

# Stress/strain behavior of dental amalgams

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The stress/strain behavior at different strain rates and the creep rate of dental amalgams were evaluated and compared to the microstructure. The results indicate that substantial differences exist both in strength and strain at fracture. The strain at fracture for high strain rates was associated with the nature of the particle-matrix interface, in that amalgams with an interpenetrating interface exhibited some ductility, while amalgams with an abrupt interface exhibited practically no plastic deformation at fracture.

The correlation between creep and slow compressive strength was verified and it was suggested that grain boundary sliding was the deformation mechanism in both cases.

*Key-words:* Dental materials; mechanical properties

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Much attention has been placed on the strength of dental amalgam while less emphasis has been given to strain at fracture (9), even though amalgams have generally been characterized as brittle materials. It has been demonstrated that, as the deformation rate was reduced, substantial plastic deformation occurred prior to fracture (4). It was also established that a correlation existed between dynamic creep, static creep, and slow compressive strength. This correlation may be the result of the same deformation mechanism being operative for all these test conditions (5, 6).

The effect of microstructure on fracture characteristics of dental amalgam has been studied (8). Intergranular and interface crack propagations were observed, and some cup and cone formation on the fracture surface were also found, indicating plastic deformation.

It was the purpose of this study to determine the stress/strain behavior of dental amalgams made from alloy powder with different particle shapes and compositions, and to relate this to the microstructure of the amalgam.

## MATERIALS AND METHODS

Details pertaining to the alloys used in the study are listed in Table 1. The amalgam samples were prepared according to the American Dental Association Specification No. 1 (10), and stored in air for 7d at 37°C prior to testing.

Measurements of static creep were performed at  $37 \pm 0.2^\circ\text{C}$  with a compressive stress of  $36 \text{ MN/m}^2$  applied for 4 h. The length of the specimen was measured at 1 h and 4 h after load application, and the difference was expressed as percentage of the original length. For the creep measurements two samples were used for each test condition.

The compression test was carried out at the crosshead speeds of 0.01, 0.05, 0.2 and 1 mm/min on a Wolpert Testatron. The strain of the specimen during testing was recorded, and the deformation of the compression plates were corrected for when the apparent modulus of elasticity was determined. The compression test were conducted at  $23 \pm 2^\circ\text{C}$  and at  $37 \pm 0.5^\circ\text{C}$ . Three samples for each test condition were used.

The amalgam specimens for metallographic examination were mounted in a resin (Epofix®, Struers) with a low temperature increase during setting, ground and polished using standard metallographic techniques (SiC paper and diamond paste with particle size down to  $1 \mu\text{m}$ ). A scanning electron microscope (Jeol 50 A) operated both in secondary and backscattered electron mode was employed to examine the microstructure.

## RESULTS

At the highest strain rate (Fig. 1) four types of behavior were observed. Two amalgams exhibited practically no plastic deformation at fracture. Two amalgams had high strength and some plastic deformation at fracture. Moderate strength and strain at fracture were found for three amalgams, while one

showed low strength and a total strain at fracture of about 3.5%. At a lower crosshead speed (0.05 mm/min, Fig. 2) two of the amalgams exhibited small plastic deformation at fracture, while all the others showed larger strain at fracture. Seven of eight amalgams exhibited strains  $> 30\%$  when tested at the lowest crosshead speed. Fracture was observed for one amalgam (Fig. 3). Large differences in the strength between the amalgams were observed. At 37°C substantially lower strength was observed as compared to the values at 23°C (Fig. 4, 5).

Fracture of the more brittle amalgams occurred at 37°C following a much larger plastic deformation both at the crosshead speed of 0.05 and 1 mm/min. Comparison between the stress/strain behavior at the four crosshead speeds for alloy S indicated that the elongation at fracture was reduced and the strength increased as the strain rate was increased up to 0.2 mm/min (Fig. 6). The strength was reduced at the largest crosshead speed.

The stress/strain behavior for alloy T indicated that strain at fracture was larger than for amalgam S, and it was decreased at the higher strain rates (Fig. 7). The strength for this amalgam increased continually with the strain rate. The most ductile amalgam SF exhibited low strength and substantial plastic deformation at fracture even though it was reduced as the strain rate increased (Fig. 8).

A comparison of the microstructures for some of the amalgams is shown in Fig. 9. Cracks were found to propagate at the  $\gamma_1/\text{Ag-Cu}$  boundary in a prestrained specimen of alloy D and at the boundary between  $\gamma_1$  and the unreacted alloy particles for alloy S (Fig. 10). No cracks could be found in the other amalgams when strained slightly beyond the strength maximum (0.05 mm/min).

