Pak. j. sci. ind. res., vol. 38, no. 7, July 1995

DEVELOPMENT OF BIMETAL TEST SPECIMEN FOR TESTING MATERIALS AT HIGH HOMOLOGOUS TEMPERATURE

MOHAMMAD JAVED HYDER AND DAVID A. WOODFORD
Mechanical Engineering Department, Rensselaer Polytechnic Institute, Troy, New York 12180-3590, USA

(Received October 2, 1993; revised March 27, 1995)

A bimetal test specimen has been developed to be used for testing materials at high homologous temperatures. The testing material selected is 50/50 lead-tin solder. At room temperature its homologous temperature is 0.6. Specimen manufacturing method adopted is simple and economical. OFHC copper has been used as a rigid support to install extensometer for strain measurements and to hold the specimen by the testing machine grips. Copper has been used because it provides a strong bond with solder and it is easy to manufacture copper to the required shape and size. The strain produced in the copper is 123 times less than that produced in solder. Formula has been developed to calculate the strain produced in the gage section using the strain value measured using extensometer installed on copper.

Kew words: Test specimen, Fatigue, Creep.

Introduction

Study of solder has recently become important. Since fatigue failure of solder joints is a major cause of concern in electrical devices including surface mounted and power devices and a large number of equipments such as automobile radiators. Also solder operates at high homologous temperature, consequently, it is expected that the phenomenology of fracture under both sustained load and cyclic deformation should be analogous in many respects to that of high temperature materials.

So far solder has been tested for fracture using joint type specimen. Either cantilever rotating bending fatigue tests were performed on a soldered joint in copper wire [1] or fatigue shear tests were performed on solder layer between two copper blocks [2]. Solomon has also used a similar type of test specimen for creep [3] and hold time [4] tests using solder. Although these experiments have given good results for a typical type of tests but they can not represent the fatigue properties of solder due to specific shape of the test specimen. Also using these specimens the study only concentrated on the joints and bonding strength. Due to the shape and size of the specimens used it is not possible to evaluate the properties of the material being used. In this paper specimen proposed can be used to solely evaluate the material properties and not the joint study.

In this paper a general bimetal test specimen has been proposed for testing material at high homologous temperature. Present work has resulted during the process of applying the specimen proposed by Lacey *et al.* [1] to the unidirectional tension - compression fatigue test with different wave shapes of applied load.

Although the specimen has been discussed using low melting alloys but the same technique can be used with alloys/metals having high melting point. In this case rigid support should be selected such that it makes a good bonding with the material under test and higher melting point compared to the material to be tested.

Specimen preparation. Specimen is prepared by melting and casting solder in a Pyrex tube. The tip of one of the copper ends is dipped in a wetting material (soldering paste). Then a closely fitted Pyrex tube is inserted over the copper end. Solder in small pieces is put in the tube while it is being heated using a Bunsen burner (as shown in Fig. 1). When the tube is filled with molten solder then the other copper end is inserted in the tube after dipping in the wetting material. The second copper end is first heated for few minutes to make sure that temperature of copper is above the melting point of solder (216°C). The specimen is then held vertically

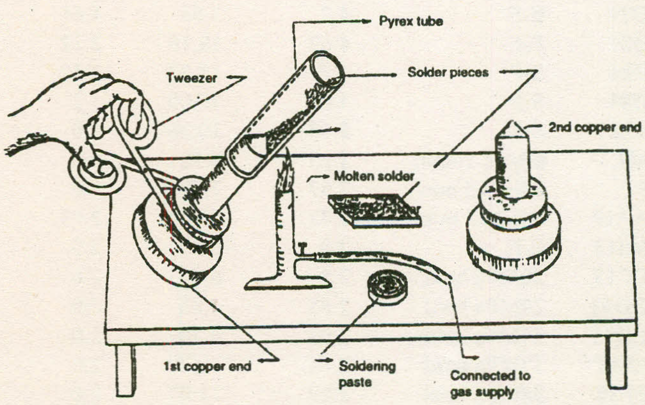

Fig. 1. Method of specimen preparation.

to allow the second copper end to slid all the way in, until the tube end touches the copper shoulder. The glass tube and copper end dimensions are such that the correct solder length is achieved. This semi-prepared specimen is left to cool for approximately 15 min. The first copper end is now heated until the copper tip begins to melt the solder attached to it. When sufficient amount of solder near the copper tip gets melted then the specimen is put vertically in such a way that first copper end is at the top. This ensures that the glass tube properly rests on copper shoulder. During the entire process it is important to keep temperature of the copper ends above the melting point of solder in order to provide a good bond.

After cooling the specimen for about an hour the glass tube is broken. The solder section of the specimen is carefully machined to its required shape and size. Finally the specimen is annealed at 85°C for 2 hrs and cooled down to room temperature in the annealing furnace.

