

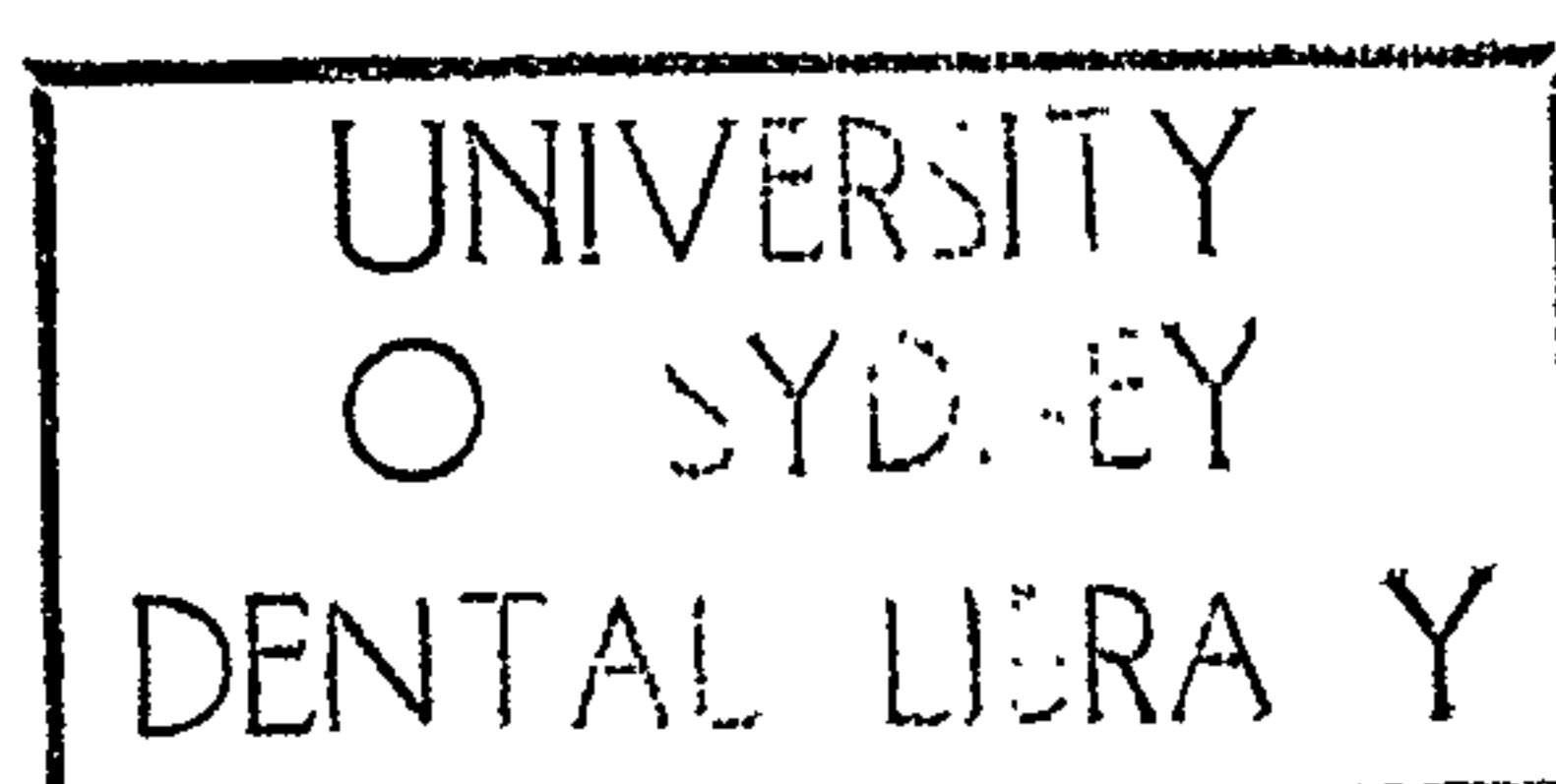
THE BEHAVIOUR OF DENTAL AMALGAM SUBJECTED TO
SUB-FRACTURE STRESSES AT 37°C

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To God

To Gerzina and Kertel

Fortiter et Suaviter

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INTRODUCTION

Studies centred around dental amalgam have contributed to an extensive body of knowledge about the metallurgical, mechanical and clinical properties of this restorative material in dental literature. Much of this work was completed in the earliest decades of this century and provided guidelines from which Specifications and Standards for Dental Amalgam were drawn. These Specifications centred around certain mechanical properties including strength and flow which have maintained their high degree of relevance subjected to some refinements over the years.

Greater knowledge about dental amalgam was afforded by improved techniques and the addition of sophisticated scientific equipment and principles so that newer amalgam formulations were easily conceived and researched.

Despite the refinement of testing procedures and data analysis, the clinical failure of any restoration including dental amalgam is unavoidable in the hostile oral environment. Several laboratory tests distinguish themselves as good predictors of restoration performance and a means of eliminating sub-standard alloys.

In the last two decades, clinical evaluation has become an extensively examined area of dental materials research. The formalizing of clinical research with the establishment of methods of quantifying the degree of restoration failure has taken place at the same time as the development of new formulation dental amalgams.

Laboratory studies have been developed in an attempt to explain the mechanism of failures observed in clinical evaluations. It is not surprising that research groups have concentrated their efforts on specific areas of expertise and equipment availability. Groups have concentrated on corrosion, microscopy, electron probe microanalysis or mechanical properties although at times combinations of research methodology have been used.

In the attempt to duplicate oral conditions, sub-fracture loading of specimens has been suggested but as yet examined in relatively few studies. A significant contribution to this branch of amalgam analysis was made by Giblin (1979) who pioneered studies of amalgam behaviour under low transverse loading.

The present study has aimed to compare the behaviour of a range of amalgams under a direct continuous or intermittent sub-modulus of rupture load at 37°C. A restricted range of mechanical properties and fracture characteristics were examined for possible inter-relationships both by data and microstructural observation. Based on the synthesis of the various trends which emerged, a limited application of additional alloys to the model was made.

The investigation has determined a mechanism of failure of amalgam beams at low loads at 37°C. By comparing results of low load testing at 37°C with 22°C, recommendations have been made for appropriate temperatures for the testing of mechanical properties of dental amalgam.

REVIEW OF
LITERATURE

CHAPTER 1

AMALGAM FAILURES AND EVALUATION

A scientific approach to the study of amalgam properties was born of the need to improve restorations and reduce early failures. A need existed for knowledge about amalgam composition, manufacturing, physical and mechanical properties and manipulation of the alloy. Concurrent with the need for an investigation of the material itself was a requirement for an analysis of cavity preparation and manipulative techniques.

At the forefront of this movement, amongst other workers, was G.V. Black (1895, 1896) who pioneered comprehensive analyses of several aspects of restorative dentistry including composition and properties of dental amalgam.

The first set of specifications relating to dental amalgam was that of the American Dental Association Specification No. 1 of 1934 following an investigation begun in 1919 by the National Bureau of Standards in U.S.A.

This specification set down standards to which amalgam formulations available had to conform with respect to chemical composition and mechanical properties; namely dimensional change, compressive strength and flow. The aim of the specification was to provide both a means whereby available amalgam alloys could be standardized and a set of properties to which new amalgams could be matched and compared, thereby moving toward improved restoration longevity.

Research into amalgam restoration failures followed the publication of the specification and such early studies cited many

factors including recurrent caries, overhanging gingival margins, broken restorations, poorly carved restorations, and discolouration for early restoration failure (Crawford 1938). Later studies added dimensional change and pulpal or periodontal involvement to the growing list of causes of restoration failure. The study of Healey and Phillips (1949) attributed over 50% of failures to improper cavity preparation and approximately 40% to faulty manipulation or amalgam contamination and, agreeing with previous studies, concluded that a reduction in amalgam failures could be achieved by greater care with alloy manipulation and cavity preparation.

Wolcott (1958) pointed out the need for clinicians to consider caries susceptibility of a patient when restorations were planned. Consideration of the possible causes of failure of two-surface restorations found such causes as inadequate proximal retention grooves, narrow isthmus areas and severe proximal flares. A need to adequately finish amalgam restorations to remove small excesses was recommended in order to achieve a higher quality restoration surface and minimize possible corrosion and tarnish.

Later studies into amalgam restoration failures and replacement cited 'operator factor' as the main cause of amalgam failures. Stibbs (1958) particularly noted the lack of diligence and attention to detail on the part of the dentist; although poor diagnosis and treatment planning were also considered. The importance and care of periodontal tissues was also emphasized.

Wing (1971) summarized amalgam failures as being the result of recurrent caries, fracture, dimensional change, excessive corrosion, postoperative pain or periodontal disease and cited 60% of such failures to be due to faulty cavity preparation. Most at

fault in cavity preparation had been management of the cavosurface margin where incomplete or ineffective finishing is conducive to marginal breakdown.

Class II Restoration Failures

Haskins, Haack and Ireland (1954) presented a study of stress in Class II cavity restorations induced by different cavity designs in primary molar teeth. Several distinct variations in features of cavities were examined by the use of an enlarged photoelastic model. These variations included rounded axiopulpal line angles, rounded and sloped pulpal floors, rounded and sloped axial walls and shallow and deep occlusal steps. Although the format was not exactly applicable to natural permanent teeth since the photoelastic material is homogenous, isotropic and elastic unlike dentine and enamel, findings about cavity design are relevant and noteworthy. Less stress concentration was associated with deeper cavities featuring rounded and sloping pulpal walls. Features having little effect in reducing stress included rounded or sloped axial walls and rounded axiopulpal line angles; this last finding conflicted with that of other studies including Noonan (1949) who also considered stress in cavity preparations using photoelasticity. Despite the finding that rounded axiopulpal line angles did not reduce stress concentration, Haskins and his co-workers recommended the inclusion of this feature in cavity design to increase the thickness of the filling material.

Mahler (1958) highlighted the importance of cavity design to structural effectiveness of both restoration and remaining tooth structure. Using photoelastic studies to investigate stresses occurring in Class II restorations, Mahler concluded that the

stresses of greatest importance were concentrated at the isthmus and were tensile in nature, echoing findings of Bronner (1930). This finding had significance not only for cavity design but in terms of the mechanical properties required by amalgam in order to resist these stresses best. Bronner (1930) analysed Class II amalgam restoration fracture at the isthmus in terms of engineering principles including location of a tipping fulcrum within the cavity and the lack of resistance to load afforded by the proximal section of the restoration. Bronner suggested the incorporation of a 'self-locking' feature to proximal sections by virtue of converging buccal and lingual walls to prevent tipping of the proximal section in isthmus fracture where the fulcrum is located at the gingival cavo-surface margin. Bronner also considered such a proximal cavity design obviated the requirement of an occlusal lock, a concept which was later evaluated by several workers, with variable conclusions.

Several studies into Class II cavity designs and isthmus fracture have been completed with several interesting findings. Guard, Haack and Ireland (1958) analysed the bucco-lingual sections of Class II restorations using photoelastic techniques and evaluated ten different cavity forms. These authors suggested that the incorporation of gently rounded pulpal walls and line angles would achieve most desirable stress distribution.

Mahler, Terkla and Johnson (1962) evaluated techniques of analysing cavity design of Class II amalgam restorations employing four different cavity designs and three different techniques. The three techniques differed in type of material used for both restorative material and 'tooth' structure. The most valuable conclusions about cavity design were made, not surprisingly, from

the technique employing amalgam condensed into cavities in natural teeth. The cavity design which best resisted fracture loads in all techniques included the following features : undercut bucco-occlusal and linguo-occlusal walls, rounded axiopulpal line angles (similar to Guard, Haack and Ireland 1958), retentive grooves in axiobuccal and axiolingual line angles and a sloped gingival wall which made an angle less than 90° with the axial wall.

Acknowledging improper cavity preparation as being the major cause of the increased rate of failure of dental restorations, Mahler and Terkla (1965) examined fundamental principles pertaining to restoration failure. In relation to the properties ideally required to adequately restore a tooth to best resist loading, these workers highlighted transverse or bending strength, modulus of elasticity and material brittleness. Amalgam, being relatively strong but brittle, does not withstand impact loading. The authors noted, that marginal fracture is caused by many factors only one of which is a discrepancy in moduli of elasticity between dentine and restorative material. Several recommendations and comments regarding cavity design were made:

- (1) Cavity outline should be kept as conservative as possible whilst satisfying requirements of 'extension for prevention' and the elimination of weakened or defective pits, fissures or enamel.
- (2) Pulpal and gingival walls should be prepared at right angles to the direction of masticatory forces.
- (3) Increased restoration strength is achieved more by greater depth than by increased width of the cavity.

- (4) Internal line angles should be rounded slightly, especially the axiopulpal angle which will increase the bulk of restoration between this angle and the load-bearing area of the external surface.
- (5) Retentive grooves placed in the proximal box are not necessary to prevent isthmus fracture.
- (6) Cavo-surface angles must be formed with due consideration of the histologic structure of the tooth in this area and dentine support of enamel. Brittle restorative materials require this angle to be parallel to enamel rods and at 90° to the tooth surface.
- (7) Occlusal anatomy of the restoration must not feature deep grooves or pits likely to induce stress, and occlusal loading must be considered. Marginal fracture will be reduced if amalgam excesses or 'flash' is removed from restoration margins.

Several of these recommendations have been supported in subsequent studies and have influenced cavity designs for amalgam restorations.

In the examination of over 500 Class II amalgam restorations in extracted teeth, Attalla and Gibb (1968) reaffirmed the recommendations of Mahler and Terkla (1965) and, stressed the importance of extension for prevention, correct matricing, adequate amalgam condensation, consideration of pulp protection and final polishing.

Johnson (1972) considered impact loading of Class II amalgam restorations with particular emphasis on the plastic deformation likely to take place. Johnson hypothesized that a Class II amalgam restoration exhibited plastic deformation when subjected to

repeated impact forces of low loads over a period of time centred over the marginal ridge. An assessment of proximal retentive grooves was also completed. No plastic deformation of the proximal contour was seen in either format of cavity design however the restorations featuring retentive grooving did resist fracture for a greater number of impact cycles.

Crockett et al (1975) in a study of the influence of proximal grooves in Class II amalgam cavities, affirmed the findings of Johnson (1972) in noting an improvement in retention and resistance characteristics. Crockett and his co-workers applied a constant load to the marginal ridge area of a range of stylized Class II amalgam cavities either with or without proximal grooving and with or without occlusal locks. Most resistance to all forces was afforded by the self-retentive proximal box featuring proximal grooving.

Yates, Hembree and McKnight (1976) compared the effect of rounded or sharp (90°) internal line angles on amalgam restoration fracture strength in Class II cavities. In contrast to other studies, these workers found that a higher load was required to fracture the amalgam in the sharp angle preparation. However, this finding is qualified by several pertinent facts including that the cavity design suggested by the authors produced a relatively bulky proximal box in the restoration which was able to resist fracture loads better. In addition, loading of the restoration specimen was positioned in the mesial fossa of the amalgam over the proximal box and not at the isthmus or marginal ridge as previous studies have done; other modifications including an increased isthmus width, increased width of gingival floor and increased depth of pulpal floor may all have contributed to overcoming the stress

concentration and fracture-susceptibility afforded by the sharpened internal line angles.

Along similar lines, Amorim et al (1978) considered the influence of axiopulpal line angles and proximal grooves in cavity design on fracture strength of amalgam restorations. Four cavity design features were considered : a sharpened axiopulpal line angle, a rounded axiopulpal line angle, a pulpal wall groove which sloped toward the axiopulpal line angle and a buccolingually curved pulpal wall which also sloped toward the axiopulpal line angle. All cavities featured retentive grooves in axiobuccal and axiolingual line angles. "Fracture strength" was determined in terms of compressive strength at a speed of 0.5mm/min and on specimens of variable ages - 1 hour, 24 hours and 168 hours, although the exact method of loading was not detailed. These workers found that fracture strength was significantly increased by the incorporation of proximal retentive grooves but rounding of axiopulpal line angles or curved, sloped pulpal walls did not achieve any improvement in strength of any significance.

The concept of proximal retentive grooves was further explored by Mondelli et al (1981), with respect to restoration fracture strength, by the evaluation of four distinct groove designs. These designs included : an angular groove in the axiogingival line angle; axiobuccal and axiolingual grooves in the proximal box (similar to previous studies of Guard, Haack and Ireland 1958, Mahler, Terkla and Johnson 1962, Johnson 1972, Crockett et al 1975, Amorim et al 1978) and a design featuring both proximal and gingival grooves. Like Yates, Hembree and McKnight (1976), load was applied to the mesial fossa of specimens at 1 hour and 24 hours after condensation, in a universal testing machine at a speed of

0.5mm/min to fracture. These authors found that proximal retention improved fracture strength and precluded the need for axiokingival retention features. These findings agreed with those of Mahler, Terkla and Johnson (1962), Johnson (1972), Crockett et al (1975) and Amorim et al (1978) but contrasted to those of Mahler and Terkla (1965) and Rodda (1972) who questioned the merit of proximal retention grooves.

In observing cuspal failures of MOD amalgam restored teeth, and from a mathematical model of an idealized molar tooth set up using a computer based software package Bell, Smith and de Pont (1982) noted that the amalgam restoration took no part of any load directly imposed on the cusps. After cavity preparation, cracks were found to invariably exist in tooth structure in the region of the bottom corners of the cavity and these cracks were found to act as initiation points for progressive failure. The authors considered that most conventional cavity designs were equally susceptible to failure and suggested that a potential way to extend restoration longevity 'indefinitely' might be in the development of 'bonded amalgam' which would permit tensile loads to be carried through the tooth/restoration interface.

Fracture resistance of amalgam-restored lower molar teeth with different cavity depths and widths was examined by Re, Norling and Draheim (1982a). The fracture resistance afforded by four cavity designs of facio-occluso-lingual amalgam restorations were compared to that of an intact tooth and to a tooth restored with a mesio-occluso-distal restoration featuring extensive cusp-capping. The four facio-occluso-lingual cavities were, with respect to each other, narrow and shallow, narrow and deep, wide and shallow, and wide and deep, and all teeth were subjected to occlusal loading

applied parallel to the long axis of the crowns at or near the central fossa. The large mesio-occluso-distal restoration proved to be least resistant to occlusal load and the tooth restored with a narrow and shallow facio-occluso-lingual restoration was best able to resist occlusal load. These workers considered the 'stapling' effect of the conservative facio-occluso-lingual restoration protected the tooth from common mesio-distal fracture. In considering the severity of fractures, deepest restorations were found, not unexpectedly, to be associated with most severe fractures. Similarly these workers, in a subsequent study, compared the fracture resistance of small and large mesio-occluso-distal restorations to that of a conservatively restored facio-occluso-lingual restoration and an unrestored 'control' molar tooth (Re, Norling and Draheim 1982b). Here, unrestored teeth proved most fracture resistant, and facio-occluso-lingual restorations were found to be least fracture resistant. Fracture resistance afforded by small and large mesio-occluso-distal restorations was comparable. Based on clinical observation and previous studies of reviewed authors, Re and his co-workers considered teeth with minimal or no restoration tended to fracture more severely than restored teeth. This suggested that restorations which encroach on vertical surfaces of teeth offer a fortifying effect on the tooth in resisting occlusal loading. However, the authors acknowledged that their study did not truly simulate oral conditions.

In a comprehensive evaluation of Class II amalgam restoration cavity designs, Sturdevant et al (1987) compared five cavity designs and four amalgam alloys selected on the basis of their particle shape and copper content. The study aimed to evaluate

whether improvements in the physical properties of amalgam would affect cavity design, particularly the necessity for an occlusal dovetail in Class II cavities. The five cavity designs included three with occlusal locks, differing in the inclusion or not of proximal retention grooves; and two designs of proximal boxes-only with or without proximal retention grooves. Cast metal replicas of the teeth were prepared and restored. Loading in an Instron Universal Testing machine was centred over the marginal ridge of the restorations at an angle of 10° to the long axis of the tooth and at a speed of 0.1mm/min until restoration fracture or displacement. The variables examined were evaluated statistically with several interesting results. The predominant failure mode was a cohesive failure of the amalgam in chipping or crushing of the marginal ridge with no fracture or displacement. Approximately 20% of the failures was by fracture or displacement, comparable to findings of Crockett et al (1975). Box-only restorations required significantly higher loads for failure than occlusally-locked restorations and proximal-retention grooves did, in fact, prevent displacement failures in both cavity designs. High Copper amalgams, although exhibiting superior compressive strength, did not produce restorations more resistant to loading. The authors concluded that box-only restorations provided good failure resistance in in vitro testing but clinical evaluation of such cavity designs must be carried out prior to the recommendation of the cavity design for routine conservative dentistry. The authors suggested that the box-only cavity might be applied in the repair of Class II restorations where only the proximal portion required replacement, but such box-only cavities should feature full length retention grooves to provide adequate retention.

Marginal Failure

Marginal fracture, like isthmus fracture in Class II amalgams, is a significant cause of amalgam failure and is one of the most common causes of replacement of amalgam restorations. The mechanism and evaluation of causes of marginal fracture continues to receive much consideration in clinical studies and laboratory evaluations. Mahler and Terkla (1965) define marginal failure as 'a loss of integrity between the restoration and the tooth where oral fluids can seep into the margin' and add that this type of failure is a direct result of a mismatch of thermal coefficients of expansion between restorative material and tooth structure.

Clinical evaluations of amalgam restorations over variable periods have been completed by many workers. Nadal, Phillips and Swartz (1961) examined amalgam restorations of varying final mercury contents in two cavity designs over two years. Another set of restorations of high mercury content were observed over one year. In all cases, evidence of dimensional change or flow suggested by Healey and Phillips (1949) was not seen. Marginal failure increased up to fifteen months, and was found to be related to mercury content. Least deterioration was found in amalgams of least mercury content. Small cavity restorations showed a high incidence of isthmus failure within 24 hours, however all gross fractures were attributed to traumatic occlusion or insufficient restoration bulk.

Jørgensen (1965) based his study on the observation of amalgam restorations in extracted teeth and found that marginal fractures could be divided into two main types depending on the surface of the fracture relative to the surface of the filling. The first type of fracture formed an acute angle with the filling surface,

thus leaving a wedge-shaped gap between restoration and cavity wall. This type of fracture is caused by occlusal pressure exerting tensile force greater than the resistance afforded by the 'wedge'; this wedge deforms elastically under occlusal load and is relieved as load is relieved; this cycle continues until fracture occurs. The second type of fracture cited by Jörgensen was that caused by the formation of an obtuse angle between the filling surface and cavity wall and is related to pulling forces such as the force exerted on a filling by chewing sticky foods. Jörgensen considered that most marginal fractures were of the first type and emphasized that a discrepancy between the restoration surface and cavity wall must exist for acute angle fracture to occur. Several factors which cause this discrepancy were suggested : corrosion, dimensional change, poor amalgam condensation, plasticity, marginal excess or 'flash', enamel fracture and caries.

The testing of marginal strength at 24-hours was considered by Nagai and Ohashi (1967) who subjected amalgam specimens of differing marginal angles to a modified hardness test which aimed to reproduce occlusal loading. Marginal angles were found to be in direct proportion to fracture resistance with marginal strengths increasing correspondingly with an increase in marginal angle.

In a study of the structure of amalgam, Jörgensen (1967) examined, in particular, how various factors affect the structure of the vertical margins of Class II amalgam fillings, especially the amount of gamma phase and porosity. The variables used included type of plugger and condensation force used, depth of restoration, mercury content, 'operator' factor, and Eames technique. Porosity was especially found in specimens prepared with low condensation pressures and Eames technique. Depth of

restoration and 'operator' factor had little effect on the structure of amalgam or porosity in the proximal section. The Eames technique yielded margins of higher gamma phase content than did the traditional technique. Jörgensen pointed out that the reduction of porosity was of particular importance for strength and for the improved resistance to corrosion.

Mahler et al (1970) examined clinical marginal fracture characteristics of three amalgams representing three alloy formulations according to the varying mechanical properties. It was concluded that only creep and slow compressive strength appeared to predict clinical marginal fracture.

In agreement with conclusions of Brekhus and Armstrong (1936), Wing (1971) found that the percentage of amalgam failures were lower than for any other dental restorative material, and re-affirmed the importance of adequate cavity preparation and controlled operator manipulation of the alloy.

Corrosion of amalgam was considered by Duperon, Nevile and Kasloff (1971) in relation to the corrosion-resistance of basic amalgam formulations in vivo. These authors found Dispersion Modified amalgam alloys were more resistant to corrosion than Conventional alloys.

Following the increased interest in corrosion of amalgam alloys, Jörgensen (1972) found corroded amalgam specimens exhibited reduced tensile strength and suggested that durability of clinical amalgams may be reduced by corrosion.

In contrast, Stevenson (1973) found neither compressive nor tensile strengths were reduced by corrosion - this discrepancy may possibly be due to the differing test formats and alloy formulations used in this study and that of Jörgensen (1972).

Mahler, Terkla and Van Eysden (1973) evaluated the marginal fracture exhibited by restorations over a four year period using alloys used in an earlier study (Mahler et al 1970). Again, it was found that marginal deterioration increased at a relatively constant rate with time and the authors suggested a minimum period of two years be required for the clinical evaluation of marginal failure.

In a two year clinical study, Letzel et al (1978) examined marginal fracture, tarnish and surface roughness of 360 amalgam restorations and related these findings to creep and amalgam characteristics. The relative influence of amalgam alloy, operator, patient and creep on restoration discolouration, roughness and marginal fracture was assessed by clinical trial employing direct observation of restoration quality and the application of a rating to the degree of deterioration observed. Marginal deterioration, however, was assessed by the comparison of a photograph of the restoration to a series of 'macrophotographic' records; a method previously used by Mahler, Terkla and Van Eysden (1973) and Osborne et al (1976). In addition, a second method of evaluation of marginal deterioration was employed where photographs of six restorations of each patient were ranked from best to worst by each evaluation and assigned a grading of one to six. Creep of the amalgams used in the restorations was determined using a quick test previous described by Vrijhoef and Driessens (1975). This test varied specimen preparation procedures by condensing the amalgam under 76MN/m^2 (instead of 14MN/m^2); and by increasing the delay between mixing and loading of specimen mould to 60 seconds (instead of 30 seconds). Specimens were tested after 24 hours storage at 37°C in compression at a stress of 116MN/m^2 at

22.5±0.5°C, using a Rockwell hardness tester and strain was recorded with a strain gauge extensometer. Marginal fracture was found to correlate positively with creep and varied with alloy formulation. Discolouration and roughness of restorations varied with alloys used and were positively correlated with each other. The rating scale and photographic ranking methods of evaluation were claimed to be equally satisfactory in discerning between amalgam alloys but the rating scale was more sensitive to differences in effects of alloy, patient and operator on marginal fracture.