The creep and modulus of elasticity results (Table 2) were used to determine correlation coefficients. The correlation coefficients (Table 3) indicated that a correlation existed

Table 1.

Code	Alloy name	Manufacturer	Alloy/Mercury ratio
SF	Standalloy F	Degussa, Pforzheim	1:1
R	Revalloy	S.S. White Ltd.	1:1,1
H	Hi-Atomic	G-C Dental Industrial Corp.	1:0,86
L	Luxalloy	Degussa, Pforzheim	1:1,2
I	Indiloy	Shofu Dental Corporation	1:0,84
T	Tytin	S.S. White Ltd.	1:0,82
D	Dispersalloy	Johnson & Johnson Dental Prod. Co.	1:1
S	Sybraloy	Kerr Manufacturing	1:0,81

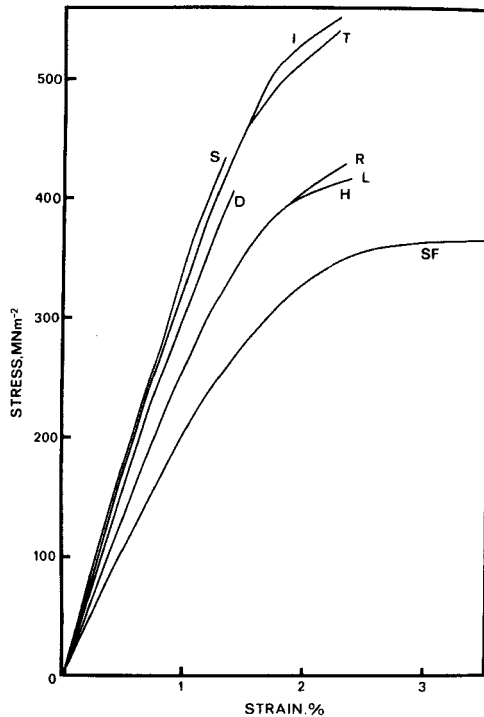


Fig. 1. Stress/strain diagram at 1 mm/min cross-head speed for 8 alloys at 23 °C.

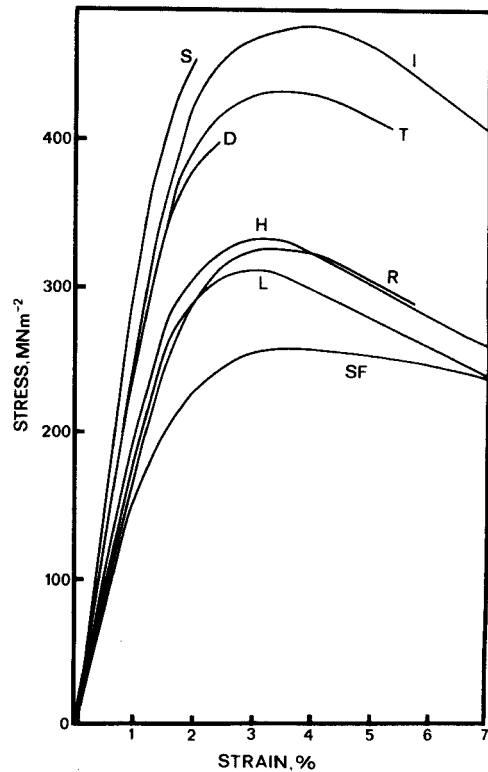


Fig. 2. Stress/strain diagram at 0.05 mm/min cross-head speed for 8 alloys at 23 °C.

Table 2. *Creep and apparent modulus of elasticity (mean and standard deviation)*

Amalgam	Creep, %	Apparent modulus of elasticity at 23 °C and 1 mm/min crosshead speed, GN/m <sup>2</sup>
SF	6.03 ± 0.45	24.5 ± 0.6
R	1.44 ± 0.02	31.2 ± 0.9
H	0.66 ± 0.10	31.4 ± 0.3
L	1.34 ± 0.32	30.5 ± 0.6
I	0.28 ± 0.01	39.3 ± 1.9
T	0.19 ± 0.01	40.7 ± 1.2
D	0.31 ± 0.01	38.7 ± 1.1
S	0.10 ± 0.02	44.9 ± 1.1

Table 3. *Correlation coefficients between creep and modulus of elasticity, and creep and compressive strength at 23 °C and at 37 °C*