Specimen dimensions. The final shape and size of the specimen evolved as a result of a number of unsuccessful experiments as shown in Table1[5]. Initial shape of the specimen is shown in Fig. 2. In all the experiments performed using this type of specimen failure took place at the copper solder interface. Initially it was thought that the bound was weak due to improper processing. To improve the bound care was taken to ensure that the temperature of the copper part was above the melting point of solder and the wetting material (soldering paste) was used. In spite of these steps, specimen continued to fail at the interface between copper and solder. Hence it was concluded that the failure was due to high shear stresses acting at the interface. In order to reduce the stresses acting at the interface the diameter of the gage section was reduced to one half of the diameter of the shoulder. This is in consistent with the ASTM standard EE-606. Also as indicated in Table 1, if the ratio of shoulder diameter to gage section diameter (i.e. d_{sh}/d_g) is less than 2, the failure may occur at the interface between shoulder and gage section. The diameter of the gage section could not be reduced further since it would reduce the machineability of the material (for being soft and thin). Also the applied load will have to be reduced for the same amount of stress, this will result in low accuracy since the range of load is reduced.

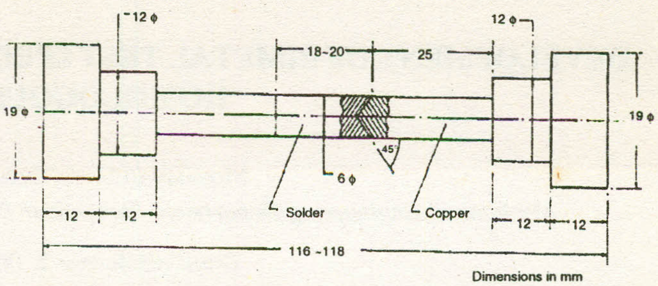

Fig. 2. Initial specimen shape.

Constraint due to the shoulder limited minimum gage length. As shown in Table-2, experiments performed with the ratio of gage length to gage section diameter of less than

TABLE 1. EXPERIMENTAL RESULTS SHOWING THE AFFECT OF GAGE SECTION DIAMETER AND LENGTH ON THE FAILURE MODE OF THE TEST SPECIMEN UNDER DIFFERENT LOADING WAVE SHAPES.

Exp. No	Experiment Type	Gage diameter mm	Gage length mm	Strain range %	Strain rate Sec^{-1}	lg/dg	ds/dg	Failure mode
Exp21	E-E	6.35	23.6	1.0	-	3.75	1	Copper solder interface
SetB11	E-E	6.35	15.25	1.2	-	3.75	1	Copper solder interface
SetB21	E-E	6.35	15.25	1.2	-	3.75	1	Copper solder interface
C21	E-E	4.93	6.3	2.32	.0001	1.278	1.29	Crack in gage section
D11	E-E	4.7	4.34	2.32	.0001	0.925	1.35	Crack in gage section
D21	E-E	4.7	3.53	1.61	.0001	0.751	1.35	Crack in gage section
D31	E-E	4.67	10.16	2.32	-	2.174	1.36	Copper solder interface
H21	S-F	4.7	12.32	2.32	10-3/10^{-4}	2.62	1.35	Shoulder gage interface
H41	S-F	4.65	15.09	1.2	10-3/10^{-4}	3.257	1.37	Copper solder interface
L32	S-F	3.18	10.26	1.0	10-3/10^{-4}	3.23	2.0	Crack in gage section
M1	ε-hold 10min	3.23	6.78	2.0	0.001	2.102	1.97	Necking in gage section
P1	ε-hold 5 min	2.57	7.52	2.0	0.001	2.945	2.49	Crack in gage section
AA11	ε-hold 5 min	2.72	8.97	2.93	0.0015	3.299	2.34	Crack in gage section
BB13	E-E	2.8	6.71	2.0	0.001	2.4	2.27	Crack in gage section
CC13	20MPa hold	2.8	6.25	2.0	0.001	2.21	2.27	Crack in gage section
DD13	20MPa hold	2.85	4.85	2.0	0.001	1.71	2.23	Did not fail in 14 hr.
DD11	24MPa hold	2.92	4.78	2.0	0.001	1.635	2.17	Did not fail in 14 hr.
EE11	17MPa hold	2.74	10.29	2.0	0.001	3.75	2.32	Crack in gage section
EE18	28MPa hold	2.69	11.07	2.0	0.001	4.11	2.36	Necking in gage section
FF13	24MPa hold	2.67	9.5	2.0	0.001	3.562	2.38	Crack in gage section
GG18	E-E	2.87	10.74	2.0	0.001	3.743	2.21	Crack in gage section

