Proceedings of IPACK'01
The Pacific Rim/ASME International Electronic Packaging
Technical Conference and Exhibition
July 8-13, 2001, Kauai, Hawaii

IPACK2001-15553

Characterization of Strain Rate-Dependent Behavior of 63Sn-37Pb Solder Alloy

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ABSTRACT

A novel punch shear testing method is introduced in this study to investigate the strain rate-dependent shear behavior of solder materials. Both static and dynamic shear strengths of 63Sn-37Pb solder were characterized. The experimental results indicate that the shear response of solder alloy is very sensitive to the strain rate and the dynamic shear strength is much higher than the static one. Besides, the localized crack band was found in the dynamic punch shear tests. This phenomenon reveals that the adiabatic shear localization should be a significant mechanism for controlling the mechanical behavior of 63Sn-37Pb solder alloy under dynamic shear loading.

INTRODUCTION

Sn-Pb solder alloy is one of the most popular interconnecting materials in the industry of electronics manufacturing. Solder joints provide not only mechanical fixture but also electrical passage for components assembled by surface mount technology (SMT). Therefore, the reliability of solder joints is a major concern for the surface-mounted devices (SMDs) [1]. For the stress analysis and fatigue life prediction of solder joints, it is very important to identify the correct material constitutive relation for the analytical model. All these require precise data from experiments that characterize the mechanical behavior of solder joints under external thermomechanical loading. However, characterizing the solder joints presents a challenge due to that the solder material is highly temperature and strain rate sensitive.

In the past decades, a substantial amount of research efforts have been made to study the mechanical behavior of solder joints using a wide range of testing methods, specimen design and the parameters [2]. Enke *et al.* [3] considers the single lap joints, Dareaux and Banerji [4] consider the double lap test, Sandstrom et al. [5] ring and plug joints, and Unal *et al.* [6] adopt the Iosipescu shear method. In addition to the experimental work, some numerical studies have been carried out in the past to address the mechanical behavior of solder alloy [7-8]. However, most of the previous research works in this field were mainly concentrated on the static behavior of solder joints. In some cases, the solder joints may be subjected to dynamic loadings (impact and vibration). The research on the dynamic effect of the solder joints is still very limited. Therefore, in order to obtain a full understanding of the overall SMT solder joints reliability issue and develop some advanced package concepts the research on dynamic behavior of the solder joints is in great demand.

In this paper, a novel punch shear testing method is introduced. With this technique, both dynamic and static shear strengths of 63Sn-37Pb solder joints are measured. The experimental results demonstrate that the pun shear behavior of 63Sn-37Pb solder joints is very sensitive to the strain rate.

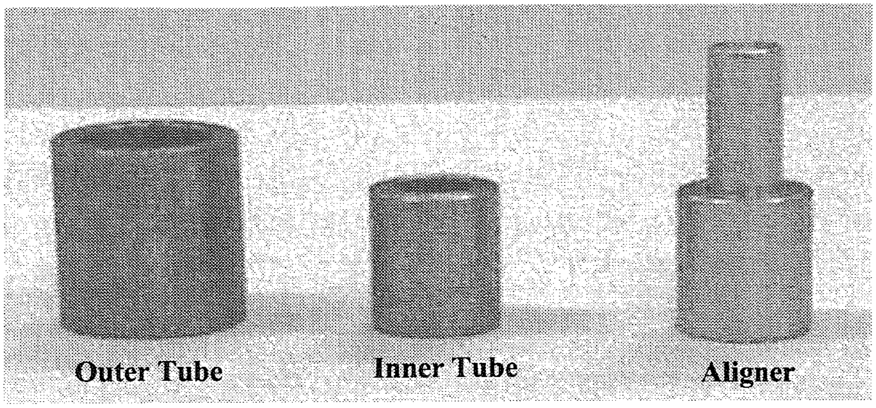
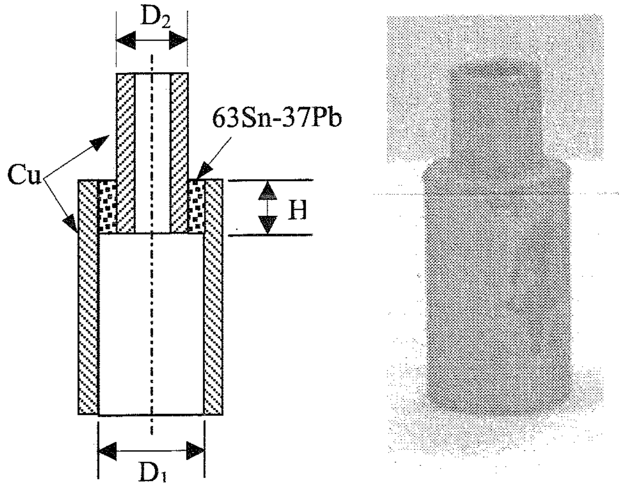


