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THE MECHANISM OF MARGINAL FRACTURE OF AMALGAM FILLINGS

by

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INTRODUCTION

In previous works by various authors it has been established that fillings of silver amalgam show a very high frequency of marginal fracture. No explanation of this phenomenon has been offered, so it has not been possible to take systematic measures to avoid it. It is well known that occlusal marginal fracture is one of the most important factors in reducing the life of amalgam fillings apparently prepared by correct technique, and that the fractures are often responsible for serious secondary injury to the tooth. It therefore seems useful to carry out an investigation on the process of fracture and its underlying factors.

The present study is based on observations of amalgam fillings in extracted teeth*), on a number of new experiments, and on

The Danish Dental Association Fund for support of scientific and practical investigations within dentistry has contributed toward purchases of the necessary materials for this study. The author wishes to express his best thanks for this aid.

*) Including approx. 1200 first molars from various school dental clinics in Copenhagen and provincial towns. This material was grouped by age of patients (7—14 years) at the time of extraction so that the approximate maximum age of the fillings was known.

a rather varied theoretical and experimental knowledge. Therefore the subject-matter can hardly be arranged under the traditional headings, and it is hoped that this will not interfere too much with the understanding of the report.

A. TYPES OF FRACTURE

Marginal fractures may be divided into two main types depending upon the direction of the surface of fracture relative to the surface of the filling. The first type (the p-type, Figures 1a, 2, 3, 4, and 5) is characteristic in that the surface of fracture forms an acute angle with the filling surface, while in the second type (the t-type, Figures 1b, 6, 7, and 8) these two surfaces meet at an obtuse angle.

Type p is a fracture caused by a pressure, while type t is a fracture caused by a pull, and both forces have been exerted on the free surface of the filling (AM in Fig. 1). The following observations have led to this conclusion,

1. In experimental investigations on the strength of amalgam margins under pressure (*Jørgensen & Palbøl,* 1964) the angle of fracture was measured and consistently found to be less than 90°.

2. Inspection in stereomicroscope (two oculars and two objectives for three-dimensional view) of several hundred amalgam fillings in extracted teeth frequently revealed the presence of loose fragments of the amalgam margin, which had been dislocated into a slit between filling and cavity wall. In all these cases fracture and displacement have evidently been caused by the same force, viz. a pressure on the free filling surface. All the surfaces of fracture were of type p.

3. Microscopic examination of sections of about two hundred amalgam fillings in extracted teeth often showed incomplete fracture surfaces (cf. Figures 4 and 9) of the p-type, where the slit formed by the fracture had its greatest width at the free surface of the filling. Such a slit can be explained only by pressure on this surface.

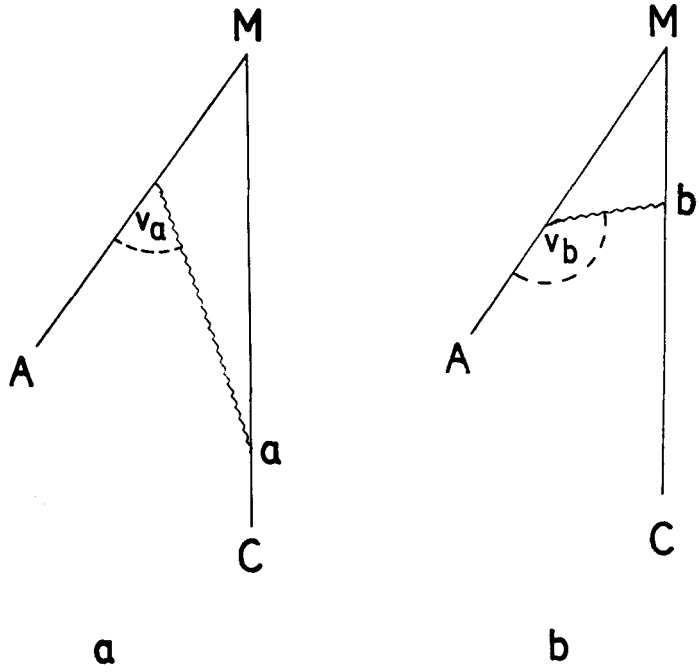

Fig. 1. The two principal types of marginal fracture. AM is the free surface of the filling, while CM is the surface facing the cavity wall. The fracture is marked by a serrated line. a is the p-type fracture, produced by pressure on the surface AM, while b is the t-type fracture, produced by different forms of tensile loads applied in the face AM.

4. Numerous unsupported amalgam margins (of fillings in teeth and of various types of experimental fillings in glass tubes etc.) were loaded until fracture by means of the point of a blunt explorer. The surfaces of fracture were all of type p.

5. The type t fracture was imitated experimentally by polishing the margins of occlusal amalgam fillings with different types of dental burs rotating from filling toward tooth. The cutting edges of the burs will be pressed down into the amalgam, which will be pulled in the direction toward the free amal-

Fig. 2.

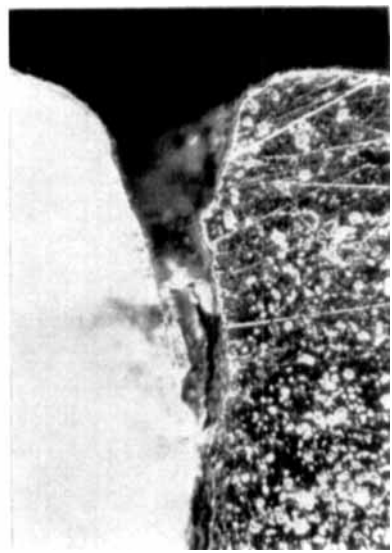

Fig. 3.

Fig. 2. p-type fracture in an occlusal filling. Note the slit between enamel and amalgam and the oblique surface of fracture, which meets the enamel surface to form a narrow V-shaped groove along the filling margin. Leitz Ultropak. 90 ×.

Fig. 3. As Fig. 2. The slit between tooth and filling widens toward the fractured area. 90 ×.

Fig. 4.

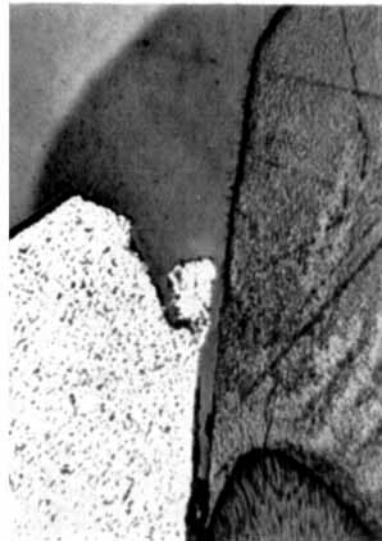

Fig. 5.

Fig. 4. p-type fractures in an occlusal filling. A piece of the margin is partially broken off and pressed against the enamel surface. Leitz Opak-illuminator. 90 ×.

Fig. 5. p-type fracture in an occlusal filling. The upper part of the surface of fracture is possibly the remainder of a t-fracture. Leitz Opak-illuminator. 90 ×.

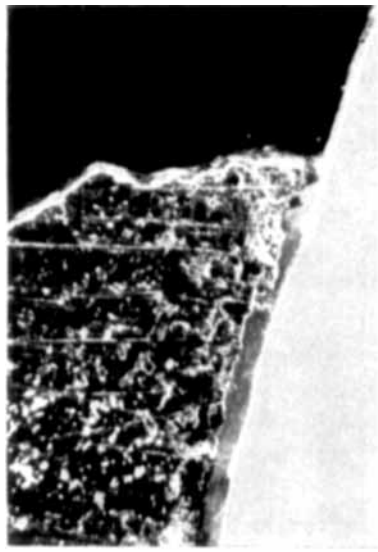

Fig. 6.

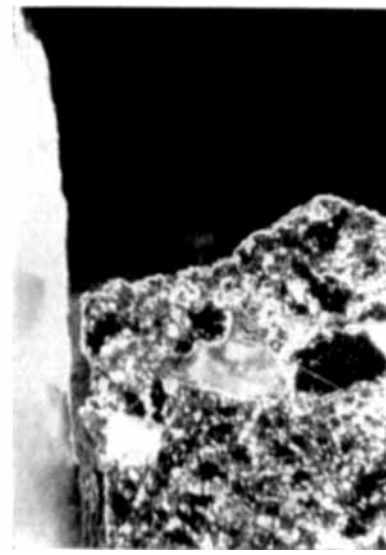

Fig. 7.

Fig. 6. t-type fracture in an occlusal filling. Note the slit between filling and enamel. Leitz Ultropak. 90 ×.

Fig. 7. As Fig. 6. 90 ×.

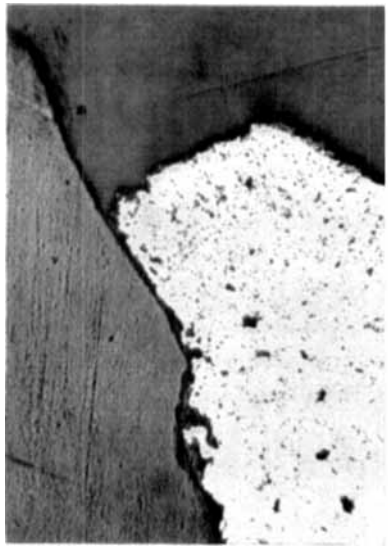

Fig. 8.

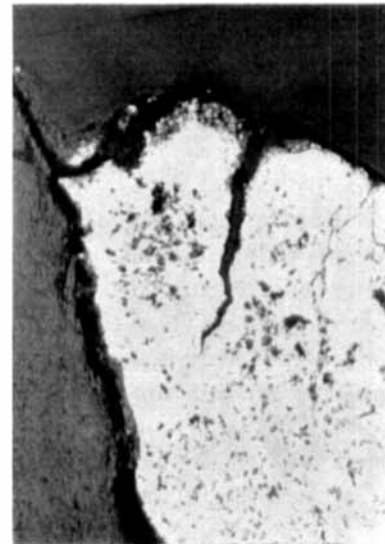

Fig. 9.

Fig. 8. As Fig. 6, but taken with Opak-illuminator. 40 ×.

Fig. 9. Incomplete p-fracture in occlusal amalgam margin. The fragment has been tilted against the tooth thereby closing the opening of the slit between filling and tooth. Leitz Opak-illuminator. 90 ×.

gam margin, and the line of fracture b (see Fig. 1) will result*). Polishing with stones considerably reduced the tendency to marginal t-fractures. Polishing of unsupported amalgam margins of occlusal fillings sometimes produced pure p-type fractures, sometimes transitions from the p- to the t-type. The former type occurred when there happened to be a relatively wide slit between filling and tooth (see Chapter III), while the latter was observed in connection with relatively narrow slits.

