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SOME TENSILE PROPERTIES OF AMALGAM

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Some Tensile Properties of Amalgam

ABSTRACT

Methods were developed for measuring the tensile properties of dental amalgam. Specimens used were dumb-bell shaped with a straight portion of 0.01 in.^{2} cross section and approximately 0.30 in. length. Tensile strengths of four amalgams ranged from approximately 7000 to 8500 psi. Elongations calculated over a 0.5 in. gage length varied from 0.3 to 0.5%. Chord moduli of elasticity from stresses of 1000 to 3000 psi for specimens of the four amalgams strained at a rate of 0.003 in. per minute averaged 3.3 to 4.1 x 10^6 psi and from 1000 to 5000 psi averaged 2.2 to 2.8 x 10^6 psi. Moduli representing instantaneous elastic response between 450 and 3500 psi for two of the amalgams were approximately 5 x 10^6 psi.

I. INTRODUCTION

Extensive research has been done on the physical properties of amalgam. Most of the research has been directed towards compressive strength, flow, dimensional changes during hardening and their relation to clinical techniques. Relatively little work, however, has been done on tensile properties which are also important factors in the clinical service of amalgam.

In a study of the causes of clinical failures of amalgam Healey and Phillips[1] reported that about 26% of the failures were due to fractures. Fracture may be caused either by faulty cavity preparation or inadequate properties of the amalgam. An amalgam restoration in a tooth is subjected to compressive, shearing and tensile stresses. Since the compressive and shearing strength of amalgam are high compared to its tensile strength, failure is more likely to occur from tensile stresses than from compressive or shear stresses.

A number of authors[2,3,4,5] have commented on the relationship between tensile properties and fracture and a few papers[2,3,6,7] have reported data on tensile strength. Mahler[4,5] after analysis of the stresses in a disto-occlusol amalgam restoration concluded that failures at the isthmus are due to tensile stresses.

M. L. Ward[7] in 1924 used a small briquette mold (patterned after one used for Portland cement) to make tensile specimens of amalgam. The briquette specimen was 0.250 inch thick and 0.200 inch wide at the narrowest point, thus having a cross-sectional area of approximately 0.05 sq. in.

Ward reported the maximum average breaking load of a high silver amalgam as 280 pounds. This is a tensile strength of approximately 5600 psi. He used a modified Trinius-Olsen universal testing machine but did not report either the head speed or the age of the amalgam specimen.

In 1930, N. O. Taylor[2], using Ward's small briquette mold, reported the tensile strength of various amalgams. The average value of the different brands tested ranged from 2,900 to 6,000 psi for 5-day-old specimens. He used a hand-operated Amsler testing machine of 600 lb. capacity and applied the load at approximately 200 lb./min. at room temperature(20 - 25°C). He stated that it was very difficult to triturate and condense the large samples in a reasonably short time and presumed that the values for tensile strength he obtained were lower than if the specimens were smaller.

Souder and Paffenbarger[8] concluded from the work of N. O. Taylor also that:

> The tensile values of specification type alloys are very low, about one-tenth the crushing values. The alloys of high tin content have high tensile strengths amounting to from one-eight to one-sixth of their compressive strengths.

Later, Coy and Liebig[3] in 1938 reported the tensile strengths of amalgam alloys having different particle sizes, the comminuted alloy had a much higher tensile strength in one day after forming of the specimen than one made from coarsely cut alloy, but only a slightly higher tensile strength after five days of age as shown in Table 1.

J. T. Sweeney[6] in 1940 gave the tensile strength of one amalgam which he did not identify. The manufacturer stated that this amalgam had a tensile strength of 7851 psi. J. T. Sweeney, using a mechanical amalgamator and a Hollenback pneumatic condenser on the same alloy, reported a tensile strength of about 11,000 psi. He used the same molds as the manufacturer used. No data are given relative to the age or size of the specimens, how many were tested, or the rate of applying the load.

No publications on the other tensile properties such as proportional limit, modulus of elasticity and elongation were found. Apparently, one of the main reasons for this lack of information is the difficulty of testing small tensile specimens of amalgam. The low tensile strength of amalgam and the inability to make large specimens by conventional dental techniques has required that the testing machine be sensitive to small loads and provide low head speeds. Until recently such equipment has not been readily available.

The objective of this study was to investigate the tensile properties of amalgam because (a) very little information is available on these properties of amalgam, and (b) more exact knowledge of the tensile properties should make it possible to avoid some of the fracture failures of amalgam restorations.

2. EXPERIMENTAL PROCEDURE

2.1 Materials Used

The brand names, manufacturers and batch numbers of the four amalgam alloys used in this investigation are listed in Table 2. Three of the four alloys are certified to comply with American Dental Association Specification No. 1 for Dental Amalgam Alloy. They were selected because they covered a wide range of particle sizes and setting times, and are widely used clinically. The fourth alloy used was a non-certified high tin alloy. The pellet form of two alloys was chosen to minimize weighing of amalgam alloys. The chemical compositions of the four amalgam alloys are given in Table 3.

All the mercury used met the requirements of American Dental Association Specification No. 6 for Dental Mercury.

2.2 Specimen Preparation

Mold

A modified form of the small briquette mold employed by Ward, Taylor, and others was used in this study. The cross-sectional area was reduced from 0.05 sq. in. to 0.01 sq. in. in order to facilitate better packing. Also, the length of the straight portion was increased to 0.30 in. to permit the attachment of quarter inch Tuckerman optical strain gages directly to the surface of the amalgam specimen. This was done in order that other tensile properties besides strength could be determined. Figure 1 shows the dimensions of the dumb-bell-shaped amalgam specimen for testing tensile properties.

Technique Used

All the weighings of alloys and mercury were made on a torsion balance to the nearest 10 mg. The alloys having the pellet form were randomly checked and weighed to verify the uniformity of pellet weights. Table 4 shows the alloy to mercury ratio and weights used as suggested by the manufacturers' directions.

Two pellets or equivalent amount in weight of alloy and the appropriate amount of mercury were placed in a Caulk capsule with plastic pestle and triturated in a Crescent "Wig-L-Bug". The trituration time was in accordance with the manufacturers' directions or until an apparently satisfactory mix was obtained if the directions did not recommend a specific time. Normal operating speed of this particular amalgamator with loaded capsule was found to be 3320 ± 20 cycles per min. The duration of the trituration was measured by the automatic timer on the amalgamator. The start of mix for measurement of the age of the specimen was taken as the start of trituration of the first capsule load of amalgam. Three capsule loads were used for each specimen of alloys C and D, whereas two capsule loads were used for alloys A and B.

Each of the capsule loads was placed in a squeeze cloth after trituration. After one minute from the time of mix, the entire amalgamated mass (consisting of either two or three capsule loads) was rolled into a rope within 15 seconds. The rope was then divided into two equal portions, using a sharp-edged stellite spatula. From each portion, the mercury was expressed with hand and cotton pliers from the squeeze cloth. The first expressed amalgam portion was then placed in the dumbbell mold. The amalgam was packed with a modified Udimcolite plugger #6,

using 1400 ± 100 psi condensation pressure and 30 thrusts with each portion (20 thrusts at 14 ± 1 lb with a rectangular point having a 0.0102 in.^{2} area and 10 thrusts at 26 ± 1 lb with a round point having a 0.1520 inch diameter 0.0181 in.^{2} area).

In the second portion, the mercury was expressed after approximately three minutes and 45 seconds and then packed similarly to the first portion. The excess amalgam on the top surface of the specimen was trimmed flush with the surface of the mold surface with a sharp-edged stellite spatula. The preparation of the specimen was finished in about six minutes ± 30 seconds. Figure 2 shows some of the equipment used in the specimen preparation.

The specimen was left in the dumbbell mold until at least 10 minutes from the start of mix to prevent possible fracture on removal. All specimens preparation, storage and testing was done in a controlled-temperature room maintained at 23° ± 1° C (73.4° ± 1.8° F) and 50 ± 4% relative humidity.