	Creep 37 °C other property 23 °C	Creep 37 °C other property 37 °C
Modulus of elasticity at crosshead speed of 1 mm/min	- 0.79	n.d.
Compressive strength at crosshead speed of		
a) 0.01 mm/min . . . . .	- 0.78	n.d.
b) 0.05 mm/min . . . . .	- 0.76	- 0.79
c) 0.2 mm/min . . . . .	- 0.70	- 0.73
d) 1 mm/min . . . . .	- 0.57	- 0.65

n.d. - not determined

between creep and modulus of elasticity, and a correlation existed between creep and compressive strength at the lower crosshead speeds. This correlation extended to higher crosshead speed when both creep and compressive strength were tested at 37 °C. With this sample size (8 alloys) a correlation coefficient less than -0.7 was necessary in order to exclude 0 from the population correlation coefficient interval (confidence coefficient 0.95) (1).

## DISCUSSION

### *Stress-strain behavior*

The comparison of the stress-strain behavior between different alloys at one crosshead speed indicates that substantial differences in the strength and elongation at fracture exist. It has previously been suggested that a better bond prevails between the particles and the matrix in spherical particle alloys (8). Microstructural observations in this

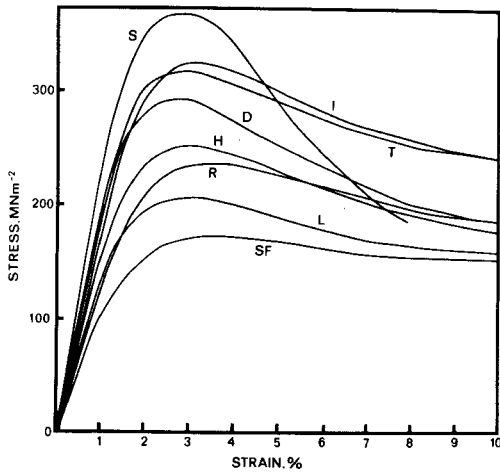


Fig. 3. Stress/strain behavior at 0.01 mm/min cross-head speed at 23 °C for 8 alloys.

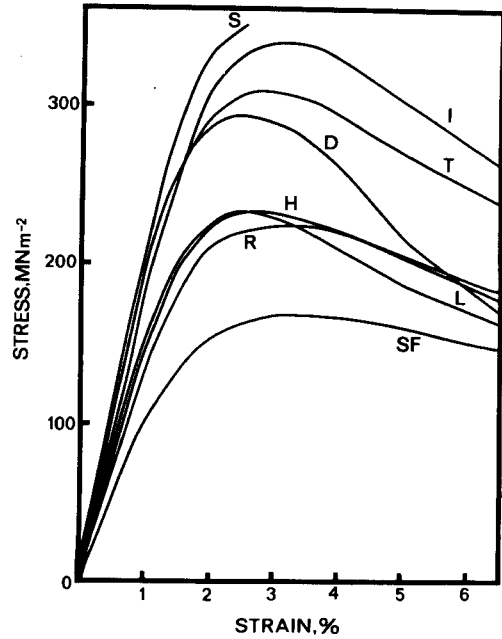


Fig. 5. Stress/strain behavior at 0.05 mm/min cross-head speed at 37 °C for 8 alloys.

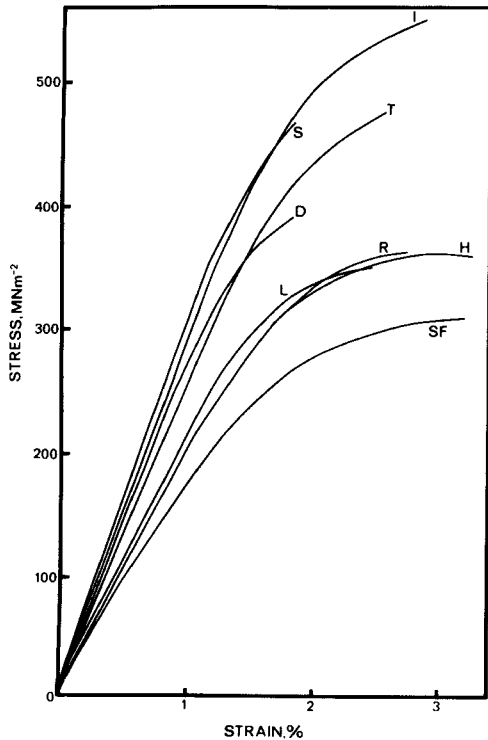


Fig. 4. Stress/strain diagram at 1 mm/min cross-head speed at 37 °C for 8 alloys.