6. The t-fracture was also duplicated by forcing teeth with occlusal amalgam fillings down into sticky food (such as softened caramels), from which they were subsequently removed using a pull. After the experiments the fragments of the amalgam margins could be demonstrated in the impressions in the tacky food. The angle of fracture (v_b, Figure 1) was in each case appreciably larger than 90°.

In amalgam fillings which have served in the mouth for some length of time (e.g. one year or more) the p-type fracture was greatly predominant; it also seems to predispose to poor hygienic conditions along the filling margins to a much higher degree than the t-fracture. Probably, marginal fractures of amalgam fillings mentioned in the literature or elsewhere will practically always be fractures of the p-type, and it is also this type which will be discussed in detail below.

B. THE PROCESS OF FRACTURE

For the purpose of a mechanical analysis of the process of fracture the amalgam margin can be considered a geometric wedge (see Figure 10). Breakage of such a wedge under pressure exerted on its free surface presupposes that the amalgam margin can be stressed beyond the crushing strength of the material. In general, this condition is fulfilled only if there is a slit between malgam margin and cavity wall of the width d or more, d (see Figure 10) being the deformation of the amalgam margin at the breaking point.

*) It should be noted that the division into p- and t-fractures is based, not upon the stress condition in the amalgam margin under load, but on the direction of the fracture-producing force in relation to the free amalgam surface

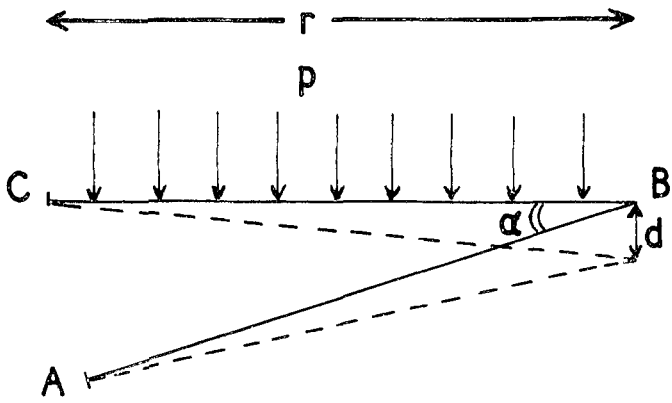

Fig. 10. Diagram of amalgam margin under load. A is the bottom of the slit, BC is the free filling surface, and d is the necessary width of the slit for fracture of the margin. The dotted line denotes the shape of the deformed margin.

The magnitude of d can be calculated with good approximation from the formula*)

$$d = \frac{p \cdot r}{E \cdot \sin \frac{\alpha}{2}} \; (1 + v + 8A\,\alpha) \text{ mm}, \qquad (1)$$

where p is the pressure on the wedge in kp/mm²
r is the length of the wedge in mm,
v is Poisson's ratio (≃0.3) for the material,
α is the angle in radians, and

$$A \text{ is } \frac{\frac{1}{4} \sin 2\alpha}{1 - \alpha \cdot \sin 2\alpha - \cos 2\alpha}.$$

Loading of the wedge with the pressure p will induce tensile stresses in the loaded side of the wedge and compressive stresses in the opposite side. Since the tensile strength of silver amalgam is much lower than its compressive strength (*Rodriguez & Dickson,* 1962, and others) it is the tensile stress condition which is of particular interest in the present analysis. This condition may

*) This and the following formulas (2) and (3) have kindly been calculated by Professor F. Niordson, Ph. D., The Technical University of Denmark, to whom the author offers his best thanks.

be expressed by the formula

$$\sigma = p \cdot \sqrt{1 + 4B + 16B^2}\ \text{kp/mm}^2, \text{ where} \qquad (2)$$

$$B = \frac{\frac{1}{4}(\cos 2\alpha - 1)}{1 - \alpha \sin 2\alpha - \cos 2\alpha}.$$

The formulas (1) and (2) apply only to loads and deformations below the elastic limit, but since the ductility of amalgam is very low (0.3–0.5 % elongation according to *Rodriguez & Dickson,* 1962), they may be used with good approximation to the breaking point of this material.

If σ in (2) represents the ultimate tensile strength of the silver amalgam, p indicates the load in kp per mm² necessary for breaking the wedge-shaped margin. If a certain value is assigned to σ it is possible, on this basis, to calculate p for marginal angles of different values.

Table 1

Maximum load (kp/mm²) on amalgam wedges as influenced by the size (degrees of arc) of the wedge angle

Ultimate tensile strength of the amalgam 8 kp/mm²

Angle of wedge	10°	15°	22½°	30°	45°	60°	75°	90°	105°
Max. load	0.08	0.18	0.42	0.77	1.89	3.62	5.93	8.00	9.09

The values in Table 1 and in Figure 11 serve as an example, where the tensile strength of the amalgam is assumed to be 8 kp/mm². Such an amalgam must be considered to be of high mechanical quality. It is pointed out that the maximum load p is proportional to the tensile strength of the amalgam, and that beyond the tensile strength the formula (2) contains no dimensions of the amalgam wedge except the wedge angle.

A simplified formula

$$p = \frac{\sigma}{3} \cdot \alpha^2 \qquad (3)$$

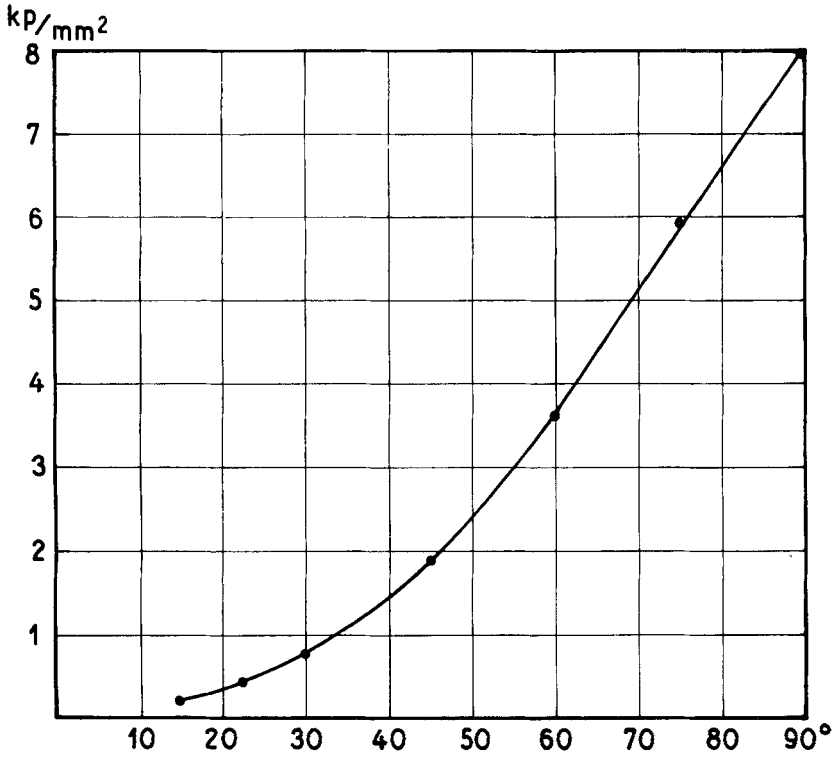

Fig. 11. Influence of the marginal angle upon the strength of a wedge-shaped amalgam margin under pressure. The curve is calculated on the assumption that the amalgam has a tensile strength of 8 kp/mm².

applies with fair approximation for angles below about 60°. From this it is seen that the maximum load on an amalgam wedge is roughly proportional to the square of the wedge angle. For angles above 60° the true values for maximum load will be relatively much — and increasingly — higher than the values calculated from the formula (3).

The size which the deflection of a wedge-shaped amalgam margin must have in order to lead to breakage can now be computed from (1) by inserting in the formula the values obtained for p (Table I). It is further assumed that r has a magnitude of 1 mm, and that the amalgam has a modulus of elasticity of

$1.4 \cdot 10^3$ kp/mm^2 (for the latter numerical value see *Rodriguez & Dickson*, 1962). The results of the calculations appear in Table II and Figure 12.

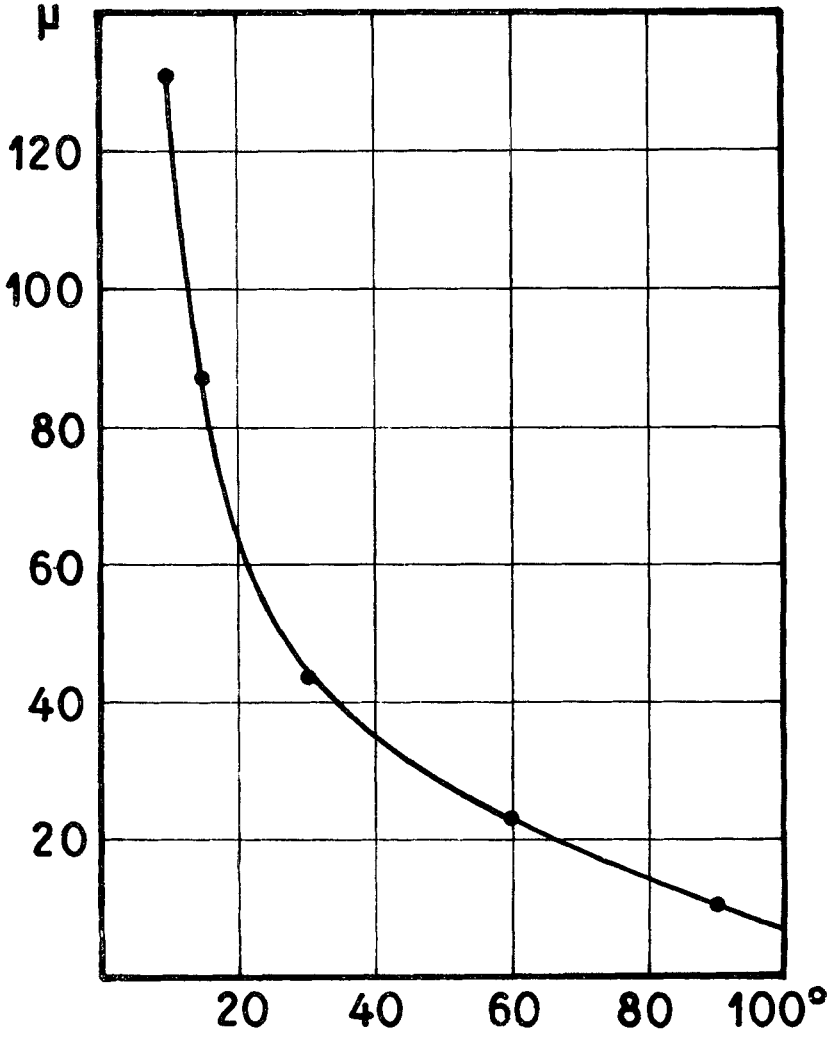

Fig. 12. Size of the maximum deflection (in μ) of the wedge-shaped amalgam margin as affected by the wedge angle (in arc degrees) on assumptions shown in Table II.