Just before the tensile testing, the edge of the gage-length portion of each specimen was trimmed smooth with a sharp-edged stellite spatula, and the specimen was then measured with a micrometer to the nearest 0.0001 inch. On all the specimens for which elongations were reported, approximately 0.50 in. gage-length distances were marked with lines ruled near the middle of the round ends of the specimen. The exact gage-length was measured in a toolmakers microscope to the nearest 0.0001 inch.

2. 3 Testing Procedure

An Instron testing machine was used for determining tensile properties. A load cell operating over a 0 to 50 kg load capacity and having at least 0.5 percent accuracy was used for determining the stresses on the specimens. The load cell was calibrated with a known 1 kg standard weight at various load ranges covering 2, 5, 10, 20, and 50 kg.

Figure 3 shows one of the dumbbell specimens just before receiving tensile stress. The alining grips were similar to the ones used by Ward. The shapes of the ends of the specimen and of the grips were designed to permit the specimen to adjust slightly so that the loads were applied axially.

Tuckerman optical strain gages[9] were employed to measure the amount of deformation under loading. The Tuckerman strain gages were mounted directly on the specimen with the aid of a metal parallelogram and rubber bands as shown in Figure 4.

The quarter-inch gage length of the Tuckerman strain gage was calibrated, using a steel ruler 16th inch scale. The knife edges of each gage were placed on the ruler on adjacent quarter-inch marks (which had been measured in a toolmakers microscope and found to be separated by 0.2500 inch). The knob on the gage was adjusted so that the image would appear on the reading range in the autocollimator. Results obtained from a series of observations indicated that the actual gage length was known to be accurate to about 1.0 percent.

To test the over-all accuracy of the method, the modulus of elasticity in tension of aluminum alloy 2024-T4 was determined, using the same cross-sectional area as that of the amalgam specimen, 0.01 square inch (0.100 inch width and 0.100 inch thick), and the same crosshead speed of 0.003 inch/min. A value of 10.4×10^6 psi was obtained for the modulus of elasticity of this aluminum alloy, Figure 5. This agreement with the accepted value of 10.6×10^6 psi[10] and the value of 10.5×10^6 psi reported by Stanford[11] using one inch Tuckerman strain gages indicates that the method was accurate to about 2.0 percent.

The seven-day-old specimens of amalgam having a cross-sectional area of approximately 0.01 $in.^2$ were loaded at a crosshead speed of 0.003 inch per min. Alternate autocollimator readings were made on the front and back gages at every kg load increment, starting at 2 kg load (450 psi). Loading was continued until a stress of 28 kg load (approximately 6,000 psi) was applied. Then the Tuckerman strain gages were removed and the stress loading was continued until the specimen ruptured in tension.

To determine percent elongation, the broken pieces were fitted together and the increase in length was measured to the nearest 0.0001 in. in a toolmakers microscope.

3. DISCUSSION OF RESULTS

3.1 Tensile Strength

Tensile strength is defined[12] according to the American Society for Testing Materials (ASTM) as follows:

> The maximum tensile stress which a material is capable of sustaining.

The load is applied under specific and prescribed conditions and is expressed as force per unit area usually in pounds per square inch (psi) based on the original cross-sectional area of the material tested. In this study, the tensile strength values are reported to the nearest 100 psi.

Table 5 shows that varying the head speed over the ranges used had no significant effect on the tensile strength of the two amalgam alloys investigated. These findings are essentially in agreement with those of Ward[7] who found that varying the rate of application of the load made less difference in determination of tensile strength than in determination of compressive strength.

The results given in Table 6 show the effect of age on the tensile strength of dental amalgam at a head speed of 0.003 inch per minute. There is a significant increase in tensile strength from one hour to five hours. There are also smaller but significant increases in strength between five hours and one day and between one day and 14 days. The one-hour specimen attained only about 10 to 15 percent of the tensile strength attained in one week.

There is a significant difference between the high tin alloy and the specification-type alloy on a five-hour-old specimen. The high tin alloy is weaker than the specification-type alloys. But for one-day to 14-day-old specimens there is no significant difference between the high tin alloy and the specification-type alloys.

It has been shown that the compressive strength of amalgam depends upon the rate of loading[7,13,14]. Table 7 shows the comparison of tensile and compressive strength tested at the same head speed. The tensile strength values of the specification-type alloys (B and D) are about one fifth to one fourth of their compressive strength values.

3.2 Elongation

Elongation is defined[12] according to ASTM as follows:

> The increase in the gage length, measured after fracture in tension of the specimen within the gage length usually expressed as a percentage of the original gage length.

Percentage elongation is an index of the brittleness or ductility of a material. Values of the elongation of the original gage length of approximately 0.50 inch were calculated to the nearest 0.05 percent. The results given in Table 8 show that the amalgams have an average range of about 0.3 to 0.5 percent elongation. The values obtained for percent elongation indicate that dental amalgam is a brittle material. Difference between the alloys are of doubtful significance.

3.3 Proportional Limit and Modulus of Elasticity

Proportional limit and modulus of elasticity are defined[12] according to ASTM as follows:

> Proportional Limit.- The greatest stress which a material is capable of sustaining without any deviation from proportionality of stress to strain (Hooke's Law).
>
> Modulus of Elasticity.- The ratio of stress to corresponding strain below the proportional limit.

Figure 6 shows typical stress-strain curves of the four dental amalgam investigated. The curves show no straight line portion from which either the proportional limit or modulus of elasticity could be calculated by means of the ASTM definition given above. Moduli of elasticity were therefore calculated as chord moduli for these materials. The slope of the chord connecting two points on the stress-strain diagram at the prescribed stress (from 1000 to 3000 or from 1000 to 5000 psi) was taken to be the modulus of elasticity and was designated as the "chord modulus". The value of the modulus of elasticity is a measure of the stiffness or degree of rigidity of the material. The chord moduli of elasticity at two stresses are listed in Table 9. The values for the chord moduli of elasticity from stresses of 1000 psi to 3000 psi range from 3.3 to 4.1 x 10^6 psi, whereas the chord moduli of elasticity from stresses of 1000 to 5000 psi range from 2.2 to 2.8 x 10^6 psi.

Examination of Table 10 shows alloys B and D have higher moduli of elasticity in tension than in compression. It was noted, however, that, when the "chord modulus" is calculated over a range of approximately 10% to 60% of the breaking load for both tensile and compressive tests (Table 10), the moduli in tension and compression are in fairly good agreement. This corresponds to a modulus of 2.2 to 2.8 in tension over the range for 1000 to 5000 psi and a modulus of 1.4 to 2.4 over a range of 5000 to 25,000 or 30,000 psi in compression.

It was thought that an investigation of the flow properties of the amalgams might provide an explanation for the shape of the stress strain curves. The flow rates of seven-day-old specimens of amalgam D under constant loads equivalent to approximately 500 psi, 1000 psi, 2000 psi, 3000 psi, 4000 psi and 5000 psi were therefore determined. The results are shown in Figure 7. These curves indicate that a significant amount of flow occurs during the running of a stress strain curve at the rate employed in this study. In order to obtain data that would provide information on the relative elastic and flow characteristics of amalgam a more detailed study of dimensional change during rapid loading and under constant load was made on specimens of amalgams A and C.

To obtain data on instantaneous elastic properties measurements of dimensional changes both during rapid application and rapid removal of stress were made. Information on retarded elasticity and viscosity effects was obtained by measurement of dimensional changes produced by constant stress for prolonged periods and by retarded recovery after removal of stress. The experimental procedure was as follows: a tensile stress of approximately 450 psi was applied to the specimen to facilitate mounting and adjustment of the Tuckerman strain gages. An additional stress of approximately 3100 psi was applied instantaneously (within one second) and the instantaneous strain was recorded. Strain under this constant stress during a period of 700 seconds for amalgam C and 5500 seconds for amalgam A was recorded. Then the additional stress of 3100 psi was removed and the instantaneous strain recovery recorded. The retarded recovery was then followed for 1000 seconds for amalgam C and over 2×10^5 seconds for amalgam A. The results are shown in Figure 8.

