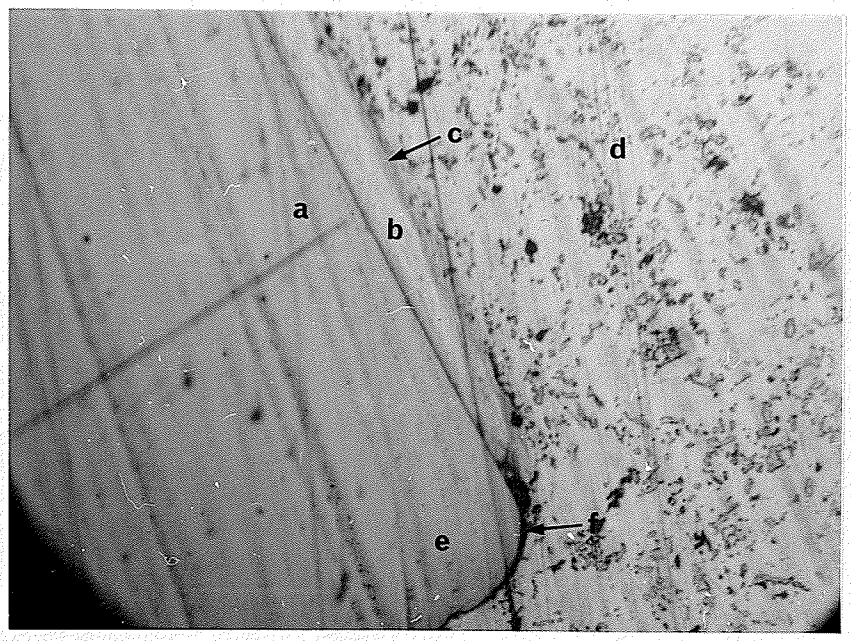


FIGURE 72

FIGURE 73 - STERLING-SILVER PIN-AMALGAM SPECIMEN FAILED IN TORSION

a- Inner half of the specimen

b- Outer (tested) half of the specimen

c- Broken pin

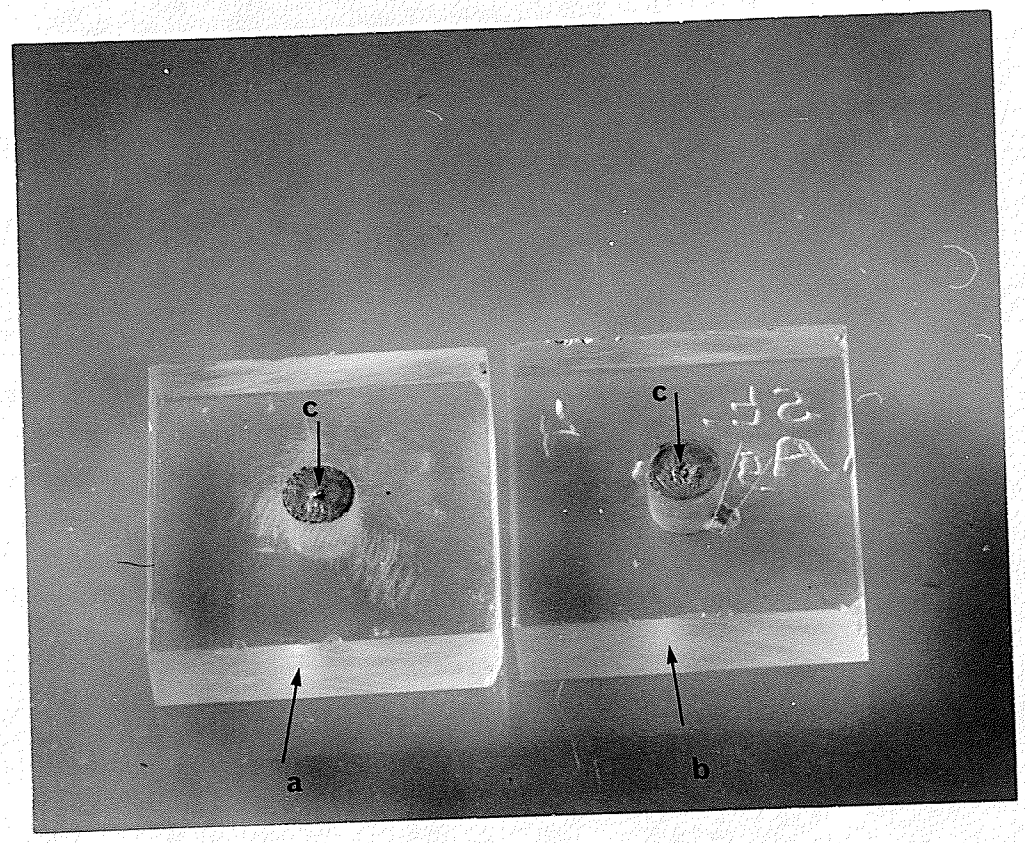


FIGURE 73

FIGURE 74 - STERLING-SILVER PIN IN AMALGAM AFTER TORSION TEST (METALLOGRAPHIC MICROSCOPE) 160 X original magnification, longitudinal section

a- Sterling-silver pin

b- Reaction layer between pin and amalgam

c- Amalgam

FIGURE 75 - STERLING-SILVER PIN IN AMALGAM AFTER TORSION TEST (METALLOGRAPHIC MICROSCOPE) 160 X original magnification, longitudinal section

a- Sterling-silver pin

b- Reaction layer between pin and amalgam - Note the continuity of the layer at the top of the pin

