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Electrically conductive adhesive and soldered joints under compression

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Abstract—Compression of soldered and conductive adhesive joints resulted in both reversible and irreversible changes in the contact electrical resistivity. At a low stress (as low as 0.02 and 0.005 MPa for soldered and adhesive joints, respectively), the resistivity increased with almost complete reversibility as the compressive stress increased. At an intermediate stress (as low as 0.03 MPa) for both soldered and adhesive joints, the resistivity decreased with partial or complete reversibility as the stress increased. At a high stress (as high as 0.21 MPa) for the soldered joint only, the resistivity increased slightly with increasing stress. The resistivity of the soldered joint at no load increased irreversibly and gradually as stress cycling progressed, even at the lowest stress amplitude of 0.12 MPa. However, the resistivity of the adhesive joint at no load decreased irreversibly and gradually as stress cycling progressed, even at the lowest stress amplitude of 0.009 MPa.

Keywords: Solder; adhesive; joint; electrical resistivity; silver; epoxy.

1. INTRODUCTION

Soldered joints are widely used for electrical interconnections in electronic packaging. Due to the tendency for soldered joints to suffer from thermal fatigue, the environmental problem associated with the use of flux in soldering, the presence of lead in typical solders and the large footprints, conductive adhesives [1–4] such as silver-particle-filled epoxy [5–11] are increasingly used in place of solder. The reliability of soldered and conductive adhesive joints greatly affects the overall reliability of microelectronic systems. Mechanical abuse, such as vibrations, is one of the causes of joint degradation or failure. The stress involved can be shear, tensile or compressive. Previous work has addressed the effect of shear and tensile stresses

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[12, 13] and the effect of temperature [14]. In contrast, this work addresses the effect of compressive stress. Because compression is expected to be less damaging than shear or tension, previous work was not given attention to the effect of compression. Nevertheless, compression is encountered in practice, particularly during vibrations and processing after joining.

This work addresses both the reversible and irreversible effects of compression on the contact resistivity of soldered and conductive adhesive joints. It should be noted that this work is not directed at studying the mechanical behavior during compression. There has been much more previous work on the mechanical behavior than on the effect of stress on the electrical behavior [12, 13]. For electrical interconnections, the effect on the electrical behavior is of practical concern. Furthermore, the electrical behavior is sensitive to even minor damage, so it serves as a sensitive indicator of the microstructural effects. In addition, measurement of electrical resistance is fast and non-destructive, thereby allowing real-time monitoring during loading and unloading.

2. MATERIALS AND METHODS

The solder used was an eutectic tin–lead alloy (63% Sn–37% Pb). Its melting temperature is 183°C. The conductive adhesive was silver particle filled epoxy (CW2400 CircuitWorks Conductive Epoxy, ITW Chemtronics, Kennesaw, GA, USA).

Both of the components to be joined by soldering or by the use of a conductive adhesive were a copper-cladded continuous glass fiber-epoxy matrix composite in the form of a laminate, as provided by Polyclad Laminates (W. Franklin, NH; product No. PCL-FR-226, tetrafunctional FR-4 laminate, $T_g = 140°C$). The glass fibers were E- (E standing for electrical) glass of style 1080. The copper cladding was 36 μm thick on each side of the laminate. The glass fiber-polymer matrix composite (without cladding) was 318 μm thick. The total thicknes of the cladded laminate was 390 μm.

Soldering was conducted by (i) applying molten solder (melted by using a soldering iron) in the absence of a flux on the surface of one of the components to be joined (width = 4.2 mm) while the surface was hot at 185°C, as rendered by a hot plate, and (ii) placing the other component to be joined (width = 3.0 mm) on the molten solder, while it was hot at 185°C, as rendered beforehand by the hot plate. Thus, the joint area was 4.2 mm $\times$ 3.0 mm. The thickness of the solder was 125 ± 75 μm, as controlled by the weight of the component placed on the molten solder.

