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The Tensile and Shear Properties of Several Solders at Cryogenic Temperatures

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Abstract

The tensile and shear properties of eight soft solders were determined at several loading rates at 78°, -100°, -320° and -423°F. It was found that, in general, the tensile and shear strengths increased with increase in loading rate and decrease in temperature. Large decreases in ductility, as measured by elongation and reduction in area, and decreased tensile and shear strengths for some of the solders at cryogenic temperatures are indicative of their low temperature embrittlement. A discussion of the experimental data and literature values is given and recommendations are made concerning the application of solders for cryogenic service.

INTRODUCTION

There have been a few investigations on the mechanical properties of soft solders at cryogenic temperatures (Ref. 1-4); however the paucity of the literature data and the need for certain data which were not available prompted this investigation. Additional data were needed for the design of electronic components, several items of plumbing hardware and even for structural applications in cryogenic tankage for missiles and space craft. These data included shear strength and tensile properties at various strain rates and temperatures. Also, a few alloys were tested for which no previous data at cryogenic temperatures existed.

The solders tested in this investigation were all lead- or tin-base alloys. Because of the embrittlement of pure tin and high tin, tin-lead alloys at low tempertures, emphasis was placed upon evaluating those solders which contained large amounts of lead which is known to have good ductility at cryogenic temperatures. Three solders having high tin contents were included in the program because they had been reported as having satisfactory low temperature properties.

It is desirable to evaluate a material as it is actually used in a component. However, the complexity and size of the program for evaluating many solders as a function of strain rate and temperature became overwhelming when other parameters such as the many variables involved in soldering applications, fluxes, type and condition of materials being soldered, solder gap, etc. were added. Therefore, this investigation was limited to the evaluation of the properties of the basic solders. The object of this program, then, was to provide data on the mechanical properties of several solders for the purpose of selecting the best solder for applications at room and cryogenic temperatures.

MATERIALS AND PROCEDURE

The solders tested in this investigation include: 10Sn-90Pb; 20Sn-80Pb; 30Sn-70Pb; 60Sn-40Pb; 1Sn-97.5Pb-1.5Ag; 45Sn-32Pb-18Cd-5Bi; 95Sn-5Sb; and 60Sn-36Pb-4Ag. The tradenames and chemical compositions are given in Table 1. Five of the solders are listed under Federal Specification QQ-S-571c, and these solders met the chemical composition requirements of that specification.

The solders were tested in the as-received condition in the form of 16 gauge (0.063 inch diameter) wire. Test specimens were made simply by shearing one to three inch long pieces of the solder. Tensile and shear (double shear) tests were performed on standard universal testing machines. The test fixtures used for gripping the specimens during testing are shown in Figure 1. Elongations reported are total elongations as measured over a one inch gauge length which was marked by means of a dye and gauge block. Reduction in area measurements were determined by use of a filar eye-piece and metallurgical microscopes. Tensile and shear tests were performed at 78°F (room temperature), at -100°F by immersion in a bath of dry ice and alcohol, at -320°F by immersion in liquid nitrogen and at -423°F by immersion in liquid hydrogen. A full description of the testing apparatus and experimental procedure is given in reference 5. The tests at cryogenic temperatures were performed as soon as the specimen had reached equilibrium temperature, as measured by thermocouples; therefore, are considered "short time" exposure tests.

EXPERIMENTAL RESULTS

Table 1 gives the chemical composition of the solders tested. The tensile and shear properties at 78°, -100°, -320° and -423°F are given in Table II. The shear strengths (obtained in double shear but reported as single shear) and tensile properties are given for three different loading rates: 0.1, 1.0 and 10 inches/minute. The values reported in Table II are averages of at least two, and generally five, replicate tests. Photographs of typical tensile fractures are shown in Figure 2. These clearly illustrate the effect of testing temperature on the elongations and reduction in area.

DISCUSSION OF RESULTS

The most noticeable results of the test (Table 2) are the large differences in tensile and shear strengths as a function of test temperature and loading rate. The tin-lead solders are apparently very strain rate sensitive, particularly so at 78°F and to a lesser extent at cryogenic temperatures. The solders experienced a 20 to 80% increase in strength at 78°F upon increasing the loading rate from 0.1 inches/minute to 10 in./min. The importance of this type of data can be readily understood since loading rates may vary from very low to impact conditions depending upon the service application. To the authors' knowledge the strain rate sensitivity of commercial soft solders has not been previously reported.

