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Standardization of a shear test method for lead-free solder paste chip joints

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Abstract The electronics industry is moving to replace Pb-based solder with Pb-free solder because of the growing environmental regulations governing the use of lead. Solder joints made from Pb-free solder paste do not yet have an evaluation method to classify its mechanical properties such as shear strength. In this study, we reflowed solder joints from Sn–3.0Ag–0.5Cu solder paste. To standardize the shear test method, we measured the shear strength of the solder joint of a 2012 ceramic chip at a shear rate of 3–60 mm/min and a shear height of 10–380 μm using different shaped shear jigs. We statistically analyzed the optimum number of shear tests by calculating the accumulative average value, standard deviation, and width of the confidence interval. The fracture surface was examined by scanning electron microscope and discussed in terms of the shear conditions.

Introduction

Packaging is extremely important in the production of electronic components, and soldering is a core packaging technique. It is necessary to replace lead solder, which has been used in the past, with lead-free solder because environment regulations governing the use of lead have intensified in many countries. Lead-free solder has been developed using various materials that provide excellent joint strength compared to lead solder.

Surface mount (reflow) components are of particular importance in solder joints to ensure the overall reliability of the packaging. The evaluation of solder joints can be classified into two categories: the evaluation of the basic properties of the solder materials, such as the chemical composition, melting point, and spread of the solder paste; and the evaluation of the strength of the soldered chip joint. The latter category has not been clearly defined by the international community. It is necessary to standardize the method used to measure the strength of a soldered chip joint in electronic components to ensure the reliability of a given product.

In this study, we performed shear tests of a soldered chip joint and determined the optimum number of tests by calculating the confidence range using statistical analysis. We investigated the influence of the jig shape, shear rate, and shear height on the shear strength of the soldered joint, and observed the fractured surface under a scanning electron microscope (SEM). The optimum conditions for shear tests of solder joints obtained from these tests will contribute to standardizing a reliable evaluation method for soldered joints in electronic components.

Test methodology

Specimen preparation

The substrates that were joined to the chip by soldering were 50 × 100 mm printed circuit boards (PCBs). The

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Table 1 Specifications of the materials used for the tests

Package		MLCC
Lead	Plating material	100 Sn
	Plating thickness	3–4 μm
PCB	Material	PCB FR-4
	Thickness	0.8 μm
	Surface treatment	Ni: 2.54–7 μm
		Au: <0.7 μm

PCB pads were plated Au plated. The multilayered ceramic chips (MLCCs) and PCBs were made following the usual reliability standard [1]. The properties of the materials are listed in Table 1. Figure 1 shows the MLCC chip; the white region is the Sn-plated layer, and the upper black region is the ceramic.

The lead-free solder paste used in this research consisted of a Sn–Ag–Cu alloy system that was mixed with a rosin mildly activated (RMA) flux. Table 2 gives the properties of the solder paste.

The heating process during reflow consisted of three stages as shown by Fig. 2, including preheating at 150–180 °C for 110–120 s, soldering above 217 °C for 40 s, and heating at a peak temperature of 245 °C for 4 s.

Shear tests

Standardization of the number of tests

A jig with a 1 × 8 mm rectangular cross section was used for the shear tests. Just before testing, the shearing jig was

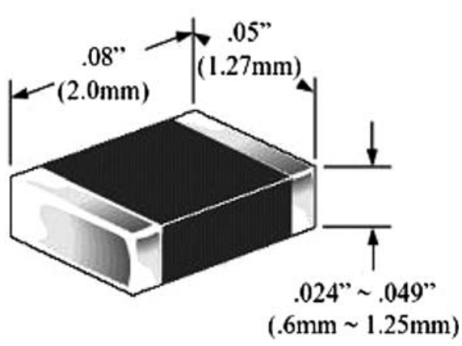


Fig. 1 A standard 2012 chip

Table 2 Specifications of the solder paste used for the tests

Composition	Melting temperature (° C)		Type
	Solid	Liquid	
Lead-free (Sn–3.0Ag–0.5Cu)	217	220	Cream