Table II

The size of the maximum deflection (in μ) of the wedge-shaped amalgam margin as influenced by the wedge angle (degrees of arc)

Height of wedge 1 mm, modulus of elasticity $1.4 \cdot 10^3$ kp/mm², tensile strength 8 kp/mm²

Angle of wedge	10°	15°	30°	60°	90°
Max. deflection	132	87	44	23	11

As mentioned above, the maximum deflection of the amalgam wedge indicates the width of the slit between amalgam margin and cavity wall that is necessary for breakage of the margin when subjected to loading and deformation. *It should be noted that the magnitude of this critical value ($d_{max.}$) is proportional to the strength of the amalgam and the depth of the slit between amalgam filling and cavity wall, and that it is approximately inversely proportional to the marginal angle and the modulus of elasticity of the amalgam.* This relation can be expressed by the simplified formula

$$d_{max.} = 240 \cdot \frac{t \cdot r}{E \cdot v} \text{ mm, where} \qquad (4)$$

t is the tensile strength in kp/mm²

r is the depth of the slit in mm

E is the modulus of elasticity in kp/mm² and

v is the marginal angle in degrees.

With slits of less width than $d_{max.}$ the amalgam margin will deform elastically under load (perhaps until contact with the cavity wall), and after the load is removed the margin will return to its original shape. After repeated elastic deformations there is a possibility of fracture due to fatigue. Experiments by *Wilkinson & Haack* (1958) have shown that the critical value for frequently repeated pressures exerted on silver amalgam

amounts to about one fifth of the static crushing strength. In view of the low ductility of amalgam it can be assumed with good approximation that the critical deformation for frequently repeated pressure deformations amounts to about one fifth of the maximum static deformation. If similar conditions exist for tensile loads, the abovementioned calculations (Tables I and II) for maximum load and deflection must be divided by five to give the approximate values for critical load and deformation for fatique of amalgam. The values obtained by the division show that below the critical value the material can endure an indefinite number of loads and deformations without breaking. Further studies on fatigue of amalgam are, however, necessary before these properties are completely unravelled.

All the considerations contained in this chapter show that a slit between amalgam and cavity wall is a prerequisite for p-type fracture of the amalgam margin. The risk of large marginal fractures increases with the depth and the width of the slit and with decreased strength of the amalgam; low strength may cause the amalgam margin to break, even at relatively slight deformations. Microfractures (invisible to the naked eye) may occur owing to poor adaptation of the amalgam to the cavity wall, but are scarcely of clinical interest. Macrofractures presuppose a slit with a depth measurable in tenths of millimeters and a width of several microns.

The question is whether such slits actually occur.

The answer to this question must be that they definitely do. The presence of these slits was clearly demonstrated both in amalgam fillings in extracted teeth observed in the stereomicroscope and in sections of such fillings examined in metallographic microscope. These examinations further established that for occlusal fillings there is a correlation between slits and marginal fractures which is in good agreement with the theoretical mechanical laws outlined in this chapter.

Another question arises, viz. what the causes of such slits are, and how these causes can be eliminated more or less completely. The following sections are devoted to these problems.

C. CAUSES FOR SLITS BETWEEN AMALGAM FILLINGS AND CAVITY WALLS

I. Corrosion

Previous studies by *Schoonover & Souder* (1941) and others, have shown that corrosion of amalgam fillings consistently occurs on the surfaces enclosed by the cavity walls. The two au-

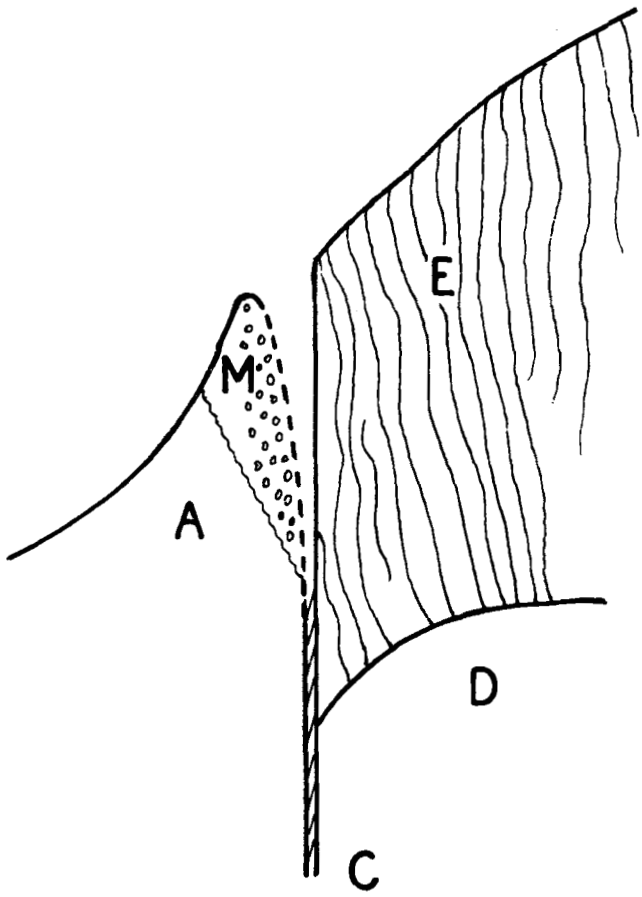

Fig. 13. Appearance of section of amalgam margin, typical of both young and old fillings in the experimental material of extracted teeth. C (hatched) represents solid corrosion products. The margin M has bent away from the cavity wall and is porous due to advanced corrosion. The location of a possible p-fracture will roughly correspond to the serrated line. Normally, the slit between M and E is not filled with corrosion products.

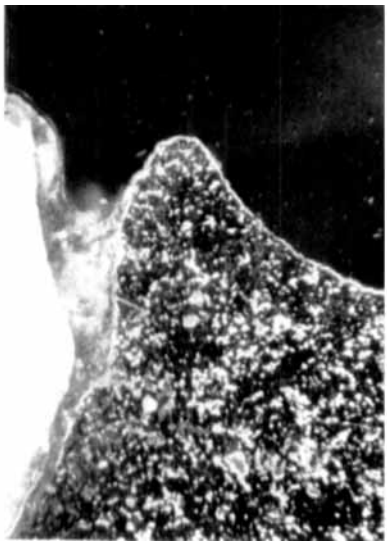

Fig. 14. Fig. 15.

Fig. 14. Marginal deflection of occlusal amalgam filling. Leitz Ultropak. 90 ×.

Fig. 15. As Fig. 14.

thors demonstrated the presence of corrosion products in these areas, and found that the corrosion might be so far advanced that the amalgam had lost most of its strength.

The present author has demonstrated that similar corrosion products were of common occurrence in a great number of amalgam fillings in extracted teeth intentionally crushed to remove the fillings. Corrosion products could occur on any filling surface, but as a rule the layers were thickest on the sides and thinnest on the bottom surfaces. Layers up to 10—20 μ in thickness were frequent, while layers exceeding 50 μ rarely occurred. Examination of the fillings in the stereomicroscope revealed in nearly all cases the heaviest corrosion attacks in the marginal areas.

By comparing stereomicroscopic observations of filling margins with sections of fillings in extracted teeth, it was very often possible to characterize the marginal areas morphologically as shown in Figures 13—20.

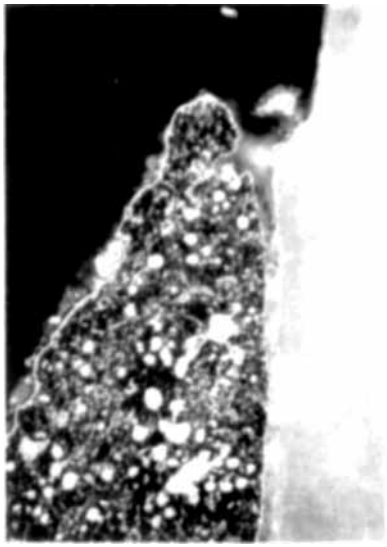

Fig. 16. As Fig. 14.

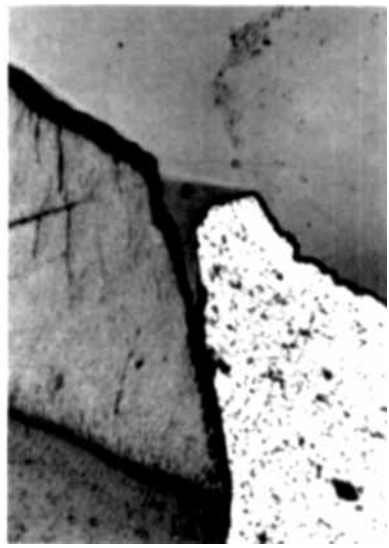

Fig. 17. As Fig. 14.

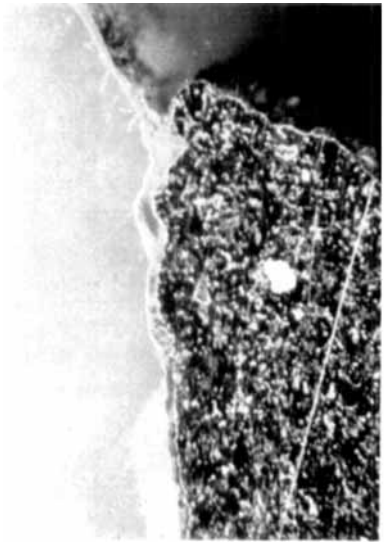

Fig. 18. As Fig. 14.

Fig. 19. As Fig. 14.

Fig. 20. Fig. 21.

Fig. 20. Marginal deflection at the gingival margin of a Class 5 amalgam filling. 90 ×.

Fig. 21. As Fig. 14. The V-shaped slit partially filled with crystalline corrosion products. Leitz Opak-illuminator. 90 ×.