In order to better determine the extent of the strain rate sensitivity of the soft solders, a few tests were made on the 95Sn-5Sb (Sb-5) solder at loading rates of 0.01 in./min. This solder had a tensile strength of 2620 psi at 78°F when loaded at 0.01 in./min. Compared with the data in Table 2, it may be seen that the tensile strength of the Sb-5 solder at 78°F increased by 165% upon increasing the loading rate from 0.01 to 10 in./min.

The explanation of a material's sensitivity to strain rate generally involves a diffusion mechanism. There does not appear to be any clearly defined dependency of the amount of strain rate sensitivity of the solders upon their chemistries. However, the decrease in strain rate sensitivity with decrease in testing temperature is indicative that diffusion is responsible for the soft solders' strength dependency upon loading rate. As would be expected, the tensile and shear strength increase with decrease in testing temperature.

The tensile and shear strengths, at a constant loading rate, of the tin-lead solders is dependent upon the amount of tin present. The dependency of the strength upon the tin content is small as compared to its dependency upon loading rate, particularly at 78°F; however, of the Sn-Pb alloys (e.g. 10/90, 20/80, 30/70 and 60/40) the ones containing the most tin are the strongest. It is also quite apparent that the tensile and shear strength are dependent upon the presence of other elements since those alloys containing large amounts of Ag, Cd, Bi and Sb are stronger than those solders containing primarily Sn and Pb. The strongest solder is Claude Michael's #275 which contains large amounts of Cd and Bi. Also, it appears that the strength of lead base alloys is appreciably increased by silver, in amounts as small as 1.5%, since the strength of Claude Michael's #20 (1Sn-97.5Pb-1.5Ag) is greater than that of the Sn-Pb solders containing as much as 30-60% Sn.

In comparing the strength data obtained in this investigation with that reported in the literature on soft solders, there are several possible discrepancies. For example, Kaufman (Ref. 4) reports the tensile strength of Claude-Michaels #20 as 3,600 psi at 80°F and 9,000 psi at -320°F; and Claude-Michaels #275 as 8,750 psi at 80° and 7925 psi at -320°F. The reason for these, as well as several other discrepancies with literature data, is believed to be primarily due to the strain rate sensitivity. Much of the literature data does not include the strain rates or loading rates and thus inhibits direct comparisons. Although commercial solders were not tested in the investigation by Jaffee, et al (Ref. 3), the tensile data (obtained at a loading rate of 0.06 in./min.) on alloys similar to those tested in this investigation compare more favorably.

The ductility of many of the soft solders is severely affected by the testing temperature. "Ductility", as discussed herein, is the ability of the material to plastically deform prior to fracturing, and is measured by elongation and reduction in area. All of the solders tested have adequate ductility at 78° and -100°F; however, the ductility of many of the solders sharply decreases from -100° to -320°F. The photographs of typical tensile failures as shown in Figure 2 clearly illustrate the effect of testing temperature on the ductility of several of the soft solders. Although the minimum amount of ductility required for satisfactory performance is dependent upon the particular application, it is recommended that soft solders have a minimum of about 10% total elongation and 30% reduction in area for structural type applications.

The toughness of many soft solders is also severely affected by the testing temperature. "Toughness " is defined as the ability of a material to resist brittle failure. The best test to determine a material's toughness is the low temperature impact test since this test involves a high strain rate, a stress concentration and low temperature, all of which promote brittle failure. There are, however, several other methods of determining toughness. The methods used in this investigation include an analysis of the tensile fractures to determine the amount of plastic deformation as compared to the amount of brittle cleavage failure; an analysis of the tensile strength data as a function of increasing loading rates and decreasing temperature (in some cases the strength decreased instead of increased which is indicative of embrittlement); and primarily, an analysis of the shear strengths at high loading rates and low temperatures. It is believed that the high loading rate, low temperature shear tests simulate the impact test. The stress concentration is imposed by the relatively sharp edges of the shear testing fixture. It is therefore believed that this test is quite severe since there was a decrease in shear strength at the high loading rates for 60/40, #275, Sb-5 and 604-Ag solders at -100°F whereas the ductility and failure appearances do not indicate embrittlement. However, at -320°F each of these solders lacked toughness and ductility and therefore are not recommended for structural use at -320°F or below. Shear tests at -320°F indicate severe embrittlement of these solders as well as possible embrittlement of the 30/70 solder. Analysis of the test results and fractured edges of broken tensile specimens definitely indicate a lack of toughness of the 60/40, #275, Sb-5 and 604-Ag solders at -320°F and of the same solders as well as 30/70 at -423°F. These results are not surprising since those solders which remained tough and ductile to -423°F contained primarily lead. It is recommended that only those Sn-Pb solders containing 70% or more lead be used for critical applications at -320°F, and 80% or more lead for use at -423°F.