Fig. 1: Components of Punch Shear Test Specimen



(a) Schematic Cross-section (b) Actual Specimen

Fig. 2: Assembly of Punch Shear Test Specimen

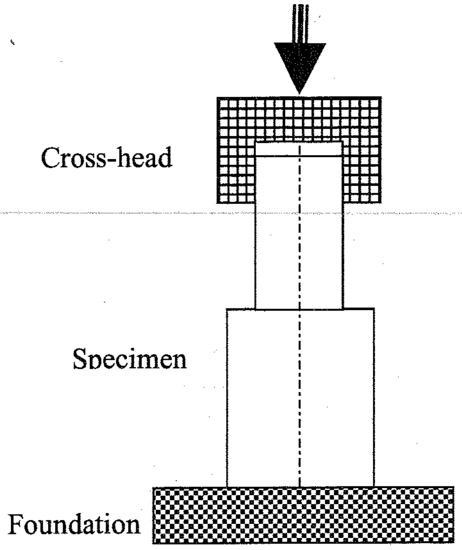


Fig. 3: Static Punch Shear Test

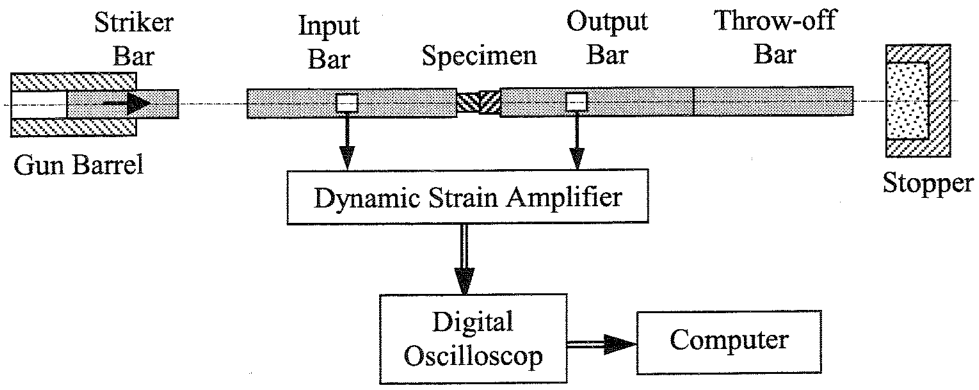


Fig. 4: Dynamic Punch Shear Test Using SHPB Testing System

EXPERIMENTAL PROCEDURES

Specimen Preparation

In the present study, a 63Sn-37Pb eutectic solder joint is made by soldering the outer surface of the inner Cu circular tube to the inner surface of the outer Cu circular tube. Fig. 1 presents pictures of the inner Cu tube, the outer Cu tube and the stepped-cylinder aligner. The objective of using Al space in preparing the solder joint is to ensure that the outer and inner tubes are coaxial. So, the ring clearance between the outer surface of the inner Cu tube and the inner surface of the outer Cu tube of uniform thickness can be kept. In order to simulate the real solder joints, the soldering is performed using solder paste and standard reflow process. In preparing the solder joint specimen, two Cu tubes with Al space are aligned. The narrow ring clearance between the outer surface of the inner Cu tube and the inner surface of the outer Cu tube is filled with solder paste at room temperature. The whole assembly is then placed in an SM500CXE-HT forced convection reflow oven and standard reflow profile is applied. After reflow process, the assembly is moved to room temperature, air cooled, and the Al space is then removed out from the assembly. Finally, a solder joint specimen is obtained. Fig. 2 shows the picture and cross-section of the punch shear specimen. Because shear takes place within the clearance between the outer surface of the inner Cu tube and the inner surface of the outer Cu tube, this clearance should be small in order to interpret the experimental results accurately. In present study, this clearance is about 0.5 mm.

Static Punch Shear Tests

To study the strain rate dependent punch shear behavior of the solder joint, punch shear tests were conducted over a wide range of strain rates. The static punch shear tests were conducted using MTS 810 material test machine. The loading head velocity was fixed at 0.5 mm/min. for all static tests. The experimental arrangement is shown in Fig. 3. According to this arrangement, the average shear stress τ can be calculated by

$$\tau = \frac{P}{\pi \overline{D} H} \tag{1}$$

where P is load, H is the length of joint and $\overline{D} = (D_1 + D_2)/2$. When the load P in Eq. (1) is taken as the maximum load P_{max}, the average shear strength of the solder joint is obtained.