The cause of marginal deterioration of amalgam restorations over time has attracted much consideration in view of the studies thus far discussed on the importance and implications of the phenomena. Mahler and co-workers (1969, 1970) suggested a relationship between creep and marginal integrity and continued to examine the clinical implications of this property. Osborne et al (1978), using ridit analysis found clinical performance correlated to creep and 24-hour compressive strength. Leinfelder et al (1978), in evaluating experimental copper-added amalgam alloys in relation to marginal deterioration, found no advantage in the complete elimination of the gamma 2 phase of the alloy. Osborne and Gale (1979), supporting findings of Mahler, Terkla and Van Eysden (1973) found a statistically significant correlation between marginal failure and creep but cautioned against the use of physical properties to predict clinical behaviour.

Wing (1979) in a comprehensive review of new amalgams encompassing structure, formulation, mechanical properties, clinical behaviour, systems of delivery and handling considered that there was no direct correlation between creep and resistance

to marginal fracture despite the finding that amalgams exhibiting creep below 1% demonstrated better resistance to marginal failure.

Gale and Osborne (1980a) considered the effect of alloy, cavity width and tooth position on marginal fracture. They found that alloy selection was important and, in contrast to Mahler and Marantz (1980), conservative preparations showed less failure than wide or medium preparations.

Continuing the study of marginal fracture of amalgam, Mahler and Marantz (1980) examined the effect of type of tooth and restoration class and size on fracture behaviour. It was found, that marginal integrity was not strongly effected by tooth type or restoration size or class, confirming conclusions of Espevik and Mjör (1979).

In affirming a relationship between clinical marginal fracture and creep, Mahler, Marantz and Engle (1980) suggested a predictive model for the clinical marginal fracture of amalgam. A regression equation relating marginal fracture to creep, gamma 2 content and zinc content was devised to gauge clinical results over three years. The regression analyses completed for a selection of alloys suggested a significant role for creep in the prediction of marginal fracture behaviour.

In a comprehensive review of factors influencing marginal fracture behaviour of restorations, Bryant (1981) highlighted the controversy of the relative influence of two basic properties of amalgam : corrosion resistance and resistance to plastic deformation. Bryant concluded that marginal fracture probably occurred ultimately because of changes induced by corrosion and that principal factors controlling marginal fracture of

restorations in turn determine corrosion resistance and resistance to slow plastic deformation exhibited by amalgam alloys.

Using the regression equation suggested by Mahler, Marantz and Engle (1980), Gale, Osborne and Winchell (1982) evaluated marginal fracture exhibited by twelve alloys over three years. The authors found good application of the equation for gamma 2 and non-gamma 2 simultaneously but not for non-gamma 2, low creep alloys.

Osborne and Gale (1980) found a correlation between creep and rate of marginal failure over two years only for gamma 2-containing alloys; no significant relationship between in vivo and in vitro data was found for gamma 2-free alloys. In an extended study of clinical behaviour of amalgam restorations, a selection of High Copper alloy formulations was compared to Conventional alloys over eight years (Osborne, Binon and Gale 1980). High Copper alloy restorations exhibited lower marginal failure rates and bulk fracture than did Conventional amalgam alloys. Marginal fracture progressed rapidly and significant differences between alloys could be determined at nine months. The authors noted that alloy selection had a more important role in bulk restoration fracture than did cavity design or material manipulation - this finding has appeared to accompany the advent and use of High Copper amalgam alloys.

The superiority of High Copper amalgams in terms of marginal integrity has been noted by several clinical evaluations (Derand 1977, Rydinge et al 1981, Hamilton et al 1983, Letzel and Vrijhoef 1984, Doglia et al 1986, Lemmens, Peters and Letzel, 1986, Lemmens, Peters, Letzel and Van't Hof 1986, Osborne and Friedman 1986).

Derand (1977) found marginal defects of amalgam restorations were related to alloy selection and bite force. 163 Class II

restorations were placed in 97 patients and bite force was determined, rather loosely, by the relative size of wear facets on the restored teeth of each patient. Derand found that the distinction between marginal breakdown of blended and single phased amalgams made by creep values alone was difficult. Derand commented that in considering a correlation between creep, marginal breakdown and corrosion, creep is conventionally determined on non-corroded specimens with little relevance to clinical restorations which suffer surface corrosion and possibly elevated creep values as a consequence. Single phase spherical amalgams may suffer deeper corrosion attacks which may explain the inferior clinical behaviour of such amalgams compared to dispersed amalgams.

With the introduction of gamma 2-free amalgams, a consideration of marginal integrity in such amalgams could provide insight into the factors involved in marginal fracture. Mahler and Engle (1983) used four gamma 2-free amalgams to restore a range of cavities, and evaluations were conducted yearly for three years. Several findings were recorded including the observation that differences in marginal integrity between differing alloys noted at the time of restoration polish persisted throughout the evaluation period. The authors suggested that variables other than the alloy itself may influence marginal integrity in gamma 2-free amalgams.

Hamilton et al (1983) determined to what extent marginal fracture influenced the longevity of certain dental amalgam alloys. Over a ten-year period, clinical failure of two amalgams was compared to their ability to resist marginal fracture.

Restorations of Dispersalloy¹ and Spheraloy² were evaluated by two independent dentists at baseline, five years and ten years. Clinical failure was defined as the need to replace the restoration. The two amalgams were found to have similar clinical behaviour despite exhibiting highly significantly different resistance to marginal deterioration. This study, using only two alloys over a relatively long clinical period, could not allow definite conclusions to be made with which other alloys could be compared.

Letzel and Vrijhoef (1984) conducted a five-year clinical study of 180 Class I and II amalgam restorations in 57 patients with respect to the influence of the factors alloy, patient influence and operator influence on marginal fracture. All factors were found to have some influence. Over time, the influence of both patient and operator appeared to diminish although initially both these factors were significant and almost equal. The effect of alloy choice, relative to the other factors, over time became the most significant influence on marginal breakdown.

Berry et al (1984) considered marginal fracture of non-zinc and zinc containing gamma 2-free amalgams using photographs taken of placed restorations at baseline, 6 months and 12 months which were evaluated by ridit analysis and a rank ordering test. At one year, zinc-containing amalgams exhibited least marginal fracture. This was similar to the findings of Mahler and Engle (1984) who confirmed the relationship of marginal fracture characteristics to zinc content, presence of gamma 2 phase and static creep of amalgam

1 Johnson and Johnson Dental Products Co., New Jersey U.S.A.

2 Kerr Manufacturing Co., Detroit U.S.A.

by the use of a regression equation. In contrast to these findings, Osborne et al (1986a) found no statistical correlation between creep and fracture at the margins but did note that the better performing amalgams, with respect to marginal fracture, contained zinc. Similarly, these authors with co-workers found the same non-correlation between creep and marginal fracture for non-gamma 2 alloys tested in an additional study.

Engle and Mahler (1985) in response to the recommendation of Osborne and Gale (1981) that six month marginal fracture data be used to predict long term clinical behaviour of High Copper gamma 2 free alloys, examined restorations over four years to clarify the controversy over this recommendation. The application of an eleven-point scale of photographs demonstrating increasing degrees of marginal failure to the restorations showed that the prediction of long term performance based on early data was doubtful, compounded by the small differences between the clinical behaviour of the alloys tested over the examination period.

Most studies thus far have indicated that zinc-containing, High Copper, low-creep amalgams are associated with superior marginal integrity. Other properties related to alloy manipulation and operator technique have also been examined with respect to their effect on marginal integrity. Osborne and Andrejkovics (1985) considered the effect of extended trituration time of Tytin on marginal deterioration of restorations over two years but no significant change in amount of marginal fracture detected was found.

Polishing techniques have also been considered by several authors (Corpron et al 1983, Carron et al 1983, Mayhew and Schmeltzer 1985). Corpron and his co-workers examined the effect

of immediate polishing of placed restorations and delayed polishing after 24 hours compared with the performance of unpolished restorations after 18 months and 36 months. Two procedures for polishing, following burnishing of margins and carving, were used. The first method was carried out at eight minutes from the start of trituration using a polishing paste slurry on a rubber cup bur rotated at slow speed applied for about one minute per surface. The second polishing method, completed at 24 hours after restoration placement included finishing of margins using a range of finishing steel burs, followed by the application of a polishing paste and concluded with a final polish with a slurry of tin oxide and water. Restorations were evaluated by both direct clinical examination with the application of prescribed criteria and the photographic comparison series developed by Mahler et al (1970). Early polishing of restorations, either at 8 minutes or 24 hours after placement exhibited a worsening of marginal adaptation of a High Copper amalgam (Tytin¹) up to 18 months of age and this trend persisted to 36 months. At baseline, the surface texture of the immediately polished restorations was inferior to those restorations polished at 24 hours but by 36 months, surface texture was comparable. These workers also compared polished and unpolished restorations after 18 months and found marginal adaptation to be comparable but surface texture of polished restorations was significantly superior to unpolished amalgams.

Mayhew and Schmeltzer (1985) in comparing wet and dry polishing techniques also found little effect on marginal integrity of Class II Dispersalloy amalgam restorations.

1 S.S. White Dental Manufacturing Co., Philadelphia U.S.A.

Letzel, Van't Hof and Vrijhoef (1987) considered differing condensation instruments and techniques on the clinical performance of Class I and II amalgam restorations in terms of marginal integrity, discolouration and surface texture. These authors concluded that the most significant effect on restoration failure was the operator technique itself and not the choice of condensation method.

Rytömaa et al (1984) surveyed the quality of amalgam restorations placed in teeth 16 and 46 amongst 186 twenty-year old students. Three characteristics : marginal adaptation, anatomical form and surface texture were classified as 'good', 'requiring refinishing' or 'requiring replacement'. Ten per cent of restorations required replacement, of which 38% was due to fracture, 23% exhibited secondary caries, 13% had inadequate anatomical form and 26% had poor surface texture. An estimate of restoration age based on available dental history found the mean age of restorations requiring replacement to be 7.3 years.

Maryniuk (1985) surveyed clinicians with respect to their perceptions of restoration longevity. Among several interesting findings which emerged were the probability of amalgam restorations surviving nine years being about 50%; 15% of cast restorations would fail in the first two years and 50% of inlays were replaced after 6.9 years. In response to the questionnaire on restoration longevity distributed to dentists attending continuing education meetings and courses, and members of restorative dentistry departments at five U.S. dental schools, most dentists considered the ideal longevity of small amalgams, large amalgams and cast restorations to be 16.7 years, 9.3 years and 20.5 years respectively. Minimums acceptable were 6.5 years, 4.0 years and 8.4 years

respectively. Significantly, respondents associated with dental schools gave shortest longevity estimates. With respect to restoration failures which could be attributed to either dentist or materials, respondents found dentists most often at fault (35% vs 26%).

Eriksen, Bjertness and Hansen (1986) evaluated the relationship between prevalence of recurrent caries, quality of Class II amalgam restorations and oral health parameters (oral hygiene and periodontal indices) by the completion of a cross-sectional clinical study. 1694 Class II restorations were examined in 144 thirty-five year old citizens of Oslo, Norway. Restoration quality was determined indirectly from comparisons with indexed photographs, as described by Mjör and Espevik (1980). 6.9% of the restorations were associated with recurrent caries and of this percentage, 4.6% were found around composite resins and 2% around amalgams. Recurrent caries was found to be the most prevalent cause of restoration replacement and the authors considered that marginal breakdown per se did not constitute a demand for extensive revision of Class II amalgam restorations in order to prevent recurrent caries.

An examination of the longevity of complex amalgam restorations was conducted by Summitt and Robbins (1987). 171 restorations in 102 patients were examined five years after placement. A complex restoration was defined as a posterior restoration which replaced one or more cusps. No difference in longevity was noted for restorations placed in premolars compared to molars, and the number of cusps replaced had no significant effect on longevity. A survival table for such restorations was drawn where a 75% survival was 5.7 years, 50% survival was 11.5 years and 25% survival was 16

years. 54% of restorations survived 10 years, 36% survived 15 years and 19% survived 20 years thus attesting to the durability of this type of restoration.

Using replicas and SEM micrographs Marker et al (1987) examined the clinical performance of two amalgam alloys. The authors aimed to discriminate between the amalgams after a short period in vivo. Class I restorations were placed in prosthetic teeth in issued partial dentures, a procedure similar to that used in studies completed by Forsten and Kallio (1976), McKinney et al (1985) and Filler et al (1986). A spherical High Copper amalgam and an admixed High Copper amalgam were used to restore the Class I cavities, and micrographs were made at four recall periods : 1, 4, 12 and 24 weeks afforded by retrieval of restorations at 12 weeks and 41 weeks. The clinical performance of Tytin was better than Dispersalloy at early times but deteriorated by 24 weeks, as evidenced by rating and micrograph evaluation. In a second study, Marker et al (1987) aimed to measure the marginal gap over time of restorations of High Copper amalgams. The measurement was made from micrographs at a 60x magnification between the outer restoration circumference at the mesial portion of the margin and the cavity wall. The gap size for both amalgams increased with time but was more severe for Tytin than for Dispersalloy.

Evaluation Methods

Mahler et al (1970) in aiming to compare marginal fracture characteristics of a selection of amalgam alloys to their mechanical properties used a system of photographic classification. This system required three evaluators to place photographs of one year old restorations into four distinct categories of increasing

marginal breakdown. Ridit analysis was then used to determine whether any differences existed in the distribution of marginal fracture characteristics among the three alloys. Mechanical properties examined were compressive strength, tensile strength, transverse strength, transverse deflection, ADA flow, dynamic creep, static creep and slow compressive strength. Mahler and his co-workers found only the rheologic properties of dynamic creep, static creep and slow compressive strength appeared to predict clinical marginal fracture.

Ryge and Snyder (1973) considered a different method for the evaluation of clinical quality of restorations. This method involved the use of ratings assigned to restorations shortly after placement. Although the system applies, by design, only to restorations which have not undergone deterioration over time, the categories of standard suggested by the system are comprehensive and yielded significant agreement amongst examiners in clinical of agreement between examiners was about 70% compared to an application. The quality evaluation criteria for amalgam restorations suggested by Ryge and Snyder are shown in Table 1-1. In a clinical application of this quality control system, 991 restorations were examined, 98% were considered satisfactory with 62% meeting all standards. For the restorations requiring replacement, reasons included recurrent caries, cracked restoration, restoration mobility and fracture of tooth structure.

Similarly, Mjör and Haugen (1976) developed a system for the clinical evaluation of restorations based on a revision of the Cvar-Ryge system. The quality criteria suggested in the new system were not as comprehensive as those of Ryge and Snyder (1973) and

TABLE 1-1 : Quality evaluation criteria for amalgam restorations.
(after Ryge and Snyder, 1973)

OPERATIONAL CATEGORY		SURFACE AND COLOUR	ANATOMIC FORM	MARGINAL INTEGRITY
S A T I S F A C T O R Y	MEETS ALL STANDARDS	Surface of restoration is smooth. No irritation of adjacent tissue.	Restoration's contour is continuous with existing anatomic form; restores contours, cusps, planes, grooves, and marginal ridges adequately.	No visible evidence of a crevice along the margin into which the explorer will penetrate.
	OBSERVE AT NEXT VISIT	Surface of restoration is slightly rough or pitted; can be refinished.	Restoration is slightly under-contoured: Occlusal contour not continuous with that of cusps and plains, OR Occlusal height reduced locally (not in toto), OR Marginal ridges slightly under-contoured (low), OR Contact slightly open (may be self-correcting), OR Facial flattening OR Lingual flattening, OR Interproximal cervical area slightly under-contoured. Restoration is slightly over-contoured, but excess material could be removed.	Visible evidence of a crevice along the margin into which the explorer will penetrate.
N O T A C C E P T A B L E	REPLACE FOR PREVENTION	Surface deeply pitted irregular grooves (not related to anatomy); cannot be refinished.	Restoration is under-contoured: Dentine or base is exposed, OR Occlusion is affected, OR Contact is faulty (self correction is unlikely) OR Interproximal cervical area under-contoured; tissue damage likely. Restoration is over-contoured: Contour cannot be adjusted properly, OR There is marginal overhang.	Dentine or base is exposed.
	REPLACE STATIM	Surface is flaking or fractured.	Restoration is missing, OR Traumatic occlusion, OR Restoration causes pain in tooth or adjacent tissue.	Mobile or fractured restoration, OR Caries contiguous with the margin of restoration, OR Tooth structure fractured.

level of agreement between examiners was about 70% compared with an agreement rate of 92% found by Ryge and Snyder.

Osborne et al (1976) considered marginal breakdown in restorations after three years in addition to examining evaluation methods used. Five methods of restoration evaluation were considered including criteria suggested by Ryge, techniques of Mahler and a photographic appraisal. These workers found good correlation between the methods but considered a system of rank ordering to be the best technique, resulting in highly significant differences between restorative materials.

Methods of clinical evaluation of restorations continue to receive much attention and improvement in studies and review (Jacobsen 1984, Smales and Creaven 1985, Molvar et al 1985, Bryant, Mahler and Engle 1985, Maryniuk 1985, Mahler, Engle and Bryant 1986, Mjor 1986, Eriksen, Brjertness and Hansen 1986, Osborne et al 1988, Miller et al 1988, Letzel et al 1988). Generally, all studies emphasized the clarity with which objectives and method of assessment must be defined in clinical trials and that a period of two years is an absolute minimum for valuable assessment.

An exceptionally long clinical study of restorations spanning 25 years of general practice was completed by Allan (1977). In comparing amalgam restoration longevity with that of silicate restorations the significant superiority of amalgam was evident. The period of analysis covered a time when the characteristics of amalgam had changed little; with spherical particle amalgams not in widespread use and creep-resistant amalgams not available. Half the amalgam restorations were lost in 8 years and about 90% were lost in 20 years. Comparable figures for silicate restorations were 90% loss in 14 years and half loss in 8 years.

Jacobsen (1984) listed the types of clinical trials as:

- (1) Retrospective trials which have tended to analyse practice records to compile failure rates and reasons for failure. Such trials are valuable for the evaluation of new materials subjected to widespread clinical use.
- (2) Handling properties trials which are short-term trials where new materials are immediately evaluated on the basis of manipulation performance and limited criteria.
- (3) Clinical performance trials which involve controlled 'double-blind' clinical evaluation of new materials over a limited period where all variables are eliminated apart from the test material itself.

Amalgam failures have been evaluated by several methods including modified forms of the clinical trials suggested by Jacobsen. Marginal failure, in particular, has been assessed by several basic methods according to Osborne et al (1976):

- (i) Ryge System (Ryge and Snyder, 1973), where features of categories of marginal breakdown are described.
- (ii) Clinical Ranking where two examiners record visual ranking of each patient's series of restorations.
- (iii) Photographic ranking.
- (iv) Ridit analysis of photographic comparisons.
- (v) Rank ordering.
- (vi) Replica method, where impression records of restoration taken at periods are obtained for the production of plated replica models which are examined microscopically, graded and photographed.

Methods (iii), (iv) and (v) require quality photographic reproduction of each restoration at X 1½ magnification.

As Jacobsen points out, clinical trials would be superfluous if a series of laboratory tests could be found that would absolutely predict clinical performance. Several physical properties of amalgam have been proposed by several workers as predictors of marginal fracture. Creep was long cited as the closest correlator (Mahler et al 1970, Osborne et al 1978, Birtcil, Pelzner and Stark 1981) but later studies see a more significant role of corrosion in marginal fracture (Sarkar 1978, Espevik and Mjör 1979).

Quality assessment of amalgam and resin restorations as described in three clinical methods was evaluated by Smales and Creaven (1985). The three methods cited were :

- (1) Direct clinical observations of specific characteristics of restorations using an extensive list of criteria. This is similar to the 'retrospective' trials noted by Jacobsen (1984).
- (2) Indirect clinical observations of specific characteristics of restorations using 35mm Ektachrome colour transparencies taken at 1:1 magnification. These transparencies are matched against 11 standard sets of transparencies with each set graduated to show progressive deterioration of the characteristic being assessed (somewhat similar to Redit analysis).
- (3) Indirect clinical observation of characteristics using die stone casts made from full-arch alginate impressions. The casts are matched against a standard set of casts illustrating progressive deterioration of the characteristic. This is similar to the sixth evaluation method cited by Osborne et al (1976).

Applying the three assessment methods to 100 amalgam and 50 composite resin restorations in 31 dental students, Smales and Creaven found a significant difference between the direct method and both indirect methods. The indirect methods gave higher mean values and allowed more critical observations of the restorations than the direct method, but no method proved clearly superior to the other two in evaluating amalgam or resin failure.

Focusing particularly on the characteristics of marginal fracture of amalgam restorations, Bryant, Mahler and Engle (1985) compared two assessment methods commonly used in evaluation of this characteristic. The two methods were : matching photographs of occlusal surfaces of restored teeth to a reference set of photographs, and matching gypsum models of the same restored teeth to a reference set of gypsum models. Restorations were made from three alloys and were assessed at baseline (after polishing), one, two and three years. These authors found close correspondence between the two methods and considered the making of models of restored teeth unnecessary and superfluous. In light of this conclusion, these authors then considered the difference between inter-examiner and intra-examiner evaluations of marginal fracture characteristics of amalgam restorations using photographic evidence (Mahler, Engle and Bryant 1986) and a method of standardizing unduly significant differences with the aim of reducing them. An interval scale method was used where photographs are compared to a set of standard photographs showing increasing deterioration of the characteristics with each photograph assigned a number. Although significant differences were found among examiners evaluations, the standardizing procedure, which compared an individual examiner's evaluation against a large standard set of 400 photographs and

allowed mathematical adjustment of his individual score, proved successful in reducing the differences between examiners to insignificant proportions.

Mjör (1986) presented a review of methods of clinical assessment of amalgam restorations. In addition to more commonly used methods of direct USPHS criteria application, the indirect clinical techniques of Mahler and replica model comparisons, Mjör includes the value of questionnaires completed by practising dentists surveying reasons for placement and replacement of restorations. Such questionnaires have been employed by several studies for example Maryniuk (1985).

Forsten and Kallio (1976) used a unique method to evaluate marginal fracture using occlusal cavities cut into acrylic premolars and molars of complete dentures issued to patients. An exaggerated cavo-surface margin bevelled at 45° was incorporated into each cavity and marginal integrity was gauged from plaster study models taken at issue and after 6 months. The two Dispersion Modified amalgams (Dispersalloy and Amalcap Non-Gamma 2¹) were found to exhibit less marginal deterioration although the degree of difference with that of the Conventional alloy (Amalcap F²) was not a significant one.

The use of dentures, either partial or complete, into which amalgam restorations have been placed, to measure marginal breakdown has since been used by several authors (McKinney et al 1985, Filler et al 1986, Marker et al 1986). In contrast to Forsten and Kallio (1976) who used a bevelled cavo-surface margin

1 Vivadent, Liechtenstein.

2 Vivadent, Liechtenstein.

in complete dentures, Filler and his co-workers used occlusal restorations placed in partial dentures to examine early detection and progression of marginal breakdown. SEM micrographs taken as early as 4 weeks exhibited significant changes in the High Copper amalgam.

Exploring new or improved methods of restoration evaluation has received as much consideration in the literature as has the clinical results of the applications of such evaluation methods. Most studies have applied modifications of the methods described by Mahler et al (1970), and Ryge and Snyder (1973) or those listed by Jacobsen (1984), Osborne et al (1976), Smales and Creaven (1985), Mjör (1986) and Forsten and Kallio (1976).

Letzel, Hendriks and Fick (1986) considered colour photographic scales of progressive marginal deterioration was a most reliable evaluation method. Miller et al (1988) compared the accuracy of the rating scale evaluation method to a quantitative method of SEM measurement of marginal gap size of restorations placed in partial denture teeth (a method similar to that previously employed by Forsten and Kallio 1976, McKinney et al 1985 and Filler et al 1986). The quantitative method was found to be more accurate and time efficient.

Jekel, Marker and Filler (1988) presented an in vitro evaluation method which aimed to simulate in vivo restoration breakdown. The model featured the testing of Class I amalgam restorations placed in acrylic denture teeth which were cyclically loaded between 2 lbs and 10 lbs at 20 cycles/min in an Instron testing machine in an environment of artificial saliva. Replica models were constructed after 500, 1000, 5000 and 10,000 cycles and examined by SEM. Results were favourably correlated to results of

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a 'parallel' clinical study suggesting an advantage in the suggested method. In additional research, Filler et al (1988) found that distinctive features of breakdown apparent in restorations placed in natural teeth were also found in restorations placed in acrylic partial denture teeth supporting the application of this method of evaluation.

Espevik and Mjör (1979) examined marginal degradation evident in retrieved amalgam restorations in terms of microstructural characteristics determined by SEM and backscattered electron microscopy. The 'Replica Method', as reviewed by Osborne et al (1976) where study models prepared from impressions of restored teeth taken at intervals are compared and evaluated, was considered by Espevik and Mjör to be the only available method whereby the topography of the degrading margins could be studied in detail. In addition to applying this method to a study of 129 Class II amalgam restorations over an unspecified clinical period, these workers also examined 'amalgam biopsies' by backscattered electron microscopy and ion probe analysis. Espevik and Mjör found that marginal breakdown was preceeded by gamma 2 phase corrosion causing cracks which filled with corrosion products well beyond the fractured interface thus suggesting an interplay between gamma 2 content and corrosion in marginal breakdown. The replica method of monitoring marginal deterioration has since been endorsed by Marker et al (1986).

Corrosion in Restoration Failure

The contribution of both creep and corrosion to marginal breakdown has been considered by many authors. Despite the findings of early clinical evaluations which supported the

relationship of creep and marginal fracture (Mahler et al 1970, Binon et al 1973, Osborne et al 1978, Letzel et al 1978 and Mahler, Terkla and Van Eysden 1973) subsequent analyses of a wider spectrum of amalgam alloys encompassing a greater diversity of alloy structure, properties and characteristics have suggested, as pointed out by Wing (1971), that marginal fracture and subsequent amalgam failure is not simply a function of creep. In fact, restoration longevity cannot safely be predicted on the basis of creep value alone. (Osborne and Gale 1979, Jordan et al 1978, Osborne, Phillips, Gale and Binon 1980, Laswell, Berry and Osborne 1980a). Sarker, Osborne and Leinfelder (1982) suggested that a new predictive model for marginal fracture must include a "hybrid function of structure (gamma 2), property (creep) and composition (zinc content)".

