Pore distribution and fracture localization of flame-soldered joints in dental gold

A metallographic and microfractographic study

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The occurrence of pores and fatigue fractures in flame-soldered joints of dental gold was measured using fractograms and metallographic preparations. All soldered joints contained pores localized mainly in the solder material adjacent to casting/solder and solder/solder interfaces. The porosity portion of these regions was 20–40 volume per cent, consisting chiefly of pores smaller than 0.1 mm. The fatigue fractures were nearly always situated in the same regions or along the casting surfaces themselves. □ *Defects; dental materials; fatigue; flux; porosity*

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A sufficient but by no means necessary condition for fracture of a construction is that maximum stress in the material somewhere exceeds its strength. Stress depends on the load and geometry of the design, on material properties such as inhomogeneity and porosity, and, in soldered joints, also on the combination of materials with different stiffnesses. The difficulties in predicting localization of fractures in soldered joints of dental bridges are evident. Load- and geometry-caused stress varies, alloys contain porosity, and joints have interfaces formed under the hazard of oxidation and fluxing. If, however, the stress caused by load and geometry is homogeneous—that is, independent of the coordinates in space—material properties should dominate in determining the path of the fracture. One such material property of decisive importance may be the amount and localization of porosity.

Previous studies of dental gold porosity (2, 3, 7–11) report the problems of its classification and possible etiology. Quantitative information on pore distribution and paths of fracture seems, however, to be lacking.

The aim of the present investigation was to quantitatively measure dental gold soldered joints with regard to pore distribution and fatigue fracture localization and to look for a possible correlation between pore distribution and fracture localization.

Materials and methods

The soldered joints tested in this investigation were designed to be representative of common soldering procedures used for dental gold bridges. This method may be roughly described as 'stuff the fluxed solder strips into the gap and melt them with the flame'. The soldering principles inherent in this short description were analyzed and fabrication of the test specimens standardized accordingly.

Ten specimens of a Type-III dental casting gold (Sjödings C-gold) with a known surface roughness (Table 1) were soldered together, two and two, using solder (JS 820 Hårdlod) and flux (JS Flytande Lödflux) recommended for this alloy. The composition and strength of the alloys are given in Table 2. Soldering was done with an oxy-propane flame generated by an apparatus allowing gas flow rate and pressure to be measured

Table 1. Some profile characteristics of cast gold surfaces to be soldered, recorded with a Tally-Surf apparatus. From Ref. 4

Profile characteristics	Mean (μm)	SD (μm)
R_a, arithmetic mean deviation	0.214	0.0142
R_{max}, maximum height of profile irregularities	1.4	0.30
S, mean crest spacing of profile irregularities (width of scratches)	15.6	1.79

and adjusted (4). The joint gap measured after soldering and grinding was 0.40 mm (SD = 0.07 mm). Two solder strips (0.2 × 2.8 × 5.3 mm) were fluxed and placed in the gap before final heating was commenced. After being soldered the specimens were left to cool in air and later ground to the same size, 2.5 × 5.0 × 34 mm (Fig. 1).

From clinical studies (11) it is known that bridge fractures are usually due to fatigue cracks. The test specimens were thus exposed to cyclic loads (50 Hz) in a fatigue-testing machine (Schenk) until total failure occurred. The 4-point testing type of bending arrangement (Fig. 1) had the advantage that maximum stress is held homogeneous between the two central F-loads. This stress may, however, vary locally owing to the material properties, as mentioned in the introduction. In the 4-point bending arrangement the material-induced fringe stresses will in reality be of decisive importance for determining into which region the fracture will propagate, indirectly thus indicating where to find strength deficiencies of material origin.

Measurements on microfractograms

The fractured surfaces were photographed using a scanning electron microscope. A linear analysis was made (6) of the resulting positive photographs at ×80 magnification. Three straight lines were drawn on each fractogram. Each line was chosen parallel to the two 5-mm-long borders of the fracture, as seen on the enface photos. One line ran through the central part of the joint, and the other two lines approximately 0.25 mm from the borders. The lines were marked where they crossed pores (Fig. 2). The relation between the sum of the lengths of these crossings and the total length of the line represents the volume per cent (6) of the measured phase—that is, the pores.

The results of the linear analyses were subsequently used to calculate arithmetic means and standard deviations of pore 'size'. Pores smaller than approximately 0.01 mm were not included in the analysis because they were too difficult to distinguish from other configurations seen on the fractograms. Only the weighted means of these measurements are presented in the Results.