In general shear strain is defined by

$$\gamma = \frac{\partial u}{\partial r} + \frac{\partial w}{\partial z} \tag{2}$$

where u and w are the displacements along the axial direction (z-direction) and radial direction (r-direction) respectively. In the present punch test, $\partial w / \partial z = 0$ and $\partial u / \partial r \approx u / B$, here $B = (D_1 - D_2)/2$. Hence, the average shear strain in the solder joint is estimated by

$$\gamma = \frac{u}{B} \tag{3}$$

and the average shear strain rate can be estimated by

$$\dot{\gamma} = \frac{v}{B} \tag{4}$$

where v is the velocity of loading head of MTS machine. Since the loading velocity v is known and the $P \sim u$ curve is recorded for each test, the static average shear strength and shear stress –strain curve of the solder joints can be obtained by making use of Eqs. (1), (3) and (4).

Dynamic Punch Shear Tests

Dynamic punch shear tests were conducted with a split Hopkinson pressure bar (SHPB). The Hopkinson bar technique has been widely used to determine the dynamic mechanical behavior of material at high rate of loading for several decades. The general theory for this SHPB is described in detail in Reference [9], so only brief description will be given here. A schematic of SHPB and recording system is shown in Fig. 4. The pressure bars are made of high strength steel, 12.7 mm in diameter and 1000 mm in length for both incident and transmitted bars. The solder joint specimen assembly is sandwiched between the incident and transmitted bars. In order to compare the dynamic results with those of static tests, the specimen assembly is identical for both cases. Strain gages are bonded at the mid-span of both the incident and transmitted bars. The strain gages used on the bars are 120Ω and connected in a half Wheatstone bridge arrangement data acquisition is performed with a TML DC-92D dynamic strain meter and a HP 54540A digital oscilloscope with a sampling rate of 1GSa/s. Velocity of the strike bar is measured using laser trigger and timer.

The pressure pulse for each test was initiated by axial impact from the striker bar that was accelerated to desired impact velocity by compressed air. The striker bar, 330 mm in length and 12.7 mm in diameter, is made the same material as that of the pressure bars. This manner of loading produces a loading pulse in the incident bar with constant amplitude that is proportional to the impact velocity of the striker. Wave propagation effect in the specimen is ignored because the loading pulse is very long compared to the specimen length.

When the striker hits the incident bar, a compressive pulse is produced, then propagates through the punch shear specimen and the transmitted bar. According the theory of elastic wave, the instantaneous stresses in the incident bar and the transmitted bar can be expressed respectively by:

$$\sigma_1 = E_0(\varepsilon_i + \varepsilon_r) = \rho_0 C_0^2(\varepsilon_i + \varepsilon_r) \quad (5)$$

$$\sigma_2 = E_0\varepsilon_t = \rho_0 C_0^2\varepsilon_t) \quad (6)$$

where ε_i, ε_r and ε_t are the incident, reflected and transmitted strain pulses respectively. ρ_0 and C_0 are the density and the longitudinal stress wave speed of Hopkinson bar, respectively .

According to the equality of the forces acted on the two interfaces between the specimen and the incident and transmitted bars, there is

$$\sigma_1 A_0 = \sigma_1^{Cu} A_1^{Cu} \quad (7)$$

$$\sigma_2 A_0 = \sigma_2^{Cu} A_2^{Cu} \quad (8)$$

where σ_1^{Cu} and A_1^{Cu} are stress and section area of the outer copper tube respectively, while σ_2^{Cu} and A_2^{Cu} are the corresponding values of the inner copper tube. A_0 is the cross-section area of the pressure bars.

In fact, shearing takes place within the ring clearance with thickness of B=($D_1 - D_2)/2$. According to the force balance in the specimen, there is:

$$\pi D_1 H \cdot \tau_1 = \sigma_1^{Cu} A_1^{Cu} \quad (9)$$

$$\pi D_2 H \cdot \tau_2 = \sigma_2^{Cu} A_2^{Cu} \quad (10)$$

Hence, one can derive

$$\tau_1 = \frac{A_1^{Cu}}{\pi D_1 H} \cdot \sigma_1^{Cu} \quad (11)$$

$$\tau_2 = \frac{A_2^{Cu}}{\pi D_2 H} \cdot \sigma_2^{Cu} \quad (12)$$

From Eqs. (5) ~ (12), one can derive

$$\tau_1 = \frac{A_0}{\pi D_1 H} \rho_0 C_0^2 (\varepsilon_i + \varepsilon_r) \quad (13)$$

$$\tau_2 = \frac{A_0}{\pi D_1 H} \rho_0 C_0^2 \varepsilon_t \quad (14)$$

The average shear stress in the solder joint specimen can be obtained by averaging τ_1 and τ_2 .

