Key Engineering Materials Vols. 177-180 (2000) pp. 267-272

Characterization of Strain Rate-Dependent Shear Response of 63Sn/37Pb Solder under Uniaxial Torsion

L.H. Dai[1, 2], S.-W.R. Lee[1] and X.J. Huang[1]

[1]Department of Mechanical Engineering, Hong Kong University of Science and Technology, Clear Water Bay, Pokfulam Road, Kowloon, Hong Kong SAR, P.R. China

[2]On leave from State Key Laboratory of Nonlinear Mechanics, Institute of Mechanics, Chinese Academy of Sciences, Beijing 100080, P.R. China

Keywords: Electronic Packaging, Shear Strength, Sn-Pb Solder, Strain Rate Effect, Torsion

ABSTRACT

In the present study, a series of uniaxial torsion tests are performed to investigate the strain rate effect on the shear response of 63Sn/37Pb solder. The specimens are two pieces of Cu cylinders jointed by eutectic solder with standard SMT reflow process. The twisting load is applied using an MTS machine with torsion capability. Although the tests are quasi-static in nature, two loading rates with an order of difference are applied. The experimental results reveal that both the yield stress and the shear strength of Sn-Pb solder increase substantially when the loading rate is higher. From the experimental results, it is concluded that the 63Sn/37Pb solder has an obvious strain rate effect on the shear response.

1. INTRODUCTION

Surface mount technology (SMT) has become the mainstream in the electronics manufacturing industry since early 1980s. One of the features of SMT is that the solder is not only an electrical passage, but also a mechanical joint to fix the components on the printed circuit board (PCB). Therefore, the solder joint reliability is a major concern for the surface-mounted components [1]. In order to ensure the reliability of electronic products, a series of qualification tests need to be conducted. During these tests, the solder joints may be subjected to thermal and mechanical loading. The former refers to temperature cycling while the latter concerns vibration and impact. Because the qualification tests usually take a long time to obtain the results, it is desirable to perform modelling and simulation for parametric studies at the design stage so that the reasonable solder joint reliability could be achieved. In order to do so, it is essential to know the mechanical properties of solder materials. Therefore, material characterization is a major issue for the study of solder joint reliability [2].

In the literature, there were certain efforts dedicated to the material characterization of solders [3-4]. Since creep is considered the major damage mechanism of solder joints, most of previous studies were focused on the investigation of thermo-mechanical behaviours. The research on the dynamic effect of solders is still very limited [5-6]. This paper presents an experimental study to characterize the strain rate–dependent shear response of 63Sn/37Pb solder. During the course of this study, a series of uniaxial torsion tests are performed. The specimens are two pieces of Cu cylinders jointed by eutectic solder with standard SMT reflow process. The twisting load is provided by an MTS machine with torsion capability. Although the test is quasi-static in nature, two loading rates with an order of difference are applied. The results from the present study would serve as a good reference for the ensuing dynamic torsion tests.

2. UNIAXIAL TORSION TESTS

2.1 Specimen Preparation

In the present study, a pair of Cu cylinders are jointed together by the eutectic solder to make the specimen. In order to simulate the real solder joints, the soldering is performed using solder paste and standard reflow process. For the fabrication of specimens, an Al fixture is designed as shown in Fig. 1. The two Cu cylinders are aligned and clamped by the Al fixture with a fixed gap apart. The gap is filled with 63Sn/37Pb solder paste at room temperature. Then the whole assembly is placed in an SM500CXE-HT forced convection reflow oven and a standard reflow temperature profile is applied. After the reflow process, the specimen is removed from the Al fixture. Certain surface polishing work may be required in order to maintain a uniform diameter for the whole specimen. In addition, it is necessary to perform X-ray inspection to check the integrity of soldering. Fig. 2 shows a typical X-ray picture of the solder joint between the two Cu cylinders. It can be seen that Cu and 63Sn/37Pb are well-bonded together and no voids are observed in the solder. The last step for specimen preparation is to cut the solder to form a "dog-bone" shape as illustrated in Fig. 3. A lathe machine is employed for the shaping. The purpose of such arrangement is to ensure that, under the applied uniaxial torsion, the failure would occur in the solder, not at the interface between the Cu cylinder and the solder.