Several authors have considered marginal fracture to be an effect of corrosion (Sarkar 1978, Jörgensen 1965, 1972, Jörgensen and Saito 1970). In an attempt to correlate in vitro corrosion and in vivo marginal fracture, Sarkar, Osborne and Leinfelder (1982) employed a potentiodynamic cyclic polarization technique to determine a corrosion index. The technique allowed determination of corrosion susceptibility of a selection of amalgams in a 1% NaCl solution at 23°C, by monitoring current generated relative to potential applied. Correlating corrosion results of the amalgams examined with marginal fracture behaviour for the same amalgams noted in clinical trials of Osborne (1980), Osborne, Binon and Gale (1980) and Mahler, Marantz and Engle (1980), a significant association between in vitro corrosion and in vivo marginal failure was found particularly in gamma 2-free amalgams. Based on these findings, Sarkar and his co-workers suggested, in view of the

'diminishing importance of creep as a predictor of marginal fracture', an in vitro corrosion test had proved most useful in marginal fracture evaluation of dental amalgam.

Williams and Hedge (1983) examined the effect of thermal-cycling on subsequent marginal degradation of specimens as a result of the creep induced by stress resulting from the mismatch between thermal coefficients of expansion of amalgam and tooth structure. Thermal-cycling was conducted using temperatures between 4°C and 50°C for 1000 cycles. Corrosion during cycling was kept to a minimum by the use of a protective varnish which was removed for microscopy. Marginal breakdown, it was found, increased with increased cycling times. Three different modes of failure were noted : interface opening, surface 'wrinkling' adjacent to the margin and frank marginal failure.

Hanawa et al (1987) examined microstructural changes associated with marginal deterioration to fracture of amalgam restorations over 49 weeks. Class I Dispensalloy restorations were periodically retrieved from cavities prepared in partial denture teeth and subjected to metallographic preparations prior to SEM examination. Microstructural findings of crack progression through the amalgam illustrated several features. Cracks were observed only near margins and initiated at or near occlusal surfaces, propagated normal to the occlusal surface and gradually bent toward the margin wall. Corrosion products were associated with some cracks but were never seen at or beyond a crack tip. In addition, these workers considered that corrosion did not play a role in crack initiation. Crack progress through phases was observed as going :

- (1) through the gamma 1 matrix and between gamma 1 and reaction layers, gamma 1 and gamma (Ag-Sn) particles and between gamma 1 and eta (Cu-Sn) particles.
- (2) occasionally through reaction layers on Ag-Cu particles, gamma (Ag-Sn) particles and eta (Cu-Sn) particles but never penetrated Ag-Cu particles.
- (3) small disconnected cracks formed in the gamma 1 (Ag-Hg) matrix ahead of the main crack tip, and around the periphery of reaction layers and eta (Cu-Sn) particles.

Corrosion was found :

- (i) isolated in the gamma 1 matrix,
- (ii) at the surface of cracks and
- (iii) at the occlusal surface.

Amalgam vs Posterior Composite Resins

The comparison of composite and amalgam restorations in terms of restoration longevity has received much attention in studies. Generally, with few exceptions, composite resin has found little clinical support in its promotion as a Class II restorative material because of its relatively rapid deterioration by abrasion of original contours (Leinfelder et al 1978, 1981), and its propensity to early marginal discolouration and poor marginal adaptation (Nuckles and Fingar 1975).

Gibson et al (1982) evaluated composite and amalgam occlusal restorations after one-year and after two-years for evidence of failure, utilizing a modified cavity preparation and acid-etch technique for the composite restoration hypothesized to improve restoration longevity. The modified composite cavities were kept minimally deep where possible and a final glaze was applied to the

restorations of Adaptic¹. All restorations were re-examined using an identical set of criteria. At one year, 67% of the amalgams and 62% of the composites were considered sound. At two years these percentages dropped to 46% and 42.6% respectively. 38% of amalgams suffered marginal discrepancies, whereas only 5% of composites had this defect. Surface wear of composites was obvious in 26% of restorations.

Derkson, Richardson and Waldman (1983) reaffirmed the superiority of amalgam over composite resin for posterior restoration in a study of 104 amalgams and 121 composite resins over a period of two years. At the end of this period, 86.5% of amalgams and 56.1% of composite resins were free of defects.

In a clinical evaluation conducted over three years, Hendriks, Letzel and Vrijhoef (1986) compared the deterioration evident in amalgam restorations (Dispersalloy) with that of a selection of composite resins including a strontium glass filled composite (Profile²), a microfilled composite (EsticMF³) and a macrofilled composite (Adaptic Radiopaque⁴). 232 Class I and II restorations were placed in 49 patients and evaluated yearly by the application of USPHS criteria (anatomic form, marginal adaptation, colour match, marginal staining and caries). At three years, the amalgams had failed by recurrent caries whereas bulk fracture and pulpal injury plagued all types of composite resin restorations.

1 Johnson and Johnson Dental Products Co., New Brunswick U.S.A.

2 S.S. White-Pennwalt, Philadelphia U.S.A.

3 Kulzer and Co., Bad Homburg F.R.G.

4 Johnson and Johnson Dental Products Co., New Brunswick U.S.A.

CHAPTER 2

TRADITIONAL TESTING OF MECHANICAL PROPERTIES

The basis for Specifications and Standards for Dental Amalgam Alloys has been centred around tests for compressive strength, dimensional change, creep, and carving properties. In addition to these properties, additional information about other properties such as marginal adaptation and resistance to corrosion also supply the practising dentist with a foundation from which he may evaluate dental amalgams. Most important is the relationship of the properties to clinical and intra-oral behaviour.

Probably the most highly examined property of all is that of strength. Strength can be manifested in at least three modes : compressive, tensile and transverse; and it is this property that enables a previously weakened carious tooth to adequately withstand multi-directional occlusal loading once adequately restored. Traditionally, the most appropriate method of strength testing of amalgam has been compressive strength, although, in view of continued study into amalgam restoration failures, a consideration of tensile strength may more accurately reflect the mechanism of amalgam failure.

Tensile Strength

Earliest consideration of tensile strength (Ward 1924) based the test on that used for cement testing. A 'dumb-bell' shaped specimen 0.25 inch thick and 0.2 inch wide at the constricted area yielded tensile strengths of approximately 5,600 p.s.i. The difficulty of specimen condensation was noted in later studies (Taylor 1930) as was a relationship between tensile strength and

compressive strength. The effect of aging of specimen and type of alloy on tensile strength was examined by Coy and Liebig (1938) who found that at age five days, fine-grained alloys were comparable to coarse-grained alloys - a contrast to one day results where fine-grained alloys displayed superior tensile strength. It was later noted that improved specimen preparation produced superior tensile strength (Sweeney 1940).

A study completed by Mahler (1958) investigated stresses acting in a Class II restoration and thereby linked tensile strength to clinical restoration fractures. Mahler concluded, from photoelastic studies, that tensile stresses were particularly significant in isthmus areas of Class II restorations. Continuing the investigation into tensile strength several authors (Rodriguez and Dickson 1962, Jörgensen 1965, Forsten 1969, Nagai et al 1971) found that tensile strength was quantitatively related to compressive strength and was independent of loading rate. Tensile strength was found to be about one quarter of compressive strength at seven days, and one tenth of fully set tensile strength in one hour.

Using a smaller specimen than previous studies, Mahler and Mitchem (1964) found an inverse relationship between tensile strength and residual mercury with a critical decrease in strength at 54% mercury content for fully set amalgams.

An examination of differences between different amalgams with respect to tensile strength, elongation and modulus of elasticity was carried out by Nagai and Ohashi (1968). Spherical amalgams displayed highest tensile strength values at one hour but values were comparable with Conventional lathe cut amalgams at one week.

Several authors (Rodriguez and Dickson 1962, Taylor 1930, Forsten 1969, Nagai et al 1970, 1971, Basker and Wilson 1973) commented on the difficulties associated with direct tensile strength testing. These difficulties included the very large specimen size necessitated by the conventional testing machines which thus had limited clinical significance and inherent 'layering' often produced by condensing such large amounts of amalgam. Specimen damage often occurred as a result of gripping specimens and premature specimen fracture often occurred upon load application.

An improved tensile test for amalgam was thus required and was introduced by Sweeney and Burns (1965) following its previous use in testing dental cements (Rudnick, Hunter and Holden 1963). The Brazilian or Diametral-Compression test used cylindrical specimens (8mm x 4mm diameter) tested in the same equipment as for compressive strength testing. The cylindrical specimen was compressed diametrically between two flat platens of a testing machine. Maximum tensile stresses result in fracture of the specimen along a diametral plane joining the contact areas of the platen to the specimen. These authors acknowledged that shear and compressive stresses had also developed but that the mode of failure of the specimens enabled a distinction to be made between such stresses.

An evaluation of efficacy of the new diametral compression test compared to the old direct tensile test (Nagai et al 1970) concluded that the diametral compression test was reliable and easy, yielding a 'minimum of data scatter'. The tensile strength values varied between amalgam products and correlated definitely with compressive strength values. Spherical amalgams achieved

higher tensile strength values than Conventional amalgams. Strength values for Spherical amalgams appeared not to be affected by condensation pressure; tensile strength of Conventional amalgams, in contrast, decreased proportional to decreasing condensation pressure. The definite correlation between compressive and tensile strength was expressed quantitatively as a ratio of 6.9 for Spherical amalgams and 7.5 for lathe cut Conventional.

In a later study Nagai and his co-workers (1971) employed the diametral test to investigate the effect on strength values of manipulative variables including time delays between trituration and condensation, and prolonged condensation. Highest tensile strength values were achieved by more increments condensed quickly. Later authors (Jørgensen 1972, Acharya et al 1973) also used the test to evaluate amalgams.

Basker and Wilson (1973) although endorsing the diametral compression test for tensile strength determination in marked contrast to Sweeney and Burns (1965), considered the specimen specifications somewhat faulty. Specimen preparation did not consider differing handling characteristics of the amalgam formulations and the specimen size was yet too large to preclude inevitable layering within the specimen. The authors suggested a 3mm x 3mm specimen size with differing hand-packing forces for differing amalgam formulations and a minimum value of one hour tensile strength be set at 8MPa (1,160 p.s.i.).

The effect of size of mix and trituration time on physical properties (including tensile strength) was studied by Ohashi et al (1975). Using diametral compression testing on one-day old specimens, these authors, in agreement with other workers (Phillips

1957, Caul et al 1962, Holst 1965) concluded that insufficient trituration time reduced strength values and extended trituration time increased dimensional change (shrinkage).

Direct tensile and diametral compression test methods were compared by Wang Chen and Greener (1976) following anodic polarization. Direct tensile testing used the 'dumb-bell' shaped specimen which was condensed mechanically as suggested by American Dental Association Specifications. Using a Conventional amalgam and a High Copper amalgam these authors found the direct tensile strength method to be sensitive to anodic polarization for the Conventional amalgam (a reduction of 27% in mean direct tensile strength). Diametral tensile strength method values were found to be unaffected by polarization. Johnson (1972) attributed this finding to the character of the diametral tensile fracture which was nucleated within the material bulk and not concentrated at the specimen surface.

Wang Chen and Greener (1976) considered the direct tensile test a more sensitive test since corrosion affected the specimen surface and thus acted as a means of stress concentration; the direct test was thus discriminating enough to allow 'in vitro testing of simulated clinical properties'.

Lautenschlager and Harcourt (1970) pointed out that the diametral test was only applicable to homogenous, single phase materials without pores and thus was not a true determination of tensile strength for amalgam.

Turchyn and Youdelis (1970) also found the diametral compression test had shortcomings since plastic deformation which occurred during testing visible by flattening of the platen/specimen contacts, resulted in artificially elevated tensile

strength values. These authors suggested a three-point loading system as a more suitable test.

Asgar, Arfaei and Mahler (1977) pointed out that the mathematical evaluation of tensile strength assumes a line contact and not an area contact and that the contact flattening depended upon the degree of flow or creep of the material. The diametral tensile test was considered to be an underestimation of the true tensile strength for low creep amalgams and an overestimation for high creep amalgams.

Notwithstanding a question as to the validity of diametral tensile strength testing, a consideration of the reliability of the specimen preparation method for initial tensile strength measurement described by the American Dental Association Specifications was completed by Spanauf, Vermeersch and Vrijhoef (1977). The method was found to be reasonably reliable for tensile strength determined at 15 minutes compared to clinical packing by a dentist.

Drawing together previous research, Vrijhoef, Vermeersch and Spanauf (1980a) pointed out the importance of early strength with regard to clinical functioning of dental amalgam and, quoting Jörgensen and Isenoumi (1969) that 'diametral tensile strength correlates significantly with carvability'. Without reference to the diametral tensile strength tests itself, a 15 minute determination was advocated since 'there is a tendency that an amalgam giving a relatively high tensile strength after 15 minutes also gives a relatively high strength after 30 or 60 minutes'.

Vrijhoef and Spanauf (1981) investigated early-stage diametral tensile strength in an attempt to resolve doubts about validity of values determined. The authors concluded that, on average,

'theoretical doubts as to the diametral tensile test have no practical consequences as to its interpretation' and that compressive strength and tensile strength values correlated well.

Several authors have considered the effects of variables; both manipulative and, compositional on physical and mechanical properties of amalgam alloys including diametral tensile strength (Taylor 1977, Johnson and Carwile 1978, Moore et al 1979, Clark et al 1979, Fainsilber et al 1980, Ohashi 1981, Clark, Farah and Clark 1981, Mueller 1982, Yi, Dennison and Asgar 1984, Murchinson et al 1986). Variables included aging of specimens by exposure to air, varying condensation pressure, saline contamination of specimens during trituration, corrosion and early polishing procedures. Results were not directly comparable due to the utilization of varying times at which tensile strength was determined by the different researchers which ranged from 15 minutes (Yi, Dennison and Asgar 1984) to 20 weeks (Fainsilber et al 1980).

As amalgam alloys with new formulations and particle characteristics are developed, laboratory evaluations and comparisons continue to include diametral tensile strength data in addition to compressive strength, creep and dimensional change. Quoting 290 p.s.i. (2MPa) as the minimum diametral strength at 15 minutes, Eames and MacNamara (1976) compared High Copper alloys and Conventional alloys, and in contrast to Ohashi (1981) considered strength the least important characteristic of new alloys.

Reisbick (1977) considered the effect of added particle inclusion on compressive and diametral tensile strength of Ag₃Sn-additive amalgams and found that physical strengthening did not occur. Younis (1977) evaluated eight new High Copper dental amalgams by comparing determined values for 15 minute-, 1 hour-, 24

hour- and 1 day diametral tensile strength for corresponding values achieved for two Conventional dental amalgams.

Vrijhoef, Vermeersch and Spanauf (1979) examined some of the newer alloy systems after aging the specimens during various heat treatments. 23 alloys were tested including Dispersalloy¹ and New True Dentalloy². The overall mean values for diametral tensile strength achieved during three heat treatments of 1 day at 22.5°C, 1 day at 37°C and 1 week at 37°C were 46.0 MN/m², 48.1 MN/m² and 48.6 MN/m² respectively and a minimum tensile strength of 35 MN/m² was cited as providing sufficient strength to avoid bulk fractures as long as cavity preparation and material handling was carefully managed.

Bryant (1979) in contrast to previous authors (Eames and MacNamara 1976) questioned the validity of 15 minute diametral tensile strength data due to the flattening of specimen contacts during testing and thereby restricted earliest valid determination of this property to 30 minutes. The rate of development of both compressive and tensile strengths of a selection of Conventional and High Copper amalgam alloys was examined using cylindrical specimens which had been stored in water at 37°C. It was noted that development of both compressive and tensile strengths for most alloys was greatest between one hour and one day, and that most amalgams tended to achieve maximum tensile strength earlier than maximum compressive strength.

Using a large cylindrical specimen size, viz. 11mm x 4.5mm, Murray and Yates (1980) examined early compressive and diametral

1 Johnson and Johnson Dental Products Co., New Jersey U.S.A.

2. S.S.White Dental Manufacturing Co., Philadelphia U.S.A.

tensile strengths of a selection of alloy systems. Samples were prepared using American Dental Association Specifications and earliest strength values were determined at 15 minutes and 30 minutes. Values for tensile strength were considerably lower than data presented by previous authors (Eames and MacNamara 1976, Bryant 1979).

A question as to how closely clinical performance of amalgam could be predicted by physical property tests was considered by Gale and Osborne (1980b). A study of twelve alloys placed in 1,041 restorations were assessed photographically for marginal failure. The same alloys were subjected to laboratory tests for compressive strength, creep, flow, dimensional change and diametral tensile strength at 15 minutes, 1 hour and 24 hours. A correlation of results showed that creep testing accounted for the most variance predicted by laboratory data and thus may be important in determining whether clinical trials should be undertaken.

Duke et al (1982) compiled laboratory profiles of 30 High Copper amalgam alloys. Specimens prepared from the High Copper amalgams were subjected to several standard laboratory tests including static creep, a compressive strength test and a diametral tensile strength test. Anodic polarization was also performed at seven days using a standard corrosion cell. A significant finding in the study was the lack of discernable correlation between copper concentration within the amalgam alloys and test results. It is probable that the most significant factors in improved properties is the form in which the copper is supplied and its availability for reaction.

Gjerdet and Hegdahl (1985) examined porosity, strength and mercury content of amalgam made by different dentists in their own

practices thereby combining aspects of clinical and laboratory testing. Cylindrical specimens 3.4mm x 5mm diameter were prepared, stored for one week and tested. Overall, absolute values obtained for tensile strength was lower than those cited by other authors but similar to variations reported for such differing alloy formulations.

In an attempt to study the fracture mode of dental amalgam, Huh and Um (1984) used cylindrical specimens which had been stored for one week. These specimens were subjected to loading in a diametral tensile mode but loading was stopped short of fracture and the cracking present on the specimen surface was then polished and examined microscopically.

Along similar lines, Sutow et al (1984), studied the fatigue fracture of dental amalgam using notched cylindrical specimens which had been aged for one week. Tensile tests were carried out in addition to cyclic loading and it was observed that fatigue loading reduced tensile strength up to 30%.

Compressive Strength

Compressive strength in addition to tensile strength, has been, and continues to be, an important property of amalgam cited in many research studies. Ease of specimen manufacture and testing allows the determination of compressive strength to be a reproducible and reliable means whereby amalgam alloys may be evaluated and compared. The test also provides a way to measure the effect of certain variables on amalgam performance.

Earliest work on compressive strength testing used cylindrical specimens of 4mm diameter and 8mm length (Taylor et al 1949). In contrast to tensile strength testing, these authors noted that

compressive strength was related directly to loading rate, an aspect noted by other workers (Mahler 1972, Peyton 1985). Mahler (1972) noted that at a very slow crosshead speed (0.001 in/min), compressive strength correlated well with dynamic creep and considered such slow cross-head speeds to have better clinical relevance.

In a study based on an extensive investigation of the physical and microstructural properties of amalgams, Wing (1965) examined the effects of variations in aspects of amalgam condensation on several properties including 1-hour and fully set compressive strength, flow and dimensional change. Variations in condensation procedures examined included force, condenser size, number of condenser thrusts, number of amalgam increments and time of force application per thrust. Early strength was found to be significantly affected by all factors examined; fully set strength was little affected provided initial alloy proportioning and amalgam trituration were carried out optimally. The study allowed several definitive recommendations for optimal amalgam condensation to be made. The most important factors in amalgam condensation are the use of small amalgam increments and multiple thrusts on each increment.

Relating mechanical properties to clinical behaviour, Mahler (1970) noted a relationship between marginal fracture and static and dynamic creep, and so too, by extrapolation could slow compressive strength be related to marginal fracture.

Many authors, by studying the rate of development of strength, found that 50% of the maximum strength was attained at 6 hours by conventional alloys, rising to 100% at 24 hours (Taylor et al

1949, Phillips 1949, Wing 1964, 1965, 1966, Bryant 1979). Attainment of maximum strength was dependent on rate of set of amalgam.

Evaluating the effect of variables upon compressive strength attained, Swartz and Phillips (1956) found a serious decrease in strength when residual mercury was greater than 55%. Wing (1961) investigated alloys differing in particle character with respect to compressive strength at recommended and varied mercury : alloy ratios. At one hour, fine grained alloys displayed higher strength; and one-hour strength increased when the initial mercury : alloy ratio was decreased. When the mercury : alloy ratio was increased, one-hour and fully set compressive strengths were decreased for all alloys.

Wing (1961, 1964, 1965, 1966, 1967), Caul et al (1963) and Schultz (1979b) considered further variables likely to affect compressive strength. Caul et al (1963) found under-trituration produced inferior strength in specimens, and lower strength was also noted in specimens tested at 60°C. Schultz (1979b) found that greatest compressive strength was attained when mixing time was twelve seconds, in a Silamat¹ amalgamator for the Conventional amalgam (New True Dentalloy). High Copper alloys showed higher strength when mixing time was extended. Delayed condensation adversely affected strength of Conventional alloys but had little effect on High Copper amalgams.

In an evaluation of the Eames' technique, Wing and Hewitt (1965) examined the relative merits of amalgams prepared from a low initial mercury : alloy ratio and a conventional mercury : alloy ratio with respect to 1-hour and fully set compressive strength,

1 Silamat-Vivadent. Schaan-Liechtenstein.

dimensional change and mercury content. The Eames' technique consists of several deviations from manufacturers recommendations, lower mercury : alloy ratio, longer amalgamation time, no removal of excess mercury from the mix prior to condensation and the use of a lower condensation load. In the study of Wing and Hewitt, cylindrical specimens were prepared from amalgams where mercury : alloy ratios of 7:5 and 5:5 were used and trituration was completed using a Wig-1-bug¹ at times of 6 seconds, 15 seconds, 25 seconds and 1 minute. These authors found no significant difference to fully set compressive strength in the variations of amalgam manipulation examined. An improved 1-hour compressive strength was provided by the use of a slight mercury excess as recommended by manufacturers. The claimed increased early compressive strength of Eames' technique amalgams were considered to be due to more thorough trituration rather than to the low mercury content.

The effect of mercury : alloy ratios on compressive strength has been considered by several authors (Abdel-Azim 1977, Louka 1977, O'Toole et al 1982). Abdel-Azim (1977) found that compressive strength varied with alloy type but was highest when the mercury : alloy ratio was 5 : 5. It was also noted that the Eames technique of minimal mercury did not yield amalgams of highest strength, supporting findings of Wing and Hewitt (1965) for fine-grained alloys. Louka (1977) noted that High Copper alloys suffered most when mercury : alloy ratios were varied. The effect of variations in mercury dispensed from clinical dispensers on compressive strength was considered by O'Toole et al (1982) and Von Fraunhofer et al (1983). The dispensers tested showed a variation

1 Crescent Dental Manufacturing Co., Chicago Illinois, U.S.A.

of 2% in mercury amounts delivered which had varying effects on compressive strength of the amalgam alloys particularly at one hour and three hours after mixing.

Several authors (Wing 1965, Louka 1977, Clark et al 1979, 1981, Schultz 1979, Bistritz et al 1984, Bowman et al 1984) have considered the effects of condensation pressure variations on compressive strength. Increased condensation pressures reduce the porosities and voids of the amalgam mass. Compressive strength was found to vary directly with condensation pressure by Clarke et al (1981) but decreased pressure did not necessarily reduce strength (Clark, Farah and Clark 1979). Bowman et al (1984) found delayed condensation decreased strength. The effect of mechanical condensers has also been examined. Comparing impact condensers and vibratory condensers, Palmertree et al (1978) found impact condensers to be more effective; and hand condensation employing heavier force and lateral thrusts was comparable to mechanical condensation.

Trituration time was examined as one of the variables having an effect on mechanical properties of amalgam alloys by several authors (Wing 1965, Osborne et al 1984, 1985, Jones et al 1982, Iglesias et al 1984, Murchinson et al 1986). Generally, deviation from recommended trituration time had an effect on compressive strength, diametral tensile strength and creep of amalgam according to most workers. Osborne and his co-workers (1984, 1985), examining vacuum trituration of amalgam both in vitro and in vivo, noted that the technique decreased the number of voids in the amalgam mass and hence increased compressive strength and also decreased the incidence of marginal fracture in restorations placed. Several workers noted that delayed trituration or

under-trituration resulted in amalgams of reduced compressive strength (Jones et al 1982, Murchinson et al 1986) and that High Copper amalgams appeared less sensitive to trituration changes (Iglesias et al 1984, Murchinson et al 1986).

Changes in composition of original alloy powder by substitutional additive metals or variations in basic formula proportions produced a variety of effects on mechanical properties of amalgam alloys as noted by several authors, (Demaree and Taylor 1962, Wing 1966, 1970, Malhotra and Asgar 1977, Reisbick 1977, Vaidyanathan, Schulman and Greener 1977, Johnson and Paffenbarger 1980, Dermann and Leistner, 1985, Mahler and Adey, 1985, Routray and Prasad, 1986, Chung, Lin and Greener 1986).

A consideration of the physical properties and microstructure of spherical particle amalgam introduced by Demaree and Taylor (1962) was completed by Wing (1966). In addition to compressive strength and dimensional change, Wing examined several pertinent clinical aspects such as adaptability to cavity walls and polishability and, in a later study, made several recommendations about clinical handling techniques (Wing 1970). Both compressive strength and dimensional change were found to be comparable to those of well manipulated lathe cut alloys. Improved marginal adaptation and polishing was afforded by the blending of several different particle sizes in the amalgam. The recommended technique forwarded by Wing (1970) for optimal clinical use of spherical particle amalgams is quite different to that suggested for Conventional lathe-cut amalgams. The main advantage of the spherical particle amalgam is that optimal properties are achieved at easily maintained condensation loads but the necessity for mercury removal throughout condensation must be borne in mind.

With the emergence of copper enriched amalgam alloys, the effect of variations of copper levels on mechanical properties and the comparison of copper levels on mechanical properties and the comparison of copper-containing alloys to non-copper containing alloys has been considered widely. Reisbick (1977) found that added copper particles had failed to increase compressive strength of amalgam alloys when powders of pure copper or silver-copper binary in other than eutectic composition were admixed with Ag_3Sn powder. It was suggested that great strength could be obtained when the additive particles were fewer in number but higher in copper content than those of Dispersalloy. Slow compressive strength, using a cross-head speed of 0.03 mm/min, significantly increased as the additive quantity increased.

Mitchell, Mohme and Okabe (1979) varied the volume fraction of the Cu_6Sn_5 phase in a High Copper Single Composition amalgam by varying mercury levels to determine the effect on compressive strength and creep resistance. The alloy had a copper content of 30 weight % and mercury levels were varied from 46 weight % to 63 weight %. Compressive tests were carried out on week-old specimens which had been stored at 37°C. Compressive strength was found to decrease from 500 MPa to 200 MPa when mercury content increased from 47 weight % to 53 weight %. A slower decrease in strength then followed with additional mercury. The volume fraction of the Cu_6Sn_5 phase reached a maximum at 50 weight % mercury and thence gradually decreased.