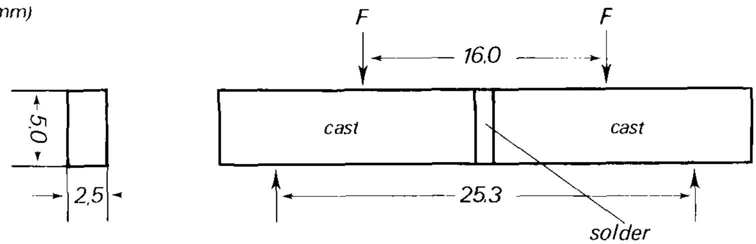
Measurements on metallographic preparations

The fatigue-fractured specimens were embedded in resin (Buehler Castolite resin) for ordinary metallographic preparation at three levels. These were approximately perpendicular to the fractured surfaces, which thus were seen in profile. Two metallographs were prepared from periphery and one from a central part of the joints. The preparations were then photographed at approximately

Table 2. Composition and strength of the dental golds used for testing soldered joints. From Refs. 1 and 4

	Weight per cent						Yield strength (MPa) after	
Dental gold	Au	Ag	Cu	Pt	Zn	In	Softening heat treat.	Hardening heat treat.
Casting gold	76.5	8.5	11.5	3.0	0.5	—	280	400
Gold solder	71.0	5.75	15.2	2.75	0.3	5.0	270	600

Fig. 1. Soldered specimen exposed to a 4-point bending load. The maximum bending moment is constant between the two central F-loads.



×120 magnification. Two variables were measured on each photo. The first variable, pore distribution, was measured by the linear analysis as previously described. Measuring lines were chosen to coincide with non-fractured solder zones adjacent to the casting/solder and solder/solder interfaces. The reason for this choice is explained in the Results. The second variable, the perpendicular distance from the casting/solder interface to the fractured surface, was measured and grouped by three criteria: zero distance (along the interface), closer than 0.03 mm to the interface, and >0.03 mm and <0.06 mm from the interface.

Only the weighted means of these measurements from the three preparations are presented in the Results.

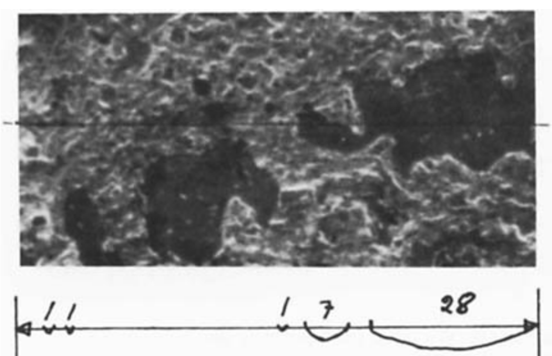


Fig. 2. Example of linear analysis of a fractogram. (Magnification ×80.) Note that the big pore to the right is registered as two pores. This does not alter the results of the volume calculations but tends in reality to make the estimate of true pore size smaller. Sum of the lengths of pore crossings = 38 mm; total length of the line = 85 mm; approximate volume per cent ≈3800/85 ≈45%.

Results

Pore distribution within the fractured surfaces could only be measured on the fractograms (Fig. 2). This was because the pores were difficult to identify as pores in the metallographic preparations (Fig. 3). It was also obvious from these preparations that pore occurrence was clearly localized to the casting/solder and solder/solder interface

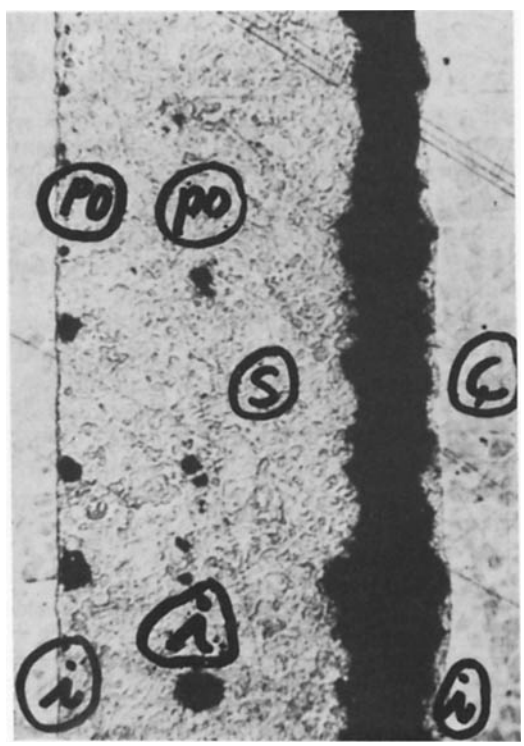


Fig. 3. Fatigue fracture (black) mainly located within the solder zone 'closer than 0.03 mm to the casting/solder interface'. Interface (i), porosity-rich interface zone (po), solder (S), casting gold (C). (Magnification, ×120.) Note that most of the pores in the left interface zone seem to touch the casting surface.