Adhesive joining using silver epoxy as the adhesive was conducted by (i) mixing equal amounts of Part A (epoxy) and Part B (hardener) of the silver epoxy for at least 2 min, (ii) applying the mixture within 5 min on the surface of one of the components to be joined (width 5.1 mm), (iii) placing the other component to be joined (width = 4.9 mm) on the adhesive, (iv) applying a weight of 0.95 kg on

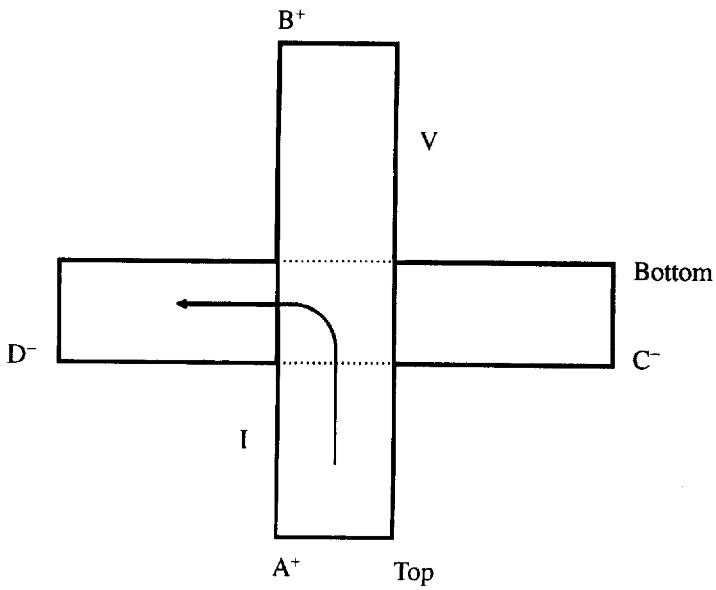

Figure 1. Specimen configuration.

the joint area (5.1 mm $\times$ 4.9 mm) to give a compressive stress of 38 kPa, and (v) allowing the epoxy to cure at room temperature under the compressive stress for 24 h. The compressive stress of 38 kPa was not critical; it was conveniently obtained through the use of known weights. The thickness of the epoxy was $152 \pm 76\ \mu m$.

An electrical contact in the form of silver paint in conjunction with copper wire was applied to the copper cladding of each of the four legs of the crossed bars (Fig. 1) in order to make electrical connections with appropriate electronics. In the four-probe method, two of the electrical contacts (A and D in Fig. 1) were for passing current; the remaining two contacts (B and C) were for measuring voltage. The voltage divided by the current gave the 'contact resistance' of the joint. This resistance is that of the overall joint, with contributions from the volume resistance of the solder and the contact resistance of each of the two solder-copper interfaces. This overall joint resistance is practically important. When multiplied by the contact area, it gave the 'contact resistivity'. A Keithley 2001 multimeter was used.

Compressive stress, as provided by a screw-action mechanical testing system (2/D, Sintech, Stoughton, MA, USA), was applied to the entire square area of the joint in the direction perpendicular to the joint area. The stress was cycled for at least 12 cycles (2000 s) at a fixed amplitude, which ranged from 0.08 to 1.2 MPa and was increased step by step (at least 12 cycles for each step). The contact resistivity was measured continuously during the cyclic loading.

Multiple specimens were similarly tested for each experimental condition in order to ascertain the reproducibility of the results.