An examination of the mechanism whereby copper affects the properties of amalgam was carried out by Mahler and Adey (1985). These authors compared the effect of copper and zinc on properties including dimensional change, creep, strength and grain size within

the Ag-Hg phase. Copper and zinc were substituted atomically for silver at two levels, 0.5% and 2.0%. Despite no change in gamma 1 grain size, compressive strength was found to increase significantly. This contrasted with the findings of Reisbick (1977). Properties generally improved equally with the copper or zinc substitutions indicated by a reduced negative dimensional change and reduced creep.

Routray and Prasad (1986), also examining the effect of copper content on properties of amalgam, consolidated the findings of previous authors (Mahler and Adey 1985) in noting a linear relationship between copper content and mechanical properties.

Malhotra and Asgar (1977), aiming to establish a relationship between microstructure, corrosion and mechanical properties substituted varying atomic percentages of tin in several Ag₃Sn amalgam alloys. Such amalgams were examined by X-ray diffraction and specimens were produced for mechanical testing. Tin content varied from 0 atomic % to 24.1 atomic %. An examination of gamma 1 phase lattice characteristics was completed and correlated to physical properties. The presence of varying amounts of tin in the gamma 1 lattice led to variations in its unit cell dimensions and affected its corrosion behaviour and mechanical properties. Vaidyanathan, Schulman and Greener (1977) found a deterioration of mechanical properties when titanium and aluminium alloying was carried out. Additive phases used were Ag-15% Ti and Ag-10% Al.

In a definitive analysis of 'new amalgams' Wing (1979a) summarized many pertinent aspects of available amalgam alloys. These alloys were discussed from not only a metallurgical view-point but from a clinical view-point. In summary, an 'ideal' amalgam should be encapsulated, of a non-gamma 2 Dispersion

Modified or Ternary High Copper formulation. Its formulation would require no pre-condensation mercury removal but allow the easy removal of mercury-rich phases during and after condensation. In addition, polishing of the amalgam should be carried out without undue temperature elevation to avoid approaching solidus temperature of inherent phases.

Under conditions of saline contamination of 20 weeks storage in 0.5% saline at 37°C, Fainsilber et al (1980) found that the strength of zinc-containing amalgams had significantly deteriorated but creep values remained relatively unaffected.

The effect of zinc content on properties of amalgam alloys was examined by Johnson and Paffenbarger (1980) who tested twenty-five alloys containing additions of zinc varying from 1 to 7 atomic %. Compressive strength was determined at one hour, one day and seven days using a crosshead speed of 0.20 mm/min - lower than that suggested by American Dental Association Specification. Slow compressive strength as proposed by Mahler (1972) was also determined. These workers found that to obtain 'proper' consistency, mercury : alloy ratio must increase as zinc content increases. Increased zinc content was also found to be associated with less dimensional change, less creep and increased compressive strength.

The correlation of creep and slow compressive strength was first examined by Mahler (1972) and verified by Espevik (1978). Compressive strength was found to increase with increasing zinc content. The authors did not determine creep values for the amalgams tested but inferred, from results for slow compressive strength, that creep was inversely related to zinc content. The relationship of zinc content and compressive strength noted by

Johnson and Paffenbarger (1980) was consolidated by Mahler and Adey (1985). Chung, Lin and Greener (1986) found that the addition of palladium to a blend of a spherical conventional alloy and a Ag-Cu eutectic alloy produced no significant effect on 1-hour or 24-hour compressive strength. However, 4-hour and 24-hour creep was markedly decreased by palladium additions. It was also noted that palladium substitution for copper was more effective in decreasing creep than its substitution for silver.

Focusing on the wettability of alloy powder particles, Dermann and Leistner (1985) examined the effect of electrolytic removal of the oxide and sulfide films from particles which, it was claimed, left the particles nonwetting without mechanical agitation. Following film removal by exposure to hydrogen in a sodium chloride solution, alloy powder was easily wetted by mercury. However, the amalgam formed from the alloy powder particles thus treated with no further mechanical amalgamation, failed to improve strength and 24-hour compressive strength was, in fact, half that of a control group. Creep of Low Copper alloys was comparable for treated and non-treated alloys whereas creep of High Copper alloys was doubled for treated alloys.

Other treatments and variables have been suggested by authors; these included variables like amalgamation time and frequency (Dermann 1984) ageing (Moore et al 1979) temperature (Chen and Greener 1977) cyclic stressing (McCabe 1984) and early polishing (Yi, Dennison and Asgar 1984). Referring to axial tensile strength, Chen and Greener (1977) examined the effect of temperature on the deformation behaviour of amalgams. A temperature range of 0°C to 60°C was used and it was observed that strength remained constant for the lower range of 0°C to 25°C and

thence decreased with further temperature increase. Three types of amalgams were tested and temperature dependence of fracture stress was smallest for the High Copper amalgam tested.

Moore et al (1979) found that ageing heat treatment of High Copper alloys significantly degraded strength but had no effect on creep. Dermann (1984) examined the influence of amalgamation time and frequency on properties of dental amalgam. Amalgamation time was varied from 2 seconds to 14 seconds depending on alloy selected. Frequency varied from 30 Hz to 70 Hz. Generally, it was found that compressive strength and creep increase with amalgamation time for all alloys. Creep values for Conventional alloys were sensitive to amalgamation frequency also, increasing with frequency.

The effect of cyclic stressing on mechanical properties of amalgams was considered by McCabe (1984) following similar work of Kusy and Greenberg (1981). Specimens were subjected to a maximum of 1000 compressive cycles in a range of 20 MPa to 190 MPa at a rate of 1 cycle per 10 seconds. Compressive strength was determined following creep, and was found not to be increased by the dynamic stressing in Conventional and Dispersed Phase High Copper alloys.

Fatigue behaviour of amalgam and the relationship of fatigue to subsequent failure of amalgam restorations and fracture toughness has been explored by many authors. Sutow et al (1979, 1980, 1985) examined aspects of dynamic loading and fatigue failure of amalgam specimens at various cyclic frequencies. Circular cross-section specimens with tangentially blending fillets were hand condensed and stored at 37°C for a week prior to axial, sinusoidal loading to failure. By varying compressive stress

levels and loading frequency, it was found that dynamic loading decreased fatigue strength significantly and that fatigue behaviour was dependent on frequency within a range of 80 to 3600 cycles/min, 80 cycles/min being cited as a representative chewing frequency.

Mueller (1983) evaluated compressive failure of amalgam in air and in saliva noting a significant difference in the number of cycles to fracture of the various representative amalgams. Zardiackas, Bayne and Carlson (1982) used low cycle frequency to examine fatigue cracking and corrosion in crevices of High Copper amalgams. Anderson, Zardiackas and Bayne (1983), continuing the study into amalgam cracking, varied strain rates ranging from 0.025mm/min to 250mm/min and loads of between 30% and 90% of compressive strength. Significant differences in ultimate strength and percentage of compressive strength required to initiate cracking was noted at the different strain rates.

Comparison and evaluation studies of new amalgam formulations continue to include compressive strength determination, creep tests and diametral tensile strength tests as discriminating tests. With the advent of copper-enriched amalgam alloys, comparison studies have tended to evaluate these new formulations from many aspects. Generally, the various studies attest to the superiority of High Copper formulations in terms of strength, dimensional change and creep.

Eames and MacNamara (1976) in addition, found superior 3-hour flow characteristics for a selection of eight High Copper alloys compared to six Conventional alloys. Further comparison studies also conclude in favour of copper-enriched amalgams (Younis 1977, Dermann 1977, Taylor and Leinfelder 1977, Dermann 1977, Rhodes,

Swartz and Phillips 1979, Duke et al 1982, Cochran and Moore 1983, Vrijhoef et al 1984, Johnson 1985).

Taylor and Leinfelder (1977) used amalgam formulations varying in amount and particle size of copper additions. Particle size varied from 4 μ m to 50 μ m diameter and copper amount varied from 17% to 34% by mass. Such additions were found to consistently increase strength of fully hardened amalgams, and to increase setting expansion. Custer, Flynn and Moyer (1977) in comparing compressive strengths of different amalgam alloys found, in contrast to other authors, that the newer copper alloys did not demonstrate higher strength.

Marker and Marshall (1979), using a selection of copper-rich amalgams including Dispersalloy and Tytin found compressive strength was not enhanced by copper enrichment but noted a marked increase in corrosion resistance and a decrease in static creep.

Rhodes, Swartz and Phillips (1979) noted that High Copper amalgams exhibited no classic expansion during setting and thus displayed decreased dimensional change. Bryant (1979) found that the ratio of compressive strength to tensile strength was higher for High Copper alloys and that the major increase in strength occurred between one hour and one day. This was later noted also by Cochran and Moore (1983). Dermann (1977) compared two High Copper amalgams Luxalloy-non-gamma ²¹ and Optalloy II² to Dispersalloy and concluded that although the High Copper amalgams displayed higher early strength, Dispersalloy could be expected to provide a greater 'lifetime expectation' due to lower creep. A

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question as to the accuracy of predicting clinical performance of amalgam by physical property tests was addressed by Gale and Osborne (1980b) who found creep to be the only physical property which could 'account for the most variance that is predicted from laboratory data'. Furthering this dilemma, Laswell, Berry and Osborne (1980b) found that alloys exhibiting less flow and creep and greater compressive strength 'did not necessarily form restorations with better marginal integrity'.

Duke et al (1982) formulated a laboratory profile of 30 High Copper alloys and pointed out that the superior performance of High Copper amalgams cannot be directly correlated to copper concentration but rather to the form in which copper is supplied and its relative availability for reaction within the alloy. Similarly, Vrijhoef et al (1984) completed laboratory characterization of some new amalgams including copper-enriched and palladium-containing formulations. Mechanical tests included compressive strength testing at 30 minutes, 1 hour and 1 day, static creep at 1 week and diametral tensile strength testing at 1 day.

Moore et al (1979) found that ageing of High Copper amalgams degraded physical properties including compressive strength at 1 hour and 24 hours. Johnson (1985) attributed improvements in strength and creep of new amalgam alloys to improved wetting of the alloy with the addition of indium. The superiority of High Copper amalgams was further supported by a microstructural examination by Butts, Okabe and Galloway (1982) who noted that the fine alloy microstructure resulting in rapid amalgamation gave the alloy its high early strength and large gamma 1 grains with the Cu-Sn phase appeared to endow the amalgam with lower creep.

Transverse Strength

Information about the strength of amalgams afforded by compressive strength and diametral tensile strength testing can be complemented by the determination of the modulus of rupture or transverse strength. This strength is considered to be a composite strength reflecting compressive and tensile stresses. Transverse or bending strength is obtained by loading a supported beam or bar specimen at one or two points thereby achieving three-point or four-point loading respectively (Peyton 1985).

The information afforded by this test can provide a means of evaluating new amalgam alloys by virtue of comparison to strength achieved by similar alloys (Roark 1965). A greater consideration of this test will be presented in Chapter 3.

With increased interest in the mechanism of amalgam fracture, more valid laboratory tests aiming to simulate clinical behaviour are constantly being sought. The transverse strength test, combining components of compressive and tensile stresses, has been considered as a fair general test in relation to clinical fracture strength although it by no means supersedes compressive or tensile tests and can only supply a limited duplication of clinical performance (Peet 1971). Compressive strength continues to be a more convenient and plausible test and, as Wing (1971) has suggested, certain ratios do exist between compressive strength and other strengths including transverse.

Creep

The specified test for static creep involves the use of a cylindrical specimen which is subjected to a constant compressive load of 36 MPa at a temperature of 37°C. The change in length of

the specimen between the first and fourth hour of testing is expressed as a percentage of original length.

Creep of dental amalgam has been considered in depth by many authors (Bryant 1980, Mahler 1972, 1977, Mahler et al 1965, 1969, 1970, 1972, 1975, 1977, 1981, 1982, Vrijhoef et al 1974, 1980, 1983, 1986, Osborne et al 1974, 1977, Sarkar 1978, Sarkar et al 1980, 1983, 1984, 1987, Spanauf et al 1977, Espevik 1975, Espevik et al 1975 Wing 1975, 1979a b, 1982, 1984, 1985, 1986, 1987, 1988).

In a study on the condensation of dental amalgam, Wing (1965) found that static-flow was reduced slightly by efficient condensation. The true clinical importance of a static-flow test was queried but a clinical advantage for a reduction of this property was acknowledged. With the introduction of spherical particle amalgams and the improved physical properties afforded by these amalgams, direct comparison of spherical to lathe-cut formulations gained some attention in the literature. Wing (1970) found flow values of spherical amalgams investigated to be less than 1% and noted a significant relationship between flow and rate of setting of the amalgam. With greater detail available about the identification and properties of phases within amalgams and knowledge about setting reactions of the various phases in 'newer' amalgams, creep determination has emerged as a valuable physical property (Wing 1966). The 3-hour static creep test has since 1970 been a standard test used in laboratory testing, replacing flow determination in clinical significance.

In contrast, Vrijhoef et al (1983) saw disadvantages of 3-hour creep testing including the requirement of an oven for testing at 37°C and the time required for the test. These authors suggested

an accelerated creep test which used a temperature of 22.5°C, testing period of a half to one hour and a compressive stress of 116 MPa in a Rockwell hardness tester. Creep was measured by determining the slope of the strain-time curve in the early steady-state creep stage. In a comparison of specification creep values and those determined by the accelerated test, a positive correlation was observed.

Dynamic creep, as considered by Mahler and Van Eysden (1969), was thought to relate to the clinical phenomenon of amalgam restoration extrusion. Specimens identical to those used in static creep testing were aged for seven days and compressive loads were cyclically applied where the range of stress was 35 to 703 kg/cm², at a frequency of 1,800 Hz. The range of stress represented a minimum to ensure positive contact of the load on the specimen, and a maximum approximating masticatory stress. Herö et al (1983) compared surface corrosion of amalgam specimens with respect to static and cyclic creep values determined. Cyclic loading was carried out using a stress range of 0-70 MPa and a frequency of 0.25 sec⁻¹ with specimens immersed in saliva. Creep was found to significantly affect the degradation of the gamma 1 phase and minimal differences in surface attacks for the two modes of creep testing were noted.

Taira et al (1984) investigated the effect of dynamic creep on the transformation of gamma 1 to beta 1 in a copper-enriched amalgam. Cyclic compressive loads of 5 lbs to 350 lbs were applied at a frequency of 1 Hz and immersed in 37°C Ringer's solution, creep was gauged at 3 hrs, 7.5 hrs and 30 hrs. Dynamic creep testing was found to induce the phasic transformation as postulated, but not to the degree achieved by corrosion.

Wing (1984, 1985, 1986, 1987, 1988) considered long term or extended creep as a valuable physical property. The 72-hour creep behaviour of a selection of amalgams was found to allow greater discernment between formulations than did the 3-hour creep test. After loading for 72 hours, creep increases tended to relate to type of amalgam not to 3-hour creep value. Gamma 2-containing, low 3-hour creep alloys exhibited significantly greater 72-hour creep values than non-gamma 2-containing alloys of comparable 3-hour creep. These observations allowed a possible explanation of amalgam behaviour under other low loads, for example, sub-modulus of rupture loading.

The relationship of amalgam creep to other mechanical properties has been investigated by many authors allowing possible clinical correlations to be drawn. Mahler et al (1970) related slow compressive strength to dynamic creep and also to marginal fracture (Mahler et al 1970, 1973).

Binon et al (1973) conducted an in vivo examination of occluso-proximal restorations with respect to marginal defects and amalgam characteristics. It was noted that amalgams exhibiting high creep also exhibited more marginal fractures and other properties of these amalgams such as strength and flow did not correlate well with the restoration fractures observed.

Galan, Phillips and Swartz (1973) related cavity design and alloy formulation to plastic deformation of the restoration. A selection of amalgam alloys was packed into four prepared mesio-occluso-distal cavities with each cavity containing a modified feature hypothesized to influence restoration deformation. A load of 11,935 p.s.i. at a frequency of 7,560 load cycles in 21-hours was applied at two positions - the marginal ridge or the isthmus.

The authors concluded that the alloy formulation was a more significant influence on restoration deformation than any cavity feature.

Osborne et al (1974) found no correlation between creep and compressive strength, a finding which supports that of Mahler and Van Eysden (1969) and Binon et al (1973).

Vrijhoef and Driessens (1974, 1975) investigated the effect of Conventional alloy content on creep in Dispersion Modified amalgam and found that creep of the amalgam was dependent on creep of the Conventional alloy content. These authors confirmed that creep was determined by the low melting phase of the reaction product matrix when alloy and mercury were amalgamated. Schulman and Vaidynathan (1976), continuing an investigation of Dispersion Modified amalgams, found that these amalgams exhibited significantly lower creep values and consequently improved marginal integrity than Ag₃Sn type amalgams.

Giblin (1979) and Giblin and Wing (1979b, 1982, 1983) considered transverse fatigue testing of amalgam beams under sub-modulus of rupture loads and found a distinct relationship of the amalgam behaviour with creep. Times to failure of specimens were found to be inversely related to creep. Alloys containing gamma 2 exhibited significant deformation under static loading manifested by a significant degree of bend and a distinct susceptibility to fracture after a relatively short time. Dispersion Modified amalgams, of low creep, resisted significant deformation and fracture. High Copper amalgams exhibited imperceptible deformation despite extended periods of loading.

The relationship of microstructural characteristics to creep has been considered by several authors. In examining gamma

2-containing amalgams, Mahler, Adey and Marantz (1977) found that the grain size of the Ag-Hg phase (gamma 1) was a predominant factor influencing creep. In addition, creep was reduced by decreased trituration and alloy annealing. Hausseilt and Blum (1980) noted, in using a wide range of stresses, that the creep rate increased, probably due to the formation and growth of voids during deformation. In examining creep of the various matrix phases of dental amalgam, Averette and Marek (1980) found, similar to Mahler, Adey and Marantz (1977), that the pure Ag-Hg phase (gamma 1) had a higher creep rate than most dental amalgams. Tin strongly increased creep rate while creep was decreased by zinc content.

Sarkar (1978), in a review of available research into creep and corrosion, pointed out that due to the multiphasic character of amalgam, the overall creep resistance of the amalgam mass depends not solely on one individual component but on the volume percentage of the particular high creep phase and therefore quantitative metallography was the only reliable means of determining creep resistance. Sarkar and Eyer (1987), in seeking to provide a microstructural basis of amalgam creep, demonstrated that creep of gamma 1 is controlled by an intergranular SnHg precipitate and that creep was more influenced by the nature of Sn distribution than absolute Sn content.

The relationship of creep resistance and marginal integrity was suggested by Mahler et al (1970, 1973). In a microscopic study of dental amalgam fractures, Sutfin and Ogilvie (1970) noted that the fracture surface revealed evidence of plastic deformation and compositional inhomogeneity across the diameter of larger Ag-Hg grains.

Jordan, Suzuki and Mills (1978) conducted a clinical study of restorations using four amalgam alloys exhibiting a wide range of creep values to determine the reliability of creep as a predictor of marginal integrity. Patients were examined at intervals to a maximum of three years following restoration placement. Where a mechanism for decreasing or eliminating the gamma 2 phase existed within the amalgam used, enhanced marginal integrity was noted but the authors considered equating low creep with improved marginal integrity was a 'hazardous clinical speculation'. Sarkar (1978) also considered that a 'cause and effect relationship does not exist between creep and marginal fracture' and cited corrosion of dental amalgam as responsible for marginal breakdown due to the presence of the gamma 2-phase.

Likewise, Sarkar, Eyer and Norling (1983) found that creep of a conventional amalgam was not dependent on gamma 1 content but rather creep is strongly influenced by gamma 2 and its volume fraction. Creep was found to be strongly dependent on the gamma 2 phase and Sn-rich gamma 1 grain boundaries.

Williams and Hedge (1985) suggested 'creep fatigue' as contributing to marginal failure. Creep fatigue is the failure resulting from cyclic loading at stresses below the material's ultimate strength and at temperatures greater than 0.4 of the material's fusion temperature.

Vrijhoef and Letzel (1986) concluded from clinical trials that in Conventional, low copper amalgams creep correlated with marginal fracture but no such correlation could be found for non-gamma 2, High Copper alloys.

With the continued interest in amalgam failures, many researchers have considered corrosion to be the sole factor

responsible for marginal breakdown. Marginal integrity, as observed by Sarkar (1978) is dependent on adaptability, dimensional change and porosity. Such factors mechanically favour corrosion mechanisms by the set-up of a differential oxygen concentration cell at the cavity wall-restoration interface. Creep, being a time-dependent deformation of the amalgam mass under constant stress resulting from the presence of the gamma 2 phase, is related to corrosion by its common relationship to the silver-mercury phase. Butts et al (1980) determined creep for High Copper amalgams corroded by immersion in a NaCl solution for one year. Such corroded specimens achieved lower creep values than those determined for control specimens which had been exposed to a humid air atmosphere at 37°C for two years or for seven days. It was also suggested that the reduction in creep of corroded specimens could be accounted for by the transformation to the gamma 1 (Ag-Hg) phase.

Mahler, Adey and Marek (1982) investigated the relationship between creep and corrosion of amalgams containing either no gamma 2 or various amounts of gamma 2. Creep was determined as required by specifications and corrosion tests were conducted using anodic polarization which utilized a 1% NaCl solution at 37°C. Several High Copper Single Composition alloys were tested. These alloys exhibited gamma 2-containing and gamma 2-free transitional phases depending on specific Hg content. A definite relationship between creep and corrosion current was found since both exhibited high values when gamma 2 was present. Microstructural examination suggested that creep was influenced by gamma 1 grain boundary effects and not gamma 2 content.

Jendresen et al (1984) considered corrosion to be the prime cause of marginal fracture but also noted that the mismatch of thermal coefficients of expansion of amalgam and tooth resulted in stress which induced creep and so contributed to margin degradation.

The influence of variables, including handling and manipulation, on the creep values achieved by amalgam formulations has been examined extensively. Spanauf, Vermeersch and Vrijhoef (1977) and Patel and Cruickshanks-Boyd (1979) found that creep was inversely related to ageing time but appeared not be affected by packing technique.

Mahler and Nelson (1981) found that creep tests conducted on specimens aged for three and six months showed a sudden increase in creep at a higher Hg content than younger specimens. Okabe et al (1985), however, found that specimens aged for 30 days or less resulted in decreases in creep. This effect was noted in all specimens aged at 37°C, 50°C, 60°C, 70°C or 80°C; and at 60°C, this decrease was attributed to an increase in gamma 1 grain size; above 60°C the observed decrease in creep was attributed to the appearance of large gamma 1 grains.

Papadogiannis, Boyer and Lakes (1986) investigated the age dependence of creep in a selection of amalgam alloys. In contrast to previous authors, it was found that there was no change in creep values with ageing up to six months once the amalgamation reaction was completed. Steady-state creep compliance was found to be stress dependent for Conventional and Single Composition Spherical alloys but independent for Admixed Lathe Cut Eutectic alloys.

Osborne et al (1977) found that both trituration time and condensing procedure affected the creep of amalgam, and that creep

was reduced by increased condensation pressure. Higher creep amalgams tended to be influenced appreciably by trituration time. Rehberg and Gramberg (1979) also noted that trituration time changes were related to changes in creep values. Only when condensation pressure was increased beyond 42 MN/m² (specifications) was the effect of different trituration times on creep values negated. Osborne and Wolff (1984) found that a technique of vacuum trituration did not affect creep and Iglesias et al (1984) confirmed the superiority of mechanical trituration over hand trituration for achieving lower creep values.

Espevik (1977) examined the relationship of creep to temperature and stress using temperatures of 22°C, 37°C and 50°C and a compressive stress range of 10.3 MN/m² to 58.4 MN/m². Creep rate was found to vary directly with stress and inversely with temperature. Greener, Szurgot and Lautenschlager (1980) found that creep behaviour did not vary linearly with temperature and questioned the convention of calculating 3-hour creep.

Rupp and Paffenbarger (1980) considered the effect of increased residual mercury content on creep values. Increased mercury content caused by compaction delays increased creep although low creep high copper amalgams were less sensitive to increased mercury content. Holland et al (1985) similarly varied trituration time, condensation pressure and mercury : alloy ratio to gauge creep dependency of Conventional and High Copper amalgam alloys. Lowered condensation pressure increased creep for all amalgams. Conventional amalgams also exhibited increased creep with lowered mercury : alloy ratio.

The significance of amalgam additives on creep has also received some attention. Johnson and Paffenbarger (1980) found

that increased zinc content tended to decrease creep due to the increased mercury content produced by delayed compaction. Chung, Lin and Greener (1986) examined a spherical Conventional alloy containing a Ag-Cu eutectic into which Pd was substituted for Ag or Cu. Creep, determined at 4 hours and 24 hours, was found to decrease markedly with the Pd additions although Pd substitution for Cu was more effective in decreasing creep.

Aspects of the mechanisms of creep have been considered by many authors. Lautenschlager, Szurgot and Greener (1979) investigated the creep behaviour of a selection of amalgam alloys related to temperature in the range of 0-60°C. Largely, the tested amalgams followed the creep-time curves where over 50% of the total deformation occurred within one hour followed by a region of time dependent creep. At times greater than 6 hours and temperatures higher than 40°C, creep-time behaviour deviated from the expected curve and the authors suggest multiple creep mechanisms must come into play.

In order to account for the lower creep of High Copper amalgam alloys, Okabe et al (1980) considered the restriction of grain boundary sliding. High creep amalgams exhibit most grain boundary sliding which occurs between gamma 1 grains. Such sliding did not occur in High Copper Single Composition amalgams. The 'accommodation' of gamma 1 grain sliding by gamma 2 deformation - characteristic of Conventional gamma 2-containing alloys and hence contributing to relatively high creep values - does not occur in High Copper alloys containing little gamma 2. Sarkar, Renz and Norling (1980), in order to investigate the microstructural role of gamma 2 in creep, determined creep for a variety of blends of phases and of pure phases (gamma 1 and gamma 2). Quantitative

metallography was carried out using X-ray diffraction techniques on pore-free samples. The creep rate was found to be directly proportional to the gamma 2 content and the creep of the gamma 2 phase was one order of magnitude higher than that of the gamma 1 phase. Oden (1984), along similar lines as previous authors, examined the microstructure of amalgam specimens in view of creep mechanisms. It was suggested that creep deformation was mostly controlled by 'recovery' creep and Nabarr-Herring creep in the gamma 1 phase.

Sarkar and Eyer (1984) examined the relationship between Sn-rich grain boundary segregations and gamma 1 creep using annealed and unannealed samples. Creep was found to be controlled by the Sn-rich segregations, particularly the morphology at these sites and not on gamma 1 grain size.