SUMMARY

The tensile and shear properties were determined on several soft solders at 78°F, -100°, -320° and -423°F. From the results obtained in this investigation the following conclusions and recommendations are made:

1. The soft solders tested in this investigation are strain rate sensitive; very much so at room temperature and to a lesser extent at cryogenic temperatures. The amount of strain rate sensitivity does not appear to be dependent upon the lead or tin content.

2. In general, the tensile and shear strengths of soft solders increase with increase in loading rate and decrease in temperature.

3. The tensile and shear strengths of the Pb-Sn solders are directly proportional to the tin content.

4. A decrease in the tensile or shear strength with reduction in temperature and increase in loading rate is believed to be indicative of embrittlement. A sharp decrease in the ductility is also indicative of low temperature embrittlement.

5. The low temperature embrittlement of Pb-Sn solders is dependent upon the tin content. The solder containing the largest amounts of tin are the most brittle at any given cryogenic temperature.

6. Based upon the tensile and shear strengths and ductility data the following recommendations are made:

   a.) All of the solders tested in this investigation are sufficiently tough for use at 78° and -100°F.

   b.) The following solders are sufficiently tough for use at -320°F: 10Sn-90Pb; 20Sn-80Pb; 1Sn-97.5Pb-1.5Ag.

   c.) The following solders are sufficiently tough for use at -423°F: 10Sn-90Pb; 1Sn-97.5Pb-1.5Ag.

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Table 1. Chemical Composition of Solders

Tradename	Nominal Composition (%)	Chemical Composition (%) by Analysis										
		Sn	Pb	Sb	Bi	Ag	Cn	Fe	Fn	Al	As	Cd
10/90	10Sn-90Pb	9.81	Bal.	0.064	--		--	--	--	--	--	--
20/80	20Sn-80Pb	21.46	Bal.	0.9	<0.029	<0.02	<0.01	≤0.002	<0.013	<0.03	<0.08	--
30/70	30Sn-70Pb	29.74	Bal.	0.079	Trace	<0.02	<0.05	≤0.002	ND	<0.03	<0.08	--
60/40	60Sn-40Pb	59.83	Bal.	0.38	≤0.01	≤0.015	<0.05	--	--	--	--	≤0.01
Claude-Michael #20	1Sn-97.5Pb - 1.5Ag	0.99	Bal.	0.036	--	1.37	--	--	--	--	--	--
Claude-Michael #275	45Sn-32Pb-18Cd- 5Bi	43.82	Bal.	0.071	4.72	--	--	--	--	--	--	
5-Sb	95Sn-5Sb	94.07	<0.2	4.7	<0.01	ND	<0.02	<0.04	<0.03	<0.03	ND	--
604Ag	60Sn-36Pb-4Ag	60.56	Bal.	<0.35	≤0.01	2.86	<0.04	<0.04	--	--	--	<0.02