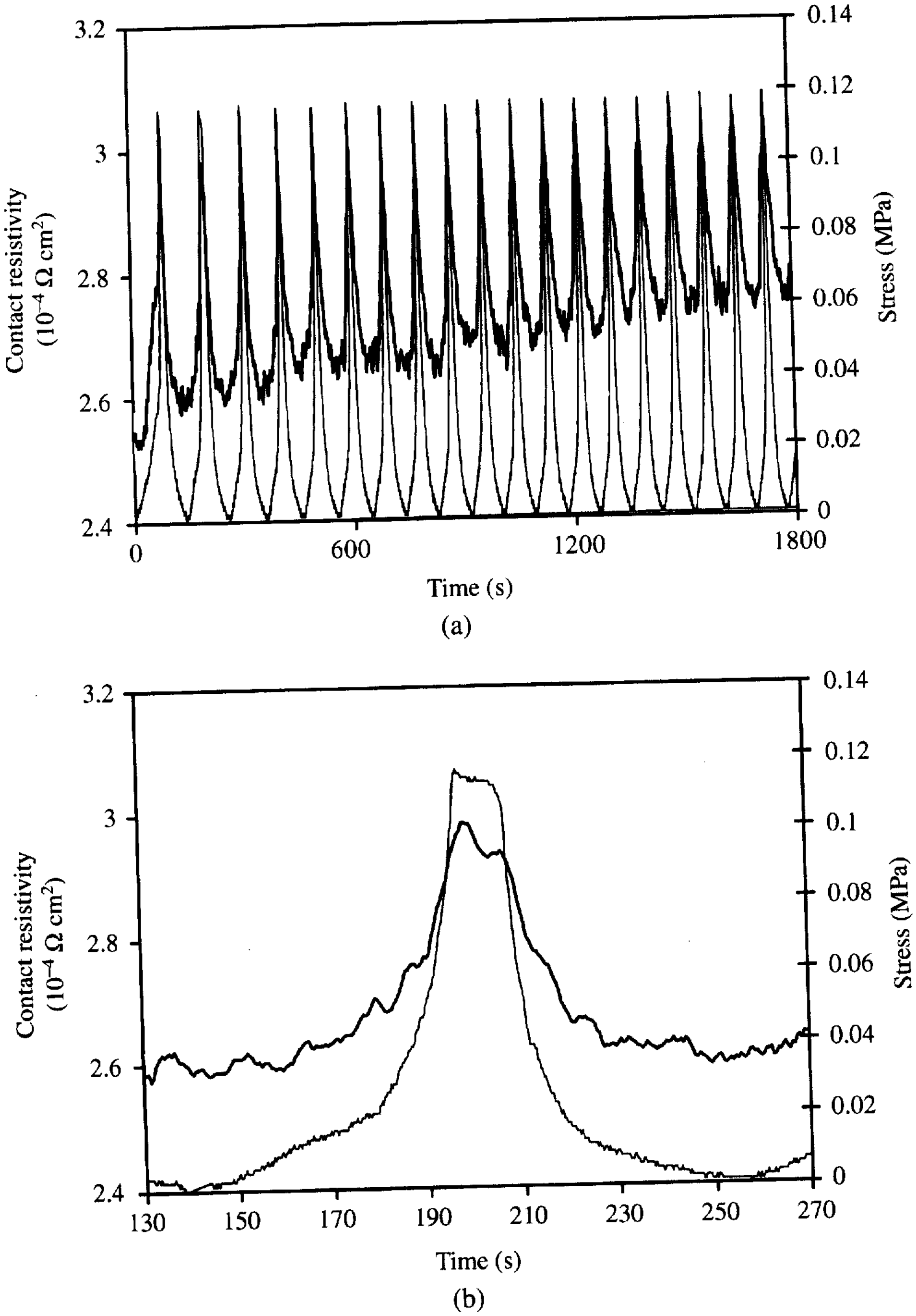

Figure 2. Contact resistivity *vs.* time during stress cycling of the soldered joint at an amplitude of 0.12 MPa. (a) Multiple cycles. (b) One of the cycles in an expanded view. Thick curve, resistivity; thin curve, stress.

3. RESULTS

3.1. Soldered join

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3.2. Adhesive j

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3. RESULTS

3.1. Soldered joint

Figure 2a shows that the contact resistivity of the soldered joint increased upon loading in every stress cycle (amplitude = 0.12 MPa), such that the effect was essentially reversible upon unloading. The slight degree of irreversibility resulted in an increase of the resistivity baseline as cycling progressed. The expanded view in Fig. 2b shows that, within a stress cycle, the resistivity started to climb at a stress of 0.02 MPa. The resistivity dropped slightly after reaching the maximum stress, such that the drop was partically reversible, as observed in each of the 12 cycles.