Hero (1983) examined creep mechanisms in terms of dislocation creep and superplastic flow using a 'stress-dip' technique on pre-polished cylindrical specimens. In such tests, specimens are tested at the same temperature and a constant load with initial stresses of 20, 28, 36, 40, 45 and 57 MPa. After 2 hours when a constant strain rate is achieved, the load is suddenly reduced by 10% and kept so until strain rate achieved is again zero. Then the original load is reapplied until a constant strain rate as previously achieved is again obtained. The load is continually reduced in this fashion by increasing steps of 10% or 5% to the level where strain rate is zero, for as long as possible without a negative strain rate. Specimens are then ground and polished in preparation for metallographic study. Hero concluded that the main deformation mechanism during creep was superplastic flow although evidence of dislocation creep was also present. The overall

microstructural view of the deformation mechanism was considered to be grain-boundary sliding with dislocation slip in the gamma 1 grains and concomitant grain-boundary diffusion.

In examining the relative effect of 'factor alloy' on creep mechanisms, Vrijhoef, Lourens and Leijdekkers-Govers (1983) used a selection of nineteen alloys. Applying a previously described formula 'model' to describe creep, it was found that certain constants in the suggested equation were strongly sensitive to choice of alloy. Ageing time was found to effect creep substantially, supporting the conclusions of Spanauf, Vermeersch and Vrijhoef (1977) and Patel and Cruickshanks-Boyd (1979).

Creep, with compressive strength, diametral tensile strength and transverse strength, continues to be employed as a parameter whereby new alloy formulations are judged and compared by workers (Marker and Marshall 1979, Rhodes, Swartz and Phillips 1979, Esperik 1980, Duke et al 1982, Greener and Szurgot 1982 and Sutow et al 1985).

Flow

The determination of flow of dental amalgam is carried out in a test similar to that of static creep but differing in the time after trituration when the test is carried out. Flow tests are completed on specimens which have not attained full set, at 3 hours after trituration. The significance of flow as a property by which clinical behaviour of an amalgam may be predicted has been a controversial issue. Wing (1971) considered that 'flow is primarily a measure of the rate of setting of the amalgam and probably bears little relationship to clinical behaviour of the material'. Earlier, Skinner (1938) found flow to be a property

clinically manifest by the loss of contact points, the development of gingival overhangs and marginal fractures. Later authors Healey and Phillips (1949), in contrast to Skinner (1938), found that flow was not of a sufficient magnitude to induce restoration degradation but did concede that flow, together with faulty cavity preparation, contributed to early restoration failure.

Several authors have continued to be critical of the clinical significance of flow testing (Mosteller 1953, Phillips 1945) noting that conditions of static testing are not comparable to oral conditions.

Modifications to the flow test in order to evaluate early resistance to flow were considered by Kimmel (1961). A load of 1,500 p.s.i. (10.3 MPa) was used to test flow on specimens at 10 minutes and 15 minutes after trituration. A significant difference in flow exhibited by the various groups of amalgams led Kimmel to suggest that the early flow test be considered in later specifications for amalgam alloys.

Caul et al (1964) began flow test measurements on specimens at three minutes after the end of trituration by subjecting specimens to a load of 4.9 MPa for ten minutes. These workers found that the rate of hardening was similar to that shown by compressive strength testing and concluded that the early flow test was a method for determining rate or hardening of dental amalgam.

Several authors have investigated the effect of variables on flow of dental amalgam. Sweeney and Burns (1961) found that initial mercury : alloy ratio had little effect on flow provided adequate condensation has been carried out and excess mercury removed. Caul et al (1964) also found that an altered mercury : alloy ratio had little effect on flow. Fuse (1969) found flow to

be temperature dependent and varied according to alloy particle morphology. Basker and Wilson (1971), following a suggestion by Braden (1967), examined flow properties of amalgam by subjecting specimens, 3mm diameter and 2mm height, to repetitive cyclic indentation. A 2mm hardened steel ball indenter was used to strike the specimen at a frequency of 120 times/minute and a maximum force of 150 N/thrust. A non-linear relationship between depth of indentation and number of thrusts was observed but age of specimen was inversely related to indentation depth. These authors attributed their results to the procedure itself which was effectively a method of work hardening and porosity elimination. Moore et al (1979) found that accelerated ageing treatment by exposure of specimens to air at 60°C for 336 hours, significantly degraded physical properties of amalgam including flow.

Flow is sometimes cited in evaluations and comparisons of various amalgams. Acharya et al (1973) found admixed High Copper amalgams exhibited low flow (0.56%) compared to Conventional amalgams (0.91%) although flow of both formulations fell well below the specification maximum of 3%. Eames and MacNamara (1976) found that High Copper alloys showed 47% less flow than Conventional alloys. The low flow, characteristic of High Copper alloys, was observed by many authors (Younis 1977, Dermann 1977, Rhodes, Swartz and Phillips 1979, Espevik 1980, Laswell, Berry and Osborne 1980a).

Espevik (1980) evaluated two High Copper lathe cut alloys. An alloy containing 13% copper exhibited a 2.4% flow, whereas a 0.44% flow was obtained by an alloy containing 25% Cu. Laswell, Berry and Osborne (1980b) compared the clinical behaviour of two low creep amalgam alloys, Tytin and Dispersalloy to their physical

properties and concluded that such alloys exhibiting less flow did not necessarily form restorations with better marginal integrity. Likewise, Gale and Osborne (1980) considered flow of little 'predictive value' in clinical performance.

Flow stress, defined as the uniaxial stress required to cause plastic deformation at a particular value of strain, has been considered by Herö and Jörgensen (1985) particularly in relation to an evaluation of condensation properties. Using a range of alloy formulations, a 4mm diameter amalgam mass housed within a mould cavity was subjected to a maximum stress of 14 MPa, at a speed of either 50mm/min or 10mm/min which was applied via a 2mm diameter plunger within 60-70 sec. after trituration. Resistance to plastic deformation was investigated by examining the load-indentation depth curve generated. It was noted that flow stress increased with deformation time and no threshold or typical flow stress independent of indentation depth could be observed. Similar curves were found for the other alloys investigated.

The flow test has largely disappeared from the traditional test armamentarium since the development of the creep test and the incorporation of this in Specifications.

Dimensional Change

Wing (1964) acknowledged the importance of the dimensional change of amalgam taking place during setting and considered slight expansion of amalgam to be preferable to contraction in a clinical situation. The extreme accuracy demanded of the measuring device by the test restricts the choice of such instruments. Wing used a Mercer Dial Gauge capable of accuracy to 0.5 μ m which exerted a load of 5 grams. Cylindrical specimens 10mm long with a 4mm diameter

were prepared in an ejection type die. Initial measurements were taken within 15 minutes of the start of condensation, and subsequent readings at 15 minute intervals for 90 minutes, then 30 minute intervals for 4 hours, then hourly until 24 hours after specimen preparation. It was noted that only one amalgam achieved an initial contraction as required by Specifications. Wing concluded that determined dimensional change may be a combination of true dimensional change and early flow or compression of the amalgam. The determination of dimensional change of an amalgam alloy is considered to be related to restoration adaptation to cavity walls.

Wing and Lyell (1966) in examining the marginal seal of amalgam restorations aimed to quantitatively assess adaptability of amalgam to cavity walls. The size of spaces occurring between the amalgam restoration and several sites in the cavity was examined using a reflected light microscope and measured using a filar eyepiece following sectioning of specimens. Both lathe cut and spherical alloys were used and the restored molar and premolar teeth were stored at 37°C in distilled water, saliva or 10% sodium sulphide solution for a varying period of one day to three months. Both storage times and storage solutions were found to have no significant effect on space sizes. The largest spaces observed were at the cavosurface region of the cavity which the authors attributed to the mercury-richness of this layer and the unrestricted expansion that may take place there. Adequate condensation was considered to have a more significant effect on reduction of the spaces than subsequent expansion of the amalgam.

Vrijhoef, Vermeersch and Spanauf (1980a); however, pointed out that adaptation of an amalgam restoration involves not only

dimensional changes inherent in the restoration but adaptability of the material. Adaptability, defined by Jörgensen (1965), is the ability of the material to reproduce surface details of the cavity wall.

Dimensional change as determined by Australian Standard 2110 (1983) involves the measurement of changes of length of a specimen at specified times after trituration and the recording of the average of two determinations to the nearest 0.01%. These recordings are taken at 5 minutes following the end of amalgamation and at 24 hours. The measuring instrument used must be accurate to the nearest $0.5\mu\text{m}$ and exert no more than 0.1 N of force since, as Wing (1964) pointed out, laboratory measurement of dimensional change reflects changes taking place within the specimen due to the low loads applied by the measuring device in addition to inherent expansion and contraction of the material. In the light of informed comments on instrumentation, techniques and timing of dimensional change determination several workers have investigated various methods to record dimensional change.

Souder and Paffenbarger (1942) considered a light interferometer whilst optical micrometers were used by many investigators. In the attempt to test a highly accurate method which did not require specimen contact, Fusayama et al (1964) used an air micrometer. Times at which readings were taken have varied considerably between authors. Fisher and Lehwald (1954) used readings at seven to eight minutes after the start of trituration; Mitchell, Schoonover and Dickson (1955) at ten minutes whilst Fusayama et al (1964) used readings at five minutes.

Mahler and Van Eysden (1972) found faults in the use of the interferometer to measure dimensional change although conceded its

extreme accuracy. These authors suggested a new test instrument capable of testing ten specimens simultaneously and producing a dimensional change vs time curve on a multipoint recorder chart.

Vrijhoef, Spanauf and Driessens (1974) found the dimensional change test described in ADA Specification No. 1 (ADA, 1968, 1970) unsatisfactory because of its 'high dependence on experimental variables'. These authors suggested a method whereby dimensional change was directly determined from measurements of the diameter of set cylindrical specimens prepared by 'clinically simulated' packing techniques. Packing was accomplished with a Bergendahl vibrator and following storage at 37°C for 1 week, diameters of the specimens were determined at several positions by a micrometer at an ambient temperature of $22.5 \pm 0.5^{\circ}\text{C}$. Dimensional change data thus determined was compared to corresponding data for adaptation measurements. The two sets of data were found to correlate well. Lemaitre, Moors and Van Peteghem (1979) found the determination of free axial dimensional changes as ascribed by specifications incomplete and suggested a method to measure radial dimensional change.

Habu (1984) acknowledged that in measuring dimensional change, the influence of the measuring load creates a 'partial flow' and the reading will reflect this influence confirming the suggestion of Wing (1964). In order to restrain this flow and thereby allow the measurement of pure inherent dimensional change of the amalgam, Habu suggested the attachment of a metal disc or 'cap' on each end of the specimen against which a condensation force was applied. Determination of dimensional change thus took place with an electric micrometer level contacting the 'cap' on the specimen. The detectors themselves were of two types, a lever-type exerting

7g load and a plunger-type exerting 15g load. Specimens were strengthened by the incorporation of caps and flow was successfully restrained. A dimensional change vs time curve derived was found to be of a classic nature.

The relationship of dimensional change data to clinical behaviour of amalgam restorations has led various authors to re-evaluate dimensional change determination techniques. Fusayama et al (1964) considered that 'marginal closure' of amalgam restorations correlated better to horizontal dimensional change in the top most layers of the restoration. These authors also noted that the significant initial contraction taking place during the first ten minutes was not apparent in readings made at 15 minutes as advocated by the specified test required. From this, the authors concluded that transverse expansion of top most layers of amalgam was more significant than vertical expansion possibly suggesting that a modification of the dimensional change determination test was required.

Vrijhoef, Spanauf and Driessens (1974) in a literature review of amalgam restoration adaptation to cavity walls noted that no study could confirm a clinical parallel of laboratory measurements of dimensional change. In fact the non-correlation of dimensional change and adaptation has been widely reported. In light of deficiencies in current studies, Vrijhoef and his co-workers considered a clinically relevant method for determining dimensional change. Cylindrical specimens of 4mm diameter were removed from moulds at varying periods according to mercury content. Following storage at 37°C, the specimen diameter was determined and compared to results of specified dimensional change measurements. It was

noted that specimens of 60 weight % mercury yielded significant long-term dimensional change.

Paffenbarger (1979) aimed to correlate marginal integrity and creep by observing dimensional change of amalgam. Specimen preparation differed from specifications in mercury : alloy ratios, in methods of trituration and in schedule of specimen preparation. Results for cylindrical specimen dimensional change and creep were correlated to extrusions of 'restorations' placed in prepared steel-block cavities 17mm deep and 6mm diameter. This specimen size is extremely large and would require approximately fifteen 600 mg capsules of amalgam for hand condensation or five 600 mg capsules for "one shot" machine condensation. The validity of the results would be doubtful. A linear relationship was noted for the correlation of creep and extrusion, and extrusion and marginal integrity. In contrast, Paffenbarger and Rupp (1983) following years of research into dimensional change determination, found a proportional relationship between expansion and clinical behaviour of a selection of amalgam alloys.

The influence of variables on dimensional changes occurring in amalgams has been addressed by many authors. Dimensional change was found to be highly temperature dependent by Dickson, Waterstrat and Rupp (1977) in examining a selection of Conventional, High Copper and Dispersion Modified amalgams. Extending storage of specimen at 60°C, 37°C and 23°C to five years in air, Paffenbarger et al (1979, 1982a,b) found that all amalgams suffered some expansion and was greatest in all cases at 60°C. It was also noted that approximately 60% of specimens had elongated more than they had increased in width. The dimensional behaviour of copper-free amalgams at various temperatures examined in later research

(Paffenbarger et al, 1982a) concluded that high silver content, copper absence and inclusion of zinc seemed to each promote excessive expansion at 60°C. An alloy containing 33% tin (Paffenbarger et al 1982a) exhibited a uniquely linear relationship between cylinder expansion and storage temperature. The effect of cooling rate of dental alloys on amalgamation properties excluding dimensional change during setting was considered by Johnson and Carwile (1978). Cooling rates of alloys from the melt were varied from 50°C/hr to 10°C/sec. Although it was concluded that a faster cooling rate reduced grain size which in turn enabled faster and more uniform amalgamation; effects on dimensional changes were inconclusive. Katora, Sprecher and Deuben (1978) examined the effect of thermocycling between 5°C and 55°C, at a rate of 5 seconds in each bath. They studied gap size of cavosurface margins in restored extracted human mandibular molars for a variety of amalgams. Dispersed Phase amalgam restorations were found to produce smallest gap sizes. Spanauf, Vrijhoef and de Graaf (1977) found operator skill, packing technique and alloy selection had no effect on dimensional change although these factors significantly affected creep.

Variations in trituration methods and trituration times, however, do influence dimensional change of amalgams as noted by Espevik (1977). Specimens were mechanically condensed and dimensional change was determined with the use of a mikrokator exerting a measuring load of 1g. Hand and mechanical trituration methods were studied and trituration times were 3, 5 or 8 seconds. All amalgams expanded when triturated by hand and significant porosity was noted with this method. Dimensional change was

definitely sensitive to trituration method used, suggesting this to be due to the presence of irregular lathe-cut particles.

Ekstrand, Jörgensen and Holland (1985) examined the influence of deviations from recommended preparation procedures on dimensional stability of a variety of dental amalgams. In addition to varying trituration time, mercury : alloy ratio and condensation pressure were also varied. Trituration time was in one sample decreased by 40% and in another sample, increased by 50%. Condensation pressure was varied from 8 MPa to 28 MPa and mercury : alloy $\pm$ 20 (sic). Conventional and High Copper alloys were compared. Dimensional change, measured at 37°C with a linear variable differential transformer was found to be sensitive to all variables tested. Under-trituration caused increased expansion and porosities, whilst lowered condensation pressure and increased mercury : alloy ratio increased setting expansion.

Schultz (1979b) following Wing (1971) compared the effect of varied mixing times (7 seconds and 12 seconds) on dimensional change in addition to examining the effect on other properties. Specimens of New True Dentalloy and Dispersalloy were prepared using a mould similar in design to that of Wing (1964) which allowed easy removal of the uppermost mercury-rich layer from each specimen. Trituration of amalgam was carried out using a Silamat and the amalgam mix was divided into six equal portions for condensation. Following condensation and removal of the mercury-rich layer at $23 \pm 0.5^\circ\text{C}$, samples were stored at 37°C in an incubator which also housed three Johansson's microcators (sic). The force exerted by the microcators on the samples was 5 ± 0.1 grams (sic) and readings were taken at varied intervals starting within five minutes after mixing with the last reading being taken at

sixteen hours. Marked initial contraction was observed in both amalgams, around 0.07% for Dispersalloy and 0.2% for New True Dentalloy. This was considered to be reflective of the very early first measurement and the quality of the highly condensed specimens. Schultz attributed his observations to the 'marked expulsion of mercury during condensation' afforded by the procedure used. Smaller amounts of gamma 1 and gamma 2 were thus produced resulting in diminished expansion or increased contraction. Extension of the mixing time did not appear to significantly affect the dimensional change observed.

Saline contamination of specimens with 20 μ l of 0.5% NaCl solution during trituration was found to lead to significant delayed expansion of zinc-containing amalgam alloys suggesting that clinically zinc-free amalgams be considered if a moisture-contaminated field cannot be avoided (Fainsilber et al 1980).

Batchelor, Lewis and Wilson (1981) found that setting expansion of Conventional lathe-cut alloys was lowered when specially roughened pestles and mortars of specific grades of coarseners were used to triturate amalgams. Dermann (1984a b) found dimensional change of Dispersion Modified amalgams to be sensitive to variations in amalgamation time and amalgamation frequency with short amalgamation times and low frequencies causing expansion of the amalgams. Mahler and Adey (1985) found that a negative dimensional change was reduced with the incorporation of copper and zinc in alloy formulations.

In order to understand the mechanism of dimensional change within dental amalgam better, Jensen and Jörgensen (1984) examined three amalgam formulations for phase composition following storage in air for three years at 37°C or 50°C. After determination of

dimensional change, specimens were crushed and hand-ground in mortar and pestle and sieved. Linear dimensional change was found to be dependent on alterations of gamma 2 and beta 1 content.

Using a photonic sensor to determine dimensional change thereby precluding direct contact with specimens during measurement, Johnson et al (1978) examined this property during the setting reaction. Data was obtained as a continuous curve commencing at two minutes past trituration and stopping at 6 hours or 24 hours. Changes noted in dimensional profiles were significant. Taylor, Kusy and Greenberg (1979) utilized dimensional change in addition to compressive creep and mercury absorption to examine setting of dental amalgam. Two distinct stage in setting were observed, characterized by mercury exhaustion and the end of further dimensional changes.

Amalgam formulations have been evaluated using several mechanical properties including dimensional change. Copper addition to amalgams was found to increase setting expansion (Taylor and Leinfelder 1977). Spherical amalgams contracted only slightly during the first 24 hours and showed more marginal leakage when compared to lathe-cut amalgams. Brockhurst and Beech (1982) in evaluating Low and High Copper amalgams found no difference in dimensional change. Johnson (1985) evaluated two new dental alloys, a High Copper admixed alloy and an alloy containing 1.5% germanium, dimensional change and creep were significantly lower for these new alloys compared to Dispersalloy.

When specifications were first developed, dimensional change was considered to be of paramount importance. As alloy formulations have been developed and refined, methods of measurement varied and trituration almost universally carried out by mechanical

amalgamators, the true validity and significance of dimensional change has become less certain. A wide degree of latitude $\pm 0.2\%$ expansion is permitted by standard specifications to cater for the large numbers of variables.

CHAPTER 3

TRANSVERSE STRENGTH TESTING

To enable valid predictions of performance of materials in service, several laboratory tests have been devised attempting to reproduce demands of service and thereby simulate likely performance. Of these suggested tests, a few gain inclusion in standard specifications providing parameters by which new materials may be evaluated. The use of one such test, transverse strength test or bending strength test, has been largely ignored in favour of simpler strength tests but persists as a valuable means whereby similar materials may be compared and thereby evaluated.

The transverse strength test is a mechanical evaluation of the behaviour of a beam specimen subjected to a bending stress. The specimen is usually a beam which, in the test, is supported at either or both ends and loaded until fracture occurs. Commonly a static load is used although variations in loading are sometimes employed with the objective of more closely reproducing service conditions or to allow the microscopic examination of material distortion under loading (Peyton 1985). Generally, the test has been described as a 'bending test' by most authors (Doan 1953, Fenner 1965, Tweeddale 1973, Davis, Troxell and Hauck 1982, Ray 1987). Other terminology used includes a 'transverse test' (Rollason 1961, Bailey 1964, Ormandy 1968), a 'transverse bending test' (Callister 1985), a 'flexural strength test' (Wyatt and Dew-Hughes 1974, Davis, Troxell and Hauck 1982) and a 'bending strength test' (Guha 1985).

Doan (1953) used the 'bend test' to derive tensile strength in bend by applying the modulus of rupture derived to a formula based

on the stress in the outermost fibres of the specimen. Doan suggested that the test be used chiefly for brittle materials since it yielded fairly accurate results where little plastic flow took place. This observation has since been made by several authors (Fenner 1965, Tweeddale 1973, Wyatt and Dew-Hughes 1974, Davies, Troxell and Hauck 1982, Callister 1985).

Gabel (1954) suggested that the beam specimen must not be permanently deformed, and that maximum bending stresses must not exceed the known proportional limit of the material. Such bending stresses occur at the upper-most and bottom-most points of the beam suffering the greatest bend. Constraints on specimen size were considered important.

Several authors have acknowledged the application of the transverse strength test to cast iron (Rollason 1961, Bailey 1964, Ormandy 1968). Rollason (1961) noted that the transverse test for cast iron used a round bar, with size varying according to thickness of representative casting. The bar specimen used was supported at the ends and loaded at the centre until breakage. Fenner (1965) pointed out that, with reference to specimen shape, tests of differently shaped cross-sections were not directly comparable and that the bend stress on a round bar was a more severe test than that on a rectangular bar.

Tweeddale (1973) considered the derivation of the modulus of rupture from results of the simple bending test an appropriate means to evaluate brittle materials exhibiting little plastic behaviour where normally negligible variations in structure have a great effect on strength and so prevent realistic results for tensile strength.

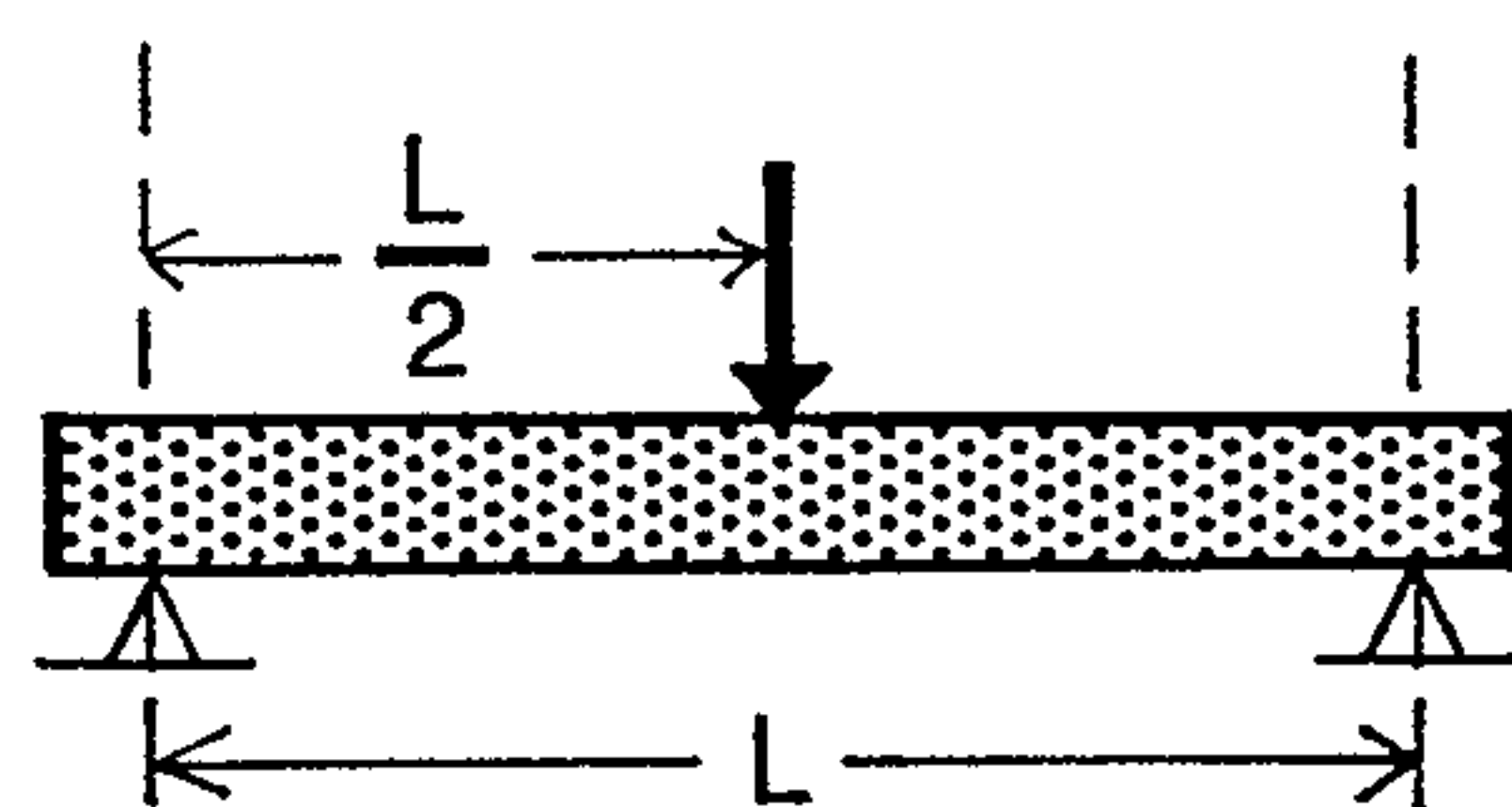
Phillips (1973) commented that the transverse test was a 'collective measurement of all types of stresses simultaneously'. Wyatt and Dew-Hughes (1974) also defined 'modulus of rupture' or 'flexural strength' as 'the maximum longitudinal (fibre) stress' occurring at the specimen surface and the value being equal to that obtained at failure from the elastic theory. Like Phillips (1973), these authors considered the bending test to combine both tensile and compressive behaviour of the materials being tested. Davis, Troxell and Hauck (1982), in addition, commented that in materials in service bending was also accompanied by direct stress, transverse shear and torsional shear; and that the bending action in beams was often referred to as 'flexure'.