According to Eqs. (2) and (3), the shear strain γ can be estimated by

$$\gamma = \frac{\Delta u}{B} \quad (15)$$

where Δu is the relative axial displacement and defined by

$$\Delta u \equiv u_1 - u_2 = \int_0^t C_0(\varepsilon_i - \varepsilon_r)dt - \int_0^t C_0 \varepsilon_t dt \quad (16)$$

From the uniform assumption in the SHPB technique that $\varepsilon_i + \varepsilon_r = \varepsilon_t$, the shear strain can be determined by

$$\gamma = -\frac{C_0}{B}\int_0^t (\varepsilon_i - \varepsilon_r - \varepsilon_t)dt = -\frac{2C_0}{B}\int_0^t \varepsilon_r dt \quad (17)$$

Shear strain rate can be determined by

$$\dot{\gamma} = -\frac{C_0}{B}(\varepsilon_i - \varepsilon_r - \varepsilon_t) = -\frac{2C_0}{B}\varepsilon_r \quad (18)$$

Therefore, the average dynamic shear strength and dynamic shear stress – strain curves of the solder joint can be determined by means of Eqs. (13), (14),

Table 1: Static Punch Shear Test Results

#	D_1 (mm)	D_2 (mm)	H (mm)	P_{max} (N)	τ_b (MPa)
1	9.01	7.97	4.01	4012	37.5
2	9.01	7.97	4.02	3716	34.7
3	9.03	7.97	4.01	3167	29.6
4	9.02	7.97	4.00	3098	29.1
5	9.00	7.97	3.98	3098	29.2
6	9.02	7.97	3.98	2883	27.2
7	9.01	7.97	4.01	3757	35.1
8	8.96	8.40	4.00	3300	30.3
Ave					31.6

Table 2: Dynamic Punch Shear Test

#	D_1 (mm)	D_2 (mm)	H (mm)	τ_1 (MPa)	τ_2 (MPa)	τ_b (MPa)
1	9.00	7.97	4.02	67.8	76.5	72.2
2	8.99	7.97	4.02	66.4	75.1	70.8
3	9.00	7.97	4.00	63.1	71.0	67.1
4	8.99	7.97	3.98	71.3	80.9	76.1
5	8.99	7.97	3.97	68.5	77.7	73.1
6	9.00	7.98	3.98	64.3	73.1	68.7
7	8.98	7.97	3.98	70.3	79.7	75.0
Ave						71.9