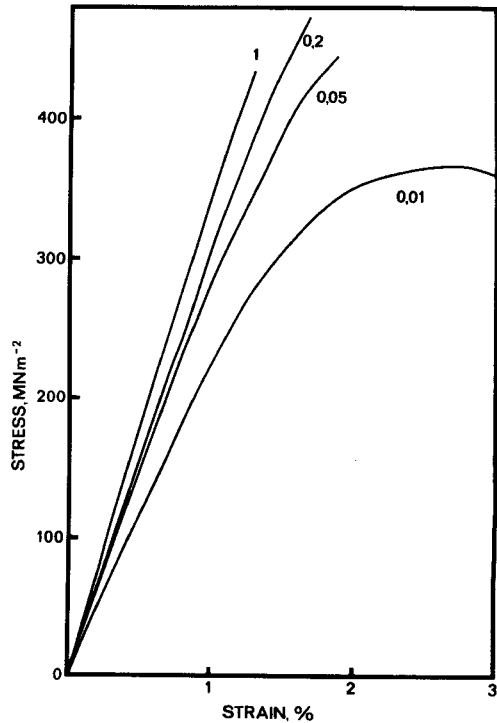


Fig. 6. Stress/strain behavior as a function of cross-head speed for alloy S at 23 °C. The cross-head speed in mm/min is shown on the figure.

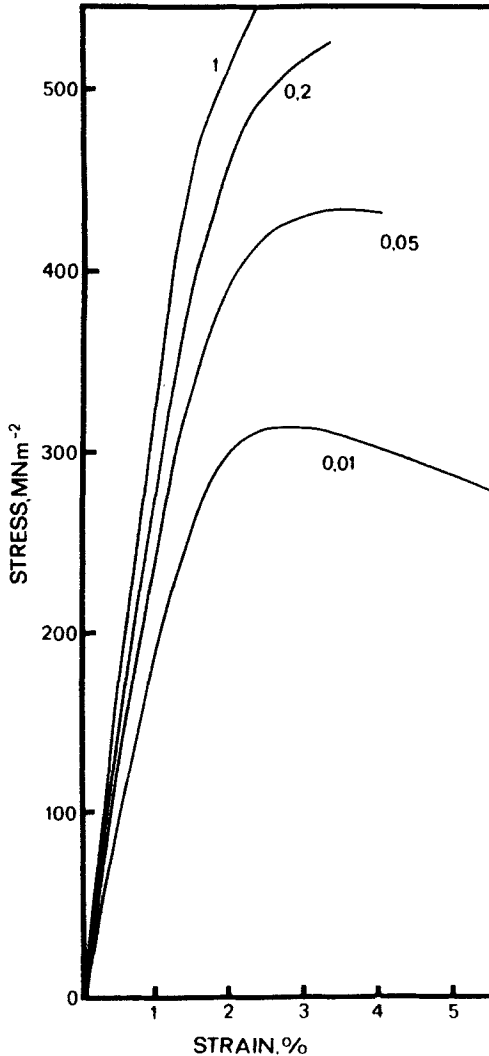


Fig. 7. Stress/strain behavior as a function of crosshead speed for alloy T at 23 °C. The crosshead speed in mm/min is shown on the figure.

study indicate an interpenetrating interface between the matrix and the original alloy powders for the two amalgams with high strength and elongation. The interface between the spherical powder and the matrix in the amalgams exhibiting the lowest elongation at fracture, are much more abrupt and may possibly have larger stress concentra-

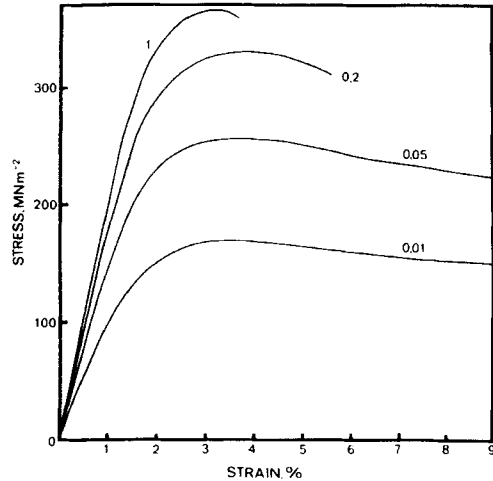


Fig. 8. Stress/strain behavior as a function of crosshead speed for alloy SF at 23 °C. The crosshead speed in mm/min is shown on the figure.

tions associated with it. The observed cracks at this interface indicate that the low strength of these amalgams may be caused by fracture initiated or propagating at the particle-matrix interface.