The results shown in Figure 8 can be analyzed in terms of a mechanical model[15] in which the properties of the amalgam specimen are represented by a combination of springs and dashpots, Figure 9. In this model E_1 represents instantaneous elastic response (modulus of elasticity) E_2 and η_2 represent retarded elastic response and η_3 represents the flow mechanism or viscosity. Values for these elements are given in Table 11. As would be expected the values of E_1 are considerably higher than the chord moduli values reported in Table 9. While the values for E_1 are the same for the two amalgams, large differences between the two materials were observed in the values for E_2, η_2, and η_3. It must be emphasized that the data reported were obtained on a limited number of specimens and additional data will be required to verify the reproducibility of the results and the apparent difference between the two amalgams. It is believed that additional data of this type including results for different stress ranges, different temperatures, and larger time periods will more clearly define the properties of dental amalgam.

The moduli of elasticity of dentin and some filling materials are shown in Table 12. Values for amalgam are not significantly different from those for human dentin and silicate cement but are much higher than the value for a direct filling resin.

4. SUMMARY AND CONCLUSIONS

1. A method of preparing specimens for testing tensile strength and other tensile properties was developed.

2. Varying the head speed over a range of 0.003 in. per min. to 0.050 in. per min. produced no significant differences in tensile strength of seven-day-old amalgam specimens.

3. One-hour-old amalgam specimens attained only about 10 to 15% of the tensile strength of amalgam (7000 to 8000 psi) attained in one week.

4. The tensile strength values of specification-type alloys were about one fifth to one fourth of their compressive strength.

5. Amalgam had a low percentage elongation, about 0.3 to 0.5, indicating its brittleness or lack of ductility.

6. The chord modulus of elasticity of amalgam from stresses of 1000 to 3000 psi ranged from 3.3 to 4.1 x 10^6 psi, whereas the chord modulus of elasticity from stresses of 1000 to 5000 psi ranged from 2.2 to 2.8 x 10^6 psi.

7. Exploratory investigation of stress-strain-time characteristics of amalgam indicated a need for more intensive studies of this type.

8. The tensile properties of amalgam are summarized in Table 13.

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TABLE 1

Tensile Strength of Amalgam
(Coy and Liebig [3])

Alloy	Tensile Strength			
	1 day		5 days	
	kg/cm^2	psi*	kg/cm^2	psi*
Coarsely cut	267	3,500	457	6,000
Comminuted	383	5,100	477	6,300

* Strength reported in kg/cm^2 by Coy and Liebig

Specimen cross section 6mm by 5 mm (approximately 0.05 in^2)

TABLE 2

Amalgam Alloys Used

Alloy	Manufacturer	Batch Number
Aristaloy -(pellets)	Baker and Co.	590815
20th Century Regular	L. D. Caulk Co.	8L59R
20th Century Micro-(pellets)	L. D. Caulk Co.	2159 College
High tin alloy	W. E. Mowrey Co.	

TABLE 3

Chemical composition of amalgam alloys

Alloy	% Composition Ag	Sn	Cu	Zn
A*	69.7	26.3	3.8	0.2
B**	70.0	26.0	3.5	0.5
C*	60.0	35.0	4.0	1.0
D**	69.0	26.7	3.8	0.5

*Manufacturer's data.
**Date obtained by the Dental Research Section, NBS (different batch numbers).

TABLE 4

Alloy-mercury ratio and trituration time of amalgam alloys

Alloy	Alloy:Hg Ratio	Wt. of Alloy g	Wt. of Hg. g	Trituration time sec.
A	5:7	0.78 ± 0.02	1.10 ± 0.01	20.0
B	5:8	0.69 ± 0.01	1.10 ± 0.01	17.5
C	5:8	0.69 ± 0.01	1.10 ± 0.01	15.0
D	5:8	0.58 ± 0.02	0.96 ± 0.01	15.0

TABLE 5

EFFECT OF HEAD SPEED ON TENSILE STRENGTH OF DENTAL AMALGAM*

Head Speed (inches/min.)	Alloy A			Alloy D		
	No. of Specimens	Tensile Strength (psi)	S.D. (psi)	No. of Specimens	Tensile Strength (psi)	S.D. (psi)
0.003	8	7,000	720	11	8,100	630
0.005	12	6,300	840	5	7,400	1,450
0.010	7	7,900	1,020	5	7,400	1,560
0.025	5	7,400	560	6	7,800	560
0.050	5	7,700	190	7	7,800	860

* Seven-day-old specimens.

S.D. Standard deviation $=\sqrt{\frac{\sum(x-\bar{x})^2}{n-1}}$

TABLE 6

Effect of age on the tensile strength of dental amalgam

Age	Alloy A psi	Alloy A S.D. psi	Alloy B psi	Alloy B S.D. psi	Alloy C psi	Alloy C S.D. psi	Alloy D psi	Alloy D S.D. psi
	Tensile strength in pounds per square inch							
1 hr	700	130	1,100	90	-		900	210
5 hr	4,600	430	6,500	320	3,300	350	6,500	420
1 day	5,800	950	6,700	960	6,300	520	7,500	820
7 days	7,000	720	7,600	970	8,400	760	8,100	630
14 days	7,200	520	8,100	570	8,300	870	8,200	720

*At least five specimens were used for each age at 0.003 in./min head speed.

S.D.-Standard deviation.

TABLE 7

Comparison of the tensile and compressive strength ‡

Age	Tensile strength (psi)		Compressive strength (psi)		Compressive to tensile strength ratio	
	Alloy B	Alloy D	Alloy B	Alloy D	Alloy B	Alloy D
1 hr	1,100	900	6,000*	-	5.4	-
1 day	6,700	7,500	33,100 †	29,200 †	4.9	3.9
7 days	7,600	8,100	37,800 *	34,600 *	5.0	4.3

‡ 0.003 in. per min heed speed.

*Data from Taylor et al[14].

†Data from Sweeney and Burns[13].

TABLE 8

Elongation of dental amalgam*

Alloy	No. of Specimens	Elongation %	S. D. %
A	5	0.50	0.12
B	6	0.50	0.16
C	6	0.45	0.12
D	5	0.30	0.09

*Seven-day-old specimens at 0.003 in./min head speed.
S.D. - Standard deviation.

TABLE 9

Chord moduli of elasticity for dental amalgam*

	Chord moduli of elasticity in tension from stresses of 1000 psi to					
	3000 psi			5000 psi		
Alloy	No. of Speci-mens	E / 10^6psi	S.D. 10^6psi	No. of Speci-mens	E / 10^6 psi	S.D. 10^6psi
A	7	3.3	0.30	7	2.2	0.13
B	9	3.6	0.60	9	2.6	0.46
C	6	3.9	0.55	6	2.7	0.24
D	6	4.1	0.17	6	2.8	0.12

*Seven-day-old specimens at 0.003 in./min head speed.
E - chord modulus of elasticity.
S.D. - Standard deviation.

TABLE 10

COMPARISON OF THE MODULUS OF ELASTICITY IN TENSION AND IN COMPRESSION OF DENTAL AMALGAM

	MODULUS OF ELASTICITY					
	In Tension x 10^6 psi		In Compression x 10^6 psi			
From Stress of to psi	1,000 3,000	1,000 5,000	1,000 10,000	1,000 25,000	5,000 25,000	5,000 30,000
Alloy B Alloy D	3.6 σ=0.6 4.1 σ=0.2	2.6 σ=0.5 2.8 σ=0.1	- -	- -	1.4 - 1.8⁄ 1.2 - 1.7⁄	- -
Range of Average for Several Alloys	3.3 - 4.1	2.2 - 2.8	4.4 σ=0.6	3.2 σ=0.3*	1.4 - 1.8⁄	2.0 ± 0.5≠

* Data from Smith, Caul, and Sweeney [16].