Figure 3 shows similar effect at an amplitude of 0.17 MPa, though the resistivity drop (beginning at 0.11 MPa, as observed in every cycle) was more pronounced (Fig. 3b) and the resistivity baseline increase was less (Fig. 3a).

Figure 4a shows similar effect at an amplitude of 0.23 MPa, though the resistivity drop (beginning at 0.12 MPa, as observed in every cycle) was even more pronounced (Fig. 4b) and the resistivity baseline increase was even less (Fig. 4a).

Figures 5–9 show similar effects at increasing stress amplitudes, such that the resistivity drop was progressively more pronounced, beginning at 0.13, 0.14, 0.03, 0.06 and 0.03 MPa at stress amplitudes of 0.35, 0.46, 0.58, 0.87 and 1.16 MPa, respectively. The resistivity drop was partially or completely reversible. The reversibility was more complete as the stress amplitude increased, as shown by comparing Figs 5b, 6b, 7b, 8b and 9b.

A feature absent in Figs 2–4 was present in Figs 5–9 in every cycle of each plot. This feature is a slight resistivity increase near the peak stress of a cycle, as clearly shown in Figs 5b and 6b. This feature occurs in every cycle, as clearly shown in Figs 6a and 8a.

3.2. Adhesive joint

Figures 10–15 show the effects of compression on the contact resistivity of the adhesive joint at progressively increasing stress amplitudes, with the initial amplitude at 0.009 MPa. The effects are similar to those in the case of the soldered joint, except that (i) the resistivity changes were noisier, (ii) the resistivity baseline decreased upon stress cycling (Figs 10a, 12a, 14a and 15a), in contrast to the baseline increase in the case of the soldered joint (Fig. 2a) and (iii) within a stress cycle, the resistivity started to climb at a stress of 0.005 MPa (Figs 10b and 11b), in contrast to a much higher stress of 0.02 MPa for the case of the soldered joint. By having the intial amplitude at 0.09 MPa (Fig. 16) instead of 0.009 MPa (Fig. 10a), the decrease of the resistivity baseline upon stress cycling was observed with less noise.

The solder and adhesive joints are similar in the level of contact resistivity (though the resistivity is higher for the adhesive joint) and in the effect of a sufficiently high stress (⩾0.03 MPa) in causing the contact resistivity to decrease with increasing stress. Due to the greater noise in the resistivity data of the adhesive joint, the