2.3 provided unsatisfactory results. The time per cycle for the test CC13 should have a value in between the tests EE11 and EE18 (Table 2) since the hold stress value is 20 MPa (between 17 and 28 MPa). But the time per cycle was observed to be extremely high (200 min. for the first cycle as compared to the range of 41 to 2 min.). This is due to the constraint posed by the shoulder, since length to diameter ratio (L/d=2.27) is less than 2.3. The minimum gage section length is found to be equal to 2.3 times the gage diameter (i.e. lgiv 2.3 dg). The factor 2.3 is obtained considering geometrical shape (Fig. 3) and was confirmed experimentally (Table 1). This minimum limit on the gage length can best be explained as follows:

In order to have a cross-section in the gage section which is un-affected by the shoulder requires that there should be at least one plane of maximum shear stress (planes at 45°) that does not pass through the shoulder (Fig.3). For this purpose (Fig. 3) straight lines at 45° angle are drawn tangential to the curvature of the shoulder and these lines have to end at the same cross-sectional plane at the centre of the gage length of the specimen. By doing so a plane at the center of the gage section is obtained which does not have any shoulder affect. This gives the minimum gage length for a given gage section diameter and the ratio of the 2 turns out to be 2.3. If the gage length is less than this ratio then a fraction of the cross-section is affected by the constraint of the shoulder. This results in a higher resistance to deformation. Considering all this the final shape of the specimen is obtained as shown in Fig. 4.

Strain distribution in copper and solder. One of the advantage of this proposed bimetal test specimen is that the extensometer used for the measurement of strain can be attached on the copper part (the rigid body) of specimen. It can

TABLE 2. EXPERIMENTAL DATA FOR THE ANALYSIS OF RESISTANCE OFFERED BY SHOULDER.

Experiment Number	Time per cycle (min) Cycle 1	Cycle 2	Cycle 3	Stress MPa	RatioL/d
EE17	41	45	34	17	2.315
CC13	200	160	87	20	2.273
EE18	< 2	< 2	< 2	28	2.358

TABLE 3. EXPERIMENTAL DATA TO STUDY STRAIN DISTRIBUTION ON COPPER AND SOLDER.

Load applied	p = 300 N
Diameter of copper	d_c = 6.35 mm
Youngs modules for copper	E_c = 117000 MPa
Extensometer length	L_G = 25.4 mm
Solder length	L_s = L/2
Copper length	L_c = L/2
Total strain measured	ε_G = 0.5%

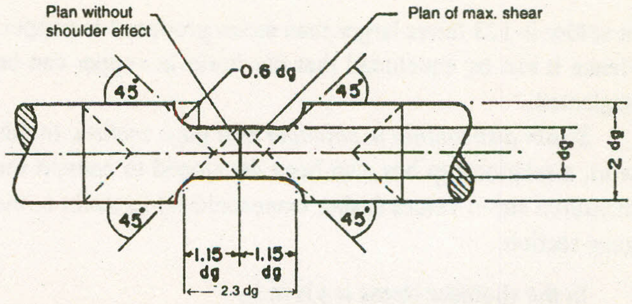

Fig. 3. Method of obtaining minimum gage length without the affect of deformation resistance offered by the shoulder.

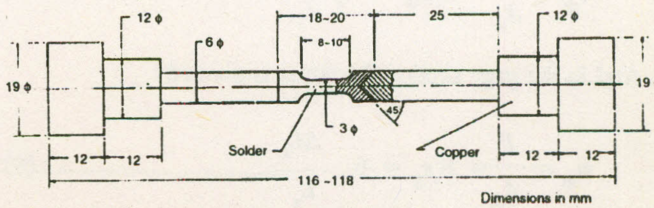

Fig. 4. Final specimen shape and dimensions.

not be attached on the solder because solder is very soft and the blade edges of the extensometer can cut through the solder. Hence it is required to know what percentage of strain measured corresponds to the strain in copper. A simple calculation based on experimental result demonstrates that strain in the copper part can be neglected.

The strain in copper can be written as:

$$\varepsilon_c = \frac{\sigma_c}{E_c} = \frac{P}{A_c E_c} \quad \text{......} (1)$$

and the total elongation measured using extensometer is

$$\Delta L_G = \Delta L_s + \Delta L_c \quad \text{......} (2)$$

Therefore elongation in the solder is

$$\Delta L_s = L_G \varepsilon_G - \frac{P}{A_c E_c} L_c \quad \text{......} (3)$$

Hence the strain in the solder is

$$\varepsilon_s = \frac{L_G \varepsilon_G}{L_s} - \frac{P}{A_c E_c} \frac{L_c}{L_s} \quad (4)$$

Now using the experimental result (Table 3) and using Eq.1.

