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Characterization of Strain Rate-Dependent Behavior of 63Sn-37Pb Solder Using Split Hopkinson Torsional Bars (SHTB)

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ABSTRACT

The present study is aimed at the experimental characterization of strain-rate dependent behaviour of solder materials under impulsive shear loading. In order to achieve this objective, a unique testing technique, namely, split Hopkinson torsion bar (SHTB) is employed. The solder material under investigation is 63Sn-37Pb. The experimental results indicate 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 much higher than the static one.

INTRODUCTION

Surface mount technology (SMT) was developed in the 80s and has become the main stream for board level assembly in the electronics manufacturing industry [1]. For surface mounted components (SMC), the solder joints are not only the passage of electrical signal and power/ground, but also the mechanical fixture to hold the components in position on the printed circuit board (PCB). Since the solder joints are rather small and are subjected to various thermal mismatch during service, they are relatively susceptible to temperature cycling (TC) [2]. Because the thermal fatigue life of solder joints is a critical issue for SMCs, the investigation on solder joint reliability under TC has been a popular research topic in the past decade [3-5]. Besides thermal loading, in practice, the electronic components may be subjected to mechanical vibrations and shocks during shipping and service [6]. For instance, automotive electronics are constantly under vibrations and hand-held devices may easily drop on the ground. As a consequence of these undesired loading conditions, severe solder joint reliability issues may be induced. However, the investigations on the aforementioned topics are relatively scarce, especially in the area of modeling [7]. One of the major reasons for this situation is that the dynamic mechanical properties of solder materials are not yet available [8]. Before any meaningful modeling can be reached, the mechanical behavior of solders under impulsive loading must be characterized [9].

In the present study, the strain-rate dependent mechanical behavior of 63Sn-37Pb solder under impulsive shear loading is characterized using the split Hopkinson torsion bar (SHTB) technique [10-12]. The solder specimen is reflowed to joint two split torsion bars, which are made of copper (Cu). Two dynamic shear strain gauges are installed on the input bar and the output bar, respectively, for data acquisition. Part of the input bar is clamped and subjected to a twisting torque. Once the clamping force is suddenly removed, the pre-stored energy will turn into a sharp torsional pulse to load the solder specimen. With the signals from the two strain gauges on the torsion bars, the dynamic shear modulus and strength of solder specimen can be characterized. The outcome of this study should be very valuable to the researchers in the area of solder joint reliability and will provide a foundation for modeling solder joints under dynamic loading in the future.