The characteristic feature of this picture is the deflection of the filling margin away from the cavity wall. The bend may be more or less pronounced, but shows a clear tendency to be largest when the marginal angle is small (occlusal fillings). The result of the deflection is a rather narrow V-shaped slit, the bottom of which often continues into a narrower slit between filling and tooth with nearly parallel walls. The V-shaped slit is usually empty or filled with soft detritus (it may in very rare cases be filled with hard, crystalline corrosion products, see Figure 21). The narrower extension, on the other hand, is generally filled with semi-transparent, crystalline corrosion products. The original contour of the amalgam wall in the V-shaped slit has often been retained. This can be seen because the amalgam surface reproduces the surface details of the cavity walls. Therefore the V-shaped slit cannot be a direct result of loss of amalgam by corrosion, but must be ascribed to a deflection of the margin away from the cavity wall. In the great majority of cases the

Fig. 22. Corrosion porosities in the marginal area of an amalgam filling. The upper part of the margin is crushed and pressed down into the widest part of the V-shaped slit between filling and tooth. Leitz Ultropak. 90 ×.

margin-destructive fractures of the p-type originate in these V-shaped slits, which accordingly represent an essential stage in the process of fracture.

In explanation of the marginal deflection the following theory is advanced: *Due to the corrosion of the amalgam margin metallic mercury is set free; during the corrosion the amalgam surface against the cavity wall is anodic, while the free amalgam surface is cathodic. The corrosion attacks in particular the* γ_2*-phase (the tin-mercury crystal). The mercury liberated by the corrosion diffuses into the amalgam from the cavity side causing this part of the amalgam to expand; the deflection of the amalgam margin is a direct result of this unilateral expansion. For this special type of expansion the term mercuroscopic expansion is introduced.*

The correctness of this theory is supported by the following points,

1. Corrosion resulting in loss of substance attacks in preference amalgam surfaces enclosed by the cavity walls. The loss of

Fig. 23 a.

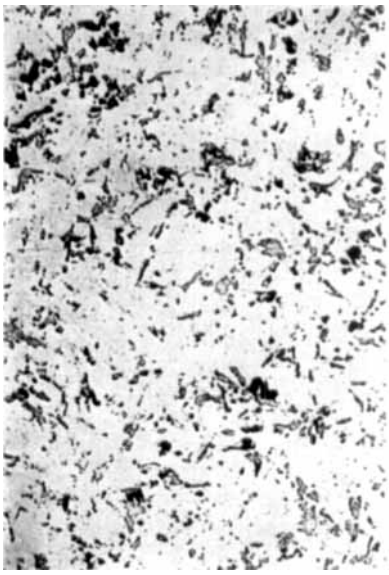

Fig. 23 b.

Fig. 23. γ_2-phase in silver amalgam with a mercury content of 54 % and of 39 %. Leitz Opak-illuminator. 90 × and 125 × respectively.

substance can be seen directly by microscopic inspection of the amalgam surfaces, which take on a more or less cindery appearance. The loss of substance can also be observed on polished sections of amalgam margins; porosities, which is an evident consequence of the corrosion, occur here especially in the part of the amalgam facing the cavity walls (Fig. 22).

2. In amalgam surfaces which have been polished with a relatively mild abrasive (such as diatomaceous earth) the γ_2-phase appears as shallow depressions in the otherwise flat surface (Figure 23). The cause of this is probably the difference in hardness between the three components of the set amalgam (γ_2 is by far the softest). In a number of the metallographically examined amalgam fillings it was possible to demonstrate corrosion attacks with partial loss of substance on the so identified γ_2-phase. Corrosion with loss of substance could not be shown on either the γ-phase or the γ_1-phase (in specimens prepared as described, the γ-phase often appears as almost black grains when studied by Leitz Ultropak technique).

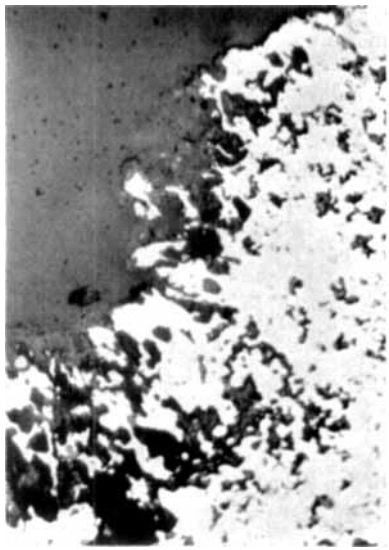

Fig. 24.

Fig. 25.

Fig. 24. Grossly corroded amalgam surface in slit between filling and tooth. Leitz Opak-illuminator. 125 ×.

Fig. 25. Crystalline corrosion products on the surface of a cubic amalgam specimen. Experiment for illustrating formation of concentration cell element. 8 ×.

The finding that the γ_2-phase is most susceptible to corrosion is in good agreement with chemical analyses by *Schoonover & Souder* (1941) and with various German investigations (see *Wagner,* 1962).

It should be added that the structural studies show that the γ_2-phase corrosion may penetrate deep into the amalgam, and if the phase is present in abundant amounts its dissolution may cause all the amalgam to crumble (Figure 24).

3. The corrosion of the amalgam margin is probably due to formation of a concentration cell, where in particular the oxygen concentration within the slit may be lower than on the free amalgam surface. This will render the walls of the slit anodic, and the following reaction will take place,

$$Sn \rightarrow Sn^{++} + 2\,e^{-}\,, \qquad (\alpha)$$

while the free surface becomes cathodic with the following electrochemical reaction

$$2\,H_2O + O_2 + 2\,e^{--} \rightarrow 4\,OH^{-}. \qquad (\beta)$$

Fig. 26. Corrosion due to the presence of a concentration cell element between the free surface of amalgam and the surface against a glass tube. 3 ×.

It is seen that removal of the Sn^{++} ions (*inter alia* by precipitation as sparingly soluble corrosion products), increase of the difference in oxygen tension, and removal of OH^- ions will cause both (α) and (β) to proceed toward the right side.

Corrosion experiments with amalgam where differences in oxygen tension apparently was the only corrosion-producing factor, were conducted in many different ways in connection with this investigation. Some of them will be reported below. The experiments were carried out in ordinary atmospheric air; when oxygen was excluded from amalgam and electrolyte no corrosion could be demonstrated.

(a). Cubic amalgam specimens with an edge length of about 6 mm were prepared according to the manufacturers' directions for the various alloys and placed on a flat glass plate in a 1 % NaCl solution at 37° C. At the end of two weeks a layer of crystalline corrosion products, some hundredths mm thick, had formed on the underside of the specimens (Figure 25). Areas between the corrosion products showed clear signs of dissolution.

(b). Amalgam specimens prepared as under (a) were definitely corroded in porosities and other surface irregularities on the faces not in contact with the glass plate.

(c). Specimens of amalgam condensed in glass tubes (inside diameter 6 mm, length 15 mm) showed after two months in a 1 % NaCl solution at 37° considerable amounts of corrosion deposits on the outer surface of the amalgam margin (Figure 26). The amalgam showed clear traces of solution in the slit between glass tube and amalgam, which in this case represented the anode in the cell. Although the amalgam displayed great expansion (delayed expansion) the electrolyte was able to penetrate between amalgam and glass tube owing to the poor adaptability of the amalgam with an R_a value of 3—5 μ (cf. *Jørgensen,* 1964).

(d). Wedge-shaped amalgam specimens were painted on one side with cellulose varnish or silicone grease and placed at 37° C in a 1 % or 5 % NaCl solution. The wedges were roughly 10 mm in length and 5 mm in width, and the angle of the wedge varied between about 5° and 30°. The specimens were made from cylindrical test specimens of different alloys and produced under widely different condensing pressures. After some months, all the wedges showed voluminous deposits of corrosion products on the painted surface, while no or little corrosion was evident on the unpainted sides (Figure 27 a).

(e). Amalgam fillings prepared in extracted teeth and stored for several months in a 1 % NaCl solution at 37° showed formation of corrosion products partly in the slit between tooth and filling, partly along the margin of the filling on its free surface. Probably the precipitation of corrosion products on the free surface of the amalgam margin in the laboratory test will in time alter the oxygen tension in such a way that it no longer corresponds to the conditions around the amalgam margin in the oral cavity, where corrosion products deposited on the free filling surfaces are likely to be removed.

4. Liberation of metallic mercury due to corrosion can be demonstrated experimentally e.g. in the following ways,

(a). When amalgam is brought into contact with a plate of dental gold alloy in a 1 % NaCl solution (the experiments were made at 37° C) a very severe corrosion occurs, which after a few days results in formation of substantial amounts of corro-

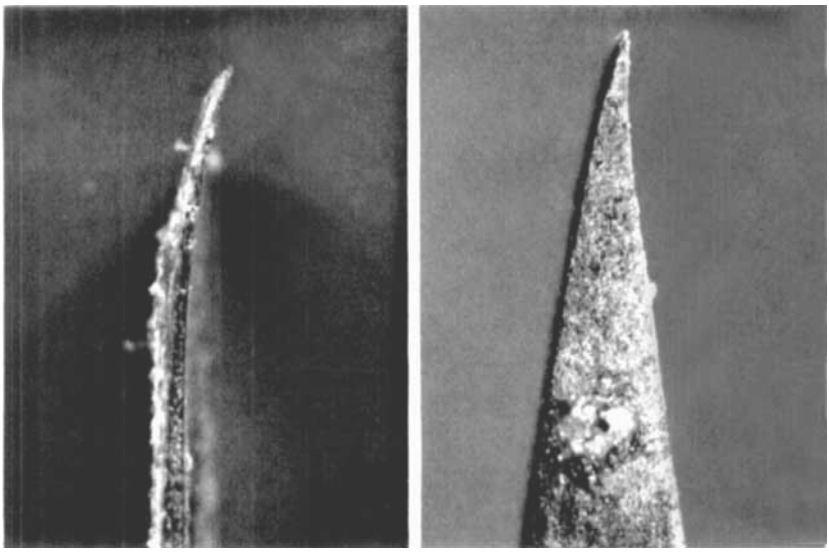

Fig. 27 a. Fig. 27 b.

Fig. 27 a. Corrosion products on amalgam wedge, which had the left side covered with silicone grease during the corrosion test. Note the large deflection. 10 ×.

Fig. 27 b. Marginal deflection of amalgam wedge after corrosion test. Left side covered with varnish during the test. 10 ×.