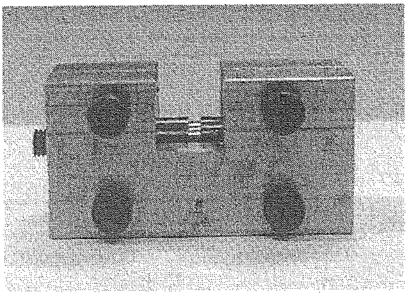


Fig. 1: Al fixture for the fabrication of specimens

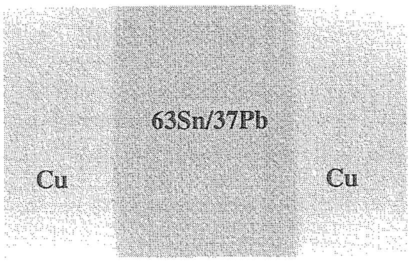


Fig. 2: X-ray inspection for quality assurance of soldering

2.2 Experimental Configuration

A series of uniaxial torsion tests are conducted in the present study. An MTS-858 machine with torsion capability is employed to perform the tests. The schematic diagram of experimental set-up is illustrated in Fig. 3. Although the test is quasi-static in nature, two loading rates with an order of difference (2°/min and 20°/min) are applied to investigate the strain rate-dependent shear response of 63Sn/37Pb solder.

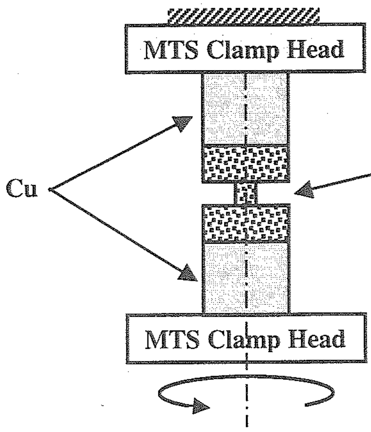


Fig. 3: Schematic diagram for the solder specimen subject to uniaxial torsion

2.3 Evaluation of Shear Strength

For the characterization of shear strength under uniaxial torsion, the specimens are usually prepared in the shape of a thin-walled tube in order to achieve uniform shear stress in the material. However, in the present study, it is rather difficult to make the specimen a thin-walled tube because the solder joint is formed by the reflow process. Therefore, the specimens are prepared in the form of solid cylinders. As a result, the shear stress in the solder varies along the radial direction. For the evaluation of shear strength in the present case, a sophisticated stress analysis is needed to extract the shear response from the experimental torque-twisting angle data. The procedures to derive such result are given as follows.

Consider a solid cylinder subjected to pure torsion, in which the twist θ has the unit of radian per unit length. The shear strain is then given by

$$\gamma = r\theta \tag{1}$$

where r is the radius of the field point under consideration. It should be noted that this relation is considered valid even if the deformation is in the plastic range. Within the elastic range, the shear stress is proportional to the shear strain and can be determined by the following relation

$$\tau = G\gamma \tag{2}$$

where G is the shear modulus of materials. However, for uniaxial torsion in the plastic range, the shear stress inside the solid cylinder no longer has a linear relationship with the distance from the axis of torsion. The derivation of explicit functional form is given below.

When a pure torsion is applied to a solid cylinder, the torque on a cross-section can be expressed as

$$M = 2\pi\int_0^R \tau r^2 dr \tag{3}$$

where R is the outline radius of the cylinder. Assume the shear stress is related to the shear strain by a general constitutive relation

$$\tau = f(\gamma) \tag{4}$$

Substituting Eqs. (1) and (4) into (3) and changing the variable from r to γ lead to

$$M = 2\pi \int_0^{\gamma_R} f(\gamma(\left(\frac{\gamma}{\theta}\right)^2 \frac{d\gamma}{\theta} \quad (5)$$

and

$$M(\theta)^3 = 2\pi \int_0^{\gamma_R} f(\gamma)\gamma^2 d\gamma \quad (6)$$

where $\gamma_R = R\theta$. Differentiating Eq. (6) with respect to θ gives

$$\frac{d}{d\theta}(M\theta^3) = 2\pi R f(R\theta) R^2 (\theta)^2 = 2\pi R^3 (\theta)^2 f(R\theta) \quad (7)$$