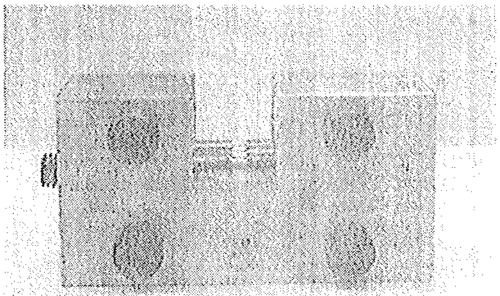


Fig. 1: Fixture for Making SHTB Specimen

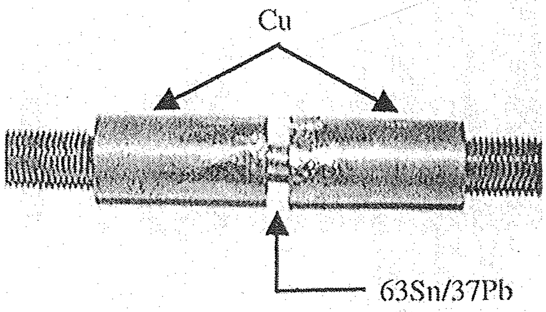


Fig. 2: SHTB Specimen with Solder and Copper

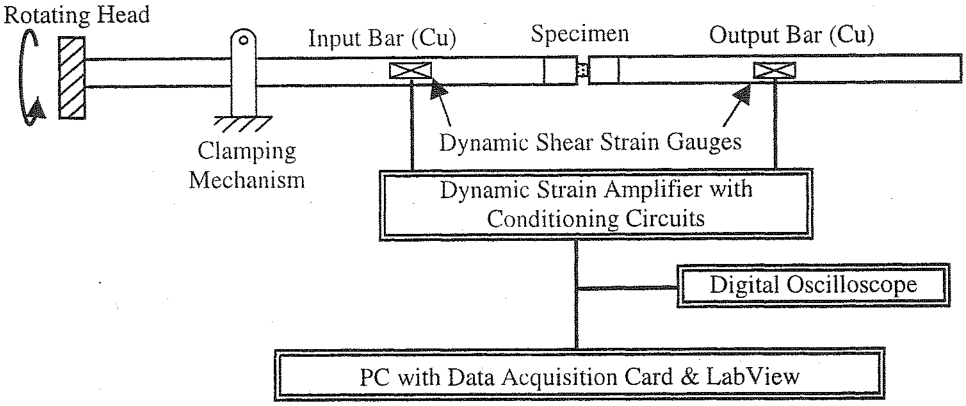
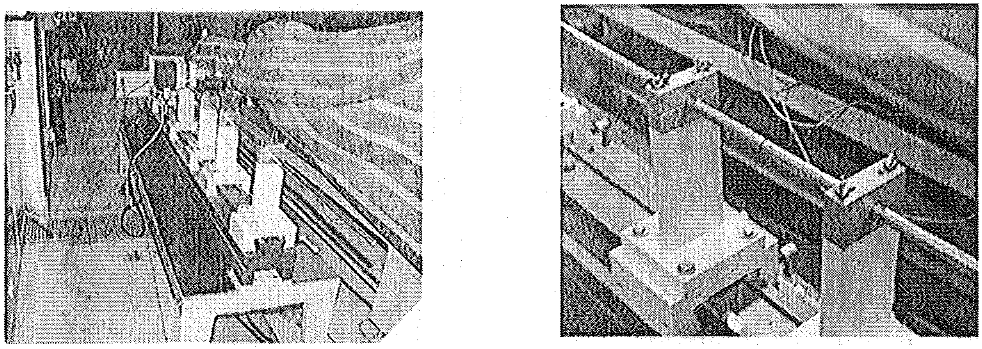
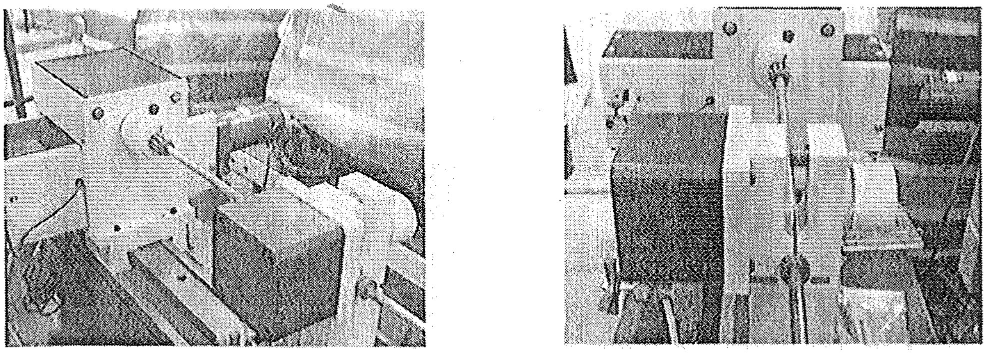


Fig. 3: Schematic Diagram for SHTB Testing System



(a) Overview of SHTB Device

(b) Testing Specimen Section



(c) Torsional Energy Storage Section

(d) Clamping Mechanism

Fig. 4: Slip Hopkinson Torsional Bar (SHTB) Testing System

EXPERIMENTAL PROCEDURES

In the present study, the SHTB specimen is made by jointing a pair of Cu cylinders with 63Sn-37Pb eutectic solder. For the fabrication of specimens, an aluminium (Al) fixture is designed as shown in Fig. 1. The two Cu cylinders (with a diameter of 8 mm) are aligned and clamped by the Al fixture with a fixed gap apart. The gap is filled with solder paste at room temperature. Then the whole fixture is placed in a bench-top forced convection reflow oven and a standard reflow temperature profile is applied to form the solder joint. 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, non-destructive inspection with X-ray imaging system is performed to verify the integrity of solder joint. The last step for specimen fabrication is to trim the solder to form a "dog-bone" shape as shown in Fig. 2. A lathe machine is employed for the trimming. 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. Note that the gauge length is 2 mm and the diameter is about 2 mm.