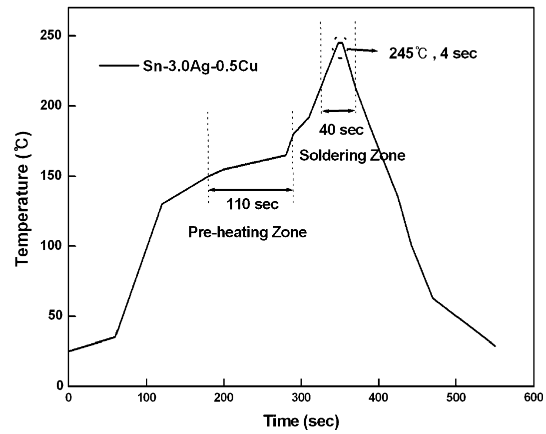


Fig. 2 Temperature profile during soldering

located 10 μm from the chip surface that was to be sheared. The shear rate was 10 mm/min, and the test was repeated 30 times under the same conditions to determine the standard deviation of the shear strength as a measure of the test repeatability. The standard deviation resulted from difficulties controlling the amount of solder on the tiny specimen. Therefore, we used an accumulative average value of the shear strength to compare the test results. The accumulative average shear strength $\bar{x}$, standard deviation S, and 95% confidence interval W were calculated from

$$\bar{x} = \frac{x_1 + x_2 + \cdots + x_n}{n}, \quad (1)$$

$$S = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}}, \quad (2)$$

$$W = \bar{x} \pm \left(\alpha \times \frac{S}{\sqrt{n}}\right), \quad (3)$$

where x_i is the shear strength determined from test i and α is 1.96 according to the statistical conditions of a 95% confidence interval.

Standardization of the jig shape

Various jig shapes were made to obtain a standardized jig, which are presented in Fig. 3. The contact widths of the rectangular chip components shown in Fig. 3a–c are 1, 2, and 3.2 mm, respectively, while the length of all three jigs is 8 mm. Figure 3d shows a trapezoidal jig and Fig. 3e shows a half-cylinder protruding jig with a base diameter of 0.5 mm, which is the same as that used in test standard JIS Z 3198-7 [2]. In these tests, the jig rate during shearing was 25 mm/min and the distance (jig height) between the jig and substrate was maintained at 100 μm.