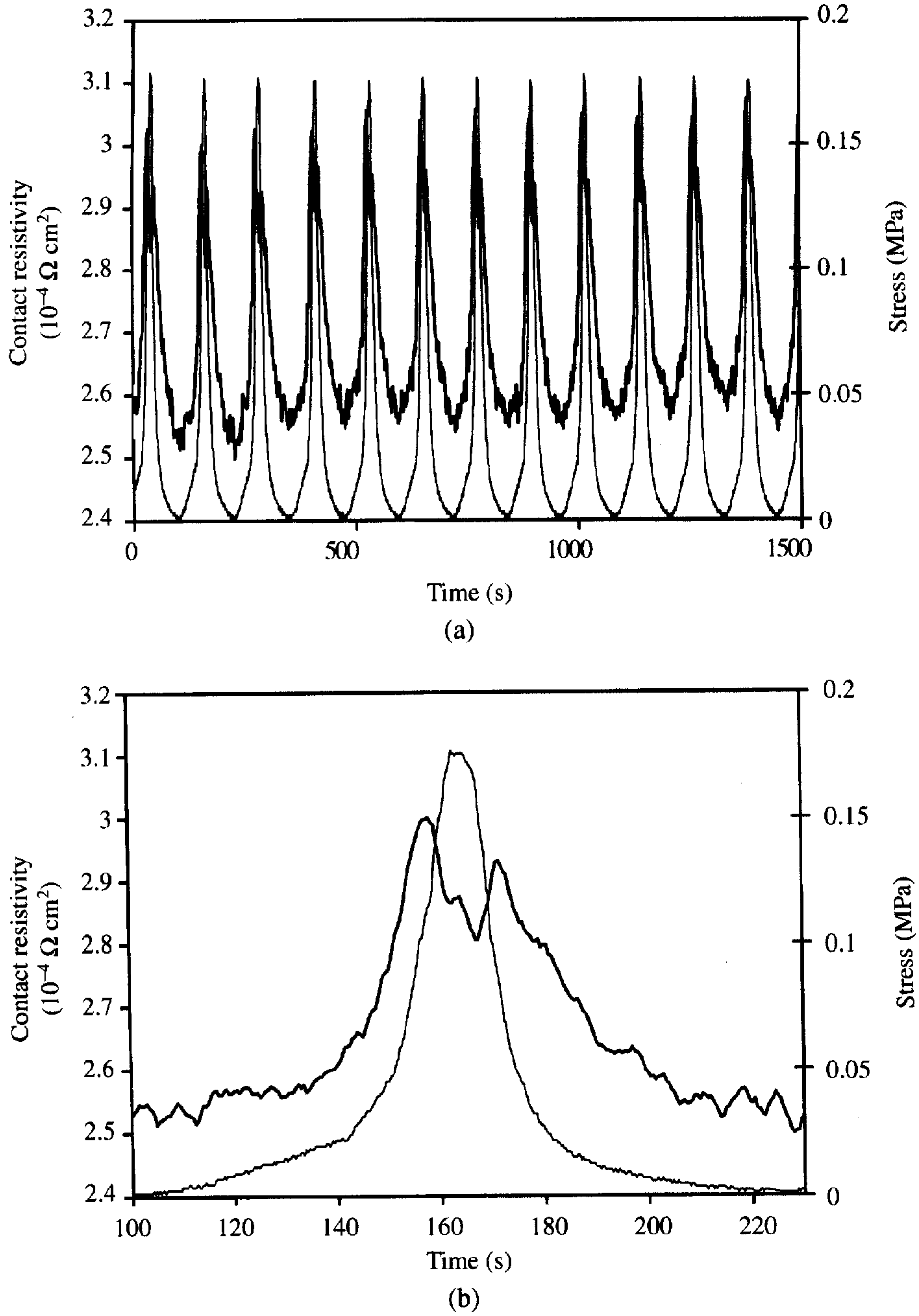


Figure 3. Contact resistivity *vs.* time during stress cycling of the soldered joint at an amplitude of 0.17 MPa. (a) Multiple cycles. (b) One of the cycles in an expanded view. Thick curve, resistivity; thin curve, stress.