c- Amalgam

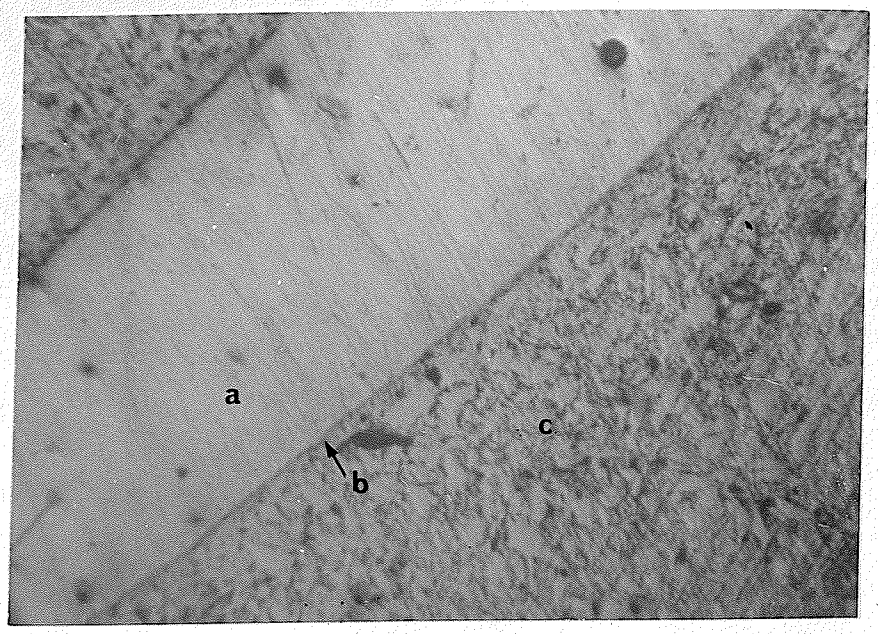


FIGURE 74

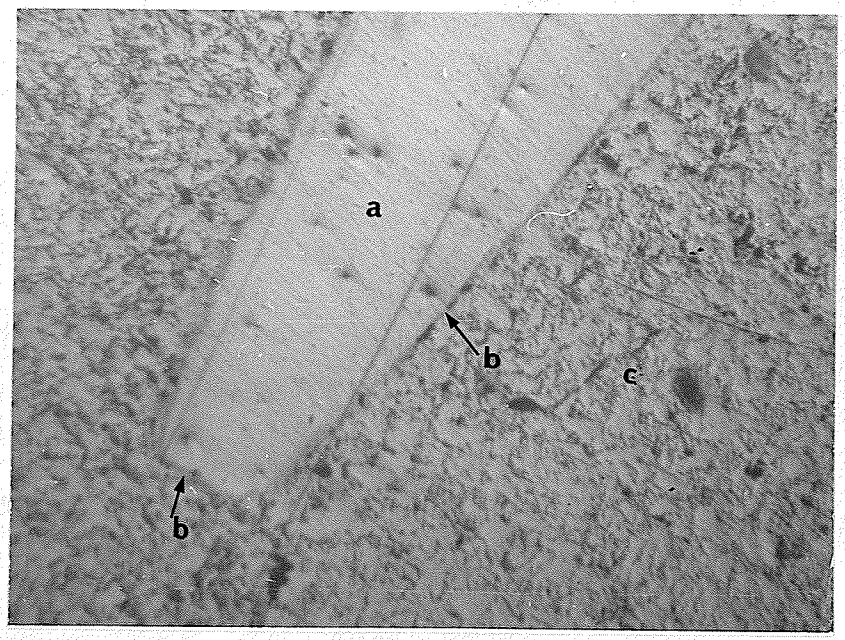


FIGURE 75

FIGURE 76 - PUSH-THROUGH TESTS - TYPICAL LOAD DISPLACEMENT CURVES

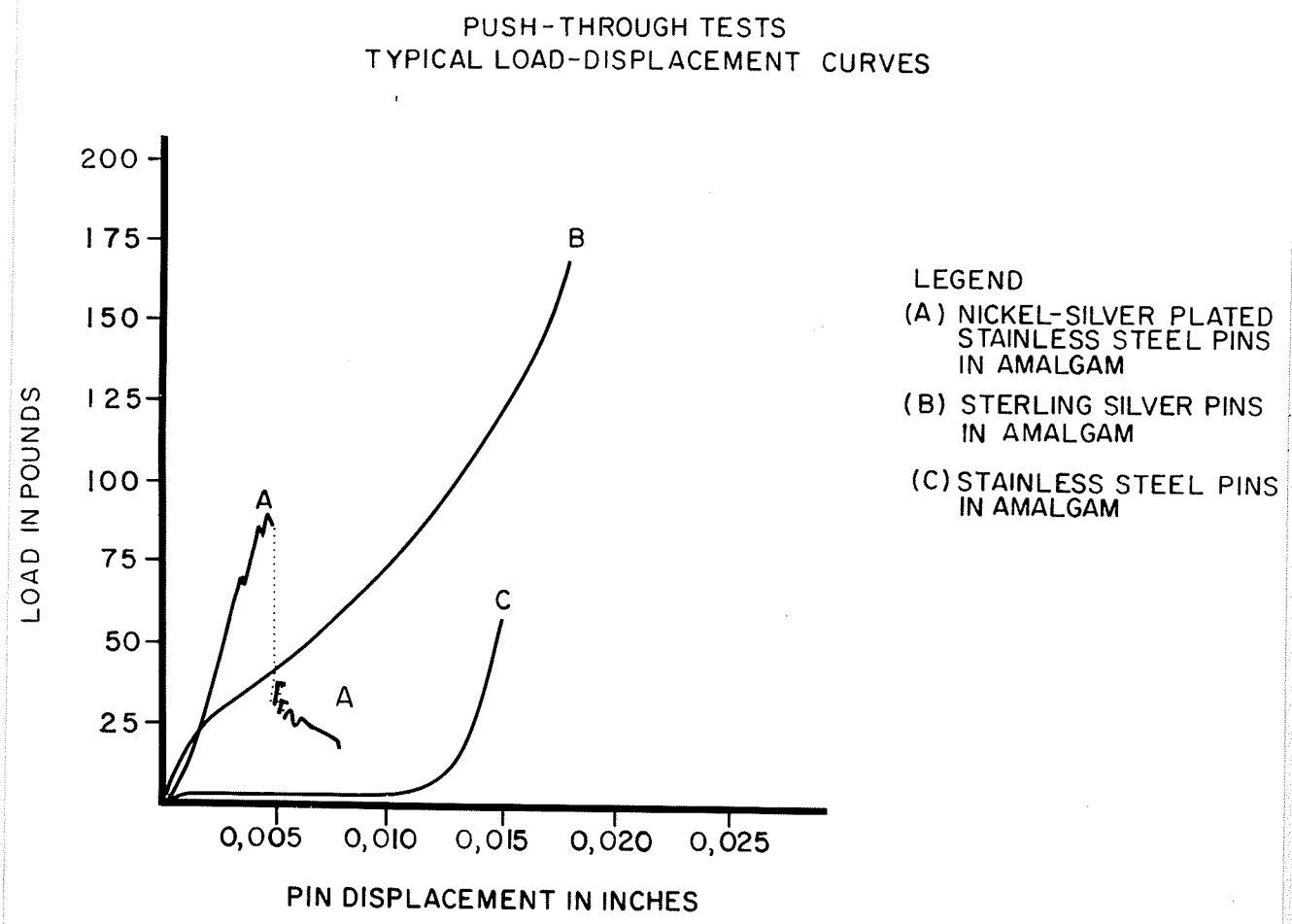

PUSH-THROUGH TESTS
TYPICAL LOAD-DISPLACEMENT CURVES
LOAD IN POUNDS
200
175
150
125
100
75
50
25
A
B
C
A
0,005
0,010
0,015
0,020
0,025
PIN DISPLACEMENT IN INCHES
LEGEND
(A) NICKEL-SILVER PLATED STAINLESS STEEL PINS IN AMALGAM
(B) STERLING SILVER PINS IN AMALGAM
(C) STAINLESS STEEL PINS IN AMALGAM