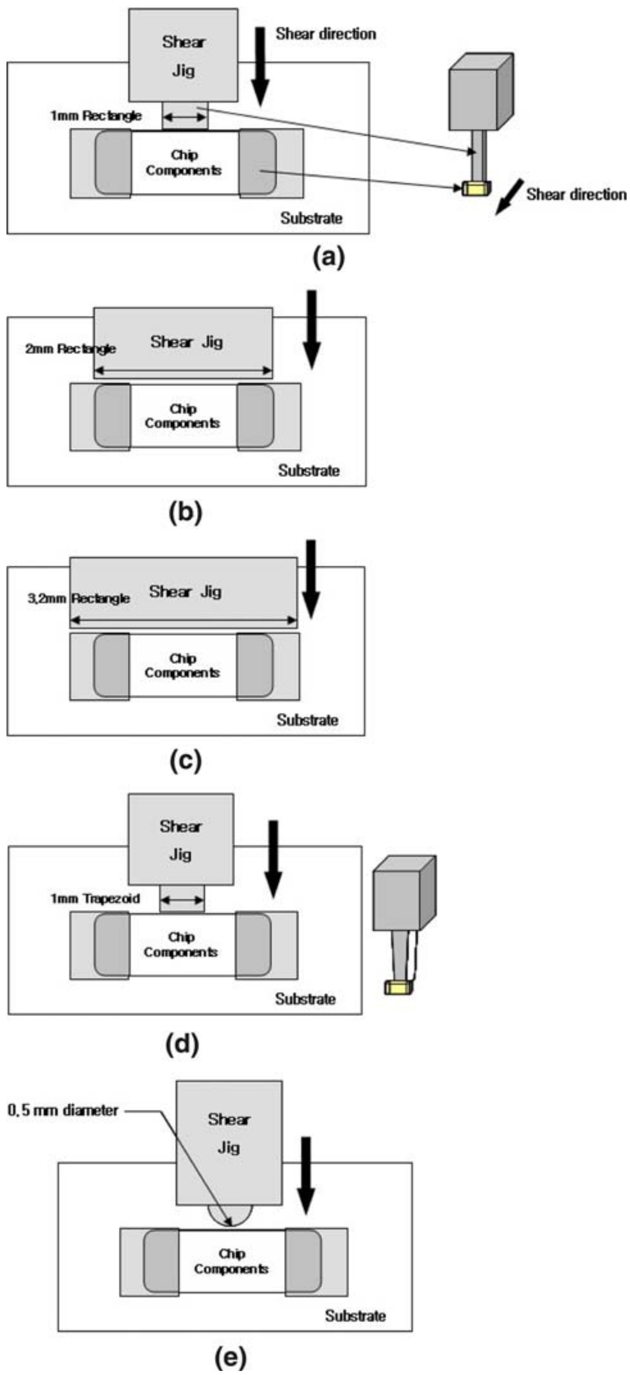


Fig. 3 Schematic illustration of the variously shaped shear jigs

Standardization of the shear rate and shear height

We tested the shear rate over a range of 2–60 mm/min to evaluate its effect on the shear strength using the 2 mm rectangular jig; the jig height was kept constant at 30 μm from the surface of the PCB substrate [3–7]. We also investigated the effect of the shear height above the PCB substrate on the shear strength. The tested shear height ranged from 10 to 380 μm using the 2 mm rectangular jig

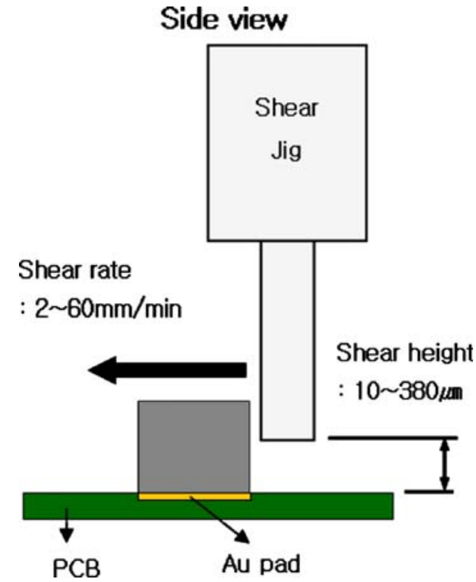


Fig. 4 Schematic drawing of the shear tests

at a constant shear rate of 25 mm/min. For both types of tests, we evaluated the accumulative average shear strength and observed the fractured surfaces under a SEM. Figure 4 shows the conditions of the shear height and shear rate standardization tests.

Results

Standardization of the number of tests

There was some deviation in the test results of 30 shear tests under the same set of conditions. The accumulative average shear strength was 9.95 kgf with a standard deviation of 0.679 kgf. The variation of the accumulative average shear strength and the 95% confidence interval are shown in Fig. 5. The thick line indicates the accumulative average shear strength and the thin lines above and below the bold line show the 95% confidence interval, which decreased as the number of tests increased. At test number 15, the accumulative average shear strength was 9.861 kgf and the 95% confidence interval was ± 0.26 kgf, which can be acceptable variation for the test. Additional tests were therefore not meaningful; reliable shear strength values for the solder joint could be obtained using only 15 tests.

Standardization of the jig shape

The highest shear strength and the minimum deviation of test value was obtained using the 2 mm rectangular jig while the lowest shear strength was with the 1 mm trapezoid jig, as shown in Fig. 6. Approximately the same values were obtained for the 1-mm rectangular, 3.2 mm

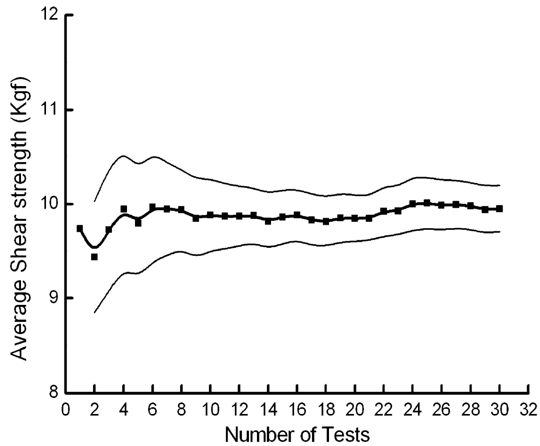


Fig. 5 Variation in the accumulative average shear strength with 95% confidence interval of solder joint