Table 3. Relation between interface zones in dental-gold-soldered joints and localization of fatigue cracks (from the metallographic study)

Specimen no.	Part of fracture located in the porosity-rich solder zone: Adjacent to the casting/solder interface (%)	In the solder/solder interface (%)	Part of fracture located in other regions of the soldered joint (%)
2	100	—	—
3	14	83	3
4	98	2	—
5	99	—	1
6	84	14	2
2–6	79	20	1

Table 4. Relation between fractured surfaces in the casting/solder interface zone and the interface line (from the metallographic study)

Specimen no.	Localization of the fracture passing through the porosity-rich zone adjacent to the casting/solder interface		
	Along the casting (%)	In the solder, closer than 0.03 mm to the interface (%)	In the solder, 0.03–0.06 mm from the interface (%)
2	10	86	4
3	36	63	1
4	31	63	6
5	55	42	3
6	51	47	2
Mean (SD)	37 (18)	60 (17)	3 (2)

Table 5. Volume per cent porosity in dental-gold-soldered joints calculated from pores larger than 0.01 mm

Interface zone	Volume per cent porosity in: The *fractured* interface zones (microfractographic method) (%), mean (SD)	The *non-fractured* interface zones (metallographic method) (%), mean (SD)
Casting/solder	42 (9)	22 (11)
Solder/solder	36 (9)	19 (6)
All zones	39 (9)	21 (9)

Table 6. Volume per cent porosity distributed amongst four pore classes. Note that the relative frequency of pore sizes seems to agree between fractured and non-fractured interface zones

	Fractured interface zones (microfractographic method)		Non-fractured interface zones (metallographic method)	
Pore size classes (mm)	Volume per cent porosity (%), mean (SD)	Relative frequency of pore size (%)	Volume per cent porosity (%), mean (SD)	Relative frequency of pore size (%)
0.01–0.1	23 (5)	59	13 (4)	62
0.1–0.2	8 (3)	21	4 (1)	19
0.2–0.3	3 (4)	8	3 (2)	14
0.3–0.9	5 (5)	13	1 (2)	5
All sizes	39 (9)	100	21 (8)	100

regions (Fig. 3). This explains the choice of measuring zones for linear analysis of the metallographs.

Table 3 shows that fractures nearly always passed through regions adjacent to interfaces. This occurred more often near the casting/solder than the solder/solder interface. A fatigue crack seldom penetrated the casting material itself.

Approximately 37% of the casting/solder fractures ran along the casting surface itself, whereas approximately 60% passed through the solder material, albeit very close to the casting surface (Table 4). The remaining 3% consisted of fracture surfaces passing from one interface region to another.

No significant difference in pore frequency between casting/solder and solder/solder interface regions was found (Table 5). The table shows, however, that the pore frequency is much larger in the fractured regions than in other non-fractured interface regions. The porosity was mainly made up of pores smaller than 0.1 mm (Table 6). The relative frequency of pore size was approximately the same in the fractured and non-fractured regions. Table 7 shows that mean pore size was 0.05–0.10 mm regardless of localization and measuring methods.

Discussion and conclusions

All specimens fractured within the solder material itself or along the casting surface. No fatigue cracks penetrated the casting. As discussed in the introduction, this suggests inferior material properties at the casting/solder interface and in the solder alloy itself.

Approximately 37% of the fractures passed along the casting surfaces, thus breaking the casting/solder interface bond (Table 4), and 39% of the fractured surfaces consisted of pores (Table 5). This close agreement between fracture localization and pore distribution in the casting/solder interface zones could mean that these pores nearly always lie in direct contact with the casting

Table 7. Pore sizes in dental-gold-soldered joints calculated from pores larger than 0.01 mm

	Pore sizes in:	
Interface zone	Fractured interface zones (microfractographic method) (mm) mean (SD)	Non-fractured interface zones (metallographic method) (mm) mean (SD)
Casting/solder	0.08 (0.09)	0.05 (0.05)
Solder/solder	0.05 (0.06)	0.04 (0.04)
Mean	0.07 (0.07)	0.05 (0.05)

surface. They may thus reduce the metallic bond between the cast and the solder material, weakening the junction. This interpretation is supported by localization of pores found in the metallographic preparations (Fig. 3).