As the crosshead speed is reduced all amalgams exhibit some plastic deformation. The relative order of strength has been changed in that the strength of the "brittle" amalgams has been increased compared to the others. This indicates that the brittle mode of fracture has become less important.

At the lowest crosshead speed the deformation mode of grain boundary sliding is probably responsible for the plastic strain of the amalgam (2). In this case, since the test is conducted at a forced strain rate, maximum stresses observed are simply an indication of the stress necessary to obtain the forced strain rate. This stress is then a flow stress.

Fracture also occurs after the samples have reached maximum in the stress/strain diagram. This fracture occurs approximately at 370–430 MN/m<sup>2</sup> and 3–4% strain, and may be associated with certain matrix properties of the amalgam. When pileup stresses

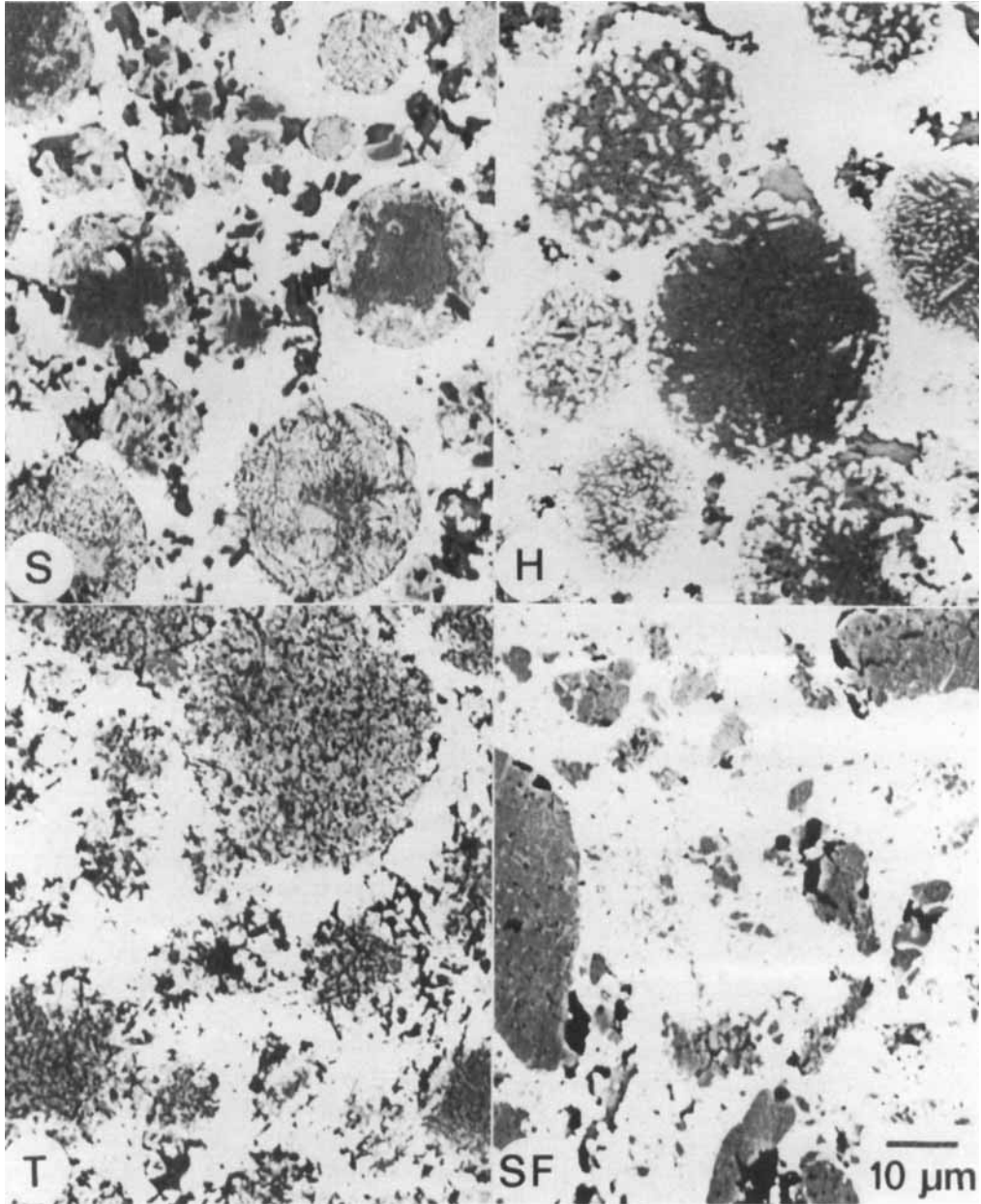


Fig. 9. Microstructure of 4 amalgams, S, H, T and SF.