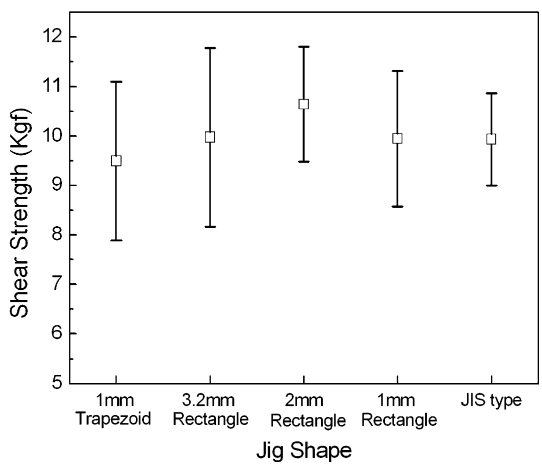


Fig. 6 Variation in the accumulative average shear strength and standard deviation after 15 tests for variously shaped shear jigs at a shear rate of 25 mm/min

rectangular, and 0.5 mm diameter protrusion jigs. The protrusion jig is used by the Japanese Standards Association, but it often fractured the ceramic in these tests due to the stress concentrations in the tiny protrusion area. Therefore, we do not recommend using a protrusion jig to evaluate the shear strength of a lead-free solder joint.

Standardization of the jig height

Figure 7 shows the accumulative average shear strength and error bar after 15 tests as the jig height was varied between 10 and 380 μm. The difference in the shear strength at shear heights of 30, 50, 110, and 170 μm was insignificant. The results obtained for a shear height of 170 μm were mostly not meaningful because the ceramic was in case of more than 80% partially fractured. In this case, a ceramic fragment and part of the Sn-plated layer

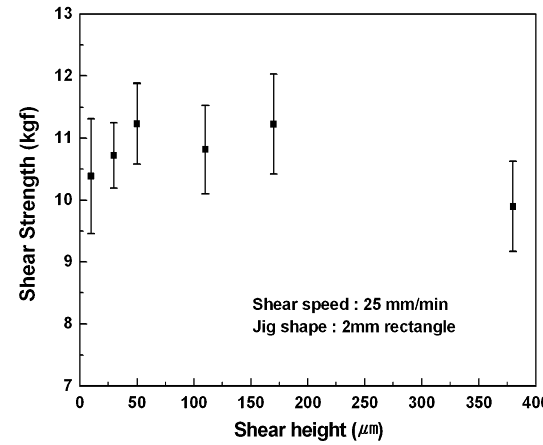


Fig. 7 Effect of the shear height on the accumulative average shear strength and standard deviation of the solder joint after 15 tests

were observed on the fractured surface of the chip specimen. The ceramic was most likely fractured due to a crack that formed at the outer surface of the specimen, which had resulted from the stress concentration caused by the small contact surface between the specimen and jig. The results at a jig height of 170 μm, which is more than one-fourth the height of the whole chip, are consistent with those reported in the JIS Z 3198-7 standardization test [8]. This test recommended that the lower contact end of the jig should not be more than one-fourth the height of the chip. For the lowest jig height of 10 μm, the average shear strength was very low because the solder joint fractured first since the jig was lower than the specimen.

Standardization of the shear rate

The accumulative average shear strength was calculated after 15 tests for shear rates ranging from 2 to 60 mm/min. Figure 8 shows the increase in the shear strength with the

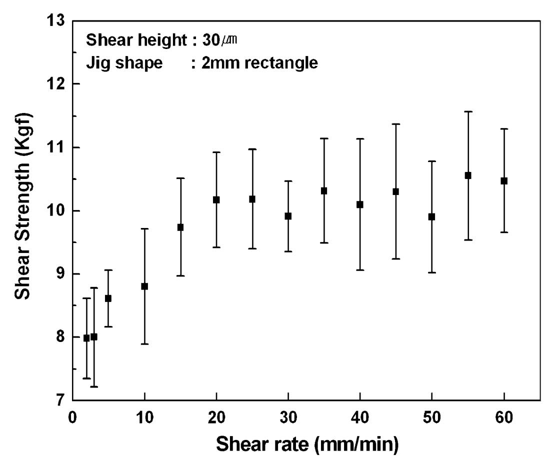


Fig. 8 Effect of the shear rate on the accumulative average shear strength and standard deviation of the solder joint after 15 tests