FIGURE 76

FIGURE 77 - STAINLESS STEEL PIN AND NICKEL-SILVER PLATED PIN-AMALGAM SPECIMENS AFTER PUSH-THROUGH TESTS

a- Stainless steel pin-amalgam specimen

b- Nickel-silver plated stainless steel pin-amalgam specimen

FIGURE 78 - STERLING-SILVER PIN AMALGAM SPECIMENS AFTER PUSH-THROUGH TESTS

a- Long pin showing buckling failure

b- One millimeter protruding pin showing barrel shape failure level with amalgam

c- Failed amalgam specimen - Note that failure occurred partially along the pin and partially away from it

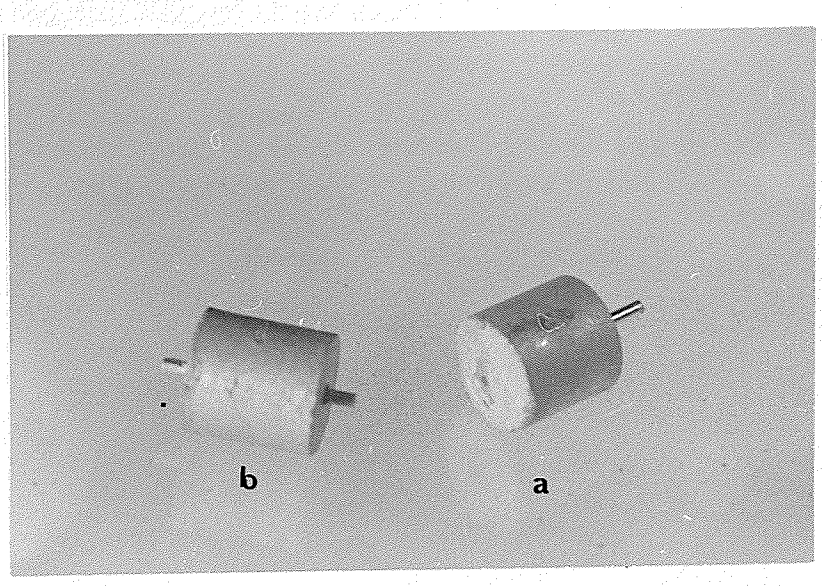


FIGURE 77

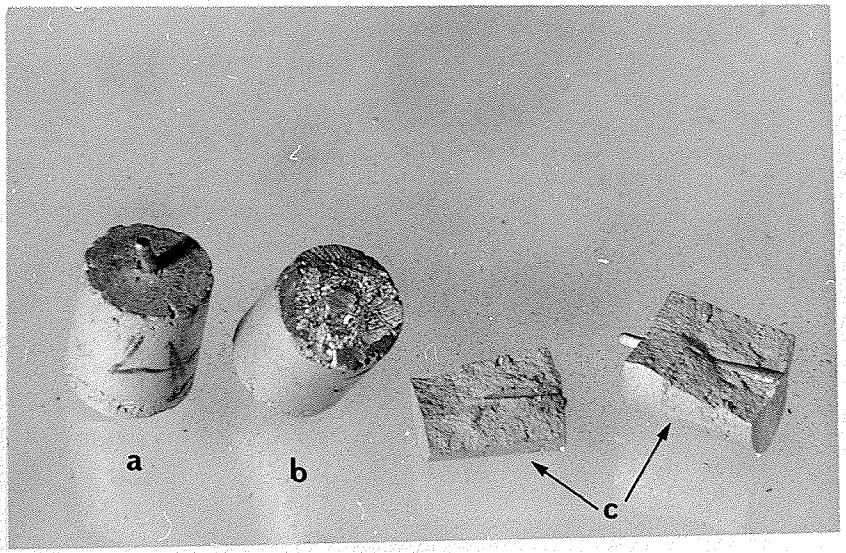


FIGURE 78

FIGURE 79 - STERLING-SILVER PIN IN AMALGAM AFTER PUSH-THROUGH TEST (METALLOGRAPHIC MICROSCOPE)

40 X original magnification, longitudinal section

a- Sterling-silver pin

b- Amalgam

c- Barrel shape deformation suffered by the initial portion of the pin material embedded in amalgam

d- Undamaged pin-amalgam bond

FIGURE 79

DISCUSSION

Stainless-steel wire has been widely used in the past for pins as retaining devices for amalgam restorations in badly broken down teeth. The high yield strength, stiffness and resistance to corrosion of stainless-steel make these alloys suitable as a material for pins. It has been shown however, that unplated stainless-steel pins, either smooth or serrated, do not increase the strength of dental amalgam. Normal masticatory loads give rise to stresses in the amalgam and attention must be given to the effect of the stainless-steel pin on these stresses. Stress concentration around stainless-steel pins has been demonstrated by photoelastic studies [129]. These showed that large stresses were present around this type of pin, especially near the top of the pin, when normal masticatory forces were applied. Ultimate breaking point tests made in the past [151] have shown that the lines of fracture through the amalgam are invariably present around the stainless-steel pins. This suggests that a much higher concentration of stresses exists around the pin than in other regions of the amalgam restoration.

From the standpoint of minimizing stress concentration, which in turn would increase the possibility of fracture of a pin-retained amalgam, pure silver seems to be the best material yet used [135]. Lines of fracture occurring through the amalgam are invariably far from the region of the pin. It is also known that a good bond between the pin and the amalgam will

enhance the retention of the pin and will minimize the stresses formed around it during mastication. Physical properties of the pin such as stiffness and compressive and tensile strengths are also very important. By plating stainless-steel pins with silver, the good bonding characteristics of silver can be combined with the desirable physical properties of stainless-steel.

An alternative to plated stainless-steel pins was sought since previous efforts to plate stainless steel have not been too satisfactory. In addition, the high Young's modulus of stainless-steel could be regarded as a disadvantage in that it tends to increase the stress concentration factor at the top of the pin. Sterling silver has a Young's modulus more closely matched to amalgam and thus would tend to distribute stress more uniformly. Because of its good metallurgical bonding properties with amalgam, its similarity in stiffness and its improved strength properties as compared with pure silver, it was chosen for this investigation. According to the results obtained, however, the physical properties of the sterling-silver pins used in this study proved to be inadequate to resist the horizontal forces which would be developed in a restoration during mastication. It is advisable to conduct further investigation to improve the strength properties of sterling-silver before using it as a pin material.