Define the shear stress on the outer surface of the solid cylinder by $\tau_R = f(R\theta)$. Then

$$3M(\theta)^2 + (\theta)^3 \frac{dM}{d\theta} = 2\pi R^3 (\theta)^2 \tau_R \quad (8)$$

Consequently,

$$\tau_R = \frac{1}{2\pi}\frac{1}{R^3}(\theta \frac{dM}{d\theta} + 3M) \quad (9)$$

Therefore, if $M \sim \theta$ curve is known, the shear stress on the outer surface of the cylinder can be calculated using Eq. (9). In the case of $dM/d\theta = 0$, the shear strength can be evaluated as

$$\tau_b = \frac{3M_{max}}{2\pi R^3} \quad (10)$$

Table 1: Shear strength of 63Sn/37Pb solder under loading rate of $\dot{\varphi} = 2^0/\text{min}$.

Sample No	R (mm)	L_s (mm)	M_{max} (N.m)	$\dot{\gamma}(s^{-1})$	τ_b (MPa)
1	3.61	2.00	2.582	1.05×10^{-3}	26.2
2	2.92	2.00	1.231	8.50×10^{-4}	23.6
3	1.88	2.00	0.345	5.47×10^{-4}	24.8
4	2.46	2.00	0.979	7.16×10^{-4}	31.4
5	2.55	2.00	1.042	7.42×10^{-4}	29.8
6	1.83	2.00	0.300	5.33×10^{-4}	23.4
7	1.94	2.00	0.448	5.65×10^{-4}	29.2
8	1.92	2.00	0.435	5.69×10^{-4}	29.4
Average	-	-	-	6.95×10^{-4}	27.2

Table 2: Shear strength of 63Sn/37Pb solder under loading rate of $\dot{\varphi} = 20^0/\text{min}$.

Sample No	R (mm)	L_s (mm)	M_{max} (N.m)	$\dot{\gamma}(s^{-1})$	τ_b (MPa)
9	1.94	2.00	0.552	5.65×10^{-3}	36.1
11	1.81	2.00	0.356	5.27×10^{-3}	28.9
12	1.82	2.00	0.494	5.29×10^{-3}	38.8
13	1.95	2.00	0.576	5.67×10^{-3}	37.1
14	1.80	2.00	0.459	5.24×10^{-3}	37.6
15	1.85	2.00	0.511	5.38×10^{-3}	38.5
Average	-	-	-	5.42×10^{-3}	36.1

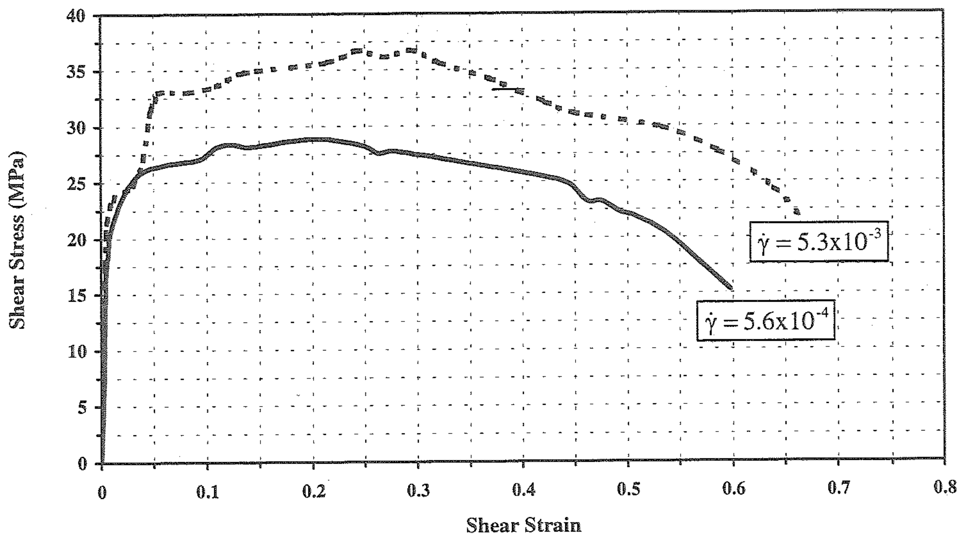
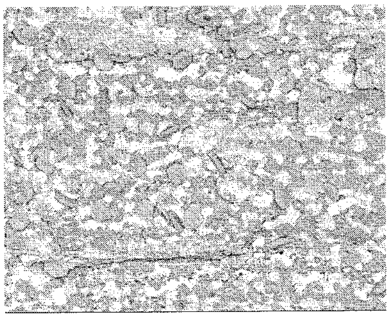
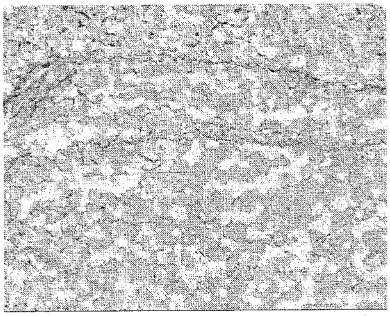