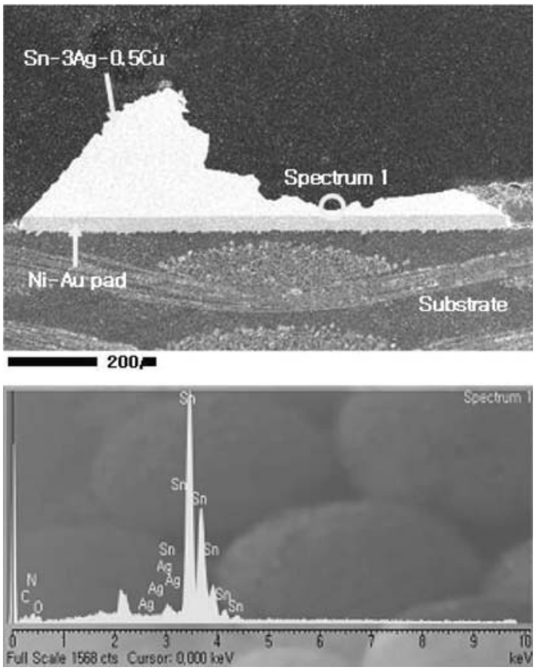


Fig. 9 SEM micrographs and EDX spectrum of the solder joint fracture surface sheared by the 2-mm rectangular jig

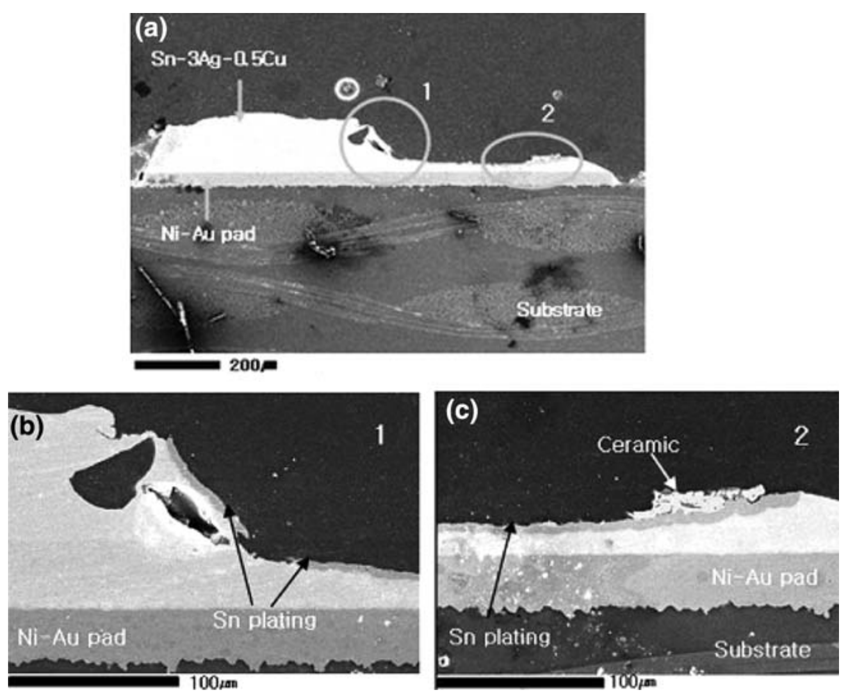
shear rate. At low jig shear rates of 2 to 10 mm/min, the actual strength value was low. At jig shear rates greater than 50 mm/min, ceramic fragments were observed at the fractured surface, providing evidence of abnormal shearing at the solder joint. Thus, an appropriate shear rate range is 20–40 mm/min.

SEM analysis

Figure 9 shows the fractured section sheared by the 2 mm rectangular jig. The surface consisted only of the solder material, as determined by an energy dispersive X-ray (EDX) analysis. This indicates that the fracture occurred only due to shearing of solder. On the fractured surface sheared by the 3.2 mm rectangular jig, shown in Fig. 10, a Sn-coated layer was deposited on the ceramic chip and fragments of ceramic were also observed. In this case, the ceramic chip fractured as the solder paste separated. Thus, the results for this case do not give the pure joint strength of the solder. The 0.5 mm protrusion and 1-mm rectangular jigs fractured 35–45% of the specimens due to the local stress concentration at the small contact surface between the jig and chip specimens. Ceramic fragments were also observed on the 3.2 mm rectangular jig. Thus, the 2 mm rectangular jig was most suitable for the shear strength tests performed in this study.