⁄ Data from Taylor et al [14].

≠ Data from Stanford et al [11].

TABLE 11

Instantaneous modulus of elasticity E_1, retarded elastic response, E_2 and η_2, and viscosity, η_3, of amalgam

Alloy		E_1 x 10^6 psi	E_2 x 10^6 psi	η_2 x 10^9 psi	η_3 x 10^9 psi
A	Loaded	4.8	2.4	1.2	4.3
	Unloaded	4.8	3.2	4.1	4.0
C	Loaded	4.8	0.46*	0.04*	1.2
	Unloaded	4.8	0.59*	0.08*	1.1

E_1, E_2 and η_3 calculated as shown in Figure 11b, from data plotted in Figure 10.

η_2 calculated from equation:

$$\eta_2 = \frac{-\,t\,E_2}{2.3 \log \left(\frac{S}{E_1} + \frac{S}{E_2} + \frac{St}{\eta_3} - \gamma\right)}$$

by graphical determination of slope of plot of

$$\frac{2.3}{E_2} \log \left(\frac{S}{E_1} + \frac{S}{E_2} + \frac{St}{\eta_3} - \gamma\right) \text{ versus } -t.$$

* These values are open to some question since they are based on relatively short time periods.

The large differences between the "Loaded" and "Unloaded" values for E_2 and η_2 appear to result from nonlinear behavior [18] of the amalgams.

TABLE 12

Comparions of the modulus of elasticity in tension of some filling materials and dentin

Material	No. of Specimens	Modulus of Elasticity x 10^6 psi	S.D. x 10^6 psi
Human dentin		2.8*	0.79
A silicate cement		3.1*	0.89
A direct filling resin		0.26*	0.01
Amalgam alloy A	7	2.2**	0.13
Amalgam alloy B	9	2.6**	0.46
Amalgam alloy C	6	2.7**	0.24
Amalgam alloy D	6	2.8**	0.12

*Date from Bowen and Rodriguez[17].

**Chord modulus from 1000 to 5000 psi.

S.D.- Standard deviation.

TABLE 13

Tensile properties of dental amalgam*

Alloy	Chord modulus of elasticity in tension (in psi x 10^6) from stress of 1000 psi to				Tensile strength		Elongation (0.50 in. gage length)	
	3000 psi	S.D.	5000 psi	S.D.	Psi	S.D.	%	S.D.
A	3.3	0.30	2.2	0.13	7,000	720	0.50	0.12
B	3.6	0.60	2.6	0.46	7,600	970	0.50	0.16
C	3.9	0.55	2.7	0.24	8,400	760	0.45	0.12
D	4.1	0.17	2.8	0.12	8,100	630	0.30	0.09

*Seven-day-old specimen and 0.003 in./min head speed (1700 psi/min).

S.D. - Standard deviation.

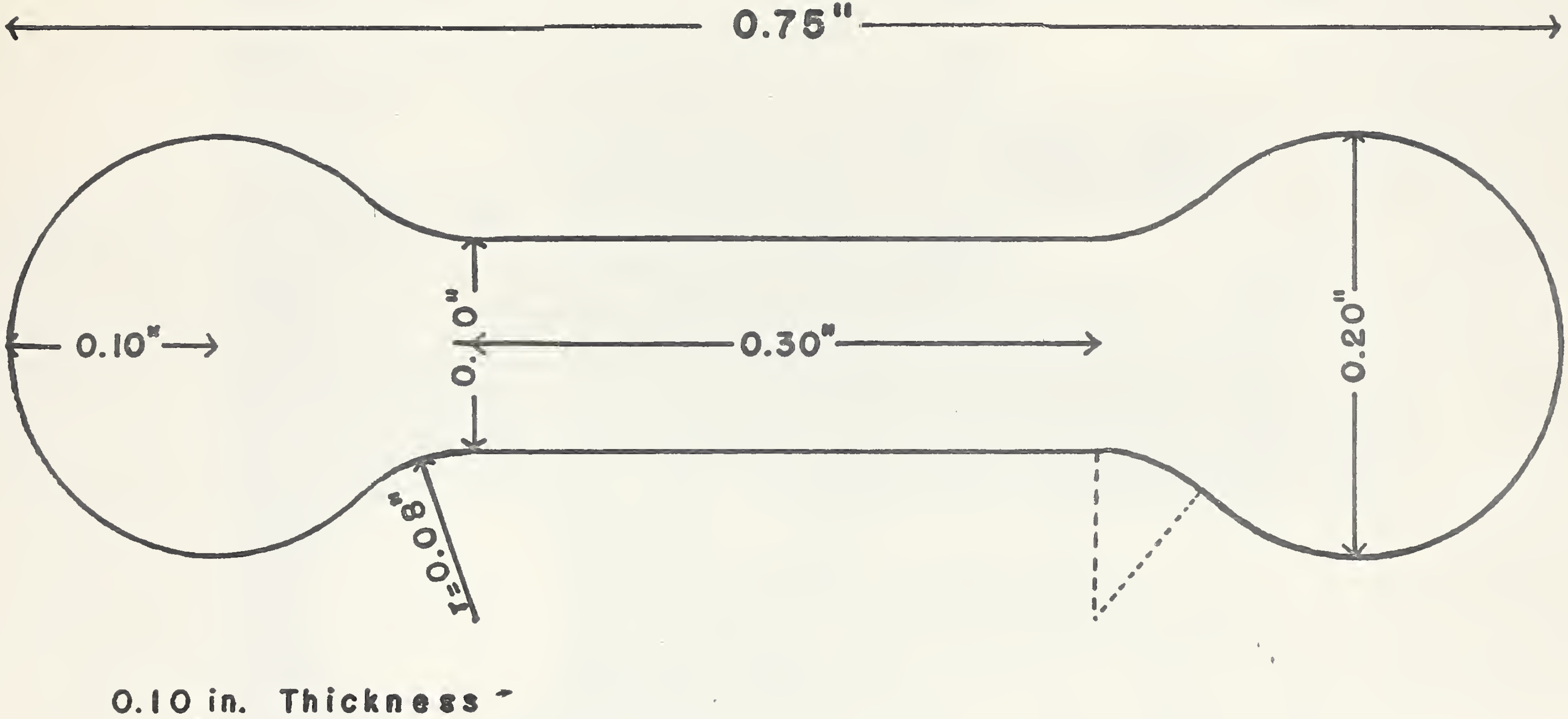


Figure 1. Dimensions of the Dumbbell Shape Specimens for Testing Tensile Specimens