Table 2. Mechanical Properties of Soft Solders*

Solder	Test Temp. (°F)	Tensile Properties: 0.1"/Min. Loading Rate F_{tu} (PSI)	0.1"/Min. e(%)	0.1"/Min. R.A.(%)	1"/Min. Loading Rate F_{tu} (PSI)	1"/Min. e(%)	1"/Min. R.A.(%)	10"/Min. Loading Rate F_{tu} (PSI)	10"/Min. e(%)	10"/Min. R.A.(%)	Shear Properties: 0.1"/Min. F_{su} (PSI)	1"/Min. F_{su} (PSI)	10"/Min. F_{su} (PSI)
10/90													
	78	2,630	42	97	3,610	51	97	4,190	46	96	2,890	3,350	3,690
	-100	5,870	34	95	6,240	52	94	6,450	39	93	4,510	4,780	5,410
	-320	8,580	27	73	10,200	27	57	10,300	22	55	6,320	8,640	10,400
	-423				11,300	14	41				11,200	11,600	10,900
20/80													
	78	2,630	68	97	4,140	69	97	5,070	42	94	3,320	3,900	4,220
	-100	7,030	32	82	7,710	38	79	7,920	35	79	5,350	5,760	6,650
	-320	12,400	30	43	12,900	21	33	13,200	22	31	8,390	9,230	11,200
	-423				15,300	8	27				14,900	15,900	14,200
30/70													
	78	3,090	56	96	4,190	39	92	4,570	38	92	3,090	3,540	3,720
	-100	6,870	43	91	7,340	54	92	7,870	48	89	5,800	6,140	7,250
	-320	12,600	30	29	13,400	16	25	13,600	18	23	11,200	9,360	6,460
	-423				15,000	4	12				14,200	11,400	7,200

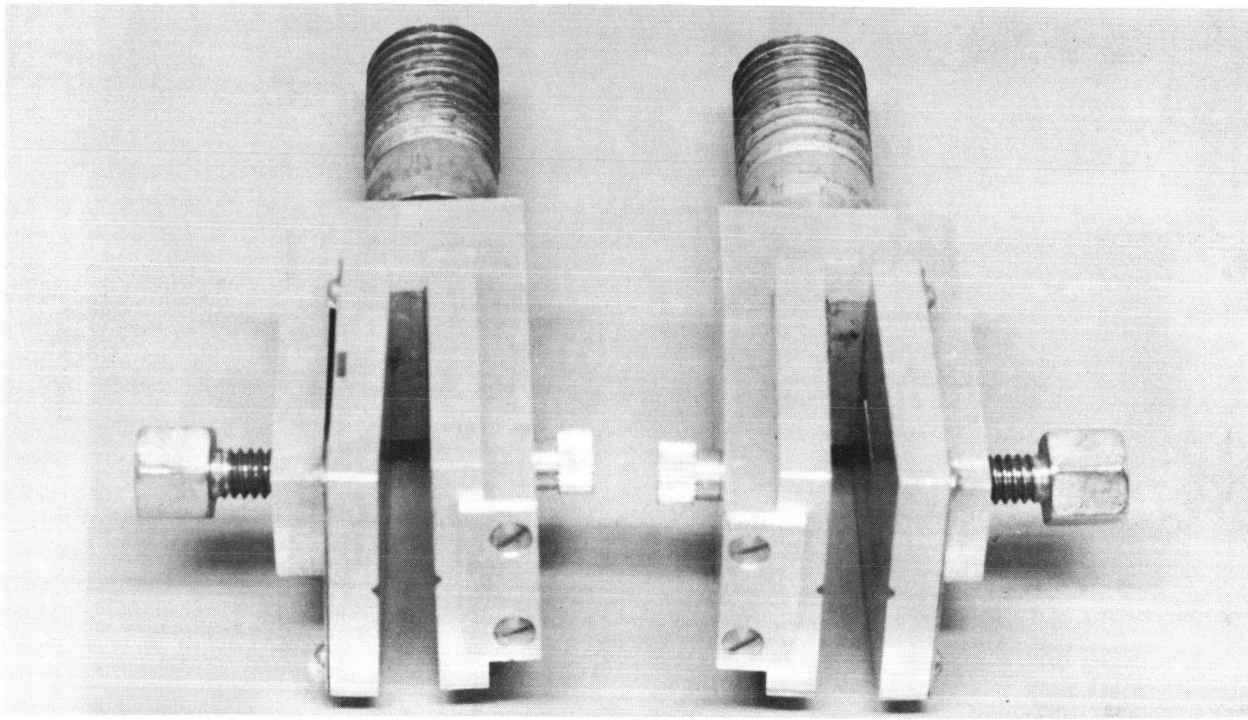
Table 2. Mechanical Properties of Soft Solders* (Continued)