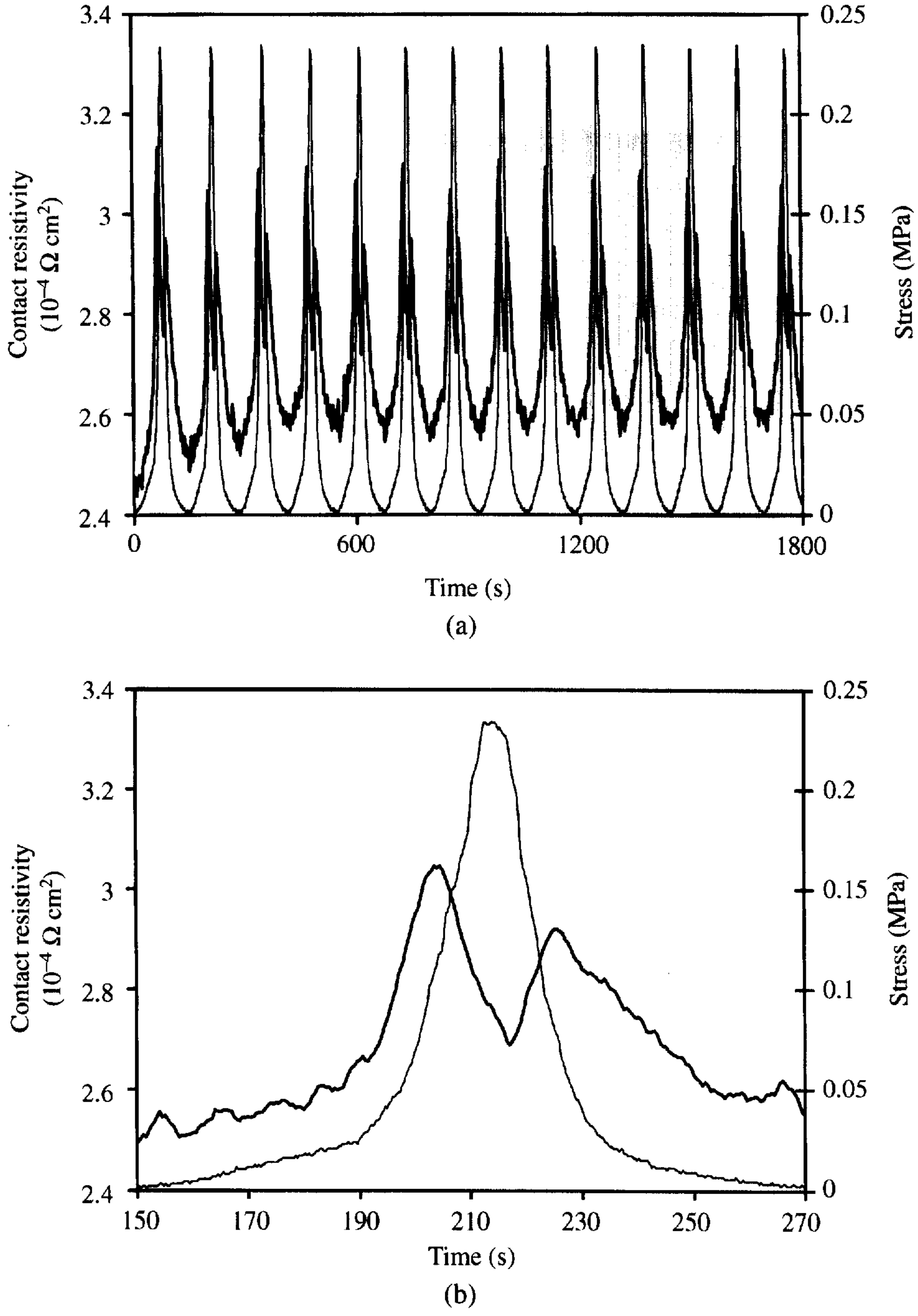


Figure 4. Contact resistivity *vs.* time during stress cycling of the soldered joint at an amplitude of 0.23 MPa. (a) Multiple cycles. (b) One of the cycles in an expanded view. Thick curve, resistivity; thin curve, stress.