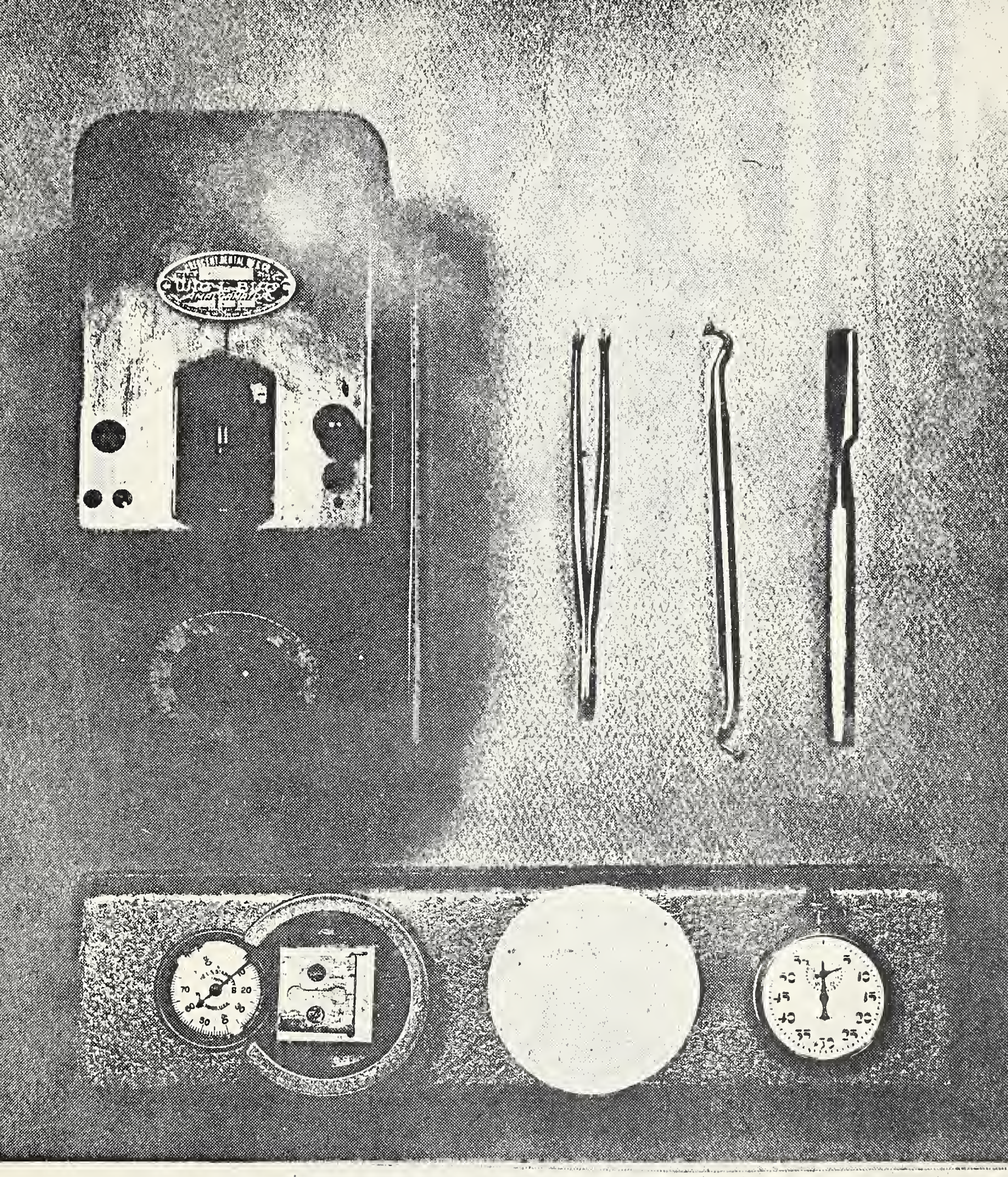


Figure 2. Equipment used in the Preparation of Amalgam Specimens for Testing Tensile Specimens

Crescent "Wig-L-Bug" mechanical amalgamator
Cotton pliers
Modified Udimcolite plugger #6
Stellite spatula
Starrett pressure gage indicator
Dumbbell shape mold with specimen
Squeeze cloth
Stop watch

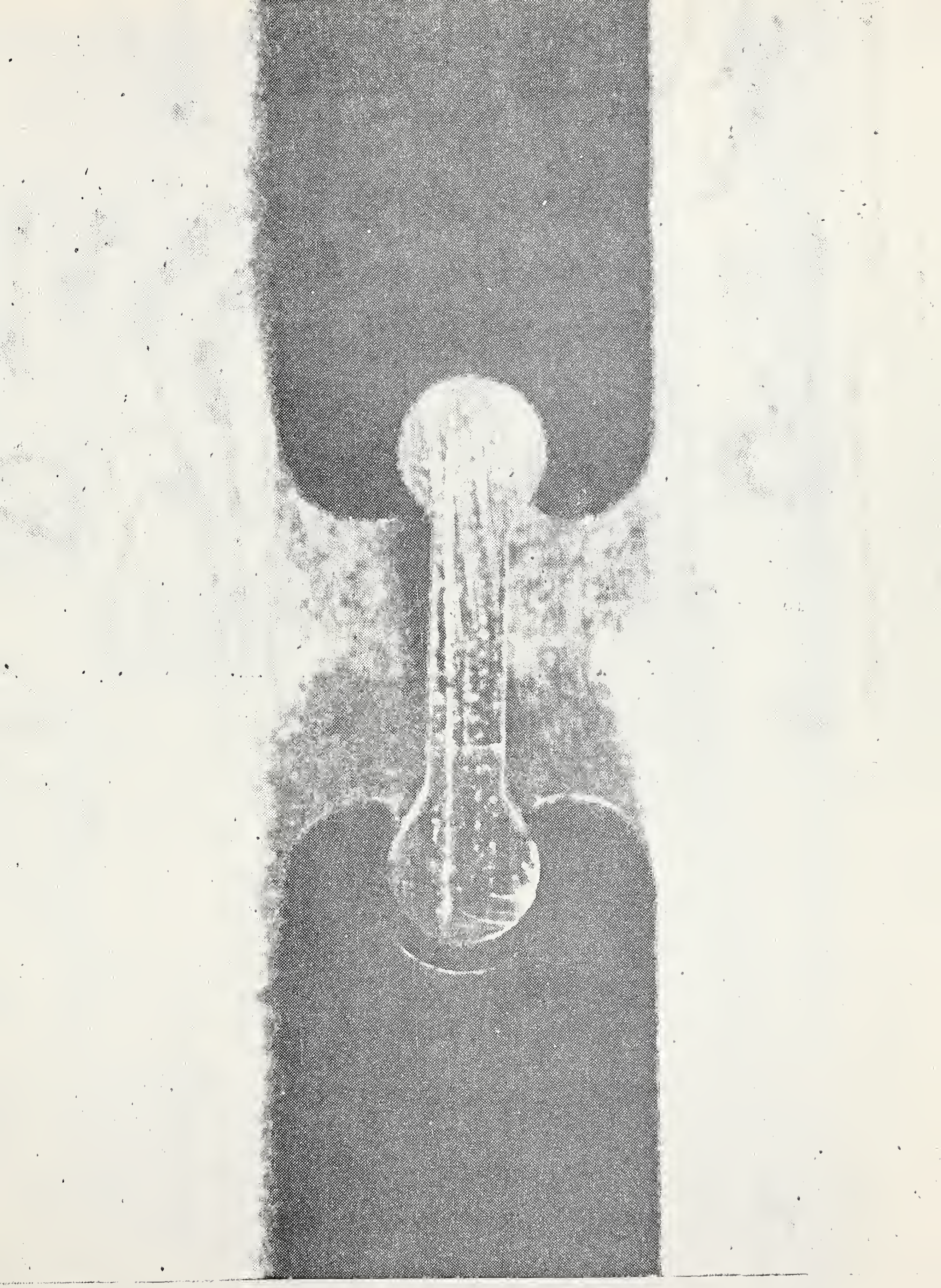


Figure 3. Dumbbell shaped specimen with the aligning grips before receiving tensile stress.