Approximately 60% of the fractures did not pass through pores but through the solder alloy itself, closer than 0.03 mm to the cast surface (Table 4). The reason for this localization is not known but may be due to the influence of neighboring pores or microphases (2).

The mean pore size of 0.06 mm (Table 7) was calculated from pores larger than 0.01 mm. This agrees well with the pore sizes estimated from the photographic materials presented elsewhere (8, 10, 11). The relative frequency of pores larger than 0.3 mm was calculated to be somewhat less than 5%, which agrees rather well with the empirical results in Table 6, despite the skew distribution. Approximately 0.5% of all pores were larger than 0.5 mm. This latter value happens to agree with the maximum defect size suggested and used in the fracture mechanics design calculations in Ref. 4.

The occurrence of porosity in the casting/solder interface zones was similar to that found in the solder/solder interface regions (Table 5). Thus solder strips melted together may sometimes be expected to form weaker junctions than the casting/solder interface region, as shown in Table 3.

The occurrence of more porosity in the fractured than in the non-fractured regions was not unexpected, as it seems quite likely that fatigue cracks would tend to pass through the regions richest in pores.

The origin of the pores is unknown, but flux retention seems a possible explanation (8). The flux may not have been fully melted (the borax part, $Na_2B_4O_7$) or in melted or gaseous form. If this hypothesis is true, the amount of porosity may decrease when solder strips are fluxed and melted outside the crevice. A wide gap between castings stuffed with layers of strips and pieces of wrought or cast dental gold might, on the other hand, create excellent conditions for the development of pores by flux retention in the many interface regions.

The pores seen in metallographic preparations of non-fractured regions (Fig. 3) appeared to be separated from each other. In the fractograms, however, they sometimes 'communicated' and formed small 'networks'. It would thus be possible to register one pore as two pores during the linear analysis (Fig. 2). Measuring difficulties of this kind do not influence the volume per cent calculations but may underestimate pore sizes in some areas. The aforementioned exclusion of pores smaller than 0.01 mm should, however, tend to neutralize this systematic error.

Despite the difficulties experienced in connection with the measuring, both methods gave results that both seem credible and invite reasonable interpretations (Fig. 4). It thus appears evident that interface zones of all kinds constitute 'locus minoris resistantiae'. It also seems probable that one of the main causes of lowered fracture resistance

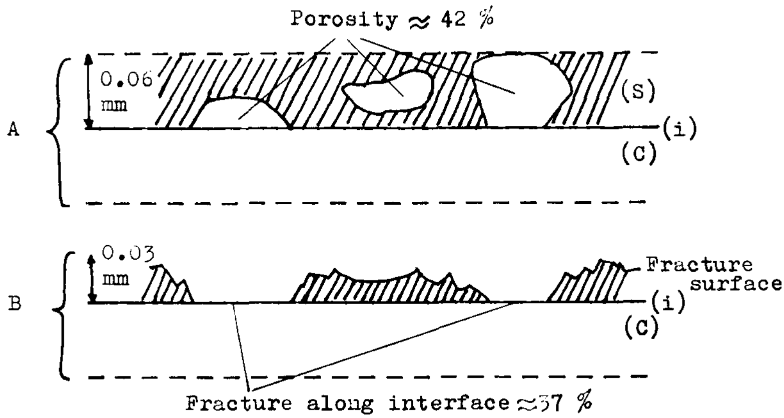


Fig. 4. A casting/solder interface zone (A) before fracture and (B) after fracture. The purpose of the drawing is to demonstrate a possible interpretation of the agreement between porosity and fracture localization. S = solder; C = casting; i = casting/solder interface. The mean pore size is 0.06 mm, and 0.03 mm is the distance within which the fracture occurred.

is the high volume of pores in the solder adjacent to the interfaces.

The conclusions to be drawn from this investigation may be applied to a common flame soldering method and may thus be valid for many soldered joints in ordinary dental gold bridges. They may be summarized as follows:

A tendency towards high pore formation can be expected in solder adjacent to all kinds of interface, including casting/solder strip and solder strip/solder strip interfaces.

Fatigue cracks can be expected to propagate in these porosity-rich solder zones adjacent to interfaces. The cracks may sometimes jump between different interfaces.

Fatigue cracks *not* propagating in a solder/solder interface zone or through pores or along the casting surface in a casting/solder zone can be expected to pass through the solder material itself at a maximum distance of 0.03 mm from the casting surface.

It is possible that fatigue cracks develop along casting surfaces only where pores lie in direct contact with the casting, hindering metallic bonding between the solder and casting.

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