Stainless-steel pins in an amalgam matrix deform

under shot impact loads when the impact energy is great enough to shatter the amalgam [135]. However, it must be noted that this kind of load is not present in the mouth, and an amalgam restoration normally breaks under much lower but constantly repeated stresses, because of "fatigue failure" [85, 171]. In the mouth, restorations are subjected to fluctuating stresses and, for this reason, the fatigue strength of the material is as important as its static strength. If the fluctuating stresses are of sufficient magnitude, even though the maximum applied stress may be considerably less than the static strength of the material, failure may occur when the stress is repeated a sufficient number of times. While an amalgam restoration might withstand a static stress up to 63,000 PSI in compression or infrequent short duration stress applications of the same intensity, the highest fluctuating compressive stress which that restoration might be expected to withstand is only 14,000 PSI [85].

The reason why an amalgam restoration does not fracture under normal conditions is because of its "endurance limit" which is a limiting stress below which a load may be repeatedly applied without causing failure [174]. The endurance limit for any restoration will depend upon the stress distribution within that restoration. Since stainless-steel retention pins adversely affect the stress distribution, it is clear that this factor is likely to reduce the endurance

limit of a pin retained amalgam restoration. This adverse effect is greatly reduced when a good metallurgical bond exists between the pin and the amalgam [129].

Two clinically important advantages result if a sound metallurgical bond can be established between a retention pin and the dental amalgam in which it is situated. Firstly, the stress levels within the amalgam are minimized for any given masticatory load. Secondly, better retention properties can be obtained.

A detailed discussion of the first of these two advantages is not required here since Dhuru [129] has shown conclusively that a perfect metallurgical bond dramatically reduces the stress concentration at the top of a retention pin. In the present work, however, it is necessary not only to show that such a bond can be produced but also that the bond strength is adequate to resist, without failing, all stress levels likely to be found in the practical situation. Consequently, tests of the mechanical properties of the pin-amalgam bond formed a significant part of the present investigation.

The second of the two advantages, namely, improved retention, accrues from the fact that the tensile properties of the pin can be fully utilized if a good pin-amalgam bond exists. For example, the superior tensile properties of stainless-steel when a restoration is subjected to a lateral

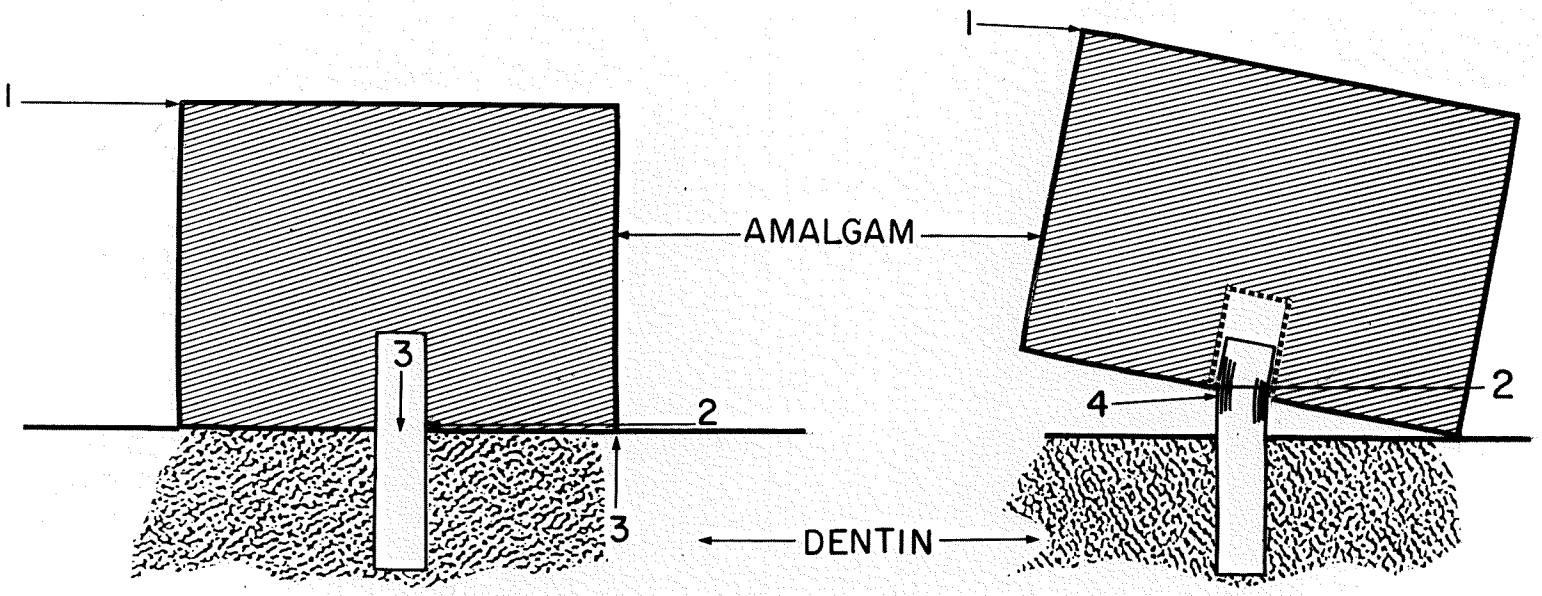
load can operate only when the retaining pin is bonded to both the amalgam and the dentin [129, 135]. The advantages to be obtained from the desirable physical properties of stainless-steel pins are not fully realized if the bond between the pin and the dental amalgam is lacking. Figure 80 shows that the tendency of the amalgam restoration to rotate when lateral forces are applied, is well resisted only if the pin has good mechanical properties and is successfully retained in both amalgam and dentin [125, 129].

At the outset it should be recognized that the properties of the bond have no first-order effect on retention when purely vertical loads are applied to the restoration. In the case of the loading situations in which a component in the horizontal plane is present, however, the bond has a first-order effect upon retention. Such horizontal loading occurs in the mouth due to such factors as dynamic mastication forces and the application of vertical forces to sloping parts of the cusp. In the latter case horizontal forces form as a result of the "wedging" action of the vertical load on a sloping surface. It is important to note that horizontal loads on a restoration can, under certain circumstances, be larger than the vertical loads. Thus, careful attention must be paid to establish a retention system that will be adequate to resist this form of loading.