Three formats of the transverse strength test are commonly employed :

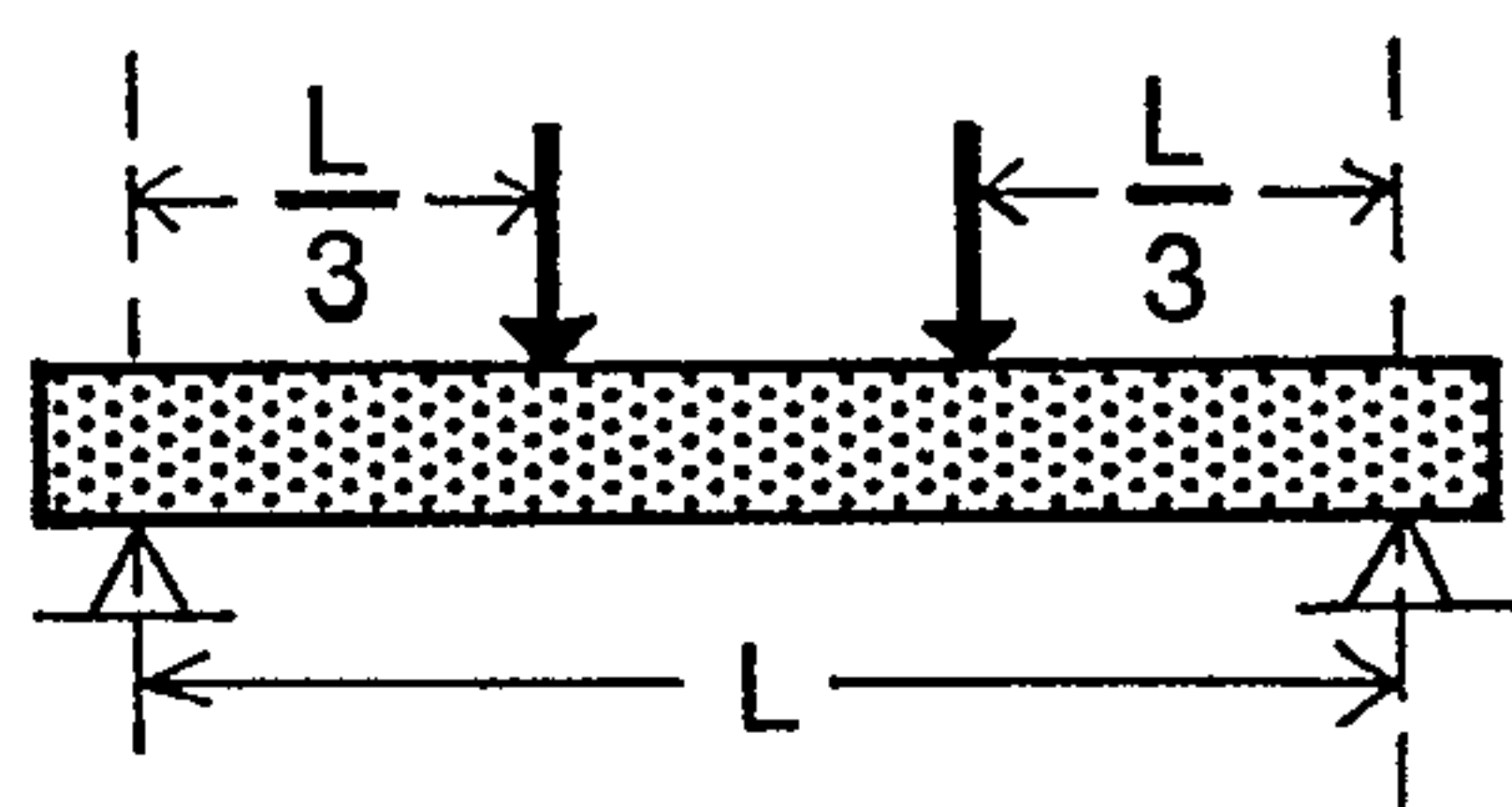
- (i) Simple beam : three-point loading.
- (ii) Simple beam : four-point loading.
- (iii) Cantilever beam.

A schematic presentation of these three formats of the test is shown in Figure 3-1.

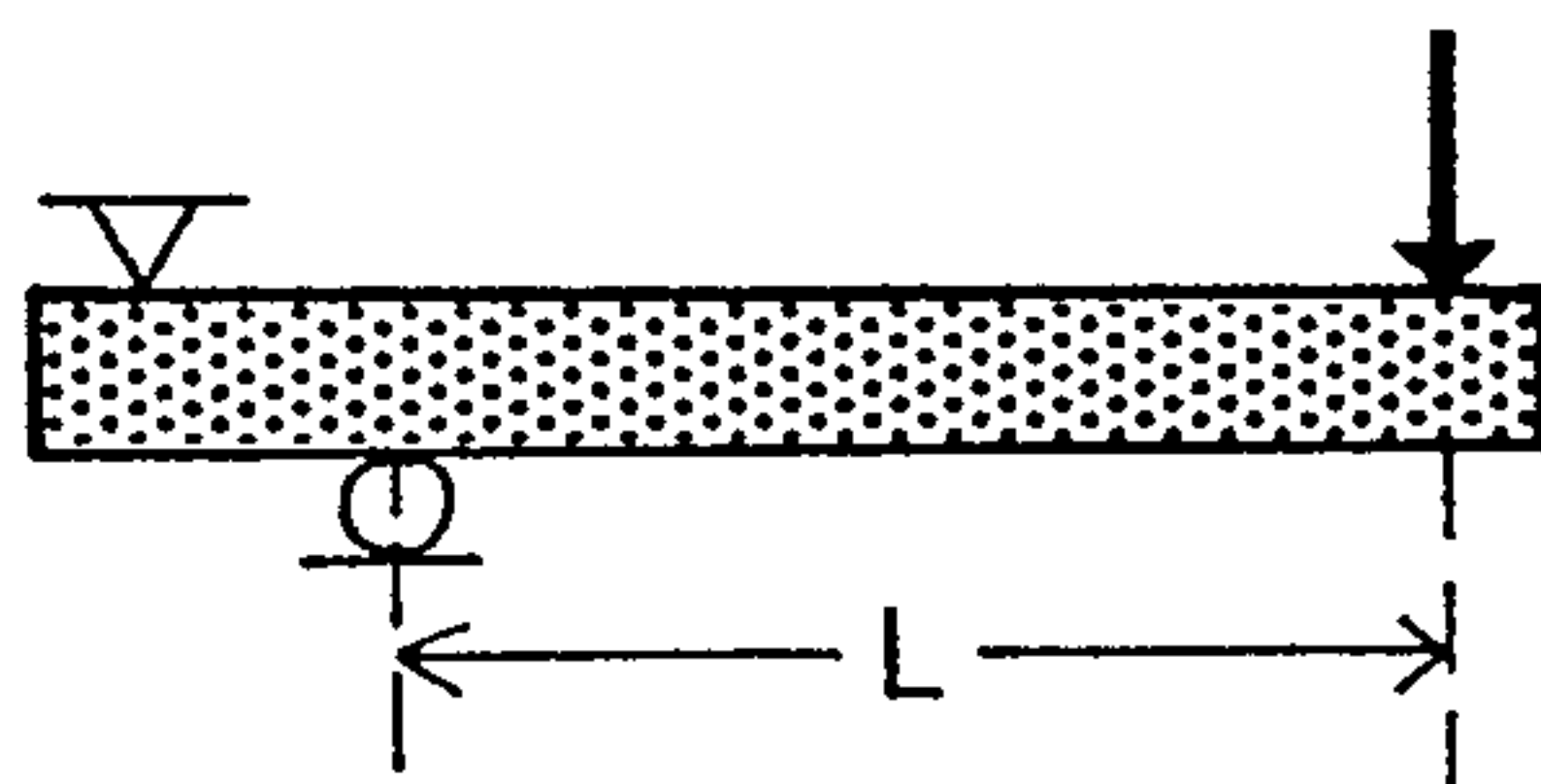
In the three-point bend test, the beam test specimen is supported near each end and is centrally loaded at a point equidistant from each support until fracture occurs. This is the most common format of the test employed. As pointed out by Davis and his co-workers (1982), it is assumed that loads are applied to the specimen so that they act in a plane of symmetry and that no longitudinal forces are induced by the loads or by the supports themselves.



simple beam:
3-point loading



simple beam:
4-point loading



cantilever beam

Figure 3-1 : Formats of the transverse strength test.

The four-point bend test consists of a simple beam specimen resting on supports at either end of the specimen but loaded at two points equally spaced from each support.

The third format of the transverse strength test is the cantilever beam bend test which consists of a beam specimen supported at one end only and loaded at the free, unsupported end. The apparatus required by this test is quite different from that employed in both three-point and four-point beam testing. The specimen is clamped into a vise, for testing, and an angular deflection indicator dial is attached. The dial face, calibrated in degrees, also features a bending pin which applies a load to the unsupported end of the specimen. The specimen is rotated against the loading pin and moment scale readings are recorded at increments of 2° angular deflection until a desired deflection, not exceeding 30° , is reached. The specimen is then unloaded and, with the loading pin still contacting the specimen, the degree of permanent set or bend is recorded by reading the angular deflection.

The modulus of elasticity in bending for methods of the test employing either three-point loading or four-point loading is obtained by the measurements of load and deflection at stresses below the proportional limit. Bending proof strength or transverse strength is determined by applying data of specimen dimensions, span between supports and load at specimen fracture to a formula. This strength is also known as the modulus of rupture. For three-point loading specimens the modulus of rupture is derived from the following formula:

$$M.R. = \frac{3 W L}{2 b d^2}$$

where M.R. = Modulus of Rupture

W = load at failure

L = span of supports

b = width of specimen beam

d = thickness of specimen beam

Modulus of rupture or transverse strength for specimens subjected to four-point loading is determined by the following formula :

$$M.R. = \frac{3 W a}{b d^2}$$

where M.R. = Modulus of Rupture

W = load at failure

a = distance from support to load application = L/3

b = width of specimen beam

d = thickness of specimen beam.

The relative positions of load applicators on the specimen in proportion to the length of specimen is illustrated in Figure 3-1.

In the cantilever beam bend test, a bending stress-strain curve is constructed from data. Modulus of elasticity and offset bending yield strength are calculated from this curve. To construct the stress-strain curve in the cantilever beam bend test, a relationship is established between applied bending moment and maximum bending stress occurring in the outer fibres at the fixed end of the specimen and bending moment deflection must be normalized with respect to specimen dimensions (Guha 1985). The modulus of elasticity in bending is determined by the slope of a straight line extending from the point of maximum deflection to a permanent set point on the stress-strain curve.

Davis, Troxell and Hauck (1982) outlined several requirements of supporting and loading blocks for beam tests. These include :

- '1. They should be of such shape that they permit the use of a definite and known length of span.
2. The areas of contact with the material under test should be such that unduly high stress concentrations do not occur.
3. There should be provision for longitudinal adjustment of the position of the supports so that longitudinal restraint will not be developed as loading progresses.
4. There should be provision for some lateral rotational adjustment to accomodate beams having a slight twist from end to end so that torsional stresses will not be induced.
5. The arrangement of parts should be stable under load.'

Specifications describe in detail the type of supports and deflection measuring devices to be used for particular materials. Apparatus for measuring deflection vary considerably but, as pointed out by Davis and his co-workers (1982), such apparatus should be designed so that crushing at supports, settling of supports and deformation of supports, loads or other parts of the machine will not introduce errors into results. To determine fibre strains, devices including surface strainometers, resistance gauges and strain gauges have been used for three-point and four-point loading bend tests.

Specimen dimensions and the effects of variations of relative dimensions on test results have been considered by many authors. Rollason (1961) in commenting on the transverse test of cast iron, suggested that the size of the round bar specimen vary with the thickness of casting it represents. Fenner (1965), noted that increasing the ratio of width to thickness of beam specimen

increased the severity of the test but that up to a thickness of $3/8$ inch, variation in width of specimen is not important provided that width is at least four times thickness. Davis, Troxell and Hauck (1982) pointed out that if a specimen is tested to failure, it must be of dimensions that will not allow failure by buckling or shear before ultimate flexural strength is reached. Beams are divided, by dimension proportions, into two groups. Short, deep beams that fail in shear where specimen width is one-sixth of specimen length; and long, shallow beams which fail in outer fibres and where width is one-twelfth of specimen length. Guha (1985) made further restrictions on specimen dimensions pointing out that width-to-thickness ratio must always be greater than ten. A recommended thickness range for cantilever beam specimens suggested by Guha (1985) was 0.38 to 3.3mm and a minimum width 12.7mm; the ratio of span length to thickness should exceed 15. Specifications for three-point and four-point bend specimens suggested that span length should be 150 times nominal thickness for specimens 0.25 to 0.51mm thick; and 100 times nominal thickness in the range exceeding 0.51mm.

Comprehensive analyses of the phenomena of bending have been completed by several authors. Fenner (1965) reduced the relationship of applied bending moment and the consequent deformation, on one hand, to that of deformation and stress, on the other hand, of a transverse loaded specimen to simple elastic formulae. These formulae, together with additional formulae expressing the second moment of the area of a section in terms of specimen dimensions, enable the calculation of bending stresses.

Davis and his co-workers (1982) pointed out that for equilibrium to be achieved, the resultant of tensile forces must

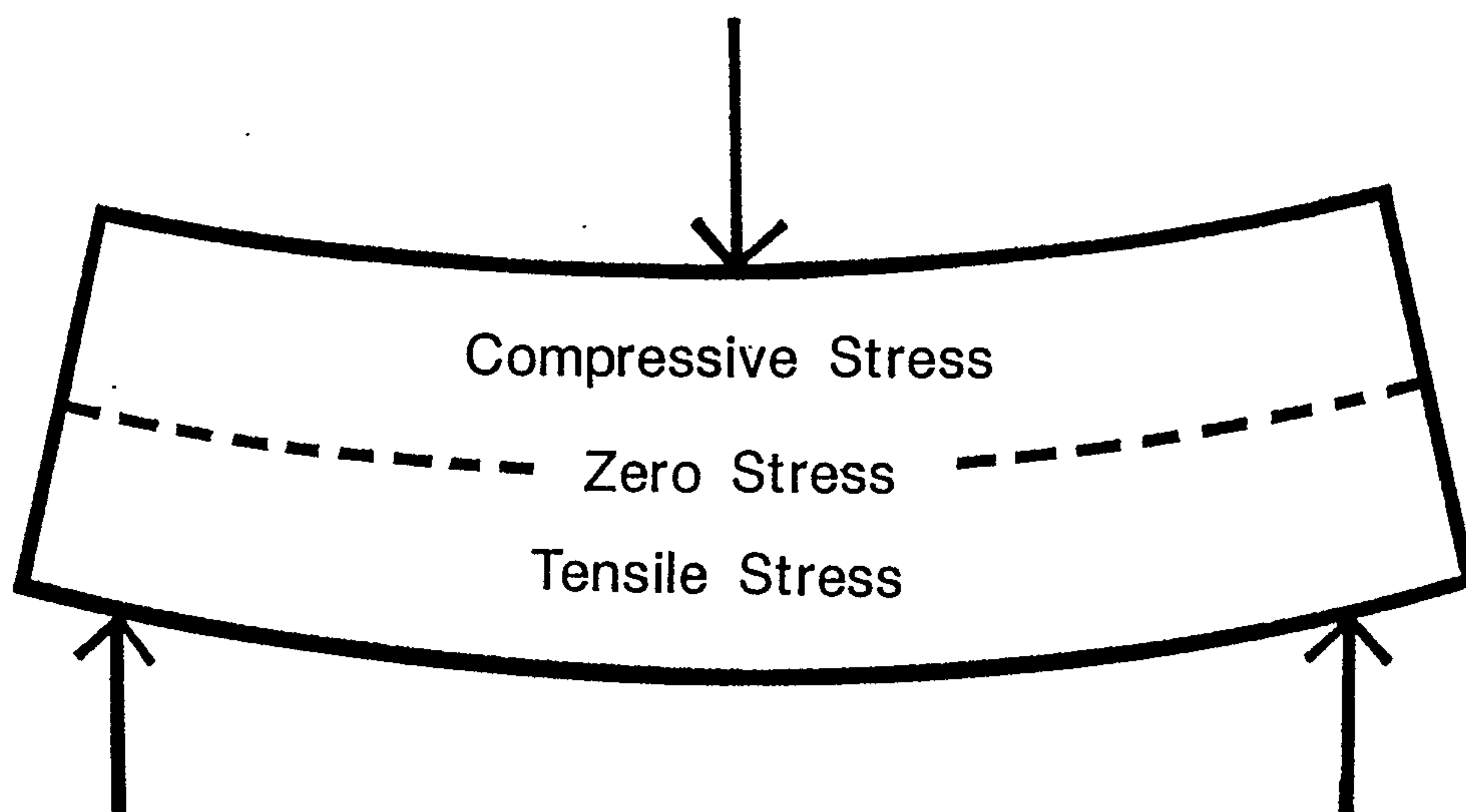


Figure 3-2 : A diagrammatic representation of stresses in a transverse loaded specimen.
(Reproduced from Gabel 1954).

equal that of compressive forces. In a cross section of a beam, the line along which bending stresses are zero is called a neutral zone; on the compressive side of the beam, 'fibres' of the beam shorten and on the tensile side they stretch as shown in Figure 3-2.

These strains are proportional to the distance from the neutral axis. When stresses are proportional to strains, stress variation across the section is linear. Above the proportional limit there is a deviation from linearity because stress is no longer proportional to strain. The maximum value of linear fibre stress is the modulus of rupture. Increasingly large moments, produced either by continuously increasing or even static load application applied for extended periods, cause increasingly large strains until the beam either breaks or permanently deforms.

Bunshah (1971) considered that the energy required to ultimately fracture a transverse specimen could be divided into two components. The first component required to initiate a surface cleavage or crack and the second to continue the crack to ultimate failure. Davis, Troxell and Hauck (1982) warned that the bending formulae gave results that only approximate real conditions due to inherent sources of error in specimen irregularities or loading conditions.

Flexural tests are usually made to determine strength and stiffness in bending and may also offer a means of determining resilience and toughness of materials. For beams of brittle materials, failure always occurs by sudden rupture; the nominal fibre stress at rupture is usually appreciably greater than the true tensile strength of the material. The relationship of the modulus of rupture to the true tensile strength is often expressed

as a simple ratio and is characteristic of the material tested. This ratio, for example, for cast iron is 1.8 and for concrete is about 1.5. Similarly the relationship between modulus of rupture and compressive strength may also be expressed as a simple ratio.

Although many forms of beams are used to test a variety of materials, standardized specimens and tests are used for routine testing of a number of materials such as concrete, cast iron, brick and wood. The test specimens for cast iron are generally cylindrical bars and tested as simple beams under three-point or central loading. Concrete specimens are generally square or rectangular in cross-section and are tested under either three-point loading or four-point (midspan) loading. Similarly wood specimens are generally square in cross-section and are tested under three-point loading.

Factors affecting results of transverse strength include loading type, length of span and cross-sectional dimensions of beam. Generally, largest values of the modulus of rupture are obtained from three-point loading of specimens; higher values are also obtained for shorter span lengths. Modulus of rupture and modulus of elasticity are lower for beams having a relatively large proportion of the cross-sectional area situated near extreme fibres. Speed of testing has the same general effect in the 'flexure test' as in the tension and compression test. The greater the speed, the higher the strength.

As suggested by Davis and his co-workers (1982), flexural or bend tests may offer a means of determining toughness of materials. Such a property is generally known as 'Plane Strain Fracture Toughness', and is related to 'work of fracture'

(Tattersall and Tappin 1966). The concept of fracture toughness is based on the mathematical derivation by Irwin (1957) of work completed by Griffith (1920). Fracture toughness is defined by British Standard 5447 : 1977 as 'a property of a material indicative of the material's resistance to crack growth under conditions in which the stress, at a short distance ahead of the crack front, is predominantly triaxial (plain strain) and in which plastic deformation is limited'. The plain strain fracture toughness of a material is equal to the critical value of a plane strain stress intensity factor derived in a mechanical test which is similar in format to a transverse test. The plane strain stress intensity factor is a function of applied force and test piece geometry and is defined as 'the elastic stress field intensification at the tip of a crack subjected to opening mode displacement'. The test involves two stages :

- (a) The development, by fatigue loading, of a crack from a machined notch in a beam specimen,
- (b) The propagation of that crack by the application of an increasing force, which may be either bending or tensile, to produce fracture.

Basically the specimen used in the fracture toughness determination test is a beam incorporating a notch in its lowermost surface. The notch dimensions bear a strict relationship to the type of material tested, the specimen size, proof stress of the material and a valid fracture toughness estimation. The notch serves as a stress concentrator and hence a crack initiator from which crack dimensions are determined. The test itself is similar to simple beam three-point loading where the line of load passes through the centre of the notch and midway between the supports.

The notched surface of the specimen corresponds to the tensile side of a loaded bend specimen. The objective of the test is to determine the force at which a given amount of crack extension has taken place and is established from a test force vs displacement curve in terms of deviation from linearity. The formula used to derive the provisional value of plain strain fracture toughness is a complicated one:

$$K_Q = \frac{3P_Q L}{BW^{1.5}} \left[1.93 \left(\frac{a}{W} \right)^{0.5} - 3.07 \left(\frac{a}{W} \right)^{1.5} + 14.53 \left(\frac{a}{W} \right)^{2.5} - 25.11 \left(\frac{a}{W} \right)^{3.5} + 25.80 \left(\frac{a}{W} \right)^{4.5} \right]$$

where K_Q = provisional value for fracture toughness.

P_Q = value of applied force read from the force vs displacement curve at a point of deviation from linearity.

L = half loading span.

B = test piece thickness.

W = test piece width.

a = effective crack length (includes notch length).

This 'provisional' fracture toughness value may be equal to the actual fracture toughness (K_{Ic}) for this material if, when this provisional value is applied to an additional formula, the value so obtained is less than both the thickness of the test piece and the crack length and all other validity criteria have been met. This additional formula is a factor denoted by :

$$2.5 \left(\frac{K_Q}{\sigma_Y} \right)^2$$

where K = provisional value of fracture toughness.

σ_Y = 0.2% proof stress or yield strength of the material for the temperature and loading rate of the test.

A simplified method for the determination of fracture toughness based on the onset of crack growth instability has been presented by Barker (1977). Barker considered that many materials had properties which made it infeasible or impossible to meet fracture toughness measurement standards. Such properties include brittleness or a combination of high toughness and low yield strength. He aimed to present a simplified method of fracture toughness determination which required only the measurement of peak force required to completely fracture a specimen and thus a force vs deflection curve would not need to be plotted. The specimen suggested was a cylindrical rod featuring a bi-bevelled notch which was tested to failure in a tensile mode where the specimen was gripped at either side of the notch and forced apart. This simplified method was found to yield results for fracture toughness (K_{Ic}) comparable to values derived from conventional fracture toughness tests.

The importance of the fracture toughness (K_{Ic}) value of a material has been pointed out by Crane and Charles (1984). They considered that 'knowing K_{Ic} , it is then possible to ensure in service either that the service stress is well below the fracture stress determined for such cracks as may unavoidably be present, or that no cracks occur that are long enough to cause failure at the service stress'. In addition these authors consider toughness to have an importance at least equal to, and maybe greater than, other mechanical properties.

Within a given class of materials, there is generally an inverse relationship between strength and toughness necessitating the matching of material toughness to the design of structure

Table 3-1 : Comparison of values of plain strain fracture toughness (K_{Ic}) and strength for various materials.

Material	Strength (MPa)	Fracture Toughness (MPa . m ^{1/2})
Medium-carbon steel	260	54
Aluminium alloy	517	24
Titanium alloy	1095	35
Polymethyl methacrylate	30	1
Concrete	-	0.8
Glass	-	0.45
Douglas fir	-	0.3

(after Crane and Charles, 1984)

required. A comparison of strength and fracture toughness values for a selection of materials is presented in Table 3-1.

According to A.S.T.M. Standard E399-83 (1987) describing the test method for plain-strain fracture toughness of metallic materials, the value for K_{Ic} may be used to estimate the relation between failure stress and defect size for a material in service.

CHAPTER 4

TRANSVERSE STRENGTH TESTING OF DENTAL AMALGAM

The ultimate significance of the determination of any mechanical property of a restorative material lies in the ability of the property to represent clinical behaviour accurately. Analysis of stresses involved in a dental amalgam restoration was made by Mahler (1958). Using a method of photoelasticity, patterns of stress were obtained when an enlarged model of a proximo-occlusal restoration in a deciduous model was occlusally loaded. Three different cavity designs were examined and evaluated. Mahler concluded that isthmus failure was due to the concentration of tensile stresses in this area and that dental amalgam restorations are subject to combinations of shear, tensile and compressive stresses. Thus the prediction of clinical strength of a restoration based only on values for compressive and tensile strength alone may not consider the 'bending' of a restoration where stresses in both modalities may occur.

Mahler and Mitchem (1961) examined the effect of variations in mercury : alloy ratio on transverse strength of amalgam. Specimens 1mm x 4mm x 12mm were placed using mercury : alloy ratios of 1:1, 1:1.4, 1:2 and 1:4. Transverse strength was found to be unaffected by these various ratios provided the same amount of mercury was present in the precondensation mix. The authors considered the transverse strength test to be 'predictive' of cavosurface marginal fracture of amalgam.

A further consideration of transverse strength of dental amalgam was carried out by Mahler and Mitchem (1964). Using specimens 1mm x 4mm x 12mm and employing a three-point load technique, transverse strength values were obtained and compared

with those of compressive and tensile strengths. Specimens were supported by two cylindrical rods, 10mm apart; and load was applied through a 1/8 inch diameter hardened steel ball. Transverse strength was determined by applying the value for fracture load to a formula :

$$S_T = \frac{3 W L}{2 b d^2}$$

where S_T = transverse strength

W = fracture load,

L = sample length between supports,

b = sample width,

d = sample thickness.

Three precondensation mercury conditions 65%, 60% and 50% were examined for samples of New True Dentalloy¹ amalgams. Condensation pressures were varied to produce samples with a final residual-mercury content ranging from 42% to 63%. Samples were fractured at seven days using one of four rates of loading; 0.001 in/min, 0.003 in/min, 0.10 in/min or 0.100 in/min. These authors considered transverse strength determination to be 'well suited to laboratory testing of the strength of amalgam' due to its direct correlation to both tensile and compressive strengths, the low variation in strength values between samples and the relative simplicity of testing procedure.

Hollenback and Villanyi (1964), in a series of articles examining physical properties of dental amalgam, commented that in clinical use of amalgam, large restorations can be subjected to transverse, tensile and compressive forces simultaneously. In

1 S.S. White Dental Manufacturing Co., Philadelphia, U.S.A.

contrast to Mahler and Mitchem (1964) these authors used cylindrical specimens for testing and concluded that using any one of these tests, (compressive, tensile, transverse) the other two can be accurately computed.

Using the transverse strength test described in their earlier studies, Mahler and Mitchem (1965) examined the effect of precondensation mercury content on physical properties of amalgam. Specimens of New True Dentalloy and Caulk 20th Century Regular¹ were prepared using conventional technique and Eames technique of precondensation mercury removal. Transverse strength was determined after one hour and after seven days. Strength was reduced when condensation force was reduced and the Eames technique did not appear to offer a method achieving increased strength. It was queried whether the confines of the transverse strength mould and the use of a closely fitted condenser adequately represented a clinical situation. In order to resolve this question, Class II amalgam restorations were placed in extracted teeth and mercury content at proximal regions and occlusal margins was determined. These values were compared to those of the transverse mould specimens and found to be not significantly different.