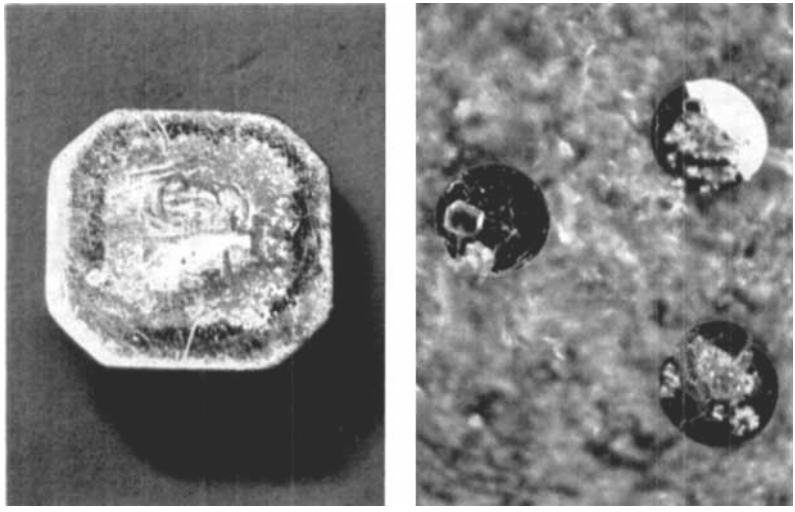

Fig. 28. Fig. 29.

Fig. 28. Gold plate with corrosion products and central discoloration by mercury liberated by the amalgam corrosion. 4 ×.

Fig. 29. Free mercury drops on the surface of corroding amalgam specimen. 170 ×.

sion products (Figure 28), at the same time as the gold plate is contaminated by mercury in the area which was in contact with the amalgam. The mercury contamination can be recognized by a discoloration of intense metalwhite. The presence of mercury in the gold plate can also be demonstrated by conventional analytic methods. This experiment was already described by *Schoonover & Souder* (1941).

(b). Occasionally the surface of amalgam specimens corroding in a NaCl solution at 37° C exhibits, in addition to the loose powderlike corrosion products, minute drops of mercury (Figure 29). The phenomenon apparently occurs when small areas of the amalgam are isolated from the remaining specimen by the corrosion products. That we are not dealing with chemically pure mercury is evidenced by crystallization of the drops when the specimens are placed in air after the corrosion test to allow excess mercury to evaporate.

(c). In laboratory corrosion tests certain amalgam types made with coarse-grained alloy show a strong tendency to form numerous small corrosion elements. The surface of such an amalgam is for the greater part covered with a powderish layer of corrosion products, perforated by numerous small spots of irregular metal drops, which may be up to about one tenth of a millimeter (cf. Figure 34 and the foot-note p. 373). Under the given conditions the metal drops must consist of mercury with dissolved alloy components. Probably the mercury has been liberated so fast by the corrosion that it has not had time to diffuse into the specimen. If the corrosion experiment is interrupted by placing the amalgam in air the drops will disappear within a few days.

5. It can often be shown that those parts of an amalgam filling which are immediately adjacent to the corroding areas are relatively rich in mercury. In this experiment a section was made through amalgam filling and tooth, and the surface of the section was then polished. By slow heating of the amalgam through the temperature range 50—70° C it was sometimes possible to localize the areas with the highest mercury content, because they are the first to exude mercury (Figure 30). Inspection of the amalgam surfaces must take place at intervals not exceeding one

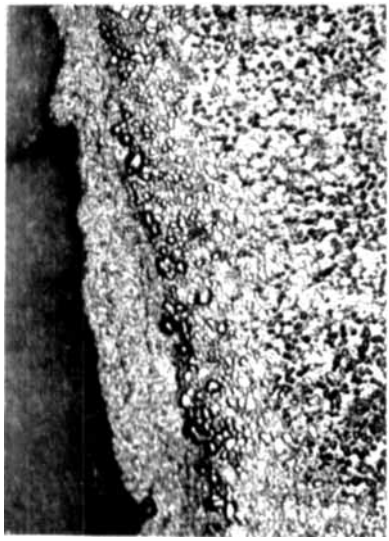

Fig. 30. Drops of free mercury along the margin of a section through a corroded amalgam filling. 90 ×.

minute in order to ensure sufficient differentiation between areas with higher and with lower mercury content. Examination of amalgam fillings treated in this way shows that the concentration of mercury becomes lower with increased distance from the corroding areas. It has not been possible to explain these observations except by diffusion of mercury from the attacked areas into the adjacent amalgam.

6. Mercuroscopic expansion of amalgam has been demonstrated by *Mitchell et al.* (1955); the expansion after 15 days at 37° C was of the order of ½- 1 %. *Mitchell*'s experiment has been repeated by the present author, though with a longer experimental period and with different alloy brands. A few results of these tests are graphed in Figure 31.

7. The following calculation gives a good approximate expression of the size of the deflection displayed by the amalgam margin as a result of the mercuroscopic expansion. In Figure 32 ABC is a schematic representation of the amalgam margin inscribed in a circle with its center in C. AB is the cavity-facing surface along which corrosion takes place; BC is the free sur-

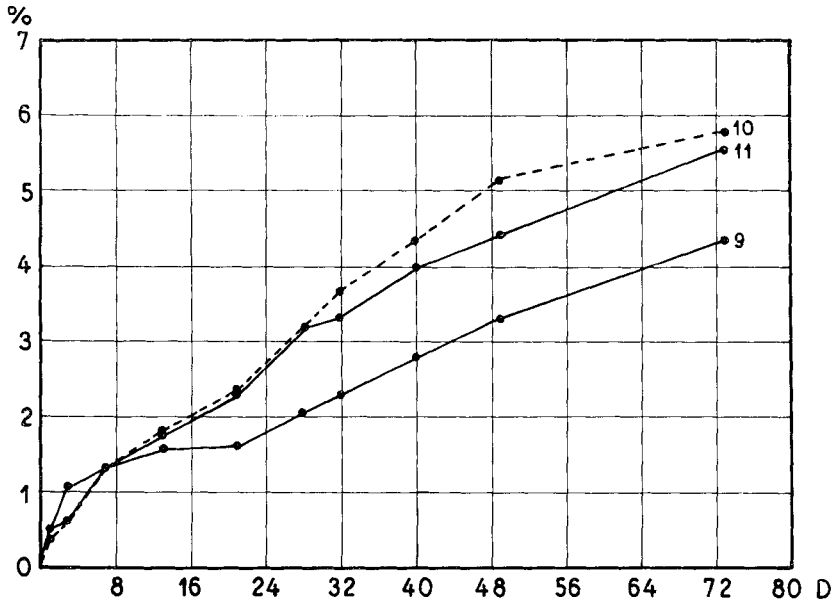

Fig. 31. Example of mercuroscopic expansion of amalgam. Cylindrical amalgam specimens, several months old, were moistened with mercury and their increase in length measured at proper time intervals. Specimen No. 9 had absorbed all the mercury at the end of approx. 12 days but was moistened again after 21 days. For a few specimens it could be shown that the mercuroscopic expansion amounted to about 5 % per 1 percentage weight of absorbed mercury.

face of the amalgam margin, and v is the marginal angle. By the mercuroscopic expansion AB is extended to AB′, and point B is shifted to B′; no change occurs in the dimension of BC, it merely gets another position B′C. In the diagram, AA′ is a measure of the maximum width of the slit resulting from the expansion. If it is assumed that AB′ = A′B′ (which can be done without introducing any appreciable error), then AA′ = d — c. This expression can be computed from the formulas given in the figure when the values for a, v, and the percentage mercuroscopic expansion are known (b = a + the expansion). The results of such calculations are shown in Table III, where a is 1000 μ. With lower or higher values of a, the width of the slit becomes correspondingly smaller or larger. Figure 33 illustrates diagrammatically the dependence of the width of the slit upon the marginal angle when a is 1000 μ and the expansion 1 %.

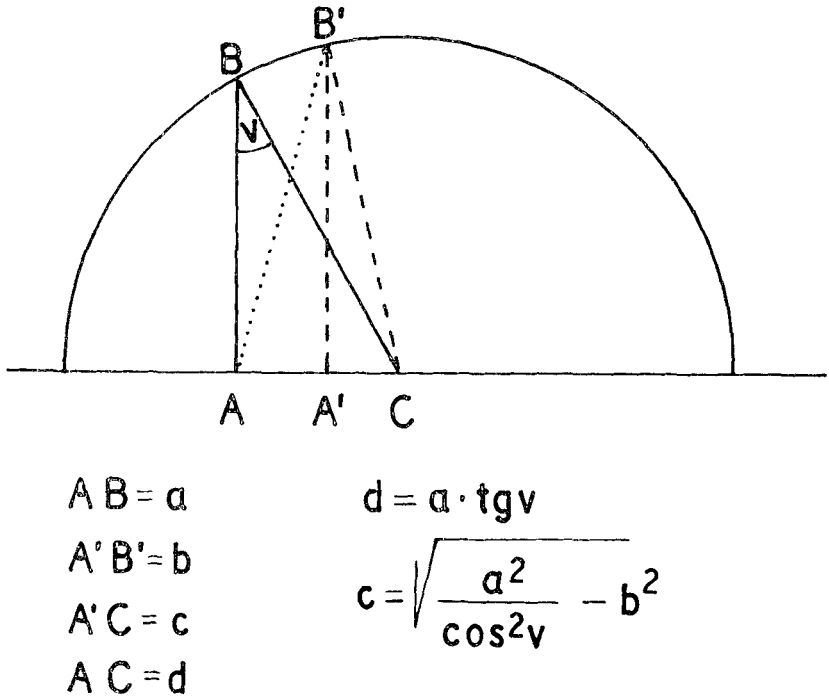

Fig. 32. Mercuroscopically expanding amalgam margin, see text p. 370—371.

The point of these calculations is that, based on acceptable assumptions, the widths found for the slit will be of the same order of magnitude as those seen along amalgam fillings; or in other words, the bend of the amalgam margins can be understood and explained not only qualitatively, but also quantitatively, by assuming conditions which must be considered to prevail in the environment under study.

8. The marginal deflection produced by corrosion can be copied experimentally by means of the wedge-shaped specimens described in section 3 d. After some months' immersion in a 1 % or 5 % NaCl solution at 37° C, the majority of the specimens showed a macroscopic deflection away from the painted wedge surface, where the corrosion was most intense (Figure 27). The

bend was most pronounced in specimens with a small wedge angle*).