From the geometry of typical restorations it can

FIGURE 80 - POSSIBLE BEHAVIOR OF PINS IN AMALGAM

POSSIBLE BEHAVIOR OF PINS
IN AMALGAM
(DIAGRAM NOT TO SCALE)



STRONG, BONDED PIN

UNBONDED PIN
(EXAGGERATED)

(1) LATERAL FORCE (2) REACTION FORCE
(3) RESISTING COUPLE RESULTING IN TENSILE FORCE IN PIN
(4) PIN BENDING FORCE IS THE ONLY ONE AVAILABLE TO RESIST ACTING COUPLE

FIGURE 80

FIGURE 81 - POSITIONS OF PINS RESISTING HORIZONTAL FORCES

Diagram of theoretical situations

POSITIONS OF PINS RESISTING HORIZONTAL FORCES
(DIAGRAM OF THEORETICAL SITUATIONS)

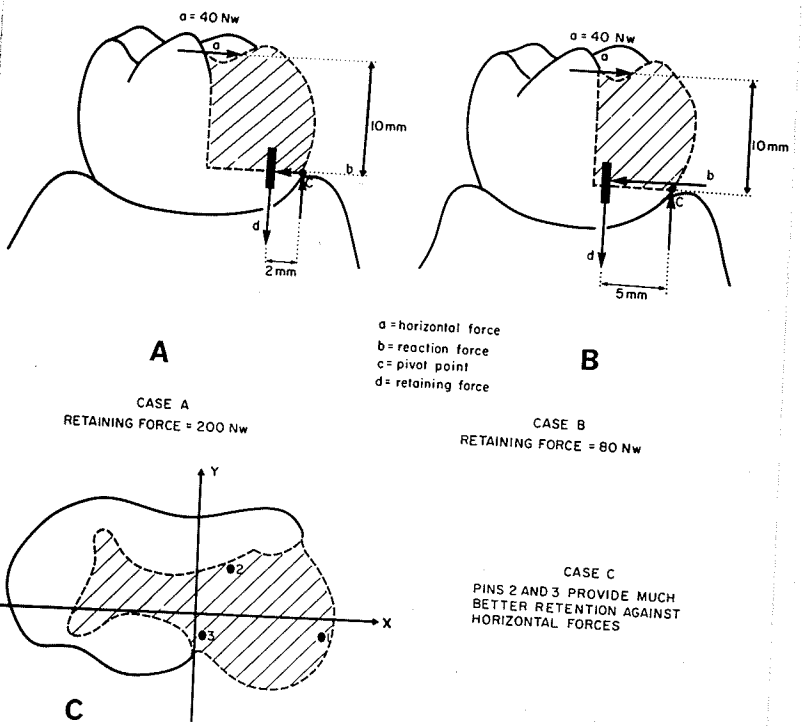


FIGURE 81

easily be seen that a horizontal force is usually applied to a cusp and, hence, it results in a couple on a restoration. Such a force tends to tilt the restoration. This tilting tendency may be very small if the direction of the horizontal force is such as to press the restoration towards the walls of the cavity. If the horizontal force is directed towards a free vertical face of the restoration, the tilting action can only be resisted by the retention devices employed, namely, pins and mechanical retention provided by the shape of the cavity. In both cases the stresses in the amalgam can be significantly reduced if pins that bond well with the amalgam and that are well retained in the dentin are used. This reduction in stress can only be realized, however, if the retention pins are properly placed. Figure 81 illustrates how the position of the pin or pins affects the retention properties when horizontal forces are applied. In particular, it should be noted that the bending stiffness of the pin is generally inadequate to resist the tilting action. This follows from the fact that bending stiffness of a pin is proportional to the fourth power of its diameter but only directly proportional to the Young's modulus of the material from which it is made. As an example we may take an amalgam cylinder of 0.1 inch diameter and a stainless-steel pin 0.02 inch diameter, of the same length. Though the stainless-steel has a Young's modulus about fifteen times that of amalgam we find that the amalgam cylinder is

approximately forty times more stiff than the pin.

The significance of these comments on the retention properties of pins can perhaps be best summarized by taking a typical clinical example. Figure 81, c, shows a restoration in which mechanical retention resulting from the shape of the cavity would alone be inadequate. A load on the restored cusp which has a component in the positive $\underline{x}$ or negative $\underline{y}$ directions would clearly produce tensile and torsion stresses respectively in or near the isthmus. Intuitively a pin in position $\underline{1}$ would seem to be the best for retaining such a restoration. From the previous arguments, however, it can be readily seen that pins in each of positions $\underline{2}$ and $\underline{3}$ are much better from the point of view of retaining the restoration against such horizontal forces as have been described. It is realized that a pin in position $\underline{1}$ might help to reinforce the restoration, but extreme doubt has been cast on the reinforcing properties of stainless-steel pins. The most important reason for including a bonded pin in position $\underline{1}$ would be that of preventing minute lifting of the restoration in those cases where a horizontal force in the negative $\underline{x}$ direction occurs.

Thus, correct positioning of the pins coupled with a sound pin-amalgam bond are very likely to yield significant improvements in both the retention and longevity of amalgam

restorations. The tests which established the high quality and strength of the bond which can be attained between plated stainless-steel and amalgam and between sterling-silver and amalgam can now be discussed.

Metallurgical examination

The nickel and the silver layers that were electroplated onto the stainless-steel wire adapted to every imperfection or roughness present at the surface of the wire. No discontinuity could be seen between the nickel and silver layers, or between the silver layer and the stainless-steel. Metallographic examination strongly suggested that a bond existed. The presence of this bond was confirmed by several mechanical tests which also showed that the stress levels that the bond could withstand were very high.

The metallographic data obtained, also suggests that a bond is present between amalgam and each of the two types of pins studied. In Figure 56, the granular silver layer electrodeposited on the surface of the stainless-steel forms a continuum with the amalgam so that it is not possible to determine exactly where one ends and the other begins. In Figures 54 and 55, the dark areas present in the amalgam, probably corresponding to the gamma-2 phase, seem to be continued in the silver plating layer. This suggests a complete metallurgical reaction taking place

throughout the silver layer. The physical appearance of the plating that remained attached to the pin after failure of the bond in torsion, points to the very strong possibility of a change in the plating composition. This fact will most probably be reconfirmed when further investigations are undertaken to study the metallographic composition of the bond at the interface.

A metallurgical reaction layer is clearly present at the surface of sterling-silver pins which were embedded in amalgam. When no rubbing is done during condensation, the surface of the sterling-silver pin is only briefly in contact with the freshly mixed amalgam. When the rubbing technique is utilized, the amalgam is forced against the pin resulting in a more complete bonding at the interface.