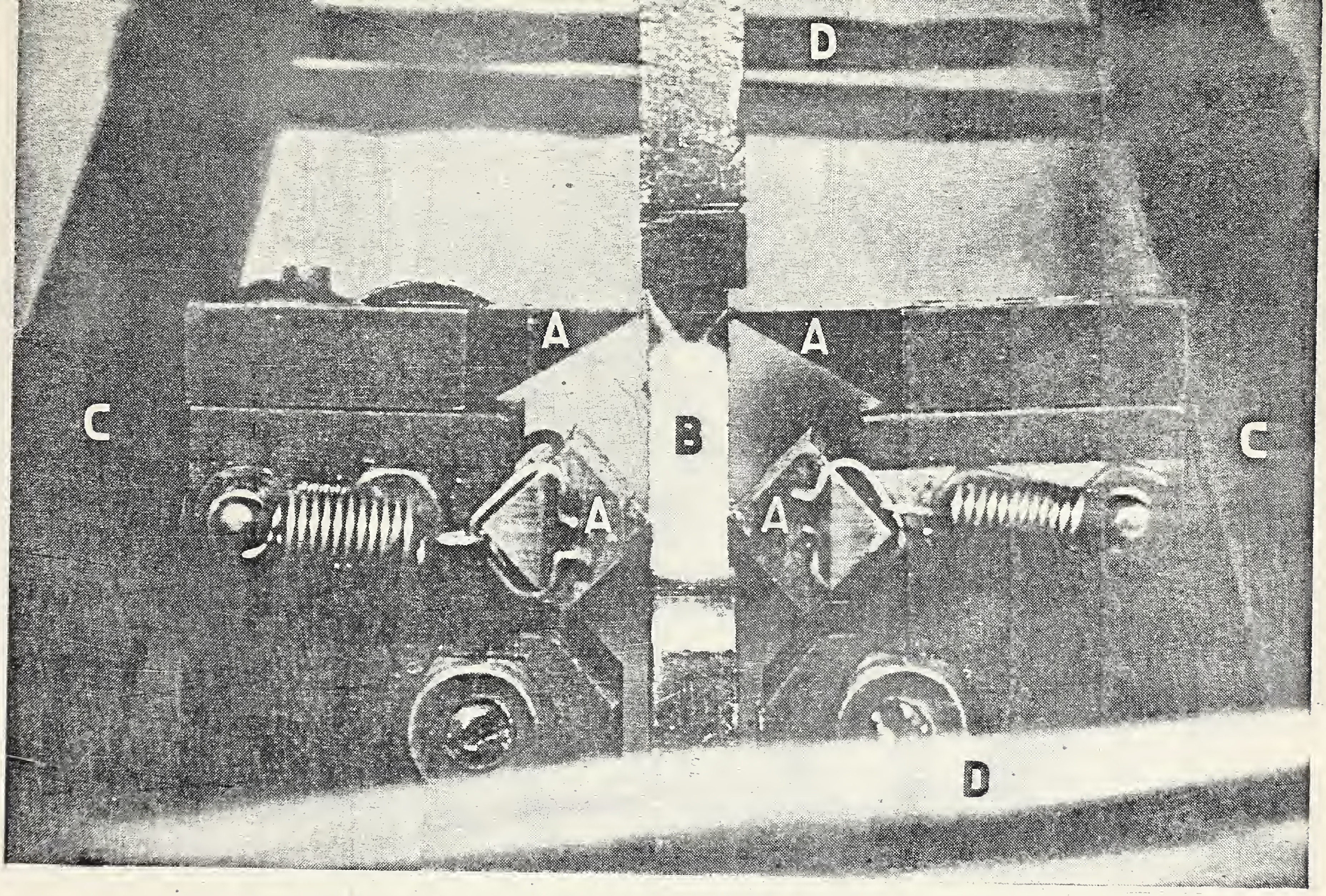


Figure 4. Position of the attachment of the Tuckerman optical strain gage knife edges (a) on the dumbbell specimen (b) with the aid of a metal parallelogram (c) and rubber bands (d).

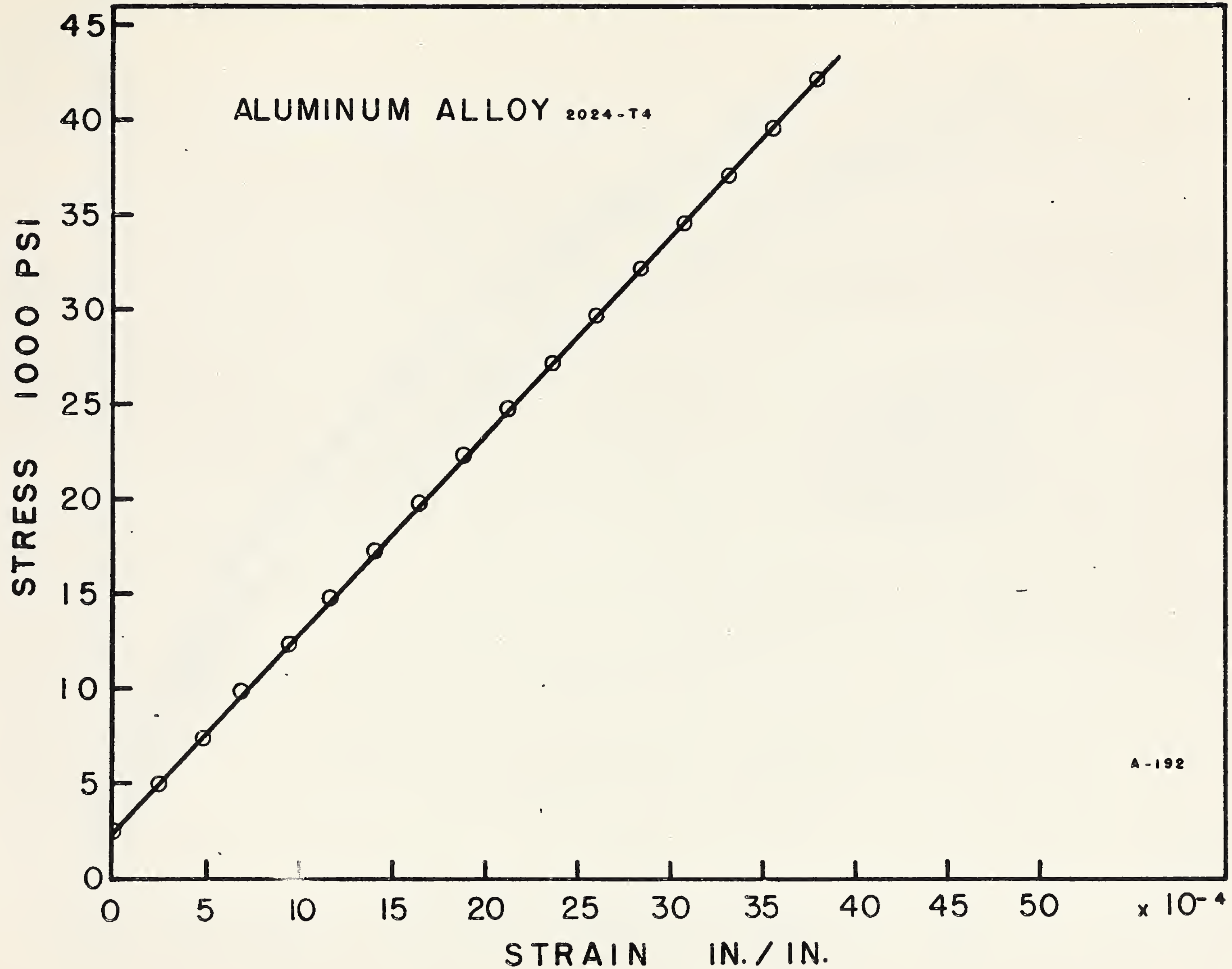


Figure 5. Stress-strain diagram of aluminum alloy 2024-T4 in tension using 0.003 in./min. head speed of the Instron testing machine and 0.01 square inch cross sectional area.