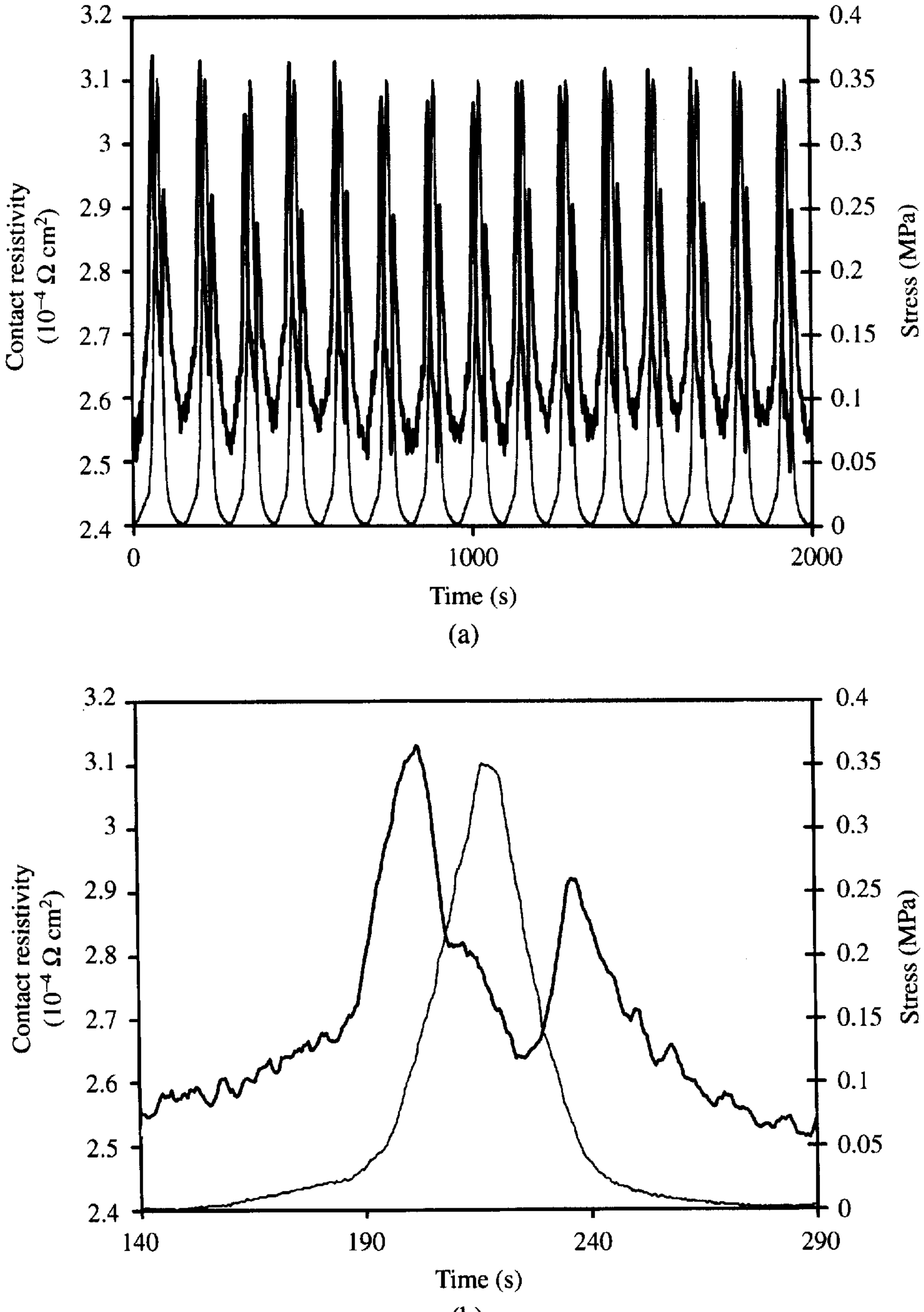


Figure 5. Contact resistivity *vs.* time during stress cycling of the soldered joint at an amplitude of 0.35 MPa. (a) Multiple cycles. (b) One of the cycles in an expanded view. Thick curve, resistivity; thin curve, stress.

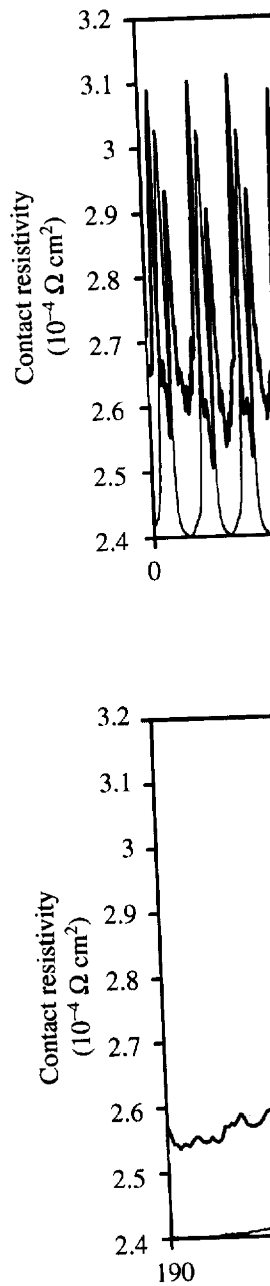


Figure 6. Contact resis
0.46 MPa. (a) Multiple
thin curve, stress.