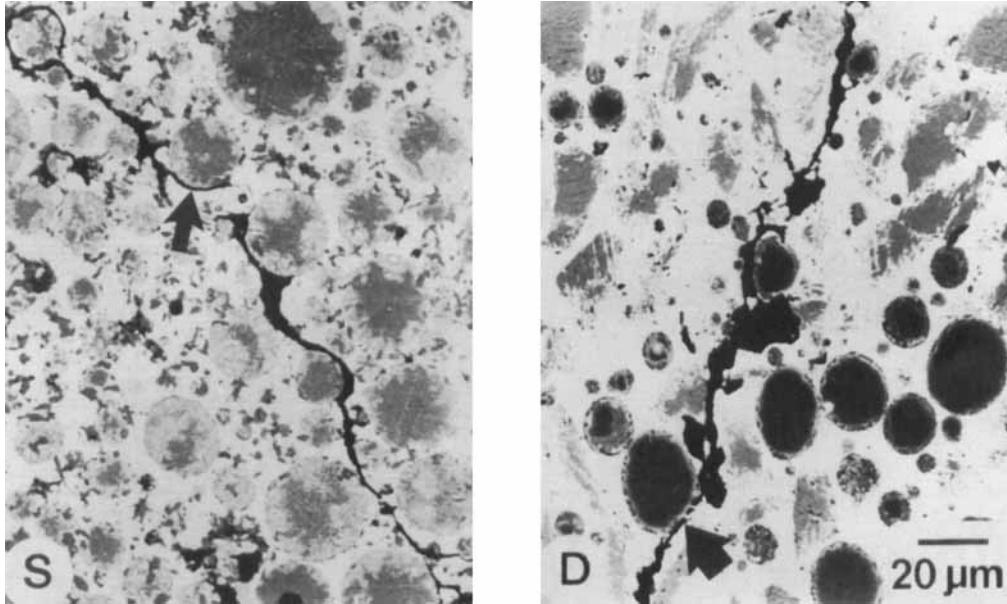


Fig. 10. Microstructure showing cracks (arrows) for amalgams S and D. The samples were strained close to fracture at a crosshead speed of 0.05 mm/min prior to examination.

in grain boundaries in the  $\gamma_1$  phase reach a certain value, fracture occurs.

#### *Correlation between physical properties*

It has previously been shown that a correlation exists between creep and slow compressive strength (4, 6), and this is verified in the present study. In addition, the dependence of flow stress (max. load divided by original cross-sectional area) on strain rate for other types of material has been compared with the dependence of creep rate on stress (3). If  $\sigma_F$ , the flow stress, is given as

$$\sigma_F = C\xi^m$$

where  $C$  and  $m$  are constants and  $\xi$  is the strain rate, the value of  $m$  was estimated to be between 0.2–0.3 for alloys D, R and SF, using the crosshead speed divided by the sample length as the strain rate. It has been shown that  $m = 1/n$  (3), where  $n$  is the stress exponent previously determined (2). When  $1/n$  is calculated using values for  $n$  obtained

in (2) 0.3–0.4 results. A reasonable agreement between the two values of  $m$  is thus obtained. The dependent and independent variable has been changed for the two types of tests. The same deformation mode, however, appears to be operative.

Previously reported apparent moduli of elasticity are comparable to the ones obtained in this study (7). Table 3 indicates that a correlation between creep and apparent modulus of elasticity exists. Because of the heterogenous nature of the amalgams, the creep and modulus of elasticity may be structure sensitive in the same manner. It may be suggested that a large volume fraction of  $\gamma$  particle with a high modulus of elasticity, carry a large portion of the stress, thus a low creep and high modulus of elasticity prevail.

Correlation between the compressive strength measured at the highest crosshead speed (1 mm/min) and creep was not demonstrated. This indicates that stress application with high strain rate may not be responsible for the marginal deterioration.

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