Table III

Maximum width of slit in μ for various mercuroscopic expansion values and marginal angles

Depth of slit 1000 μ

Exp. %	10°	15°	30°	45°	60°	75°
0.1	5.7	3.6	1.7	1.0	0.6	0.1
0.2	11.7	7.4	3.5	2.0	1.2	0.3
0.5	31.1	19.2	8.8	5.0	3.0	1.1
1.0	71.4	40.4	17.6	10.1	5.8	2.4

The marginal bend could also be demonstrated in the following way: Amalgam fillings were prepared in glass tubes with closed bottoms and with the upper end faces ground plane. In the inside edge of the open end of the glass tube a number of small facets were ground. They were filled with amalgam together with the remaining part of the tube. Twenty-four hours after preparation, the free surface of the amalgam was ground flush with the end face of the glass tube, so that wedge-shaped amalgam margins were obtained corresponding to the facets with a wedge angle of approx. 15—30°. The specimens were then placed in a 1 % NaCl solution at 37° C. After some months an unmistakable upward bend of a number of the amalgam wedges could be demonstrated on simple inspection (Figure 35). However, the experiments did not always give this result, apparently because the wedges within a relatively short time were covered with corrosion products, so that differences in oxygen tension between the upper and the lower wedge surfaces were likely to be considerably reduced. It is supposed to be for the same reason that

*) One of the alloys used in the experiments showed in a lightly condensed state a strong tendency toward localized corrosion (pitting) in numerous point-shaped areas of the unpainted surface of the wedge-shaped specimen. The corrosion appeared as small blisters and nodules, which grew out on the surface together with droplets of mercury (Fig. 34). All these specimens showed marginal deflection away from this grossly corroded surface and toward the painted side.

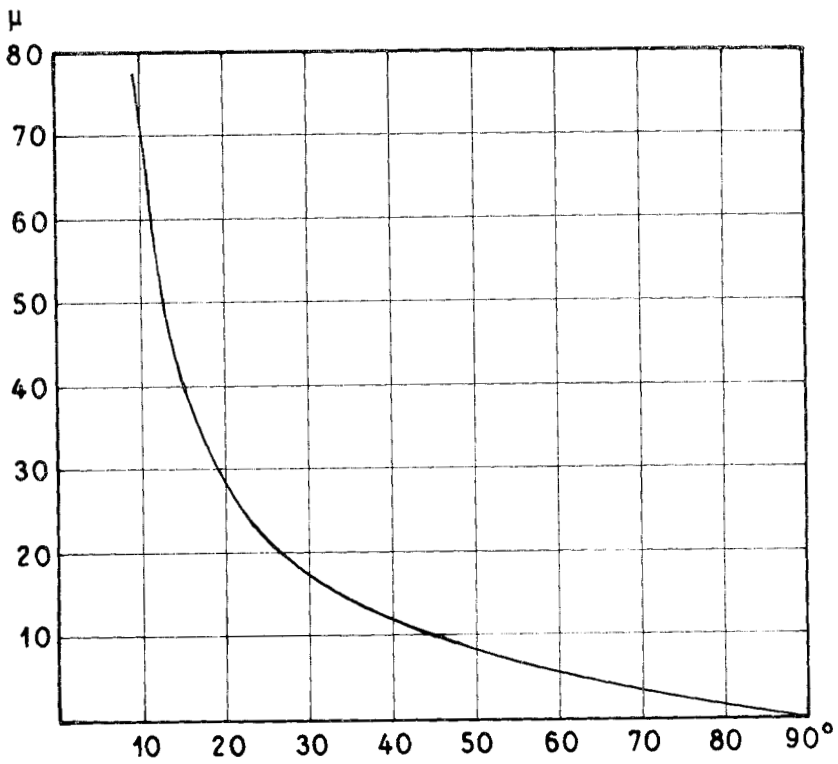

Fig. 33. The marginal angle plotted against maximum width of the slit (in μ) resulting from mercuroscopic expansion. It is assumed that the depth of the slit is 1 mm and that the expansion is 1 %.

similar experiments with amalgam fillings in extracted teeth failed to give clear marginal deflections. In the mouth, corrosion products on the free filling surfaces will — as pointed out in section 3 c — in all probability be removed so that concentration cell corrosion can go on.

9. Studies of the mercury content in amalgam fillings, which were conducted in the author's department and are to be published later, have definitely shown that the mercury content in the marginal areas often is much higher than in the remaining part of the filling. Further, it was found that relatively mercury-rich areas of an amalgam filling are anodic to areas with rela-

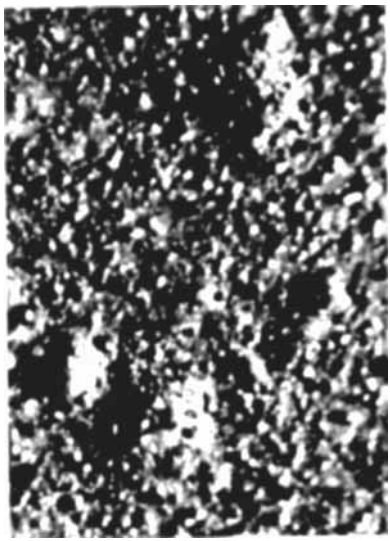

Fig. 34. Point-shaped corrosion (pitting) of amalgam surface with drops of mercury set free by the corrosion. 90 ×.

tively low mercury content. This latter condition was demonstrated by placing amalgam specimens prepared by hand condensation, but without removal of excess mercury, in a 1 % NaCl solution at 37° C for about 14 days. The last condensed, most mercury-rich parts of the specimens were in all cases covered with a thick layer of corrosion products, while the other part with less mercury showed no signs of corrosion*) (Figure 36).

From these conditions it can be deduced that relatively poor condensation of the marginal areas of an amalgam filling will lead to accelerated corrosion along its margins. The amount of mercury set free by the corrosion will probably be exceptionally large owing to the high mercury content in the corroding marginal area; therefore an increased mercuroscopic expansion can also be expected. To this must be added the low crushing strength of the mercury-rich areas, so that these, all in all, will be much less durable in the oral environment than well-condensed amal-

*) Surface defects due to improper condensation of the specimen will give rise to a relatively severe corrosion in the defective areas. If this type of corrosion is present it may interfere with the corrosion caused by difference in mercury concentration.

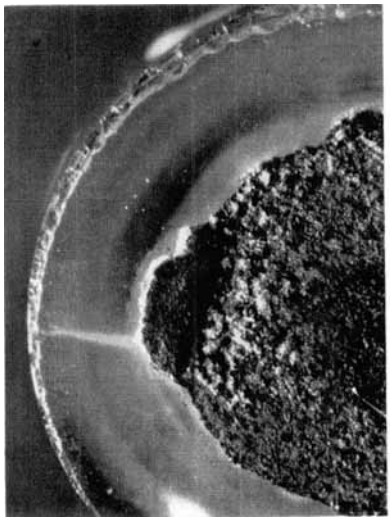

Fig. 35.

Fig. 36.

Fig. 35. Amalgam margin deformed by corrosion. 10 ×.

Fig. 36. Corrosion experiment with amalgam with uneven mercury distribution. The upper end with most mercury is anodic and presents gross corrosion; the remaining part of the amalgam is cathodic and free from corrosion. 12 ×.

gam margins. The agreement between on one hand this deduction, and on the other hand experience in practice and investigations by *Nadal* and co-workers (1961) tends to support the theory of mercuroscopic deformation of the margin.

In this connection attention is also called to the condition shown by photomicrographs in Figure 23, viz. that high mercury content in amalgams will increase the facility of communication between the γ_2-phase crystals, and hence the risk of deep corrosion.

10. In spite of thorough consideration and experiments it has not been possible to explain the marginal deformation of amalgam fillings otherwise than by the mercuroscopic expansion, which again is a result of corrosion. *Fischer & Mertensmeier* (1957) suggest that the marginal deformation is due to thrust of corrosion products. The observations made by the present author show, however, that the slit between the cavity wall and

the deformed margin is nearly always empty, and that hard corrosion products occurred only at a greater distance from the amalgam margin (cf. Figure 13).

Extensive experiments have been made to examine whether the following explanation would account for the deformed margin: When an amalgam filling is cooled in the mouth it will shrink more than the tooth, and a slit will form between filling and tooth. Saliva containing various solid particles will be drawn into this slit. On reheating of the filling to mouth temperature the solid particles may be caught between filling and tooth, and exert a pressure on the filling. If frequently repeated, this process might cause the margin to deform.

This hypothesis was tested by subjecting amalgam fillings to temperature changes. For example, freshly prepared amalgam fillings in teeth or in small glass tubes were placed alternately in liquids at temperatures of approx. 15° and 55° C for periods of about 15 seconds. The liquids were paraffin oil, distilled water, or 1 % NaCl solution, which were used either pure or with a content of suspended fine powder of zinc oxide and zirconium oxide. Each experimental series ran for about two weeks, but revealed in no case slits or deformations of the type met with in clinical amalgam fillings. Besides, the mere fact that the V-shaped slits — as pointed out above in connection with *Fischer & Mertensmeier*'s suggestion — are usually empty, shows that their formation cannot be explained on the basis of entrapped particles.

Nor could any of the following factors, when closely studied, be accepted as the cause for marginal deformation: food impaction between amalgam margin and cavity wall, plastic deformation of the amalgam margin under pressure or tensile load, artifact resulting from e.g. extraction of the tooth, drying up or other changes of tooth and/or amalgam after the extraction. Still other possibilities have been considered, but have all had to be rejected.

II. Delayed expansion

It is well known from previous studies (*Schoonover* and coworkers, 1942; *Holst & Jørgensen*, 1963) that delayed expansion may produce marked dimensional changes in silver amalgam.