It must not be forgotten, however, that amalgam was condensed using the rubbing technique for all specimens in this research and that this technique is not used in clinical situations. Investigations to confirm the practical advantages of this technique have not yet been conducted. It can be stated, however, that the rubbing technique is essential to the development of a high quality bond between the pin and the amalgam.

Axial-load deflection tests

The axial stiffness of a pin is inversely proportional to its deflection for a given load and regardless of the

material of the pin. It was demonstrated [129] that within absolute theoretical limits there is an apparent axial stiffness relationship of 5 to 1 between bonded and unbonded pins. Although unplated stainless-steel pins present the highest deflection of the three types of pins, this value was below that expected. This degree of deflection in stainless-steel pin was due to the fact that the total load applied to the pin was supported only by the bottom of the hole. Some degree of "artificial" retention was then observed.

The two metallurgically bonded pins presented lower deflection values than stainless-steel pins. Plated stainless-steel pins deflected slightly more than sterling-silver pins. There was, however, a substantial difference in the axial deflection of these two pins on the one hand and the deflection values obtained with the stainless-steel pins on the other. If the bond had broken, the pin would have been supported only at its base, and a similar situation to the unplated stainless-steel pins would exist. Therefore, similar values for the axial stiffness determination would have been expected. This difference can be explained if a good bond with amalgam exists since the bond would distribute the load over the entire interface. Thus the load per unit area would be much lower for the bonded pins than for the pins supported only by their bases and the deflection under load would

be less. The lower deflection values of plated stainless-steel and sterling-silver pins is proof of the presence of a pin-amalgam bond.

Axial-load deflection tests were judged not sensitive enough to demonstrate the quality of the pin-amalgam bond. These tests may subsequently be useful when stress distributions are studied in future investigations.

Torsion tests

When tested under torsion, stainless-steel pins showed only a very small degree of retention which was attributed to the friction between the pin and the amalgam. This demonstrated the total lack of bond between the pin and the amalgam.

Plated stainless-steel pins formed a good bond with amalgam. This bond exhibited a progressive form of failure as indicated by the low rate of curvature of the load-deflection curves. When withdrawn from the amalgam after testing, the plating remained attached to the pin. All factors point to the very strong possibility of the amalgam, and not the bond, breaking at the pin-amalgam interface.

Sterling-silver pins formed a good bond with the amalgam. Failure occurred in the pin itself while the bond remained intact. The pin material failed in shear at a

stress level in the order of 10^5 lb/in^2. This value was high if compared with shear stresses likely to be developed during mastication. The bond strength between sterling-silver and amalgam, therefore, is at least as good as the pin material itself. Failure occurred at a much lower load than that for plated pins, mainly due to the lower physical properties of sterling-silver (i.e. Young's modulus and tensile strength).

Push-through tests

Push-through tests confirmed the earlier results. Stainless-steel pins, as expected, did not form any bond with amalgam. As shown in the corresponding curve (Figure 76), the displacement of the pin occurred rapidly with only a very small, virtually constant, load being required to overcome the friction factor present. The sudden upward trend of the curve at large deflection values, is caused by the platten of the testing machine contacting the amalgam and exerting a compressive force. Thus, this upward trend is not related in any way to the pin behaviour.

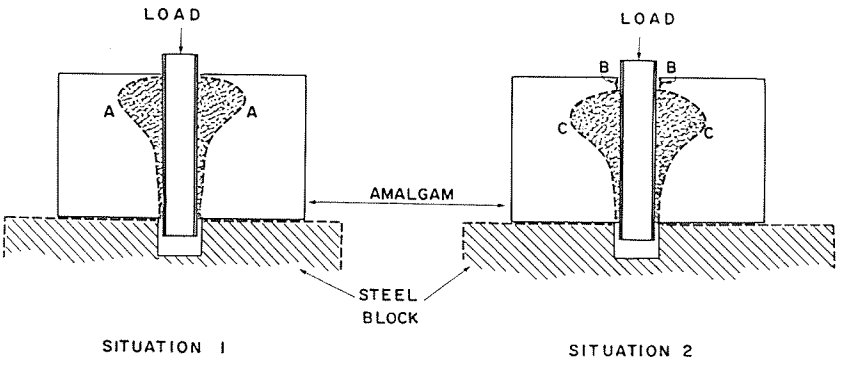
Nickel-silver plated stainless-steel pins formed a very good bond. The load-displacement curve (Figure 76) rapidly increases and shows progressive failure of the bond. The stress present in the bonded pin-amalgam specimens under this form of loading is distributed along the surface of the

FIGURE 82 - PUSH-THROUGH TESTS - STRESS DISTRIBUTION AROUND PLATED PIN-AMALGAM INTERFACE

PUSH - THROUGH TESTS

STRESS DISTRIBUTION AROUND PLATED PIN-AMALGAM INTERFACE

(DIAGRAM NOT TO SCALE)



LEGEND

A = STRESS DISTRIBUTION AT INTERFACE
B = FAILED PIN-AMALGAM BOND
C = NEW STRESS DISTRIBUTION AT INTERFACE

FIGURE 82

pin in the manner indicated in Figure 82. It will be noted that the stress reaches a maximum value just under the surface of the amalgam. When bond failure at this point occurs, a similar distribution of stresses reform along the non-failed, bonded surface of the pin. This continues progressively until complete breakage of the bond occurs. The repeated failure, and then reloading below the fracture, is revealed clearly in the load-displacement curve (Figure 76), by sudden notches in an otherwise smooth curve up to the maximum load value where complete bond failure occurs. After complete failure of the bond it is interesting to note that a resistance to the push-through force does not drop to zero nor does it remain constant, as the pin is pushed further through the amalgam.

A constant small force might be expected if the bond between the stainless-steel and the plating had failed, leaving a smooth pin in a smooth hole. It would behave in the same way as the plain stainless-steel pin. The behavior after complete failure, is, in fact, consonant with the observation of amalgam retained around the pin subsequent to torsion tests on plated stainless-steel pin specimens. The sequence of increasing and suddenly decreasing loads which occurs after complete bond failure, tends to confirm the assertion that failure of the amalgam or of the interface between the amalgam and the plating is the mode of complete

failure. Such a mode would be expected to produce a very jagged failure crack. Hence, as the push-through test progresses beyond complete bond failure, the jagged surfaces can support some axial load. As expected from this phenomenon, high points of the jagged surface get broken with a sudden release of load and load peaks of progressively smaller size are observed as the test progresses.

Because of the non-uniform distribution of stress (Figure 82), a precise calculation of maximum shear stress for any given load is a complicated process. Experience in engineering work indicates that, for similar circumstances, a good approximation to the maximum shear stress is obtained by assuming that the whole of the load is supported by one-fifth of the bond area. Using this approximation in the present case indicates that failure occurred at about 20×10^3 lb/in^2. This stress is much higher than that likely to be encountered in the mouth and is comparable with the ultimate shear strength of amalgam (20×10^3 to 30×10^3 lb/in^2).