60/40													
	78	3,110	26	97	4,810	22	96	4,980	21	86	3,880	4,480	4,660
	-100	8,510	48	96	9,670	59	94	10,700	57	93	7,910	8,750	7,540
	-320	18,800	13	7	19,500	7	6	19,400	8	6	15,900	8,750	5,500
	-423				19,800	0	0				20,600	7,700	5,300
#275													
	78	5,180	43	84	6,700	34	82	9,950	29	80	5,540	6,580	6,170
	-100	15,200	37	73	16,200	44	71	16,500	38	73	13,100	11,200	6,220
	-320	20,800	10	6	20,800	9	6	20,900	10	5	12,600	8,360	6,680
	-423				23,600	1	2				20,900	8,450	6,700
# 20													
	78	3,610	25	94	4,220	23	97	4,480	15	95	3,140	3,360	3,670
	-100	5,920	24	82	6,280	33	80	6,390	33	83	4,480	4,640	5,370
	-320	9,170	21	66	9,610	19	53	9,890	21	50	7,460	7,710	8,520
	-423				13,300	14	46				9,400	9,700	13,500
Sb-5													
	78	4,020	60	98	5,690	79	98	7,000	76	97	5,570	6,320	6,930
	-100	11,900	63	80	13,500	81	79	15,400	86	78	11,800	13,800	10,100
	-320	30,200	2	0	30,000	0	1	20,800	0	1	23,300	9,240	5,380
	-423				30,700	0	0				27,800	11,500	7,700

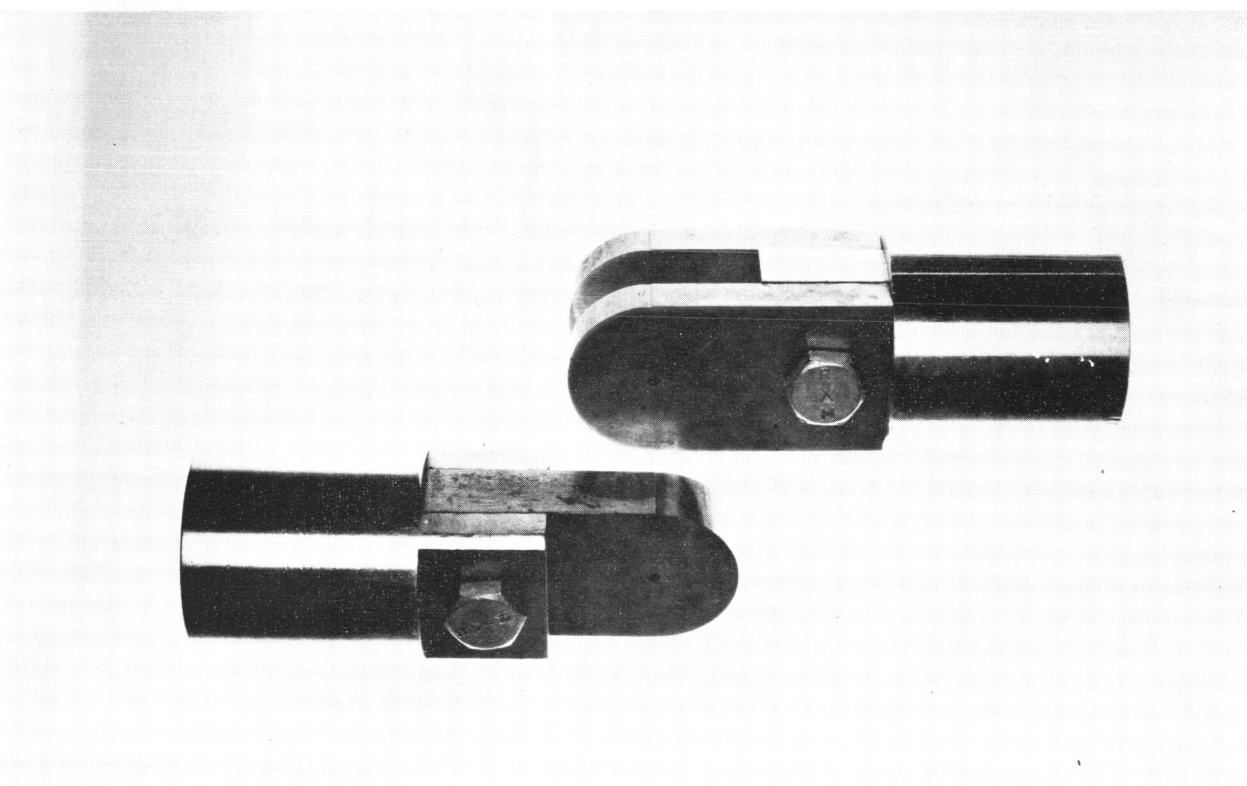
Table 2. Mechanical Properties of Soft Solders* (Continued)