Fig. 3 illustrates the schematic diagram of SHTB testing system. The actual device used in the present study is shown in Fig. 4. This equipment consists of two members, namely, input bar (1000 mm long) and output bar (700 mm long), which are made of Cu and have a diameter of 8 mm (see Fig. 4b). The afore-mentioned SHTB specimen is attached to the two split torsion bars by screw fastening (refer to Figs. 2 and 4b). Two dynamic shear strain gauges are installed on the input bar and the output bar, respectively, for data acquisition. One end of the input bar is attached to a mechanical loading device and subjected to a twisting torque (see Fig. 4c). The rotating head for providing torque pre-load is controlled by a servo-motor so that a precise initial twisting angle can be specified.

At a distance (400 mm) from the loading end, the input bar is clamped by a mechanism with special design (see Fig. 4d). This mechanism mainly consists of a U-shape clamp, a fastening bolt, and a fast-response hydraulic cylinder. The clamping force is provided by tightening the bolt. The torsional energy is stored in the front end of the input bar by twisting with the rotating head. Once the test is ready to launch, the hydraulic cylinder can provide a pulling force (up to 40 kN) instantaneously to break the fastening bolt. Consequently, the stored elastic energy will be released and generate a sharp torsional pulse to load the solder specimen. With the signals from the strain gauges on the torsion bars, the dynamic constitutive relation between shear stress and shear strain of the solder specimen can be characterized.

It should be noted that the direct output from the SHTB device is the voltage from the circuits of strain gauges. Before the actual tests, it is necessary to perform a calibration in order to turn the voltage reading into twisting torque for the subsequent calculation of shear stress and strain. In the present analysis, an initial twisting angle of 7.2° is applied to one end of the input bar. The corresponding twisting torque can be calculated as

$$T_o = GJ\frac{\phi_o}{L_o} = 5.18\ (\mathrm{N}\cdot\ \mathrm{m}) \qquad (1)$$

where G is the shear modulus of Cu (41 GPa), J is the polar moment of inertia of the input bar (402 mm^4), ϕ_o is the initial twisting angle in radian, and L_o is length of input bar between the loading end and the clamping point (400 mm). Once the clamping force is removed, a torsional pulse would be released and propagate along the Hopkinson bars. It should be noted that, for the calibration test, the input and output bars are jointed together by a single piece of Cu cylinder with screws at both ends. Therefore, the two bars may be considered as a continuous bar and the two strain gauges on input and output bars, respectively, would generate similar signals but with a time delay as shown in Fig. 5. From the peak voltage values read from the two strain gauges (~1.65 V), it is determined that the sensitivity of the present SHTB device is 0.318 (V/N m). This value will be used in the subsequent evaluation of shear stress and strain.

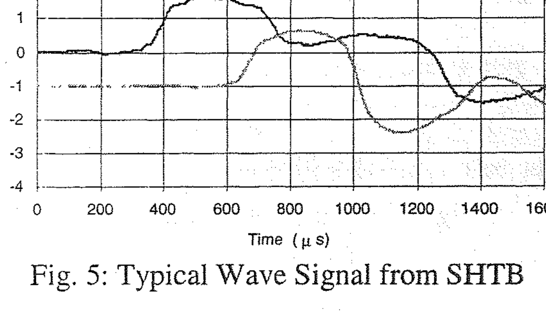
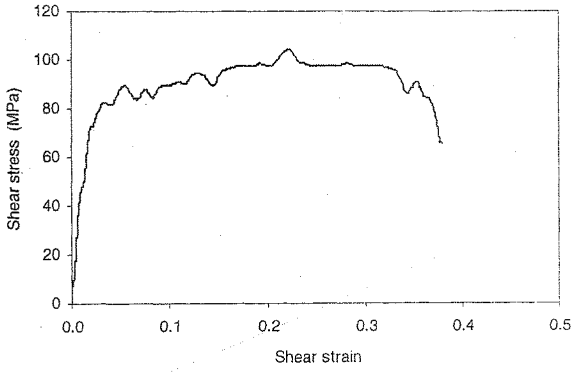
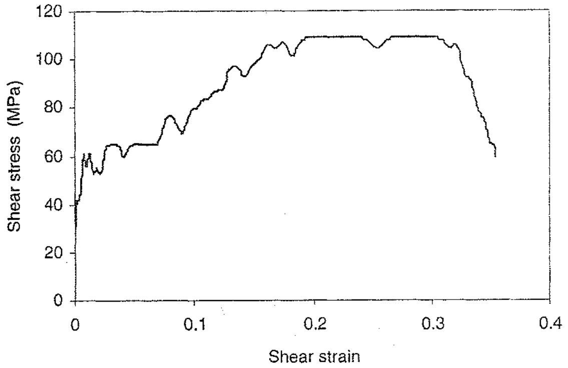