In the case of sterling-silver pins, bond failure could not be induced in the push-through tests. This was due to the fact that at a stress of about 25×10^3 lb/in^2 the pin material failed in compression. This would correspond to a bond strength of about 10^3 lb/in^2, but it is important to note that the bond did not fail. Confirmation of the integrity of the bond after pin failure was obtained by sectioning and

microscopical inspection of the pin-amalgam interface. Figure 78, b, shows a sectioned specimen in which the pin has been deformed to a point where it is flush with the upper surface of the amalgam. From the photomicrograph (Figure 79), it can be deduced that even in the region of large plastic deformation of the pin the bond has remained intact without any sign of cracks emanating from the interface. Additional confirmation was also obtained from those specimens in which the push-through test was continued until the amalgam failed under compressive load between the plattens of the testing machine. In these specimens the failure crack, though it started around the pin and in the region of plastic deformation, always digressed away from the pin into the bulk amalgam (Figure 78, c).

The upward trend of the corresponding load-displacement curve at higher deflections (Figure 76) is due to the "fattening" of the pin under compression. This was one of the specimens which was tested until the amalgam failed. The fact that the bond strength in the case of sterling-silver pins is at least strong enough to support axial failure loads in the pin material was confirmed.

General comments

It has been shown that the bond between a sterling-silver pin and amalgam is extremely good providing that the

rubbing technique is used during the condensing process of the amalgam. This fact alone, however, does not justify the use of such pins in clinical practice. Some discussion and possible tests of the other properties of sterling-silver as a retention pin material is required before clinical trials are proposed. A discussion of the properties of sterling-silver as a pin material can be conveniently pursued under four main headings: Young's modulus, yield strength, retention in dentin, cost.

The Young's modulus of heat treated sterling-silver is approximately five times greater, and that of stainless-steel is approximately fifteen times greater, than that of amalgam. It is clear, then, that for vertical loads on a restoration a sterling-silver pin will induce smaller stresses around it because of its closer match with the Young's modulus of amalgam. In the absence of a detailed stress analysis it is impossible to state the magnitude of this reduction but any factor which mitigates stress concentration around the pin is advantageous.

An obvious disadvantage which results from a lower Young's modulus is that of the greater elastic deformation of the pin when it is subjected to a tensile load. This factor is relevant to the previous discussion on the restriction of tilting by means of appropriately placed pins which bond to the amalgam. Referring to Figure 81 it can be seen that a

tensile load in any pin must cause some increase in the space between the floor of the cavity and the amalgam. A rough estimate of this increase can simply be made by assuming a tensile load of, say, 10 pounds to be applied to the pin, and by further assuming that a gap of 4×10^{-4} inches exists over which no mechanical connection to the pin is made by either the dentin or the amalgam. The amalgam, before application of the load, is assumed to be in intimate contact with the floor of the cavity except in this localized region just around the pin. With these assumptions, a stainless-steel pin when subjected to the tensile load would allow a gap of 3×10^{-6} inches whereas a sterling-silver pin would allow a gap of 9×10^{-6} inches to occur between the amalgam and the dentin. There is no pretense that this simple calculation is truly representative of clinical conditions but it does show the order of magnitude of the gap that might occur and the extent of the difference caused by the two pin materials. In both cases this gap size is considered to be unlikely to cause problems of microleakage and therefore the use of sterling-silver does not seem to be contraindicated on this count.

A less satisfactory result is obtained when the yield stress of sterling-silver is considered. The yield stress of this material is likely to be only one-third that of stainless-steel and may only be one-fifth. This

uncertainty in the ratio of yield stresses is caused by the fact that this property of stainless-steel is greatly affected by cold working and with the pins used in dentistry could be as high as 150×10^3 lb/in^2 but is more likely to be about 100×10^3 lb/in^2. Thus a stainless-steel pin of 0.02 inch diameter would yield at a tensile load of approximately 45 lb or 30 lb at the yield stresses just quoted. In contrast, a sterling-silver pin of similar diameter would yield at a load of about 10 lb.

Yielding of a bonded retention pin under a tensile load would of course be extremely undesirable for it would have a permanent set after removal of the load. Subsequent masticatory forces would almost certainly reduce this permanent set but only a few repetitions of this cycle would be needed to cause total fracture of the pin. Thus the lower yield stress of heat-treated sterling-silver pins seems to be a hazard to their use in certain clinical circumstances and more quantitative studies of the problem are required before their general use is recommended.

Another likely disadvantage of sterling-silver as a pin material is revealed when its thermal properties are investigated. Though its coefficient of thermal expansion (linear) is only twice that of stainless-steel, its coefficient of thermal conductivity is about thirty times that of stainless-steel. Thus, it is considered that this

high thermal conductivity may well give rise to unacceptable thermal shock to the pulp.

The advantages resulting from a sound metallurgical bond formed between sterling-silver and amalgam can only be fully realized if the pin is tightly imbedded in the dentin as well. Stainless-steel has been extensively used in the past to construct pins, and several methods for their retention in dentin have been tried. The self-threading and the cemented pins seem to provide the best retention in dentin, as has been shown in past investigations. If we look at the mechanical properties of sterling-silver, however, it can easily be recognized that there are many difficulties involved in using self-threaded pins made of this material.

Sterling-silver is far too ductile to be used for this purpose and would not grip properly to the dentin. The same would happen if the technique of tightly forced pins into an undersized hole in dentin is used. The only way in which a softer pin material like sterling-silver could be retained is by cementing it into the dentin. The possibility of a sterling-silver pin of given diameter bending at its point of protrusion when tightly inserted in the dentin, is clearly higher than that for a similar pin made of stainless-steel. The comments made earlier concerning the large effect which the diameter has on bending stiffness should be noted in this connection. For example an increase in pin diameter

of 30% is enough to offset the difference in stiffness caused by the difference between stainless-steel and sterling-silver.

As demonstrated by Dhuru [129], a steel pin loosely fitted in dentin but well bonded in amalgam, would minimize stress concentrations around the top of the pin. These studies, however, show this advantage to be true only under a compressive load. As was explained earlier, any other kind of force exerted on the restoration, especially horizontal forces, are likely to bend the pin. Thus, from the point of view of retention in dentin, plated stainless-steel pins present several advantages over sterling-silver pins. They are easier to retain in the dentin and for any chosen diameter they do not bend as easily. Therefore, for restorations being subjected to horizontal and diagonal forces, plated stainless-steel pins, from the point of view of the retention in dentin, are more advantageous than sterling-silver pins.