604-Ag													
	78	3,730	47	95	4,920	65	97	5,620	49	78	4,300	4,570	5,400
	-100	9,890	43	85	11,200	71	86	12,300	59	86	8,860	9,830	6,800
	-320	22,900	8	9	21,700	7	3	22,400	7	3	16,600	8,210	6,890
	-423				26,500	1	0				22,500	7,430	5,100

* Values reported are averages of at least two tests and generally five tests.



Fixture Used for Tensile Testing of Solders



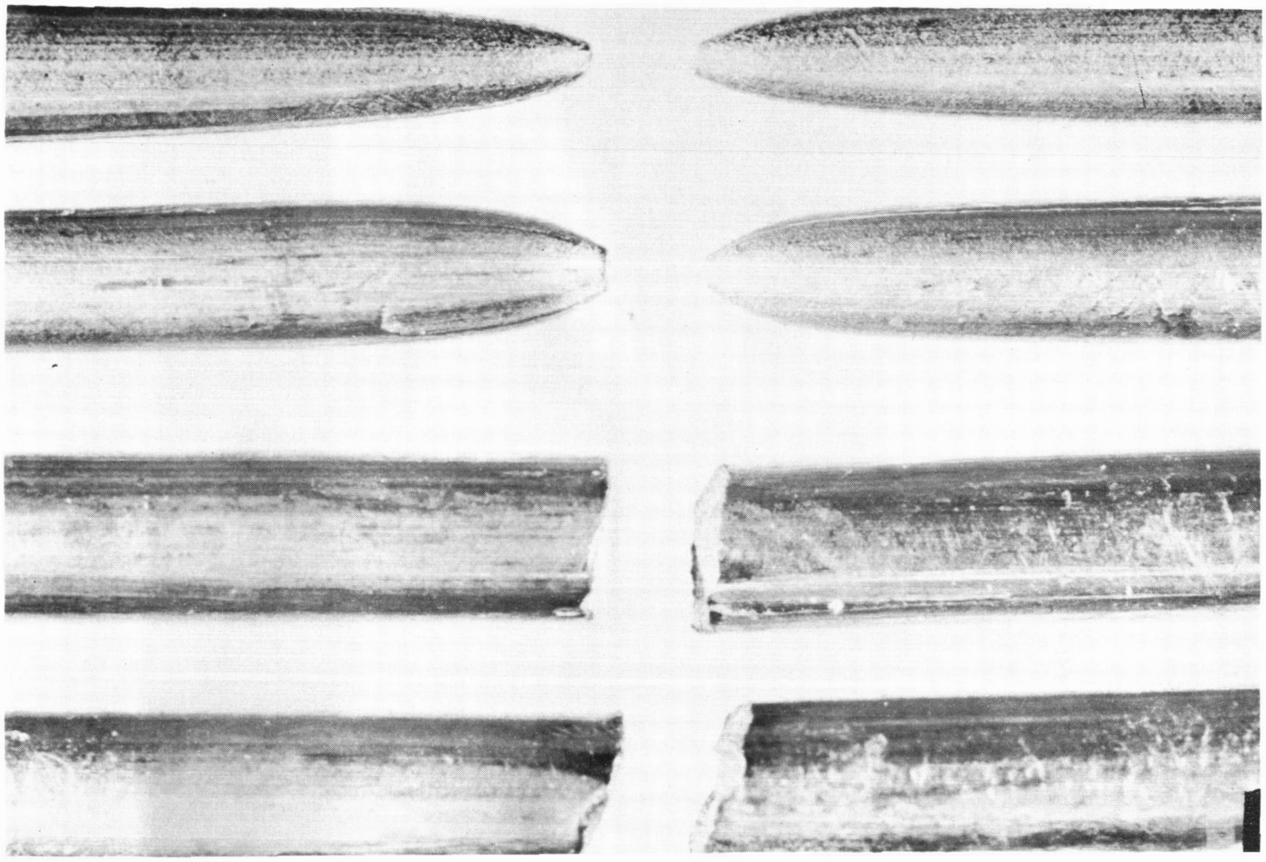
Fixture Used for Double Shear Testing of Solders