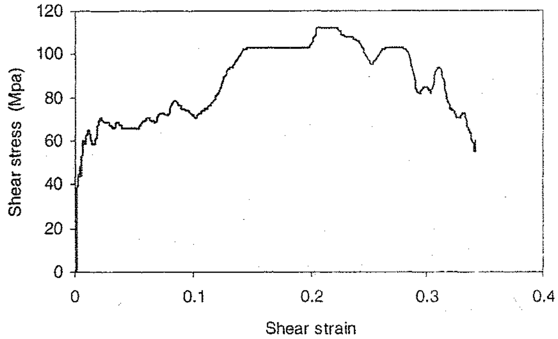
Fig. 5: Typical Wave Signal from SHTB



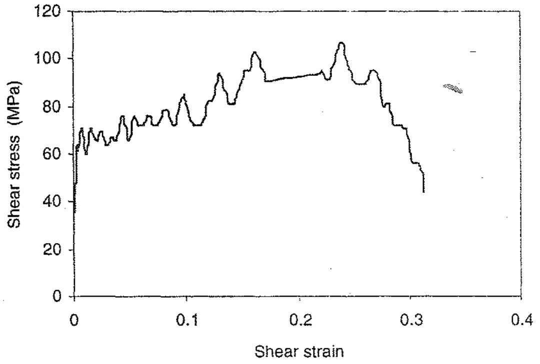
(a) Specimen #1



(b) Specimen #2

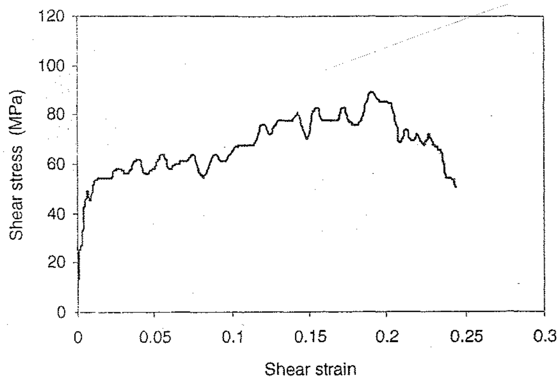


(c) Specimen #3

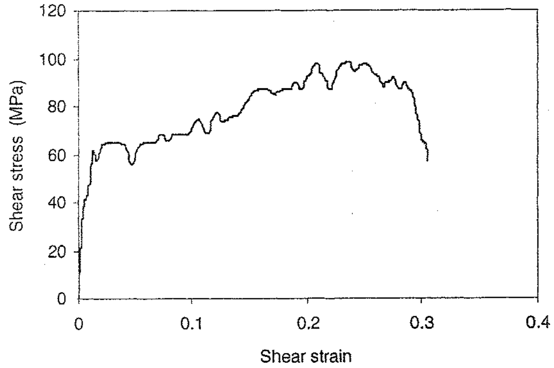


(d) Specimen #4

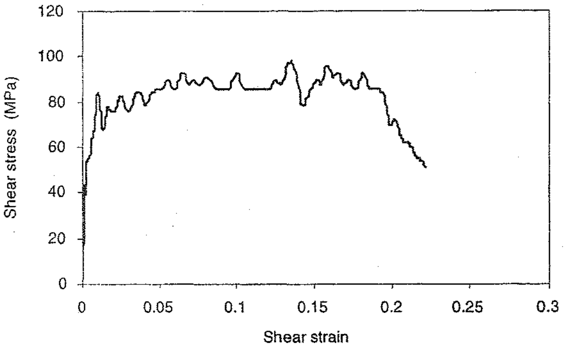
Fig. 6: Shear Stress-Strain Relation ($\dot{\gamma} \approx 1.5\times10^{3}\ \mathrm{s}^{-1}$)



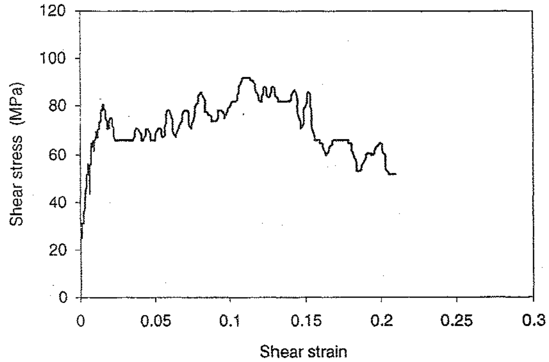
(a) Specimen #5



(b) Specimen #6



(c) Specimen #7



(d) Specimen #8

Fig. 7: Shear Stress-Strain Relation ($\dot{\gamma} \approx 5\times10^{2}\ \mathrm{s}^{-1}$)