Fig. 4: Typical shear stress-strain curves of 63Sn/37Pb solder under uniaxial torsion



(a) $\dot{\varphi} = 2^0$ / min



(b) $\dot{\varphi} = 20^0$ / min

Fig. 5: SEM micrographs of the fracture surface of 63Sn/37Pb solder

3. EXPERIMENTAL RESULTS

A series of uniaxial torsion tests were conducted on 63Sn/37Pb solder specimens using MTS 858 material test system. In order to investigate the strain rate effect on the shear response of the solder, two levels of loading rate, namely, $\dot{\varphi} = 2^0$/min and 20^0/min, were applied. The measured shear strength of the solder samples at these two levels of strain rate are given in Table 1 and Table 2, respectively. The typical shear stress-strain curves of 63Sn/37Pb solder are shown in Fig. 4. From these experimental results, it is obvious that the strain rate has a significant effect on the shear response of 63Sn/37Pb solder. There is roughly a 30 percent increase in the shear strength as the strain rate increases by approximately one order of magnitude.

Fig. 5 shows SEM micrographs of the fracture surface of the solder. A typical two-phase eutectic micro-structure (Pb in the light phase and Sn in the dark matrix) can be identified. It is found that the grains have been stretched after loading. In order to understand the strain rate-dependent behavior of 63Sn/37Pb solder, dynamic tests at much higher strain rate are necessary. A miniature split Hopkinson torsion bar device is under development. Further tests will be conducted to investigate the strain effects on the shear response of various Sn-Pb solders.

4. CONCLUSIONS

A series of uniaxial torsion tests were performed in the present study to investigate the strain rate effect on the shear response of 63Sn/37Pb solder. The specimens were two Cu cylinders soldered together with standard SMT reflow process. A torsional MTS machine was employed to apply the loading. Although the test was quasi-static in nature, two loading rates with an order of difference were applied. The experimental results revealed that the strain rate has a significant effect on the shear response of eutectic Sn-Pb solder. It was identified that there was roughly a 30 percent of increase in the shear strength as the strain rate increased by approximately one order of magnitude. The results from the present study would serve as a good reference for the ensuing dynamic torsion tests.

ACKNOWLEDGEMENTS

The Research Grant Council of Hong Kong sponsored this study through the grant HKUST6047/99E to the Hong Kong University of Science and Technology (HKUST). The authors wish to acknowledge this support.

REFERENCES

[1] J.S. Hwang, *Modern Solder Technology for competitive Electronics Manufacturing*, McGraw-Hill, New York, NY, (1996).
[2] J.H. Lau and Y.H. Pao, *Solder Joint Reliability of BGA, CSP, Flip Chip, and Fine Pitch SMT Assemblies*, McGraw-Hill, New York, NY, (1997).
[3] K.R. Stone, R.Duckett, S. Muckett and M. Warwick, *Brazing and Soldering*, 4 (1983) 20-27.
[4] Y.-H. Pao *et al.*, *Journal of Electronic Packaging,* 114 (1992)135-144.
[5] M.S. Liang, *Studies on Constitutive Relation of Sn/Pb Alloy at High Strain Rate*, MSc. Thesis, National Twain University, Taipei, Taiwan, (1996).
[6] X.Q. Shi, W. Zhou, H.L.J. Pang and Z.P. Wang, *Journal of Electronic Packaging*, ASME Transactions, 121 (1999) 179-185.