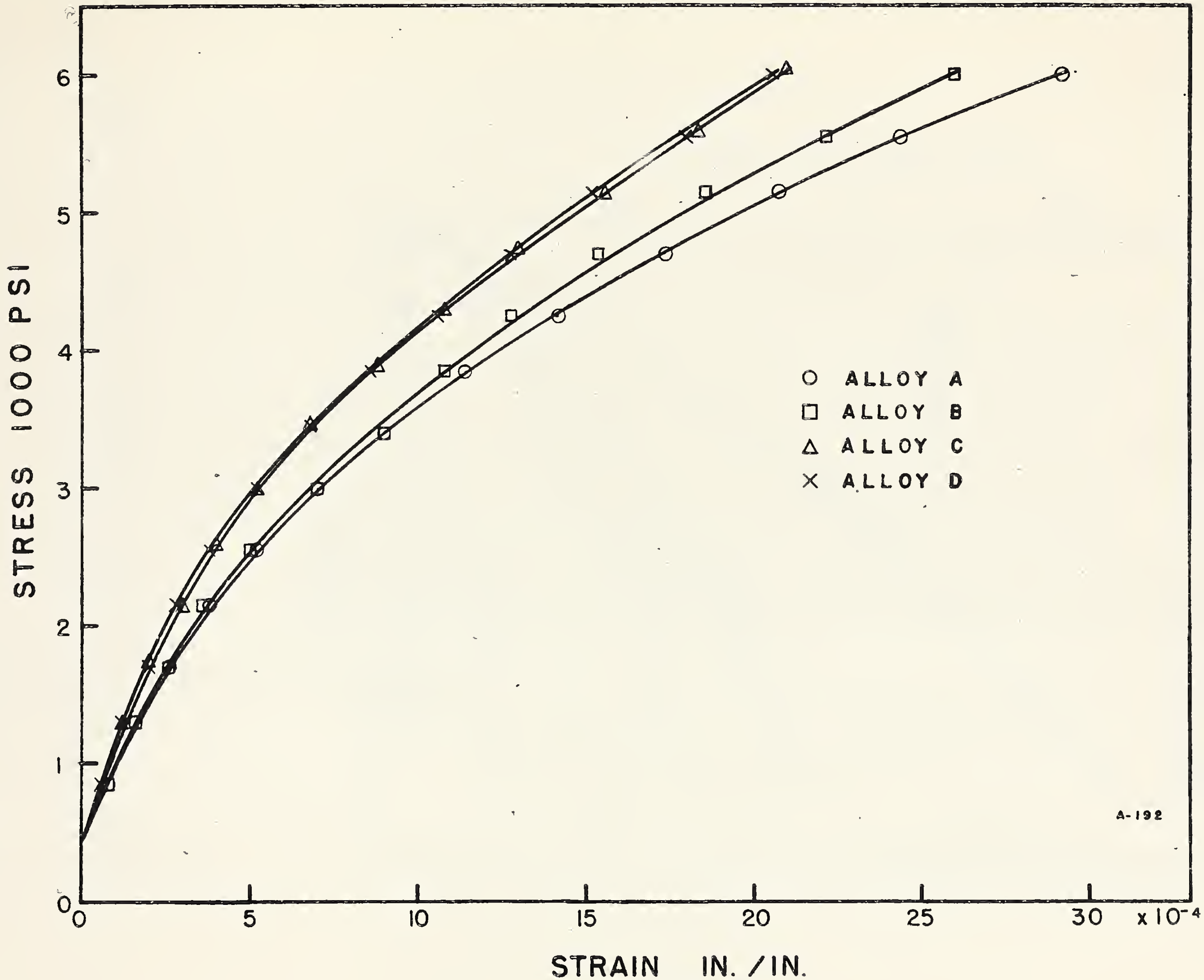


Figure 6. Typical stress strain curves of various amalgams in tension, using 0.003 in./min. head speed of the Instron testing machine and 7 day old specimens.

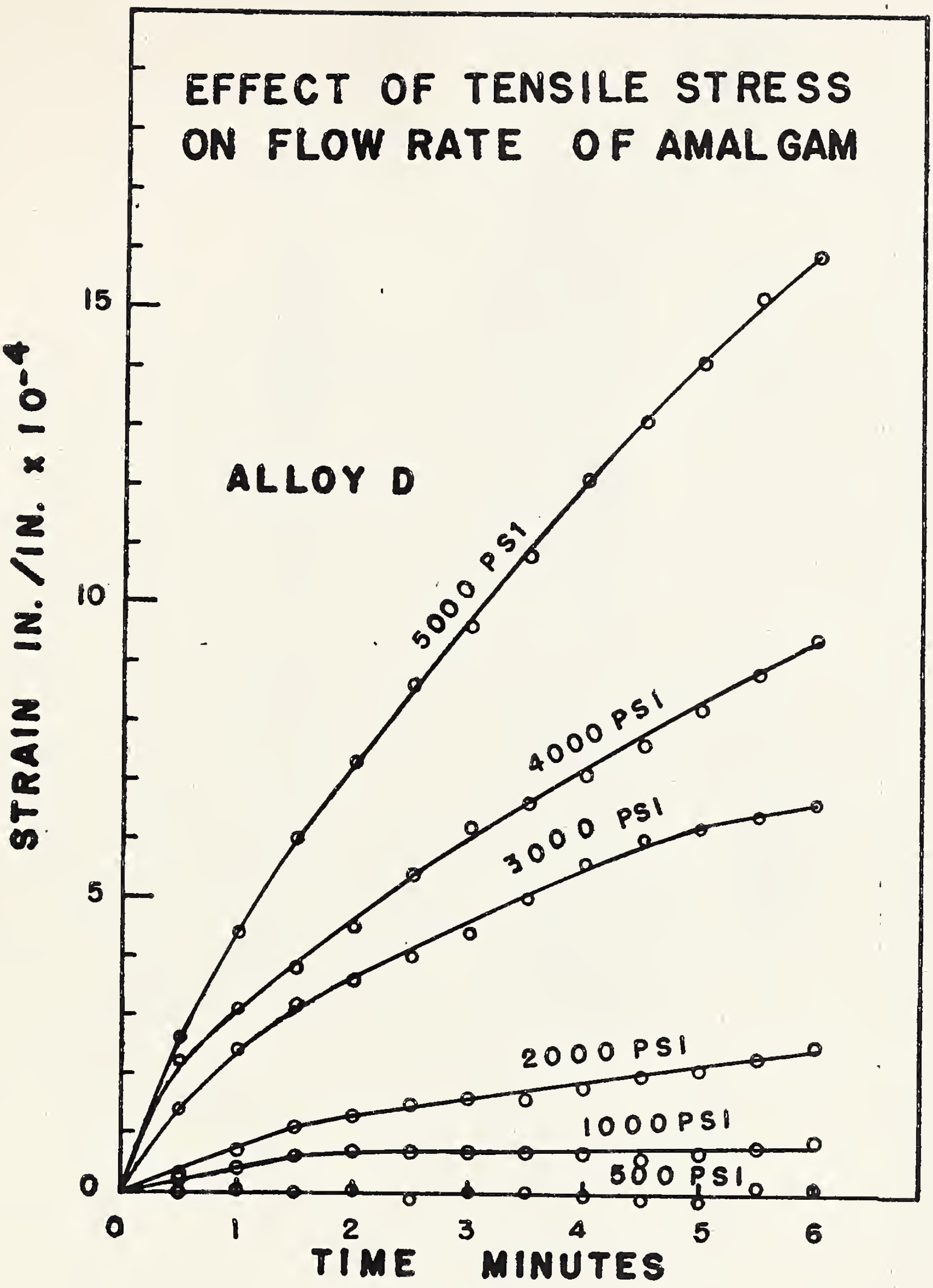


Figure 7. Effect of various constant tensile stresses on the flow rate of amalgam.