EVALUATION OF STRESS AND STRAIN

After the calibration, the twisting torques can be obtained from the strain gauge outputs. However, to deduce the constitutive relation, it is necessary to calculate the stress and the strain. Therefore, further analysis is required. From a previous study [13], the maximum shear stress in a cylindrical specimen under uniaxial torsion can be expressed as

$$\tau_s = \frac{1}{2\pi R_s^3}(3T + \phi\frac{dT}{d\phi}) \qquad (2)$$

where T is the torque applied on the specimen, ϕ is the twisting angle, and R_s is the radius of the specimen. On the other hand, the average shear strain rate in the specimen can be determined as

$$\dot{\gamma}_s = R_s(\dot{\phi}_i - \dot{\phi}_r - \dot{\phi}_t)/L_s \qquad (3)$$

where L_s is the gauge length of the specimen and $\dot{\phi}_i, \dot{\phi}_r, \dot{\phi}_t$ are the incident, reflective, transmitted angular velocities at the input and output ends of the specimen, respectively. According to one-dimension torsion elastic stress wave theory,

$$\dot{\phi} = C\frac{\phi}{L_s} \qquad (4)$$

where $C = \sqrt{G/\rho}$ (ρ is the density of Hopkinson bars) is the shear wave propagation speed of Hopkinson bars (C = 2100 m/s for Cu). Besides, the relationship between the torque and the twisting angle can be written as

$$T = GJ\frac{\phi}{L_s} \qquad (5)$$

From Eqs. (4) and (5),

$$\dot{\phi} = \frac{T}{CJ\rho} \qquad (6)$$

Consequently, with Eq. (3), the average shear strain rate in the specimen can be expressed as

$$\dot{\gamma}_s = \frac{R_s}{L_s}\frac{(T_i - T_r - T_t)}{CJ\rho} \qquad (7)$$

From the torque equilibrium of SHTB,

$$T_i + T_r = T_t \qquad (8)$$

Combining Eqs. (7) and (8) leads to

$$\dot{\gamma}_s = \frac{2(T_i - T_t)}{CJ\rho}\frac{R_s}{L_s} \qquad (9)$$

and, subsequently, the shear strain in the specimen can be evaluated as

$$\gamma_s = \int_0^t \frac{2(T_i - T_t)}{CJ\rho}\frac{R_s}{L_s}dt \qquad (10)$$

where T_i and T_t are incident and transmitted torques, respectively, and can be calculated from the strain gauge outputs and the SHTB sensitivity.

Table 1: Comparison of Shear Strength (MPa)

$\dot{\gamma}$ (s^{-1})	5×10^{-4}	5×10^{-3}	5×10^{2}	1.5×10^{3}
1	24.8	38.8	89.3	101.6
2	23.4	37.1	96.8	108.8
3	29.2	37.6	98.3	111.9
4	29.4	38.5	91.7	106.6
Ave.	26.7	38.0	94.1	107.2

RESULTS AND DISCUSSION

A series of SHTB tests was performed to characterize the dynamic mechanical behaviours of 63Sn-37Pb solder. The experimental constitutive relations between the shear stress and the shear strain under two different shear strain rates are measured and presented in Figs. 6 and 7. In general, the experimental data are quite consistent. Although the difference in loading speed is only three fold, the effect of strain rate still can be clearly observed.

Table 1 summarizes the comparison of shear strengths with various shear strain rates. The data with two rather slow loading rates are obtained in a previous study with quasi-static torsional loading [13]. From this comparison, it is obvious that 63Sn-37Pb eutectic solder has substantial strain rate-dependent mechanical properties and the shear strength under dynamic loading is much higher than that subjected to quasi-static loading.

CONCLUSIONS

In the present study, an experimental work was performed to investigate the strain rate-dependent mechanical behaviour of 63Sn-37Pb eutectic solder under impulsive shear loading. SHTB tests were conducted to characterize the dynamic constitutive relation between the shear stress and the shear strain. Comparison was made among various cases with different shear strain rates. The results indicate that the mechanical behavior of 63Sn-37Pb solder is very sensitive to the strain rate and the dynamic shear strength is much higher than the static one.

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