Figure 1. Test Fixtures

1 Sn-97.5 Pb-1.5 Ag (C-M #20) Solder 15X

10 Sn-90 Pb (10/90) Solder 15X

Figure 2. Photographs of Typical Tensile Fractures



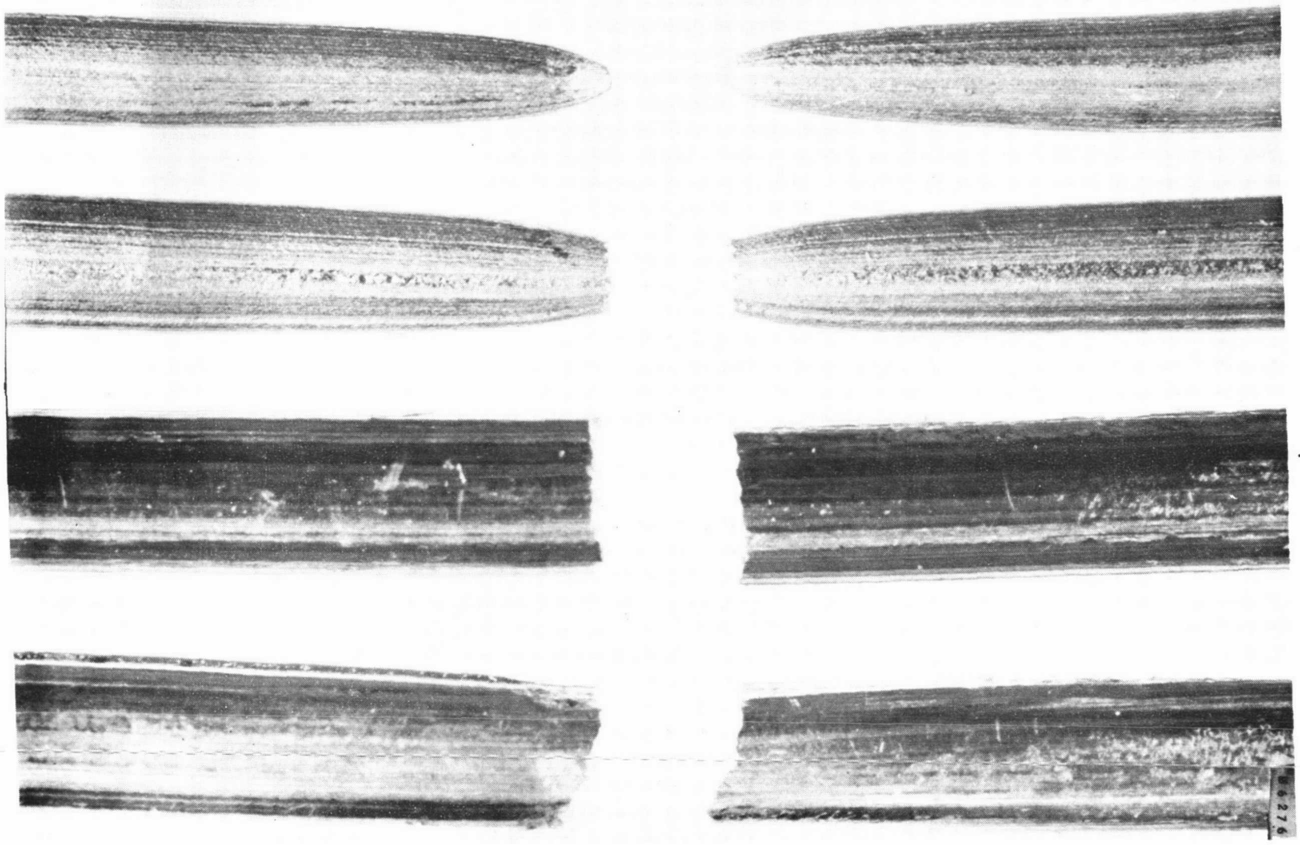
78°F

-100°F

-320°F

-423°F

60 Sn-40 Pb (60/40) Solder 15X



78°F

-100°F

-320°F

-423°F

95 Sn-5 Sb (Sb-5) Solder 15X

Figure 2. Photographs of Typical Tensile Fractures (Cont.)