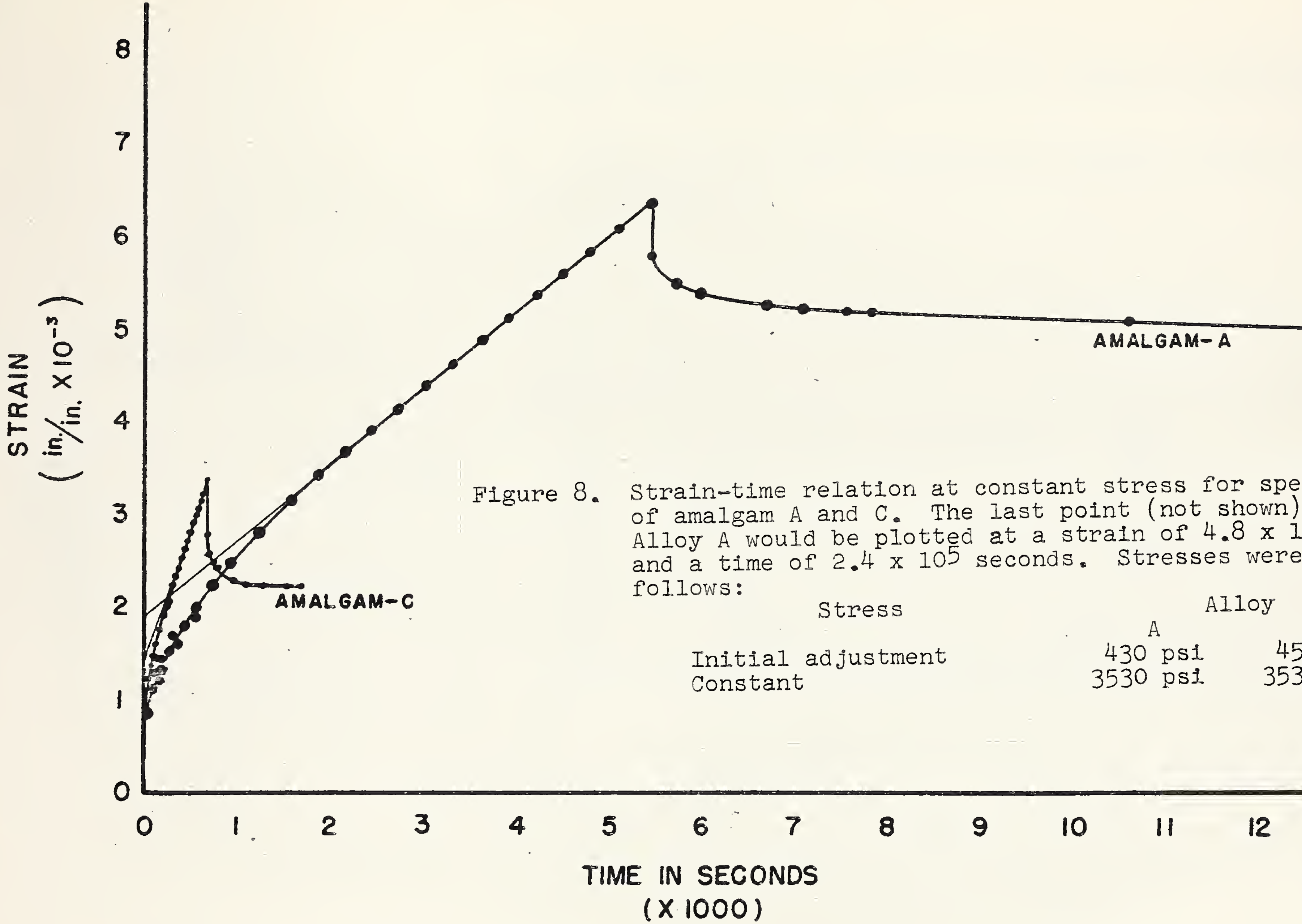
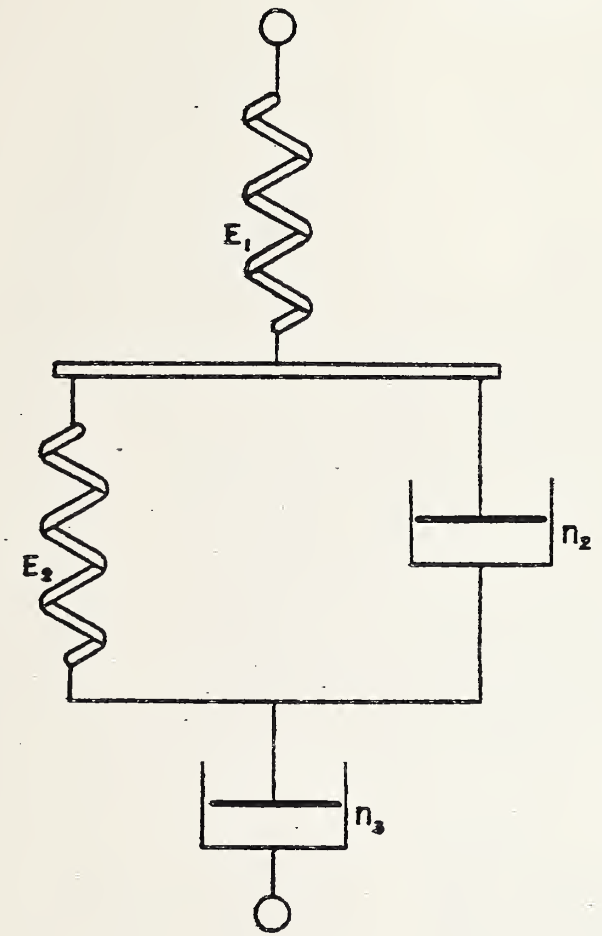


Figure 8. Strain-time relation at constant stress for specimens of amalgam A and C. The last point (not shown) for Alloy A would be plotted at a strain of 4.8×10^{-3} in/in and a time of 2.4×10^{5} seconds. Stresses were as follows:

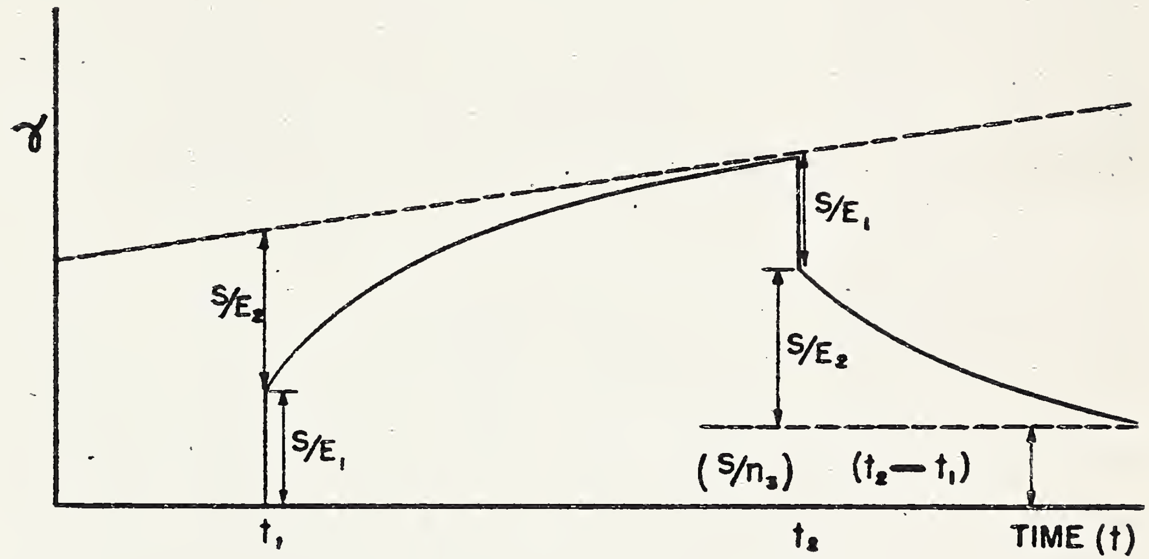
Stress	Alloy A	Alloy C
Initial adjustment	430 psi	450 psi
Constant	3530 psi	3530 psi

Figure 9. A. Mechanical model of a material exhibiting instantaneous elastic response, E_1; retarded elastic response, E_2 and η_2; and flow or viscosity, η_3.

B. Strain, γ, versus time relation at constant stress, S, for material exhibiting instantaneous elasticity, retarded elasticity and flow.



A



B

U.S. DEPARTMENT OF COMMERCE
Frederick H. Mueller, *Secretary*

NATIONAL BUREAU OF STANDARDS
A. V. Astin, *Director*

THE NATIONAL BUREAU OF STANDARDS

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RADIO SYSTEMS. High Frequency and Very High Frequency Research. Modulation Research. Antenna Research. Navigation Systems. Space Telecommunications.

UPPER ATMOSPHERE AND SPACE PHYSICS. Upper Atmosphere and Plasma Physics. Ionosphere and Exosphere Scatter. Airglow and Aurora. Ionospheric Radio Astronomy.

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