$\varepsilon_c = 8.08.10^{-5}$

and using Eq. 4

$\varepsilon_s = 9.919.10^{-3}$

And the ratio is:

$$\frac{\varepsilon_s}{\varepsilon_c} = 123$$

It is obvious from the above result that strain produced in solder is 123 times larger than strain produced in copper. Hence it can be concluded that the strain in copper can be neglected.

Strain distribution in shoulder and gage section. In this work a relationship has also been developed to convert the measured strain values (using extensometer) to strain in the gage section.

In the shoulder stress is given by

$$\sigma_{sh} = \frac{P}{A_{sh}} = E_s\sigma_{sh} = E_s \frac{\Delta L_{sh}}{L_s} \quad \text{.....(5)}$$

And in the gage section the stress is given by

$$\sigma_{sh} = \frac{P}{A_{sh}} = E_s\varepsilon_g = E_s \frac{\Delta L_g}{L_g} \quad \text{.....(6)}$$

Using eqs. 5 & 6 elongation in the shoulder is

$$\Delta L_{sh} = \frac{A_g}{A_{sh}} \frac{L_{sh}}{L_g} \Delta L_s \quad \text{.....(7)}$$

And total elongation in solder is given by

$$\Delta L_s = \Delta L_{sh} + \Delta L_g \quad \text{.....(8)}$$

and using Eq. 7 and simplifying gives the total elongation becomes

$$\Delta L_s = \frac{A_g}{A_{sh}} L_{sh}\,\varepsilon_g + L_g\,\varepsilon_g \quad \text{.....(9)}$$

Using the strain measured from the extensometer and neglecting the strain in copper

$$\Delta L_s \cong \Delta L_G \quad \text{.....(10)}$$

Using above equations the strain in the gage section is given by

$$\varepsilon_g = \frac{\varepsilon_G\, L_G}{L_s + \frac{A_g}{A_{sh}} L_{sh}} \quad \text{.....(11)}$$

Eq. 11 is the required equation to be used for calculating the strain produced in the gage section when extensometer is used for the measurement of strain in the copper part of the specimen.

Conclusion

Bimetal test specimen proves to be a useful tool for testing materials at high homologous temperature. But high resistance is being offered by the shoulder when smaller length specimen is used. Therefore shape and dimensions of the specimen proposed in this paper are to be strictly followed. That is, the diameter of gage section should be less than or equal to one half of the diameter of the shoulder and the gage length of the specimen should be greater than or equal to 2.3 times the gage section diameter.

During the process of casting the specimen temperature of copper part should always be greater than the melting point of solder. The strain produced in copper part is negligible and the strain measured using extensometer installed on copper part of the specimen can be converted to the strain in the gage section using Eq. 11.

Acknowledgements. The author gratefully acknowledges the contribution of Donald Van Steele. All the machining work of specimen was done by him. Thanks for useful discussions on the development of this bimetal test specimen.

NOMENCLATURE

ΔL_s = Elongation in solder
L_s = Length of solder
ε_s = Strain produced in solder
ΔL_c = Elongation in copper
L_c = Length of copper
ε_c = Strain produced in copper
σ_c = Stress applied on copper
d_c = Diameter of copper part
E_s = Young modules of elasticity for solder
E_c = Young modules of elasticity for copper
σ_{sh} = Stress produced in shoulder
σ_g = Stress produced in gage section
ΔL_g = Elongation in gage section
ΔL_{sh} = Elongation in shoulder
ε_{sh} = Strain in shoulder
ε_g = Strain in gage section
L_g = Length of gage section
L_{sh} = Length of shoulder
A_{sh} = Cross sectional area of shoulder
A_g = Cross sectional area of gage section
P = Applied load
A_c = Cross sectional area of copper
ε_G = Strain measured using extensometer
ΔL_G = Elongation produced in the extensometer
L_G = Distance between the blade edges of the extensometer

References

1. T.G. Lacey and D.A. Woodford, Metallurgica, 22, 1543 (1988).

2. H.D. Solomon, Low Cycle Fatigue of 60/40 Solder - Plastic Sytrain Limited vs. Displacement Limited Testing, Proceedings of Electronic Packaging: Materials and Processes (Ed. J.A. Sartell, ASM, 1986), pp. 29-47.
3. H.D. Solomon, Creep Strain Rate Sensitivity and Low Cycle Fatigue of 60/40 Solder, Brazing and Soldering, 11, 68 (1986).
4. H.D. Solomon, The Influence of Hold Time and Fatigue Cycle Waveshape on the Low Cycle Fatigue of 60/40 Solder, Proceeding of the 38th Electronic Components Conference, IEEE (1988), pp 7-13.
5. M.J. Hyder, A Study of Fatigue Damage Using the Electrical Potential Method. Ph.D. Thesis, Rensselaer Polytechnic Institute, Troy, New York, (1991).