Brittle fracture of dental amalgam was examined by Asgar and Sutfin (1965). Using a composite specimen beam whereby a strong, rigid material (amalgam) was matched with a weaker, ductile material (plastic) with the objective of retarding crack propagation, a load was slowly applied to the beam and a microscope was used to scan the specimen beam for evidence of failure. The

1 L.D. Caulk Co., Milford Delaware, U.S.A.

amalgam used was Caulk 20th Century Fine-Cut alloy¹. Mercury : alloy ratios used were 8 : 5 and 6.5 : 5 employing a 12 second trituration time to produce a specimen 1/16in x 1/16 in x 1-1/16 in. The specimen was mounted in a Flinn strain-viewer and load was applied horizontally. The microstructure of the alloy under stress was examined to follow progress of the crack through amalgam phases present in the specimen.

Iwaku et al (1966) examined the 'edge strength' of powdered gold fillings compared to that of other restorative materials using the methods of Mahler and Mitchem (1964). Specimens 1mm x 3mm x 5mm were prepared from six restorative materials including powdered gold, gold foil, amalgam and acrylic resin. A mercury : alloy ratio of 1.4 : 1 and trituration time of 90 seconds with mortar and pestle were used for amalgam specimens. The amalgam specimen was tested four days later. All beam specimens were tested in a three-point load system with support centres 3mm apart, and loaded at the rate of 125gm/sec. These authors found bending strength of amalgam to be comparable to gold foil and resin but inferior to that of powdered gold. Edge strength of amalgam was also found to be inferior to that of powdered gold. Bending strength as determined by these authors, was considered to be representative of bulk strength of restorative material.

Forsten (1969) considered transverse strength of amalgams in an extensive paper on physical properties of dental amalgam. Standard and preamalgamated zinc-containing and zinc-free amalgams were selected to produce specimens 2mm x 2mm x 12mm and transverse strength was determined using methods similar to that of Mahler and

1 L.D. Caulk Co., Milford Delaware, U.S.A.

Mitchem (1964) but using a Model FDM 40 electrical testing machine. In contrast to these authors, Forsten used a rounded steel bar to apply load, similar to the loading blade used by Iwaku et al (1966). Loading rate was 1.5mm/min and values for a total of eleven standard amalgams and twelve preamalgamated amalgams were derived. Values for transverse strength were comparable for all alloys tested. Forsten considered it appropriate that transverse strength represent the strength of amalgam in Specifications. He based his opinion on several advantages afforded by transverse strength testing. The test pieces are clinically relevant in form and size especially resembling isthmus dimensions, the test piece does not require machining of ends as required by compressive strength specimens and load application is applied parallel to the direction of condensation. Forsten noted the direct correlation of transverse strength to compressive and tensile strengths first noted by Mahler and Mitchem (1964).

Welk and Dilts (1969) looked at the influence of pins on compressive and transverse strength. Beams 6mm x 3mm x 13mm containing one, two, three or no pins through the length of the specimen were tested in a three-point loading system where distance between support centres was 10mm and loading rate was 0.05 in/min. Specimens were tested 24 hours after condensation of the amalgam. It was found that the presence of pins significantly decreased the transverse strength of dental amalgam.

Pires et al (1969) examined the effect of several methods of compaction on microstructure and transverse strength of spherical alloy dental amalgam. Several methods of mechanical compaction were compared to manual compaction on specimens subjected to four point load testing. Specimens 2mm x 2mm x 15mm were loaded on an

Instron universal testing machine at one hour and 24 hours after compaction. Specimens were examined under a microscope following failure. These authors concluded that transverse strength of dental amalgam appeared to be independent of the method of compaction as long as the specimen manufacture procedure is controlled.

The effect of packing force, rate of packing and packing time on the one hour transverse strength of amalgam was investigated by Basker and Wilson (1970). Specimens of New True Dentalloy were subjected to three-point loading in an Instron Machine. Support centres were 10mm apart and a crosshead speed of 0.5mm/min was used. A packing force range of 10-20N and packing rate range of 120-200 thrusts/min was used. These authors found that increasing the packing force from 10N to 20N resulted in an increased transverse strength of 24%. Increasing the rate of packing, resulted in an 8% increase in strength. A significant increase in strength was also found when packing time was increased from one minute to two minutes.

Sutfin and Ogilvie (1970) examined the fracture of dental amalgam using a scanning electron microscope. Specimens 2mm x 2mm x 25mm were prepared from Caulk 20th Century Fine Cut Alloy and Kerr Spheraloy¹ with a mercury : alloy ratio of 1:1. Following hardening of the amalgam for several days, the specimens were broken by bending by hand and viewed in the electron microscope within 15 minutes after failure. Stereoscopic fractographs were obtained and the fracture surface was studied. Other samples were prepared for metallographic examination using the etchant developed

1 Kerr Manufacturing Co., Detroit, Michigan, U.S.A.

by Wing (1961) to determine the nature of the surface developed by etching. These authors concluded that scanning electron microscope studies of the fracture of dental amalgams have agreed with those studies completed with light microscopes and transmission electron microscopes. The micrographs showed that grain boundaries do not contain discrete segregations; a finding common to other light microscope studies. In addition, this study found evidence of microplastic deformation in the matrix which had occurred during failure.

Turchyn and Youdelis (1970) examined the significance of flexure behaviour of amalgam in relation to the mechanical properties of compressive strength, hardness and flow rate. Cylindrical specimens of 4mm diameter and 12mm length were prepared from three dental alloys using a mercury : alloy ratio of 1:1 and a trituration time of 20 seconds. After trituration, samples were immediately condensed in a steel die and a pressure of 10,000 p.s.i. was applied. Samples were then allowed to set at room temperature for seven days before testing. These authors considered the diametral test unsuited for the determination of the tensile strength of amalgam because of the large amount of plastic deformation that occurred in the specimen prior to failure. Therefore, these authors used a centre-point loading test (three-point loading) in an Instron testing machine at a crosshead speed of 1/200 in/min. They found that flexure strength was inversely related to compressive strength and hardness and directly related to flow. To determine the extent to which specimens were plastically deformed before failing, some specimens were loaded at approximately 90% of fracture load and dimensional changes were

measured. Dimensional change was greatest for the alloy with highest flow and lowest compressive strength.

Forsten (1971) considered the influence of trituration variables on transverse strength of dental amalgams. In a two part investigation, Forsten examined the influence of different mixers, pestles and trituration times on the transverse strength of Conventional, Dispersion Strengthened and Spherical alloys in pellet form (part I of the study) and on preamalgamated alloy in filing form (part II). Specimens were prepared by condensing amalgam into a split steel mould cavity using 20kg/cm^2 pressure. No excess mercury was removed prior to condensation. Once the cavity was overfilled, a portion of 'dry' amalgam was placed on top of the specimen and the mass further condensed under a metal plate. The specimens $2\text{mm} \times 2\text{mm} \times 25\text{mm}$ were stored for 7 days at 37°C prior to testing. Testing of the pellet form alloys used an Instron testing machine with a crosshead speed of 0.005 cm/min ; testing of filing form alloys was completed in a FDM 40 testing machine used in a previous study with a crosshead speed of 1.5mm/min (Forsten 1969). In both parts of the study, support centres of the three point testing apparatus were 10mm apart. Forsten found that transverse strength was increased by increasing trituration time and that metal pestles produced greater strength in high speed amalgamators. Forsten concluded from both studies that an ultrahigh speed mixer is preferable to slower devices in triturating all forms of amalgam, but that excessive mixing should be avoided. Maximum strength can be achieved when triturating in ultra high-speed mixers for 6-16 seconds. Forsten justified the use of a transverse strength test for several reasons :

- ' (1) Clinical fracture of amalgam, and breakage of transverse strength specimens are due to a complicated mechanism involving different types of stress,
- (2) The test is easy to perform, and almost independent of crosshead speed,
- (3) Specimens of 'clinical' size and shape may be used,
- (4) Condensing procedures which are similar to clinical conditions can be used. '

Continuing the investigation into transverse strength, Forsten (1972) examined the influence of precondensation mercury content on the transverse strength of amalgam. Three precondensation mercury contents 50%, 54% and 59% were used. Specimens 2mm x 2mm x 12mm were condensed by hand using a load of 17 kg/cm². Three-point loading of specimens took place either after one hour or one week in an Instron testing machine with a crosshead speed of 0.005 cm/min. Forsten found that for some amalgams a slight reduction in early strength resulted from an increase in precondensation mercury content. Preamalgamated amalgams showed the lowest early strength, spherical amalgams had about the same early strength as Conventional lathe cut amalgam. The use of slightly more than 50% initial mercury with preamalgamated alloys was recommended for optimal strength properties.

Forsten (1972b) considered the effects of delaying condensation relative to a change in precondensation mercury content on final strength of amalgams. The effect of mulling the amalgam mix after a delay was also examined. Conditions of specimen manufacture, mercury : alloy ratio and testing procedures were identical to those used in a previous study (Forsten 1972a). Transverse testing took place one week after specimen manufacture.

A delay of 5 minutes after trituration and before condensation was used. The delayed condensation caused a reduction in transverse strength of 1% to 42% depending on the type of alloy. Preamalgamated amalgams were less affected by the delay. Both increasing precondensation mercury and mulling reduced the effect of delay on the final strength.

Younis, Asgar and Powers (1975) looked at the initiation of cracks in dental amalgam and specifically the force required by different alloys to initiate cracks and the relationship of the crack path to microstructural phases and features. Using four different amalgam alloys with a mercury : alloy ratio in the range of 48% to 54%; specimens 0.06 inch x 0.06 inch x 1.06 inch were manufactured in a steel die and allowed to set for 15 minutes prior to removal. Half the specimens were tested after two days, the other half after four months. Specimens were imbedded in cold-curing plastic to form composite beams and loaded in a Flinn Strain Viewer following the procedure of Asgar and Sutfin (1965). Force required to initiate the crack was determined and results were subjected to analysis. For all alloys tested, the load required to initiate a crack in the composite beams was greater in four-year old specimens. Beam ageing improved the quality of Optaloy¹ and Spher-A-Cap² specimens. Dispersalloy³ specimens were less improved. In spherical alloys, cracking invariably initiated in the gamma 2 phase and in the gamma 1 phase in Dispersion Modified

1 L.D. Caulk Co., Milford Delaware, U.S.A.

2 Kerr Manufacturing Co., Romulus Michigan, U.S.A.

3 Johnson & Johnson Dental Products Co., East Windsor, New Jersey. U.S.A.

alloys. These authors concluded that crack initiation was dependent on the distribution of phases on the tension side of the amalgam.

Giblin and Wing (1979a, 1979b, 1980, 1981) examined transverse fatigue of dental amalgams and, in contrast to previous authors, specifically looked at the effect of low sub-fracture transverse loads on amalgam beams with respect to the relationship of bending and fracture behaviour to creep and conventional strength values and microstructure. Specimens 12mm x 10mm x 3mm were made from several representative alloys. Determination of transverse strength was carried out at 22°C using three-point loading apparatus designed by the authors which was placed in a Hounsfield tensometer at a crosshead speed of 0.4mm/min. Using the same three-point loading system as used for transverse strength determination, static load equal to a percentage value in the range of 60% to 100% of transverse strength was applied to each specimen in the sub-modulus of rupture test. Load was maintained until fracture of the specimen occurred or until the elapse of two weeks. Application of the static sub-modulus of rupture load was achieved in apparatus designed by Peet (1971). Following fracture, specimens were re-located and cemented to allow evaluation of bending characteristics. Degree of bend was then ranked, where a value of "1" was assigned to an untested specimen and "10" to a specimen exhibiting greatest bend. Certain specimens were mounted in cold-curing clear acrylic resin for polishing and etching prior to microstructural examination.

These authors found that static fatigue fracture was inversely related to static creep values. When loaded at a range of loads representing fractions of the transverse strength from 60% to 95%,

all amalgams tended to have reduced fracture times with increases in the percentage of transverse strength applied. Very low creep amalgams, however, did not undergo fracture at any load below transverse strength. Times to fracture varied from less than five hours for Ag₃Sn-type amalgams to approximately 100 hours for high copper amalgams. All specimens subjected to 100% of modulus of rupture fractured instantly with no bending. Greatest bend was exhibited by Ag₃Sn-type amalgams subjected to lower loads for longer periods. Bending was found to be related to creep and duration of loading as well as to transverse strength and represents permanent deformation of the beam. Microscopically, fracture paths in reassembled fractured specimens could be divided into a slow zone, which formed over the whole loading time and a fast zone which formed instantaneously to produce final failure of the specimen. The slow zone was characterized by a failure of the original alloy-matrix interface (around particle) and the fast zone featured failure through original alloy particles. Relative lengths of slow and fast zones characterized different types of amalgams with higher creep amalgams exhibiting long slow zones and short fast zones.

In conclusion, it was considered that two types of failure occur in dental amalgam specimens :

- (i) failure following application of loads exceeding strength of the material, and
- (ii) failure following application of loads below the strength of the material.

Low loads applied to high creep amalgam specimens will cause bending to occur at the point of load application followed by crack initiation and subsequent fracture. Sub-fracture transverse load

testing affords time for elastic and plastic deformation to take place in the specimen and to be manifested as bending and crack initiation followed by catastrophic fracture.

Maoleekulphiroj and Wing (1981) following the methods of Giblin and Wing (1979a, 1979b, 1980, 1981) considered the effect of varying beam thickness on values of modulus of rupture and times to fracture of various amalgams. Specimens 12mm x 10mm x 3mm; 12mm x 10mm x 2mm and 12mm x 10mm x 1mm were prepared from Dispersalloy, G. & G. Superfine¹ and Hi-Atomic² amalgams. Transverse testing took place using three point loading in a Hounsfield tensometer at 22°C with a crosshead speed of 0.4mm/min. Testing of specimens subjected to sub-modulus of rupture loads was also carried out using loads equal to 90%, 80%, 60%, 40% and 20% of the modulus of rupture indirectly applied using the apparatus designed by Peet (1971). In addition, a microstructural examination was carried out to quantitatively determine phases present and crack progress through these phases.

These authors found, similar to Giblin and Wing (1977) that transverse strength did not parallel compressive or tensile strengths for all types of amalgams tested. Reducing beam thickness from 3mm to 1mm had an effect on the ability of the beam to withstand sub-fracture loads. Thinner beams exhibited longer times to fracture although dropping the beam thickness to 1mm produced no differences in times to fracture. The inverse relationship of creep and time to fracture found by Giblin and Wing was again seen and the formula for the calculation of transverse

1 Englehard Industries, Australia.

2 G. C. Chemical Co., Japan.

strength did indeed cater for varied beam thickness. There appeared to be no direct relationship between modulus of rupture and ability of beams to withstand static fatigue loads. Fracture and bending characteristics for specimens of the same amalgam but differing beam thickness were found to be different. An examination of condensation efficacy and its effect on void content and hence creep values showed that the use of fewer large amalgam increments for condensation led to void formation, retention of additional mercury and formation of a higher proportion of tin-mercury phase and a significant increase in static creep.

Cruickshanks-Boyd (1983b) looked at the physical metallurgy of dental amalgams in a three-part series. Dealing with transverse strength and fracture behaviour during setting in the third part of the series, the author used the transverse strength test to evaluate the rate of strengthening of both Low and High Copper amalgams. Specimens 12mm x 4mm x 1mm were made using the split mould designed by Mahler and Mitchem (1964). The condensation method was strictly controlled and a mercury-rich top layer approximately 1mm thick was removed from each specimen prior to storage at 37°C. Transverse strength tests were carried out at four different setting times : 1 hour, 3 hours, 24 hours and 7 days, using a three-point loading technique in an Instron testing machine at a testing speed of 1.0mm/min. At one hour, the variation in transverse strength between different amalgams was marked, with Single Composition High Copper amalgams showing highest values. At 24 hours, the differences between various amalgams had narrowed and at seven days, transverse strength values were comparable for all amalgams. Microscopic features of crack propagation was similar to features observed by Sutfin and Ogilvie (1970), however fracture

through Single Composition High Copper amalgams tended to take place through residual alloy particles.

Ogura, Miyagawa and Nakamura (1984) investigated long term behaviour of amalgam under bending stress, specifically bending creep and time taken for bending fracture. Rectangular specimens were prepared from High Copper and Low Copper amalgams and stored at 37°C for seven days prior to testing. Specimens were tested at 37°C in a three-point bending device under four different static loads (3, 5, 7 and 9 kilogram force). Bending creep was measured by an electric micrometer and recorded continuously for thirty days. Bending creep was found to increase continuously for all amalgams. High Copper amalgams were most resistant to fracture and did not fracture under lower static loads. The final creep of Single Composition High Copper amalgam was comparable to that of Low Copper amalgams.

Early transverse strength of dental amalgam was examined by Hammett and Mahler (1986) by comparing strength values to one-hour compressive strength and Eames cohesive times. Specimens 1mm x 4mm x 12mm were manufactured from ten alloys by controlled hand condensation and stored at 22°C prior to testing. To provide data with which 10 minute transverse test results could be compared; 20, 30, 45, 60 minute and 7 day specimens were also tested. Three-point loading was carried out with load applied by finger pressure through a transducer load beam to a 1.6mm steel ball which was centred on the specimen supported by two parallel steel wires 10mm apart. A modified Eames cohesive test, where post-trituration amalgam samples were milled for 3 seconds at 30 second intervals, was used. These authors concluded that any one of the three tests, one hour compressive strength, Eames cohesive time test and ten

minute transverse strength could be effective in predicting very early resistance to fracture and that the three tests correlate well.

Ogura, Miyagawa and Nakamura (1987) considered the effect of ultraslow strain rate on microstructure characteristics of fractured amalgam specimens. Specimens 4.5mm x 3.0mm x 20.0mm were made from a Low Copper alloy - Shofu Spherical¹ and a High Copper alloy - Dispersalloy. Three-point loading of specimens was carried out at 37°C at a strain rate of 1×10^{-8} /Sec. Direct SEM examination of cracked or fractured surfaces was carried out following resin mounting of specimens and metallographic examination. The effects of high and low strain rates on fracture characteristics were compared for High Copper alloys. Intergranular fracture of gamma 1 grains was a feature of high strain fracture. Low strain fracture exhibited transgranular gamma 1 grain fracture. Several characteristics of low strain rate fracture are cited :

- (1) highly localized plastic deformation of gamma 1 grains.
- (2) transgranular fracture of gamma 1 grains.
- (3) formation of gamma 1 needles and initiation of cracks at gamma 2 areas in gamma 2-containing amalgams.
- (4) partial adherence of gamma 1 to particles and reaction layers when cracks open at these surfaces.

The determination of a relatively complex mechanical 'property' - fracture toughness - has also been carried out for several dental biomaterials including dental amalgam. The fracture toughness test format is similar to that of transverse strength testing. An explanation of the format of this test is given in

1 Shofu Dental Co., Japan.

Chapter 3, Transverse Strength Testing. Fracture toughness of composite resin has been examined by Roberts, Powers and Craig (1977), Koblitz et al (1978), Pilliar et al (1981, 1986), Lloyd and Mitchell (1984), Osman, Moore and Phillips (1986) and Ferracane, Antonio and Matsumoto (1986). The fracture toughness of other dental materials has also been studied. Provisional resins by Gegauff and Pryor (1986), dental porcelain by Morena, Lockwood and Fairhurst (1986), Baran et al (1988), Rosenstiel et al (1988), Johnson et al (1988) and Mante et al (1988), glass ionomer cements by Lloyd and Mitchell (1984) and Osman, Moore and Phillips (1986), calcium hydroxide by Lloyd and Anderson (1980) and human dentine by El Mowafy and Watts (1986). The application of the fracture toughness test to amalgam has been subsequently completed by some of these authors.

Roberts, Powers and Craig (1978) examined fracture toughness of dental amalgam following a similar format to that of their earlier study of fracture toughness of composite and unfilled restorative resins (Roberts, Powers and Craig 1977). Using the identical specimen dimensions as used in the 1977 study viz., 20mm x 4mm x 2.5mm, after BS 5447, (1977), Roberts and his co-workers subjected a selection of five amalgam alloys to three-point loading. Two cross-head speeds were used for tests, 0.005 cm/min and 0.05 cm/min and the alloys tested included Dispersalloy, New True Dentalloy and Tytin¹. From results for fracture toughness it was concluded that resistance to unstable crack propagation in amalgam appeared to be dependent on phases present, amount, size and shape of these phases and their relative strengths.

1 S.S. White Dental Manufacturing Co., Philadelphia U.S.A

Cruickshanks-Boyd and Locke (1983) evaluated three testing methods commonly used for the determination of fracture toughness of dental amalgam. Specimen designs employed in these three tests are shown in Figure 4-1. Type A specimen was first reported by Tattersall and Tappin (1966) and is tested in a three-point transverse loading arrangement. Type B specimen is that described in British Standard BS 5447 (1977) and is also used for three-point transverse loading. Type C specimen is that first described by Barker (1977) who used it for the testing of aluminium, polymethylmethacrylate, quartz and rock in a tensile mode. Cruickshanks-Boyd and Locke investigated four alloys : Aristaloy¹, Ease², Sybraloy³ and Tytin employing the three specimen formats and two loading set-ups to determine work of fracture and fracture toughness. Results obtained compared favourably with those of Roberts, Powers and Craig (1978) but were somewhat less than those of Brockhurst and Murray (1979). Cruickshanks-Boyd and Locke (1983) considered the single edge notched three-point bend specimen based on BS 5447 (1977) or type B specimen provided the most reliable values for fracture toughness. The authors found an inverse relationship between creep resistance and fracture toughness and suggested that plastic deformation processes which serve to reduce the crack sensitivity in dental amalgams are similar to those which cause creep deformation. It was also noted that a wide variation of fracture toughness was observed amongst the amalgams

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- 1 Englehard Minerals and Chemical Corp. New Jersey U.S.A.
 - 2 L.D. Caulk Co., Milford Delaware U.S.A.
 - 3 Sybron-Kerr, Michigan U.S.A.

Double Tension ?

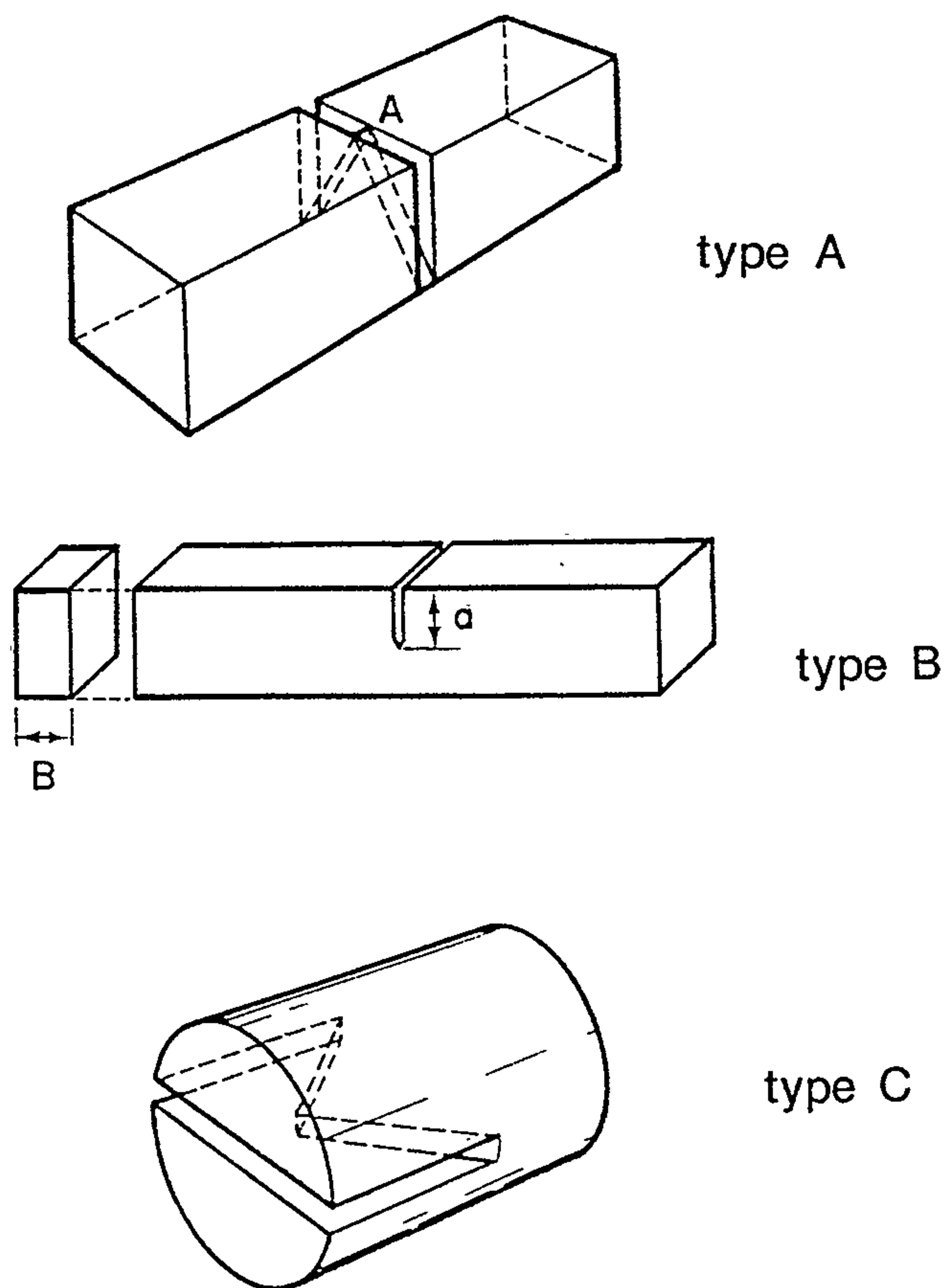


Figure 4-1 : Fracture toughness specimen formats
used in testing dental amalgam.

(After Cruickshanks-Boyd and Locke 1983)

tested. High Copper amalgams showed restricted creep deformation and low fracture toughness.