Figure 11a shows a cross section of the specimen that was fractured at a jig height of 30 µm. This specimen represents the ideal fracture that yields a high strength value. Figure 11b and c show the cross section obtained with a jig height of 170 µm in which a portion of the Sn-coated layer and ceramic fragments are visible at the solder interface, as determined by an EDX analysis (see Fig. 11d). This occurred at jig heights greater than 170 µm. Figure 11e–g show typical fracture modes of specimens sheared at various shear rates. As the shear rate increased, the solder joint was deformed and the possibility of

Fig. 10 SEM micrographs of the solder joint fracture surface sheared by the 3-mm rectangular jig



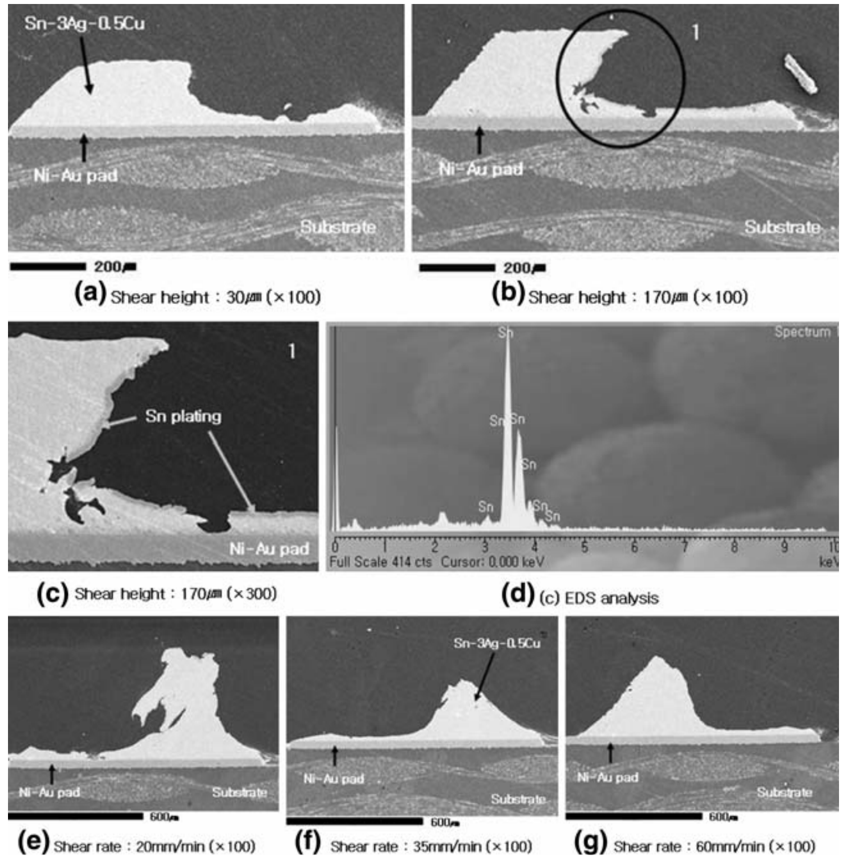


Fig. 11 SEM micrographs of the solder joint fracture cross section sheared using different jig height and shear rates

fracturing the chip specimen increased. The fracturing of the chip specimen was made more problematic by high shear rates [3, 8, 9].

Conclusions

The conclusions of this study are summarized as follows.

(1) The solder joint shear tests yielded small deviations in shear strength values. The accumulative average shear strength was calculated for 30 tests under the same conditions to determine the repeatability of the results. Using a 95% confidence interval to standardize the shear strength value, a minimum of 15 tests were required under the same conditions to obtain good results.

(2) The 2 mm rectangular jig fractured only the solder joint and had a high shear strength. It produced good results when evaluating the shear strength of a solder joint on a MLCC chip.

(3) The height of the jig over the substrate should not exceed more than one-fourth the height of the chip (170 μm) and should be greater than 10 μm to obtain accurate values for the joint strength of the solder paste. Otherwise, the ceramic specimen may fracture along with the solder joint.

(4) The shear strength increased with the shear rate. When the shear rate was greater than 50 mm/min, the ceramic specimen could fracture before the solder joint, making it difficult to determine the correct solder joint strength. A suitable shear rate was 20–40 mm/min.

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