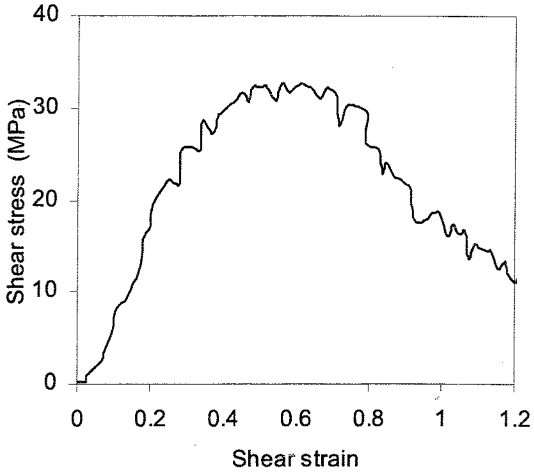


Fig. 5: Stress-Strain Response of 63Sn/37Pb Solder under Static Punch Shear

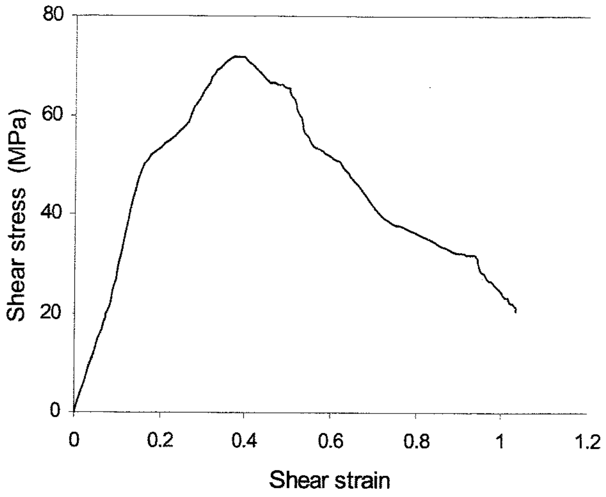


Fig. 6: Stress-Strain Response of 63Sn/37Pb Solder under Dynamic Punch Shear

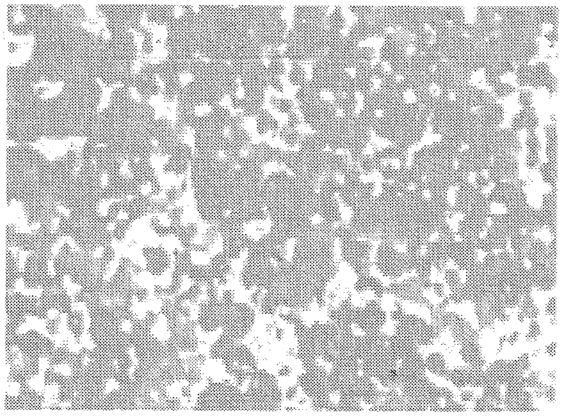


Fig. 7: Microstructure Pattern of 63Sn-37Pb Solder under Static Punch Shear

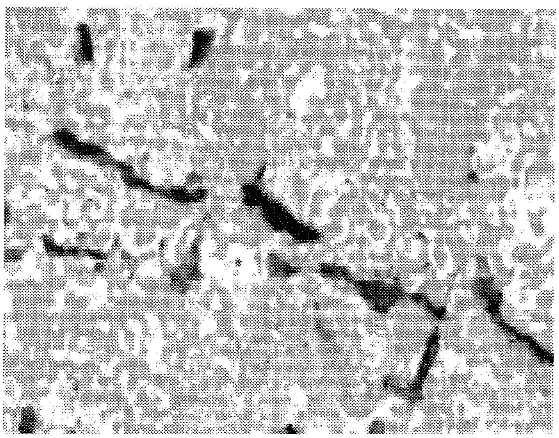


Fig. 8: Microstructure Pattern of 63Sn-37Pb Solder under Dynamic Punch Shear

(17) and (18). For all dynamic punch shear tests, the velocity of the striker is fixed at 11.6 m/s.

EXPERIMENTAL RESULTS

In both static and dynamic experiments, the average punch shear strength and stress-strain curve of the 63Sn-37Pb solder joint are obtained. Table 1 and Table 2 give the static and dynamic shear strength respectively. Figs. 5 and 6 present typical static and dynamic shear stress-strain curves respectively. From the present experimental results, one can find that the average dynamic shear strength of the solder joint is more than double the static one. Since the average shear strain rate in the static punch tests is about 1.5×10^{-2} s^{-1} and 3.0×10^{3} s^{-1}, this result demonstrate clearly that the shear behavior of 63Sn-37Pb solder is very sensitive to the strain rate. Therefore, the effect of strain rate should be considered in the reliability analysis of the solder joint. Additionally, by making use of scanning electronic microscope (SEM) was utilized to perform a post-test inspection on the solder joint specimen. Figs. 7 and 8 show the microstructure patterns in the solder joint after static and dynamic punch shear loading. The figure show a typical two-phase eutectic microstructure of the solder, with light phase of Pb in the dark matrix of Sn. Examination of the static punch shear failed specimens shows that the grains have been stretched and rotated. In the dynamic case, some micro cracks can be seen and these cracks are localized into a narrow band, as shown in Fig. 8. This is a typical failure mode that is called as the adiabatic shear localization (ASL) of materials at high strain rate. It is well known that the formation of ASL will soften the overall mechanical behavior of the material. Obviously, not only can high strain rate strengthen the mechanical behavior of the solder joint, but also soften the mechanical behavior due to ABL. So, a full understanding on the strain rate effect on the mechanical behavior of the solder joint is needed in future research.

CONCLUSIONS

In this paper, a novel punch shear test method is introduced. By making use of this test method, both static and dynamic shear behavior of 63Sn-37Pb solder joint was investigated. The experimental results have demonstrated that the shear behavior of the solder joint is very sensitive to the strain rate and the dynamic shear strength of the solder joint is more than double the static one. Additionally, the formation of the localized crack band in the dynamic punch shear solder joint post-test specimen has demonstrated that the adiabatic shear localization is important for controlling the mechanical behavior of the solder joint.

ACKNOWLEDGMENTS

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.

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