Lloyd and Adamson (1985) evaluated fracture toughness for a selection of Low and High Copper amalgams using the same procedures suggested in a previous study of fracture toughness of tooth coloured restorative materials (Lloyd and Mitchell 1984). A single edge notch specimen conforming to BS 5447 (1977) and similar to specimen B of Cruickshanks-Boyd and Locke (1983) was used and fracture toughness was determined for eight specimens of each amalgam using an Instron TTCM testing machine at a speed of 10^{-4} m/s. Lloyd and Adamson (1985) in agreement with Cruickshanks-Boyd and Locke (1983) found that fracture toughness decreased as copper content increased. Of the variables which may influence the fracture toughness, the most important were found to be alloy composition, particle morphology and alloy/mercury ratio. In comparing the fracture toughness range of composites to that of amalgams Lloyd and Adamson, who conducted the respective tests under identical conditions found the values to be :

Fracture toughness (amalgam) 0.955 - 1.602 MNm^{-1.5}

Fracture toughness (composite) 0.63 - 1.47 MNm^{-1.5}

Hassan, Vaidyanathan and Schulman (1986) considered a micro-indentation technique to study and estimate fracture toughness of amalgam. The technique was considered by the authors to be a satisfactory means for the study of localized brittle behaviour of dental amalgam at the margins or isthmus, for example. The procedure employed cylindrical discs 5mm high x 6mm diameter which were polished 24 hours after setting using a selection of graded abrasive paper. Microindentations were made in the polished specimen surface using a Vicker's diamond indenter in a hardness

tester using a 5 kg load. Measurements of the crack propagation length, hardness and impression diagonal were applied to an equation relating crack length to fracture toughness :

$$K_c = \frac{H \sqrt{a}}{\phi} \times 0.39 \left(\frac{c}{a} \right)^{-3/2}$$

where K_c = fracture toughness

$2a$ = diagonal of the indentation

H = Vicker's hardness number

ϕ = constraint factor

The authors concluded that the indentation test was very effective in estimating fracture toughness which decreased significantly from bulk to margin. At the margin it was found that different amalgams behaved differently with Dispersalloy having a superior fracture toughness close to the margin.

Osman, Moore and Phillips (1986) compared fracture toughness of several categories of restorative materials including glass ionomer cement, composite resins, prosthodontic resin and amalgam using a single edge notch bar specimen similar to Lloyd and Adamson (1985). Based on the values obtained, recommendations of materials as a restorative choice in high stress areas were made. The various material groups exhibited the following fracture toughness ranges :

Amalgam	4.83 - 3.46 MNm ^{-1.5}
Posterior composite resin	3.95 - 1.91
Anterior composite resin	3.02 - 1.57
Prosthodontic resin	2.42 - 1.40
Glass Ionomer Cement	1.00 - 1.51

The authors recommended caution in the use of prosthodontic resin

and glass ionomer cement in high stress areas, due to its relatively poor fracture toughness.

The highly specialized equipment, the demands of specimen design and manufacture, and the technique sensitivity leading to high invalidity in results combined with the lack of parity between studies unless exact conditions are duplicated all indicate that the determination of fracture toughness is not a mechanical test which can supercede other mechanical tests. Its direct application to dental amalgam and its possible relation to clinical behaviour of amalgam is questionable.

It has long been a goal, in setting up specification standards, that tests are used which accurately reflect the nature and behaviour of materials, are reproduceable and able to be carried out not only in standards laboratories but also in laboratories in manufacturing plants. The fracture toughness test does not appear to meet these criteria.

CHAPTER 5

SUB-FRACTURE LOADING OF DENTAL AMALGAM

As Wing first noted, amalgam restorations suffer fracture with surprising frequency despite the fact that the compressive and tensile strengths of such amalgams are far in excess of the occlusal loads likely to be applied to them. Much of this phenomenon however, may be explained in terms of faulty cavity design and poor manipulation of the amalgam, but even when these factors are optimal fractures are still observed as evidenced in controlled studies reviewed. Intra-orally such restorations are subjected to cyclic, 'sub-fracture' loads under conditions of variable temperatures and humidity, supporting structures may be of variable strength and loading may be multidirectional as in chewing or even parafunctional occlusal bruxing.

In order to determine the mechanism of amalgam restoration failure in terms of characteristics and mechanical properties of amalgam, most studies in the literature have focused on several laboratory tests thought to correlate closely to clinical demands. Such tests have included dynamic and static creep, corrosion testing, impact loading, fatigue loading, hardness testing and fracture toughness determination. Of these tests, only creep testing and related fatigue loading have employed the use of loads below failure loads, thereby approaching a duplication of masticatory force and intra-oral conditions. The information gleaned from these tests does not completely explain the mechanism of amalgam fracture and current literature has tended to favour a multifactorial interplay.

Creep testing has provided a technically easy and clinically relevant means by which amalgam behaviour under load may be examined. The correlation of this property to restoration marginal fracture susceptibility has been confirmed by many investigators (Mahler and Van Eysden 1969, Mahler et al 1970, Wing 1971, 1985, 1986, Mahler, Van Eysden and Terkla 1975, Vrijhoef 1975, Osborne et al 1977, 1978). In static creep testing a steady load equal to 36 MPa, a small fraction of fracture load, is applied to a cylindrical amalgam specimen at 37°C and the shortening deformation of the specimen is determined from length measurements over a three hour period. Amalgam formulations have been shown to exhibit characteristic creep values which can in turn be correlated to clinical marginal discrepancies with relative accuracy.

Mahler and Van Eysden (1969) pointed out that in duplicating clinical conditions three factors were significant. These factors were the cyclic nature of masticatory loading (equivalent to fatigue loading), the temperature of loading being at 37°C and the presence of oral fluids. To accurately reflect amalgam deformation under these conditions in the laboratory, these workers suggested a test for dynamic creep. This test used the identical specimen geometry as that used in static creep testing but in this test a fluctuating stress which cycled from 500 to 10,000 psi (35 to 703 kg/cm²) 1,800 times per minute was applied to the specimen under circulated distilled water at 37°C. To parallel static creep testing, percentage shortening of specimen length over three hours was determined. The close correlation of static creep to dynamic creep suggested that the creep mechanism occurring was indifferent to loading mode, either static or cyclic. However, this conclusion has been challenged by other workers who have found static creep

values of questionable significance in view of the non-linear steady state creep behaviour of amalgam which is not detected by static three-hour creep testing (Dickson, Oglesby and Davenport 1968, Greener, Szurgot and Lautenschlager 1980, Williams 1983). It has also been suggested that creep behaviour of High Copper amalgams is distinctly different from that of Conventional amalgams and extended creep testing such as that suggested by Wing (1986) may allow better discernment between alloys with respect to differing creep behaviour.

A consideration of dynamic mechanical properties of amalgam was completed by Kusy and Greenberg (1981), with particular emphasis on the determination of setting rate. Modulus of elasticity and compressive strength were continuously determined using compound parallel beam specimens. These authors concluded that such dynamic mechanical measurements could distinguish phase changes in amalgams manifested by the amalgam setting rate, but that the dynamic test procedure itself does not significantly influence amalgam structure evidenced by similar elastic moduli being derived for differing compression test formats. It was also suggested that microcompression specimens (3mm x 2mm x 1mm) may better represent clinical performance by virtue of such specimens being more surface property sensitive.

Hero et al (1983) compared the effect of static and cyclic loading of amalgam on surface degradation and found a distinct difference in character of degraded corrosion products in the two modes of testing. Three alloys representing both Conventional and High Copper Dispersion Modified formulations were used to prepare standard cylindrical creep specimens. Scanning electron microscopy was employed to examine specimens both before and after loading.

Cyclic loading was accomplished using loads between 2MPa and 70MPa at a rate of 0.25 s^{-1} . Specimens were initially irradiated with thermal neutrons for thirty minutes during which temperature was increased to between 60°C and 75°C . Samples were then allowed to decay for approximately five hours before cyclical loading in artificial saliva. Specimens exposed to cyclic loading were found to be less strained than those subjected to static loading and specimens of dispersed non-gamma 2 amalgams showed a greater release of Hg, Cu and Zn. Cracks that formed in specimens were considered to be a direct product of the combined action of corrosion and stress since the absence of one of these factors reduced the ease of development of the crack. Signs of similar creep processes which promote crack development were observed in both static and cyclic modes of loading.

Sutow et al (1985) considered the response of dental amalgam to dynamic loading. Fatigue testing was carried out at 1800 and 80 cycles/min under uni-axial, sinusoidal loading in compressive and tensile modes. Cyclic creep testing was also carried out. Amalgam failure demonstrated a dependence on frequency and fracture strength was significantly reduced by fatigue loading. A characteristic fatigue crack path seen in metals subjected to low-frequency, elevated temperature testing was seen. The path was primarily inter-granular in the gamma 1 phase. Ultimate fracture observed by these workers suggested that amalgam failure may be due to fluctuating compressive and tensile stresses which are considerably less than the respective static values.

Williams and Hedge (1985) considered creep-fatigue through thermal cycling as a possible cause of marginal failure. Specimens were cycled between 4°C and 50°C for 500 and 1000 cycles and

marginal integrity was evaluated by scanning electron microscopy. The authors noted that fatigue induced fracture could be caused by stresses well below the material's yield stress. Low cycling frequencies with low strain rates and stresses favoured intergranular fracture, a finding supporting that of Sutow et al (1985). High-frequency high-stress loading favoured transgranular fracture. Under static compressive loading, it was noted that void formation was severely restricted and cracking was preceded by extensive grain boundary sliding and plastic deformation. Under cyclic loading, once sliding was established, stresses at concentration sites decreased to allow easy void formation. Continued cyclic stressing provided repeated initiation of grain boundary sliding resulting in extensive fracturing. In contrast to findings of Mahler and Van Eysden (1969), Williams and Hedge affirmed the sensitivity of dental amalgam to cycling frequency when subjected to laboratory fatigue testing.

With detailed analysis of creep mechanisms completed in several studies, Huget et al (1978), following Paddon and Wilson (1975), noted that in addition to creep, viscoelastic materials such as dental amalgam show other time-dependent characteristics under constant load such as stress relaxation which is a gradual decrease in stress under load. Cylindrical specimens were compressed and held at a constant strain on development of a stress of 28 MN/m^2 . It was observed that loaded specimens then underwent relaxation evidenced by a stress loss with no change in strain. Stress plotted against time at six second intervals for a maximum of one minute was found to be similar for the amalgams tested and showed an instantaneous loss of strain energy at the onset of relaxation. Conventional alloys exhibited greatest stress loss.

Huget and his co-workers considered the finding of stress relaxation following deformation induced by transient masticatory forces may explain the clinical observation of tooth-amalgam margin opening. Thus, a sub-fracture loading test such as creep testing has been and continues to be a valuable means of amalgam evaluation and analysis.

The significance of fatigue testing of amalgam has also been examined where specimens are tested to failure, stress/strain behaviour is observed and microstructural examination of the fracture surfaces carried out (Wilkinson and Haack 1958, Sutow and Jones 1979, Kusy and Greenberg 1981, Sutow et al 1985, Bayne et al 1986). In addition, detailed analyses of crack initiation and propagation have been completed by many workers (Asgar and Sutfin 1965, Sutfin and Ogilvie 1970, Young and Wilsdorf 1969, Younis, Asgar and Powers 1975).

The advantages of testing specimens in a transverse mode have been highlighted in the literature in view of the unique interplay of tensile and compressive stresses involved in the test. The loading format also parallels likely occlusal loading of restorations and so the test also allows clinical correlations to be drawn. In view of the findings of several workers thus far reviewed, that amalgam fracture could be caused by stresses well below inherent yield stress, valuable information could be obtained from fatigue tests on amalgam using such sub-yield stress loads.

Giblin (1979) investigated the effect of transverse fatiguing of amalgam specimens in relation to mechanical properties and microstructure. The current study is an extension and extrapolation of the study originated by Giblin and Wing (1977). Giblin produced transverse beam specimens from a selection of

amalgams representing several formulations. In order to examine crack initiation, bending characteristics and microstructural features of crack progress in relation to amalgam formulation, transverse fatigue testing at low loads was carried out on beam specimens. Following the determination of transverse strength (modulus of rupture) for each representative alloy, specimens were subjected to static three-point transverse loading using loads equal to a percentage of the transverse strength in a static fatigue machine previously used by Peet (1971). The range of percentages of moduli of rupture used to determine load was 60% to 95%, and for each specimen bend characteristics and times to failure were noted. In addition, a selection of six alloys were subjected to equal, fixed loads of 135 MPa and 100 MPa and tested to failure - in this case the fixed load represented a variable percentage of the alloys' modulus of rupture (transverse strength), for example 135 MPa represented 68% of the transverse strength of Tytin but is 95% of the transverse strength of Dispersalloy. The investigation produced several observations which could be correlated to clinical restoration failure. Following the application of a 'sub-fracture' load for a period, amalgams with high creep would undergo bending which ultimately led to crack initiation and propagation and final failure by fracture. The period to fracture was found to relate to the creep value of the amalgam so that highest creep amalgams exhibited shortest periods to fracture and highest bend. Lowest creep amalgams showed least bending and resisted fracture. Microscopically, the nature of the crack path through the amalgam beam could be divided into two distinct areas of 'slow' zone and 'fast' zone referring to relative speed of crack progress. The length and width of these zones were

found to differ between amalgams. 'Slow' zone failure was characterized by around-particle cracking. 'Fast' zone failure, which forms almost instantaneously, exhibited through-particle cracking. Where loads above the strength of the amalgam were used, the specimen would fail without evidence of prior plastic deformation or bending. Giblin points out that some minute elastic bending does take place prior to failure. The investigation found a relationship between creep and transverse static fatigue and pointed to a possible cause of marginal and bulk isthmus failure. Along similar lines, Maoleekulphiroj (1981), employing the techniques of Giblin (1979), considered sub-fracture transverse fatigue testing of specimens of different thicknesses - 3mm, 2mm and 1mm-and correlated these results to mechanical characteristics of amalgams. Loading in fatigue testing represented percentages of transverse strengths of the respective amalgams in the range of 20% to 100%. In addition, the microstructure of beam specimens was compared to that of cylindrical specimens used for mechanical testing. Several interesting observations were made in this investigation. Thinner beams were found to resist sub-fracture loading better than thicker beams. Maoleekulphiroj considered this to be related to the greater void and gamma 2 content of the thicker (3mm) beam. Creep was found to be inversely related to fracture time and directly related to degree of bend (plastic deformation). The importance of effective and efficient condensation pressure on creep and hence on fracture resistance was also noted. Both the findings of Giblin (1979) and Maoleekulphiroj (1981) have confirmed the observations of previous workers with respect to crack initiation, progression and ultimate failure and the phenomena of amalgam fracture following the

application of sub-fracture or sub-yield strength stresses. However, the relationship of macroscopic and microscopic characteristics of bending and fracture characteristics to mechanical characteristics such as creep has been pioneered in these works and has significantly contributed to an explanation of the mechanism of amalgam failure.

CHAPTER 6

MICROSCOPY OF DENTAL AMALGAM

The mechanical properties of a material are a direct function of both its microstructural characteristics and the reaction of its component units to external influences. Dental amalgam, being a complex multiphasic entity, also derives its singular properties from its intrinsic components or phases and the ability of these various phases to provide adequate resistance to unique stresses which come into play in the oral environment. The original basic formula of dental amalgam first presented by G.V. Black consisted of a Silver-Tin-Copper-Zinc alloy. With improvements in techniques of clinical usage of dental amalgams came the need for more detail about amalgam microstructure and setting reactions. Several landmark microstructural studies provided this knowledge (Ryge, Moffett and Barkow 1953, Ryge 1953, Wing 1961, 1962, 1965ab, 1966a, 1976, Bryant and Wing 1976, Wing and Bryant 1977, Bryant 1977, 1980a, 1982).

The original 'balanced alloy' based on the intermetallic Ag_3Sn compound was analysed. Later, newer dental amalgam formulations offering improved properties based on modified formulae, aimed to provide an alternative to the Conventional Ag_3Sn -amalgam. Such 'new' amalgams included the Dispersion Modified formulation of Innes and Youdelis (1963) and the Ternary Single Melt High Copper alloys. The introduction of these newer amalgam formulations opened the field of clinical and laboratory studies in order to fully understand the microstructure and setting characteristics of materials so different from Conventional amalgams.

Conventional Ag₃Sn Amalgams

Many workers have contributed to the analysis of amalgam characteristics and setting reactions (Rosenhain 1926, Gayler 1937, Troiano 1938, Frankel and Fankuchen 1952, Ryge, Moffett and Barkow 1953, Taylor and Burns 1963). With the introduction of improved metallurgical principles to specimen preparation (Wing 1961, 1962, 1965bc, 1966b) greater detail about grain boundaries within the matrix and phasic differentiation was possible. Following the development of etching techniques by Wing, later studies continued and extended the analysis (Allan, Asgar and Peyton 1965, Koran and Asgar 1967) to amalgams differing in particle characteristics. Spherical amalgams developed by Demaree and Taylor (1962) enabled easier and more positive phase identification.

Wing (1966b) studied the microstructure of spherical particle Ag₃Sn type amalgams using techniques of metallographic specimen preparation described in earlier studies (Wing 1964, 1965). the technique employs a series of silicon carbide abrasive papers, grades of diamond paste and magnesium oxide powder. Etching of specimens is achieved using a double etch technique consisting of an aqueous solution of potassium cyanide and iodine followed by an aqueous solution of potassium ferricyanide and ammonia. To establish the nature of the silver-mercury (gamma 1) and tin-mercury (gamma 2) phases of the amalgams, an electron probe microanalyser was used by Wing enabling resolution of areas of approximately 1/4 in diameter. A definitive microstructural profile of amalgam phases was thus presented. Set amalgams consist of original amalgam alloys, voids and a matrix consisting of a mixture of silver-mercury and tin-mercury phases. The gamma 2 phase formed in a mercury-rich environment, forms large single crystals which

can be recrystallized by deformation. A high concentration of this phase is associated with internal voids, where mercury has been entrapped during condensation. Discrete gamma 1 and gamma 2 crystals were easily demonstrated in spherical particle amalgams but lowered mercury content, smaller grain size and difficult discrimination between gamma 2 and gamma 1 when gamma 2 is in a polycrystalline state in lathe cut alloys prevented easy recognition of these phases in such alloys.

With the use of the electron probe microanalyser further definite conclusions about the presence and composition of phases could be drawn (Wing 1966, Koran and Asgar 1967, Johnson 1967, Okabe et al 1972, 1975, Reynolds et al 1975ab, Mahler 1975, Wing 1976, Bryant 1977, 1982). These studies employing vastly differing techniques, such as theoretical reasoning following serial sectioning and corrosion (Jørgensen and Saito 1970), X-ray diffraction (Frankel and Fankuchen 1962, Ryge, Moffett and Barkow 1953, Wing and Ryge 1965a) and optical microscopy (Wing 1961, 1962, 1965b), have elaborated previous findings about the microstructure of Conventional amalgams to the extent that a general compositional 'definition' of such amalgams could be derived.

Reynolds et al 1975ab contributed to the understanding of the mechanism of amalgamation. The fractured surface of spherical amalgam specimens was examined under SEM at various times after trituration. From these observations, these workers were able to identify stages of amalgamation and relate microstructure to tensile strength. The stages were particle rearrangement, solution of

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some parts of the original particles with growth of new phases and grain coalescence with emergence of new phases.

Okabe et al (1972) considered the reactions between mercury and tin, silver, silver-tin alloys. Using both x-ray diffraction method results and electron microprobe data, these authors considered bulk and grain-boundary diffusion of silver to be a major factor in the setting reaction of dental amalgam.

In a later study, Okabe et al (1975) examined amalgamation on the surface of mercury-plated amalgam specimens. The mode of formation and type of phases appearing were found to be dependent on the amount of mercury available where a marked reduction of mercury was associated with the formation of a beta-1 phase.

Further detail about the gamma 2 phases in Conventional amalgams was presented by Bryant and Wing (1984) as part of an extensive study of amalgam microstructure using an electron microprobe (Bryant 1982). Amalgams examined included three Conventional lathe-cut types, New True Dentalloy¹, Ultracaps² and F-400³ and one spherical Conventional amalgam, G-C's Hi Atomic. The study indicated that the gamma 2 phase was most commonly observed as discrete clumps within the gamma 1 matrix. In lathe cut amalgams, the gamma 2 phase was also found in direct contact with unreacted gamma phase or epsilon (Cu_3Sn) phase.

Conventional amalgam consists of silver-tin (gamma) original alloy particles contained within a matrix of silver-mercury (gamma 1) and a tin-mercury (gamma 2) phase containing copper-tin inclusions. Spherical amalgams differ from lathe-cut in the distribution of the Cu_3Sn phase which is widely dispersed throughout the spherical particles and is discretely restricted to Cu_3Sn areas in the homogenized lathe-cut amalgams.

Dispersion Modified Amalgams

Such amalgams consist of approximately 70% Conventional Ag_3Sn particles and 30% silver-copper eutectic Dispersed Phase. The objective of the substitution of a silver-copper eutectic for part of the Conventional formula was to increase compressive strength of the product, but its real advantage has proved to be the significant improvement in creep by the removal of the weak, creep-prone tin mercury (γ_2) phase. Since the development of this formulation by Innes and Youdelis (1963), many studies have contributed to the analysis of this newer amalgam formulation (Wing 1970, 1971, 1975, 1978, 1979ab, Mahler, Adey and Van Eysden 1975, Marshall, Marshall and Greener 1977, Okabe et al 1977, Bryant 1979, 1980a). Setting of Dispersion Modified amalgam is a two-stage reaction following trituration and the final structure of the set amalgam consists of particles of silver-tin (γ) and Cu_3Sn (from the Conventional Ag_3Sn alloy) within a matrix of silver-mercury (γ_1) and original silver-copper (eutectic) spheres containing and surrounded by the newly formed copper-tin (Cu_6Sn_5) phase.

Wing (1979a) in a review of 'new' amalgams provided a summary of the three available amalgam formulations. Table 6-1 taken from this review presents details about the particle distribution and composition of 'new' amalgams and cites commercial examples of each group. Dispersion Modified amalgams contain a mixture of Ag_3Sn and a Ag-Cu eutectic which is close to the eutectic composition.

Ternary Single Melt High Copper Amalgams

These amalgams consist of alloys formed by a single melt process and generally contain up to 30% copper by weight. Many

studies have analysed these newest amalgam formulations (Asgar 1974, Wing 1977, 1978, 1979, Okabe et al 1978, Marshall, Marshall and Greener 1977, Bryant 1979, 1980a). The final structure of this type of amalgam is considered to be a blend of original ternary alloy within a gamma 1 type matrix and featuring reaction zones related to the original alloy and reaction phases containing tin, copper, mercury and some silver. Such amalgams have proved to be corrosion-resistant by virtue of the replacement of the tin-mercury (gamma 2) phases by the copper-tin (eta-prime) phase.

Bryant (1980a) considered the use of X-ray mapping, obtained from electron microprobe analysis to examine a selection of High Copper amalgams. Alloys Amalcap Non-Gamma 2 (Dispersion Modified), Sybraloy¹ (Single Melt High Copper) and Spheriphase² (Admixed High Copper) were used to prepare specimens thus representing a range of differing copper compositions. Results indicated that X-ray mapping was a reliable method providing both qualitative and quantitative analysis of amalgam.

Single Melt High Copper amalgams are also represented in Table 6-1 with Tytin and Sybraloy two prime examples. These spherical amalgams contain distributed compositional elements and develop strength rapidly due to efficient alloying between original alloy and gamma 1 matrix.

Microstructure of Amalgam Fractures

According to Asgar and Sutfin (1965) 'the brittleness of dental amalgam limits its use to sites in which tensile stresses

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Table 6-1 : Original particle distribution and composition of modern amalgams.*

	Dispersion Modified	Single Melt High Copper	Reverse Dispersion Modified	Ag ₃ Sn
	Dispersalloy Luxalloy Non-Gamma 2	Tytin Sybraloy Indiloy	Spheriphase S Spherisphase C	Lathe fine Spherical grain
Original alloy particles	 +  Ag ₃ Sn Ag-Cu eutectic	  	 +  Ag ₃ Sn  +  Ag ₃ Sn Ag ₃ Sn	  Ag ₃ Sn Ag ₃ Sn
Approximate proportions by weight	70 30		70 30 70 30	
Composition %:				
Ag	69 70	60 40 59	60 68 60 68	69 70
Sn	26	25 30 24	25 26 25 26	26 26
Cu	4 30	15 30 13	15 4 15 4	4 4
Zn	1		1 1	1
In		4		

* Table adapted from Wing, Ann RACDS 1979;6:28-35.

can be kept at a minimum. If the cause for the brittleness could be ascertained, then an approach to correct this problem could be devised'. Many studies have been concerned with the development and analysis of new amalgam formulations designed to improve fracture resistance of dental amalgams under load however the 'cause of brittleness' as suggested by Asgar and Sutfin has not been completely ascertained nor abolished. Microstructural examination of amalgam fracture with particular observation of crack progress through phases may identify crack-prone phases or characteristics.

Asgar and Sutfin (1965) in a consideration of brittle fracture of amalgam used a Flinn strain-viewer to view bending and subsequent cracking of a loaded beam specimen. In order to restrict crack propagation to allow observation, these workers used a two-phase composite material beam specimen of an amalgam bar imbedded in a plastic beam which was loaded slowly until initial failure occurred. Specimens were then etched using methods of Wing (1965) and Schmitt (1960) to define grain structure prior to microstructural examination. Maximum compressive stresses and maximum tensile stresses were found to occur in outermost fibres. Using the two-phase material beam, the axis of neutral stress was shifted from the middle of the amalgam bar to about one-quarter of the thickness from the tension (lower-most) edge. The crack originated on the tensile side and lengthened as deformation was increased, but was arrested about half-way through the amalgam. Another crack originating from the compression side completed the fracture. Analysis of photomicrographs of the cracked specimen indicated that the crack passed most frequently through voids, the gamma 2 phase and the gamma 1 phase. The gamma phase was most resistant to failure. Generally, the crack went around gamma phase particles

but at about half-way through the beam, the crack would cut through gamma particles. The cyanide etch of Wing enabled more detailed observation of crack progression and the crack, in following a path of easiest penetration, in order, went through voids and the gamma 2 phase, through the grain boundaries of the gamma 1 phase, around the gamma phase and then through the gamma phase. These findings had prompted Asgar and Sutfin to conclude that 'properties of dental amalgam may be determined by the impurities segregated at the grain boundaries of the matrix'.

Pires et al (1969), in examining microstructure of fractured beam specimens of spherical alloy amalgams, supported the findings of Asgar and Sutfin with regard to crack progression and in addition found that 15% of gamma phase particles were 'pulled apart' during testing signifying through-particle fracture.

Sutfin and Ogilvie (1970) examined the fracture surface of dental amalgam using stereographic scanning electron micrographs. These workers found that observations made using this method agreed with those studies performed with light microscopes and transmission electron microscopes. Generally, the fracture surface exhibited features of intergranular and interphase crack propagation, no discrete grain boundary inclusions were observed and evidence of microplastic deformation in the matrix was found. A less prominent feature of the fracture surface of spherical alloy specimens was the unreacted alloy particle, suggesting that such an amalgam features a better bond between particle and matrix. Evidence of cleavage of an unreacted particle was found in the spherical alloy but was not observed in fine cut alloys.