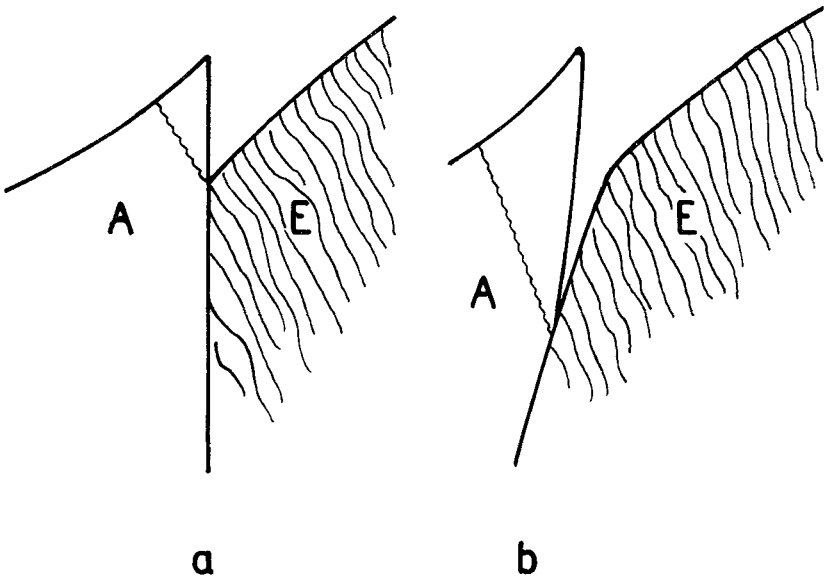

Fig. 37. Marginal discrepancy of amalgam margin as a result of delayed expansion. Any marginal fracture of the p-type will occur roughly corresponding to the serrated line.

The consequences of this expansion in terms of marginal precision were studied on about 50 experimental fillings in extracted teeth. The fillings were prepared from an alloy with 2 % Zn, and they were contaminated with a 1 % NaCl solution. Teeth with fillings were stored in a 1 % NaCl solution at 37° C for 3—24 months and then studied under the microscope. It was found that the marginal defects could be referred to two principal types, a and b, Figure 37. Type a occurred whenever the cavity wall and the expansion direction of the amalgam out of the cavity were parallel or convergent, while type b occurred in connection with divergence of cavity wall and expansion direction. Both types were observed in occlusal as well as peripheral fillings.

Loading of the margins resulted in lines of fracture as shown in Figure 37. It seems obvious that the b-fracture leads to poorer hygienic conditions along the amalgam margin than the a-fracture, which leaves the cavity area intact.

Of the two types of margin b was by far the commoner, prob-

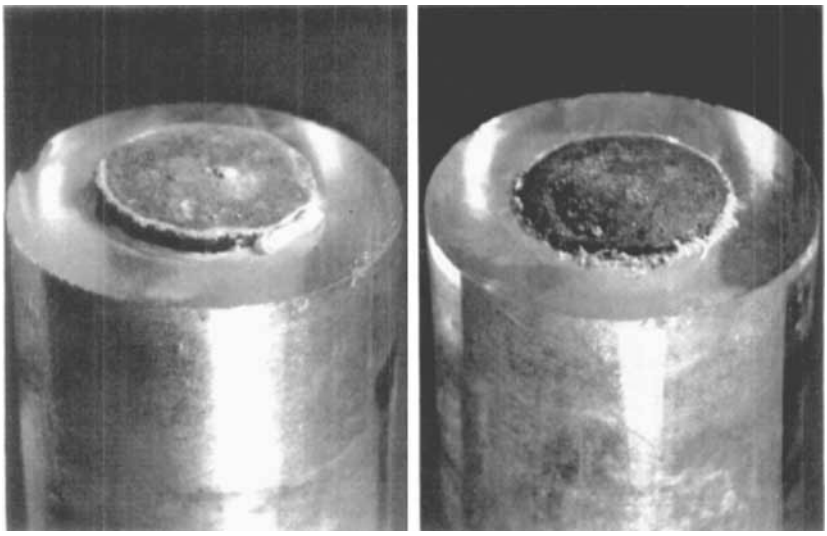

Fig. 38. Delayed expansion in glass tubes with smooth and rough inside walls respectively. The tubes were open at both ends, and their internal dimensions were 15 × 6 mm.

ably because it is difficult to prepare cavities without a slight divergence of the walls toward the marginal areas.

Delayed expansion tests in glass tubes showed that smooth tubes give a much higher expansion than tubes roughened inside before they are filled with amalgam (Figure 38).

III. Faulty condensation

In the final condensation of amalgam fillings the areas already condensed may rather easily be displaced. Three examples in Figure 39 show how such displacement may give rise to slits of quite appreciable size between cavity and condensed filling: a) is a Class I filling in an upper molar; the condenser, c, is forcing the amalgam out into the lingual extension, so that slits as indicated by the dotted lines, s, are apt to occur. b) represents a Class I filling in a lower molar, where the condenser is pressing the amalgam through an isthmus toward a wider space of the cavity; the consequent shifting of the amalgam already in place will give a slit at s. c) shows the contour of a proximo-occlusal filling seen from the occlusal surface. Insufficient matrix application may easily result in outward displacement of

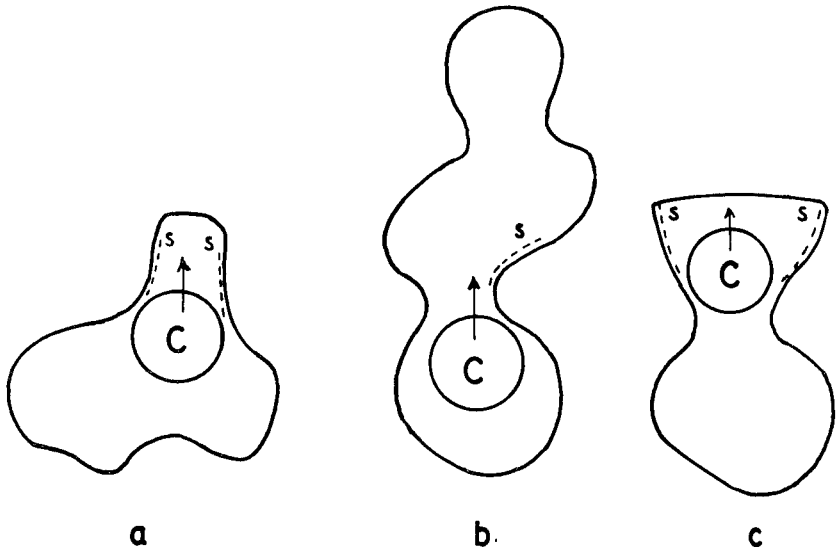

Fig. 39. Examples of displacement of amalgam in different type of cavities under vertical pressure by the condenser c. The amalgam is displaced e. g. in the direction of the arrow, so that slits corresponding to the areas s may occur between cavity wall and already condensed amalgam.

the amalgam into the interproximal space, and slits at s will ensue.

The tendency to formation of this type of slits is evidenced partly by experiments where amalgam fillings were made in extracted teeth, partly by the relatively high incidence of slits and marginal fractures in the abovementioned parts of extracted teeth containing amalgam fillings. Quite often will the margins break already on polishing of the vulnerable areas.

IV. Plasticity (flow)

Inspection of proximo-occlusal fillings in extracted teeth sometimes shows that the proximal parts of the fillings have been pressed somewhat outward in the proximal direction, at the same time as the marginal ridge area seems to have been pressed somewhat downward in the gingival direction. Possibly these deformations are due to plasticity of the amalgam under the masti-

catory load. On the other hand, the phenomenon may be the result of delayed expansion, which initially has pushed the filling outward into the interproximal space with subsequent deformation of its marginal ridge area by pressure (a reliable diagnosis of delayed expansion can hardly be made, since both internal porosities and surface blisters may be attributed to other causes). Anyhow, the displacement of the fillings has often led to slits along the filling margins of such a width that the amalgam margins would break under the load of e.g. a blunt explorer.

V. Marginal excess

Morphologically, marginal excess falls into two types, a and b, as illustrated in Figure 40. Neither type is fundamentally different from an amalgam margin without excess; both can corrode, deform and break as described in section I. It is not likely, on the other hand, that marginal excess can be the primary factor in formation of slits between amalgam and tooth which will predispose to marginal fracture.

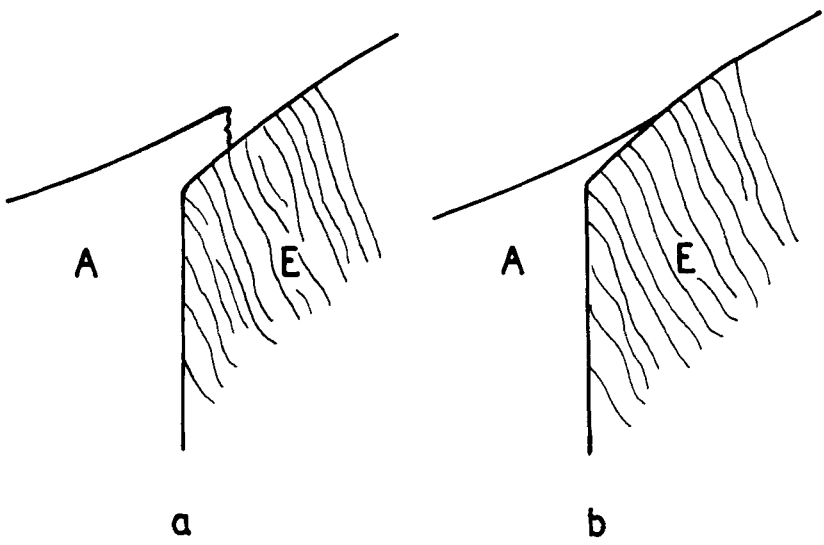

Fig. 40. The two main types of marginal excess. Type a) leads directly to poor hygienic conditions, while type b) becomes unhygienic after a fracture.

It is possible that thermal contraction of amalgam fillings with marginal excess may result in a t-type fracture in the excess material if the filling is pulled downward during the contraction. Then the marginal excess cannot be pulled down into the cavity, but will either deform or break. *Overdiek* (1962) has demonstrated chipping of marginal excess after numerous temperature changes.

VI. Enamel fracture

On the basis of examination of extracted teeth with amalgam fillings and of sections of amalgam margins, it must be concluded that enamel fractures are relatively infrequent. The great majority of defects involved the amalgam margins, while the cavity margins were intact. Therefore, since enamel fracture only exceptionally is the cause of unsupported and broken amalgam margins, it will not be considered here.

VII. Caries

In the material investigated no instance of caries was found which had started under an intact amalgam margin. Fracture of the amalgam margin seems to be the primary condition, while caries appears to be a secondary phenomenon in the environment produced by the marginal fracture. This sequence of events was clearly revealed by comparison between amalgam fillings in first molars of different age which formed a part of the material studied.

In conclusion it should be mentioned that according to the author's impression corrosion is by far the most important of the abovementioned causes for large slits between cavity walls and filling margins. As it is not always possible to distinguish between the individual causes for the marginal slits, and as several factors may undoubtedly operate at the same time, no exact statistical analysis of these factors has been attempted. Next to corrosion, delayed expansion and faulty condensation probably play a significant role, while other factors seem to be of little importance.