The above mentioned factors point to the desirability of using pins which bond to amalgam in clinical situations. When considering a new technique for clinical application, however, cost is a factor to be considered. Sterling-silver pins, at the low scale of production used in this research, are more expensive to construct than plated stainless-steel pins. The process involved in constructing

sterling-silver pins is very time consuming and requires the services of a skilled operator. On the other hand, the process of plating stainless-steel wires is less costly in materials and time. The cost differential between sterling-silver and stainless-steel pins is, however, likely to be greatly reduced if techniques for production on a commercial scale are developed.

From all the facts mentioned earlier, it can be seen that both sterling-silver and plated stainless-steel pins can be recommended for clinical use. Sterling-silver pins, because of their high bonding qualities with amalgam, and their lower Young's modulus are recommended in cases of amalgam restorations with no occlusal component. Their use can also be considered in the case of cuspid protected occlusions, when a restoration in molars or premolars has no likelihood of being directly subjected to a horizontal force. This, of course, depends on the degree of cuspid protection present. The use of sterling-silver pins is not recommended in those cases where horizontal forces are likely to be present, until further studies have been performed. The high thermal conductivity of sterling-silver pins should also be taken into account before their clinical use is suggested.

Stainless-steel pins, plated with nickel and silver as described in this study, can be recommended under

all circumstances since they have advantages over those made of plain stainless-steel. In particular, these advantages are very substantial when the restoration has to withstand tilting actions resulting from horizontal forces.

Clinical studies to confirm the validity of this recommendation are needed for plated stainless-steel pins. In the case of sterling-silver pins such studies should be conditional upon the results of a more detailed analysis of the effects of the lower yield strength of this material.

SUMMARY

The purpose of this investigation was to develop a satisfactory bond between pins and amalgam so that optimum physical and mechanical properties would be provided for such restorations requiring pins for retention. These qualities included a metallurgical pin-amalgam bond, possessing suitable mechanical properties and also a pin material with adequate physical properties.

Smooth nickel-silver plated stainless-steel and sterling-silver pins were studied. Smooth unplated stainless-steel pins were used for comparison because of their inability to bond with amalgam. A suitable technique for electroplating nickel and silver on the surface of stainless-steel pins was utilized. Nickel was first plated onto the activated surface of the stainless-steel before depositing a silver layer. Microscopic and X-ray microprobe examinations revealed the presence of a bond between the stainless-steel and the nickel, and between the two electroplated layers. The existence and effectiveness of the bond were confirmed by mechanical tests.

Pin-amalgam specimens, containing each of the three types of pins, were made to determine if a bond existed at the pin-amalgam interface. Microscopic and X-ray microprobe examinations were first undertaken. A rubbing technique was incorporated with the amalgam condensation procedure to eliminate voids around the pin and thus obtain a continuous and close adaptation of the amalgam to the pin. In the case

of sterling-silver pins a perfect adaptation and a reaction layer appearing around the pin could be seen. Thus, the possibility of a metallurgical reaction zone existed, and therefore a bond. In the case of plated stainless-steel pins, there was a complete continuity between the silver layer and amalgam. This suggested the existence of a metallurgical bond between the plated pin and amalgam.

Mechanical properties of the pin-amalgam bond were determined by performing several kinds of tests. The first test consisted of taking axial load-deflection measurements. The existence of a pin-amalgam bond was confirmed by this form of test when using nickel-silver plated stainless-steel or sterling-silver pins. As expected, no bond was found to be present at the unplated stainless-steel pin interface with amalgam. To determine the strength of the metallurgical bond, a torsion test was used. The bond between amalgam and sterling-silver pins or nickel-silver plated stainless-steel pins remained intact. Torsion tests also confirmed that the plating applied to stainless-steel produces an adequate bond strength. Restorations are not subjected clinically to torsional forces. Thus, push-through tests were selected because they represent a condition which is closer to that encountered in the mouth. Nickel-silver plated stainless-steel pins produced a strong bond with amalgam displaying a non-uniform axial shear stress

distribution along the pin. This bond was capable of resisting stresses up to 20×10^3 PSI. Sterling-silver pin material failed under both torsion and push-through tests, while the pin-amalgam bond remained intact. The physical properties of sterling-silver were considered inadequate for clinical purposes.

Results demonstrate that nickel-silver plated stainless-steel pins possess superior properties necessary to retain amalgam restorations. Their bond with amalgam is capable of resisting stresses likely to form in a restoration when subjected to masticatory forces. If properly positioned in the cavity, plated stainless-steel pins are recommended for clinical application, based on the present evidence. It is suggested that clinical investigations should be conducted to support the laboratory findings.

C O N C L U S I O N S

1. Both nickel-silver plated stainless-steel pins and sterling-silver pins form a very good metallurgical bond with amalgam. This is confirmed by mechanical tests and from metallographic evidence. From the point of view of the physical properties of the pin material, plated stainless-steel is considered superior.

2. Complete adaptation of the amalgam to the surface of the pins is obtained only by using the rubbing technique during amalgam condensation. Full advantage of the bonding properties of plated and sterling-silver pins can only be taken if the rubbing technique is used.

3. Nickel-silver plated stainless-steel pins in amalgam have a bond strength in shear of at least 20×10^3 PSI. The shear stress distribution along the axial direction of the pin-amalgam interface is a non-uniform one. This, together with metallographic evidence, establishes that with the plating technique described, good bonding between the stainless-steel and the plating is achieved.

4. The failure at the plated stainless-steel pin-amalgam interface is due very likely to amalgam failure in shear. Thus, the magnitude of the bond strength would be at least of the same order as the shear strength of amalgam alone.

5. The bond strength formed between sterling-silver and amalgam is beyond that which could be tested due to torsional or compressive failure of the pin material. There is no evidence to suggest that the bond strength in this case is less than that observed with plated stainless-steel.

6. Considering the general nature and magnitude of the stress distribution in a typical restoration, failure stresses would not be reached in either the bond with plated stainless-steel pins or the one with sterling-silver pins. Stress concentration factors are small, as demonstrated in past investigations [129].

7. Mechanical tests conclusively show that smooth stainless-steel pins do not form any bond with amalgam. Any kind of retention afforded is only due to friction factors and is therefore inadequate under clinical conditions.

8. Bonded pins are ideal for retaining amalgam restorations. If side loads have to be supported, however, another important factor to be taken into account for an optimal retention is their correct distribution in the tooth. This will allow for a correct distribution of forces.

9. Clinical trials with plated stainless-steel pins should be conducted.

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