D. DISCUSSION

It is too early to draw far-reaching conclusions with regard to the amalgam properties and technique which would eliminate, to the greatest possible extent, the abovementioned causes for marginal destructions. The causes grouped in sections II—VII will not be discussed here, because they are already relatively well known and because it often is obvious how they can be reduced or eliminated. There may, however, be reason to make the following suggestions for reduction of the tendency to marginal corrosion.

Since marginal corrosion obviously is a question of formation of a concentration cell, it follows that this corrosion can be controlled by excluding the electrolyte (the saliva) from the surface of the amalgam margin facing the cavity. To achieve this it is necessary, among other things, 1) that the amalgam has complete adaptability, 2) that the amalgam neither expands nor contracts during hardening, and 3) that the amalgam does not change dimensionally over a long period owing to e.g. thermal expansion, mechanical deformation, or delayed expansion. None of these requirements can be fulfilled (except perhaps the last-mentioned). Nevertheless, the nearer these aims are attained, the slower will the corrosion probably advance.

Good adaptability with R_a values of approx. 0.5 μ (see *Jørgensen,* 1964) means that the areas where saliva can penetrate between amalgam and cavity wall are relatively small, while poor adaptability has the opposite effect. Similarly, there is doubtless a certain correlation between the degree of corrosion and the other slit-producing factors.

Cavity shape and surface roughness of the cavity walls are important in determining whether a tendency of the amalgam toward dimensional change will be manifested to a higher or lesser degree, by formation of a marginal slit for example. In this connection it should be emphasized that in itself, the width of the slit has scarcely much influence upon the rate of corrosion. The average current necessary for producing quite a severe corrosion, e.g. with dissolution of 1 mg of tin per year, is only of the order of a few hundredths microampere. It is the alter-

native, slit or no slit, electrolyte or no electrolyte, that is decisive.

To reduce the degree of corrosion it must also be remembered that the residual mercury content must not be higher in the margin than in the bulk of the filling. Exactly how this can be accomplished is neither known for occlusal nor for peripheral fillings.

The size of the marginal angle of the amalgam filling has influence on the marginal deflection produced by the mercuroscopic expansion. The marginal angle will also influence the strength and flexibility of the margin. Since the mercuroscopic deflection is greatly reduced with increasing values for the marginal angle and is zero at 90°, a marginal angle as close as possible to this value must no doubt be preferable.

SUMMARY

It is the purpose of the present study to analyze the complicated mechanism which leads to fracture of the margins of amalgam fillings.

Section A contains a short description of the two main types of fracture, viz. the pressure fracture and the tensile fracture, of which the former is much more common than the latter; the pressure fracture is the one which causes the most unhygienic conditions.

In section B mathematical formulas are presented by means of which it is possible to calculate the maximum strength and deflexion of the amalgam margins under static load. Calculations have been made of the strength of amalgam margins and of the critical width of the slit between amalgam margin and cavity wall, i.e. the width which is necessary for the fracture of the margin.

In section C an analysis is made of the reasons why such slits can occur between amalgam margin and cavity wall that lead to fractures visible to the unaided eye.

As an essential (probably the most essential) reason is mentioned corrosion with resulting mercuroscopic expansion: the amalgam surface facing the cavity wall acts as an anode in a

concentration cell element, where the cathode is the free surface of the filling. Due to the anodic corrosion metallic mercury is set free; the mercury diffuses into the amalgam from the cavity side and causes a unilateral expansion of the wedge-shaped amalgam margin, which bends away from the supporting cavity wall.

Other reasons for formation of slits are in order of importance: delayed expansion, condensing failures, plastic deformation (flow), marginal excess, enamel fracture, and caries. Among these probably only delayed expansion and condensing failures can be classified as essential.

In section D is discussed which factors may be of significance for reducing the mercuroscopic marginal deflexion. These factors can be classified as follows,

1) Omission of electrolyte from the interface between amalgam and tooth. This can be attained only in part, namely by aiming at the greatest possible adaptability, the smallest possible setting expansion or contraction, a certain degree of roughness of the cavity wall not yet precisely definable, the greatest possible parallelism between opposite cavity walls, and omission of delayed expansion; the greatest possible strength of amalgam will probably also improve the stability between filling and tooth.

2) Reduction of the mercury content in the margins to a minimum and to the same value as in the bulk of the filling.

3) The angle of the margin of the filling should be as great as possible.

RÉSUMÉ

LA MÈCANISME DES FRACTURES MARGINALES DES OBTURATIONS D'AMALGAME

La présente étude se propose d'analyser le mécanisme complexe aboutissant à la fracture des bords des obturations d'amalgame.

La partie A contient une courte description des deux types principaux de fracture, à savoir la fracture par pression et la fracture par traction cette dernière étant beaucoup moins fréquente que la première; la fracture par pression est celle dont

découlent les conditions les plus défectueuses du point de vue hygiénique.

Dans la partie B sont présentées des formules mathématiques permettant de calculer la résistance maximum et la déformation des bords d'amalgame sous l'action d'une charge statique. La résistance des bords d'amalgame et la largeur critique de la fente formée par le bord d'amalgame et la paroi de la cavité, c'est-à-dire la largeur nécessaire pour que se produise la fracture du bord, ont été calculées.

Dans la partie C est présentée une analyse des raisons pour lesquelles de telles fentes peuvent se produire entre le bord d'amalgame et la paroi de la cavité, déterminant des fractures visibles à l'œil nu.

Une raison essentielle (probablement la plus essentielle) mentionnée est la corrosion dont résulte une expansion mercuroscopique: la surface d'amalgame tournée vers la paroi de la cavité se comporte comme une anode dans une pile à concentrations différentes dont la cathode serait la surface libre de l'obturation. En raison de la corrosion anodique, du mercure métallique est libéré; le mercure diffuse dans l'amalgame à partir de la face tournée vers la cavité et provoque une expansion unilatérale du bord cunéiforme de l'amalgame qui se plie et s'écarte de la paroi de la cavité le soutenant.

D'autres raisons provoquant la formation de fentes sont par ordre d'importance: expansion tardive, défauts de condensation, déformations plastiques ("flow"), excès au niveau des bords, fractures de l'émail et caries. Parmi ces raisons, seuls les défauts de condensation et l'expansion tardive peuvent être classés parmi les causes essentielles.

Dans la partie D, l'auteur présente une discussion sur les facteurs pouvant présenter une signification pour réduire la déformation marginale mercuroscopique. Ces facteurs peuvent être classés de la manière suivante:

1) Suppression de l'électrolyte au niveau de l'espace formé par les faces en regard de l'amalgame et de la dent. Ceci ne peut être atteint que partiellement, en s'efforçant d'obtenir la plus grande adaptabilité possible, le plus petit changement possible de dimensions par contraction et par dilatation à la prise, un certain degré

de rugosité de la paroi de la cavité, degré ne pouvant encore être défini de façon précise, le plus grand parallélisme possible entre les parois de la cavité opposées, et l'absence d'expansion tardive; la plus grande résistance possible de l'amalgame améliorerait aussi probablement la stabilité entre l'obturation et la dent.
2) Réduction de la teneur en mercure des bords à la plus petite valeur possible, et à la même valeur que dans la masse de l'obturation.
3) L'angle du bord de l'obturation doit être aussi grand que possible.

ZUSAMMENFASSUNG

DIE KANTENFRAKTUR VON AMALGAMFÜLLUNGEN

Die vorliegende Untersuchung bezweckt eine Analyse des komplizierten Mechanismus, der die Fraktur der Kanten von Amalgamfüllungen bewirkt.

Abschnitt A behandelt in Kürze die beiden Fraktur-Haupttypen, die Druckfraktur und die Zugfraktur, von denen die erstere dominierend und auch diejenige ist, die die quantitativ schlechtesten hygienischen Verhältnisse zur Folge hat.

Abschnitt B enthält mathematische Formeln, die die Berechnung der maximalen Festigkeit und der Deformierung von Amalgamkanten bei statischer Belastung ermöglichen. Es sind Berechnungen angestellt worden über die Kantenfestigkeit und über die kritische Spaltbreite zwischen Amalgamkante und Kavitätenwand, d.h. die Spaltbreite, die erforderlich ist, um eine Fraktur der Kante herbeizuführen.

In Abschnitt C ist eine Analyse der Ursachen dessen enthalten, dass Spalten einer solchen Grösse zwischen Amalgamkante und Kavitätenwand entstehen, dass makroskopisch sichtbare Brüche entstehen können.

Als wesentliche (wahrscheinlich weitaus wesentlichste) Ursache wird Korrosion mit daraus sich ergebender merkuroskopischer Expansion angeführt: die Amalgamfläche, die der Kavitätenwand zugewendet ist, fungiert als Anode in einem Konzentrationszellenelement, dessen Kathode die freie Oberfläche der Füllung ist. Durch die anodische Korrosion wird u.a. metalli-

sches Quecksilber frei; dieses diffundiert von der Kavitätenseite in das Amalgam und bewirkt eine einseitige Expansion in der keilförmigen Amalgamkante, die von der unterstützenden Kavitätenwand weggebogen wird.

Als andere Ursachen zur Bildung von Spalten der angeführten Grössenordnung werden genannt: verzögerte Expansion, Kondensierungsfehler, plastische Deformierung, marginaler Überschuss, Schmelzfraktur und Karies. Von diesen letztgenannten Ursachen sind vermutlich nur die verzögerte Expansion und Kondensierungsfehler wesentlich.

In Abschnitt D wird erörtert, welche Faktoren für die merkuroskopische Kantenabbiegung Bedeutung haben können. Diese Faktoren lassen sich folgendermassen klassifizieren:

1. Vermeidung von Elektrolyt an der Grenzfläche zwischen Amalgam und Zahn. Dieses Ziel lässt sich nur teilweise erreichen, und zwar durch Anstreben grösstmöglicher Adaptabilität, kleinstmöglicher Abbindungsexpansion oder -kontraktion, einen bestimmten, noch nicht näher definierten Grad der Rauhigkeit in der Kavitätenwand, grösstmögliche Parallelität zwischen gegenüberstehenden Kavitätenwänden und Vermeidung verzögerter Expansion; grösstmögliche Amalgamfestigkeit wirkt sich sicher ebenfalls fördernd auf die Stabilität zwischen Füllung und Zahn aus.
2. Reduktion des Quecksilbergehalts in den Amalgamkanten auf ein Minimum und auf den gleichen Wert wie in der Füllungsmasse.
3. Der Kantenwinkel der Füllungen muss so gross wie möglich sein.

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