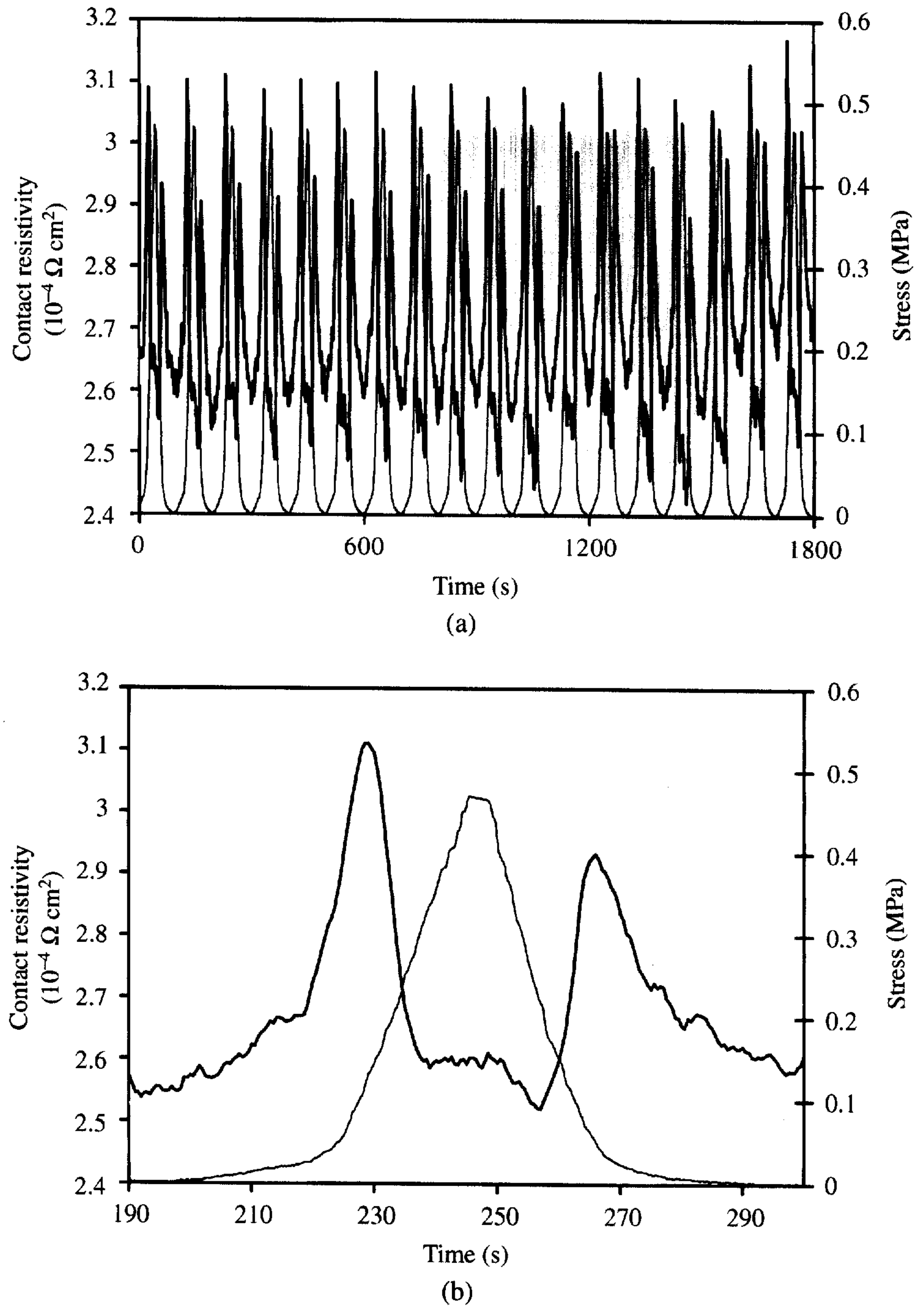


Figure 6. Contact resistivity *vs.* time during stress cycling of the soldered joint at an amplitude of 0.46 MPa. (a) Multiple cycles. (b) One of the cycles in an expanded view. Thick curve, resistivity; thin curve, stress.

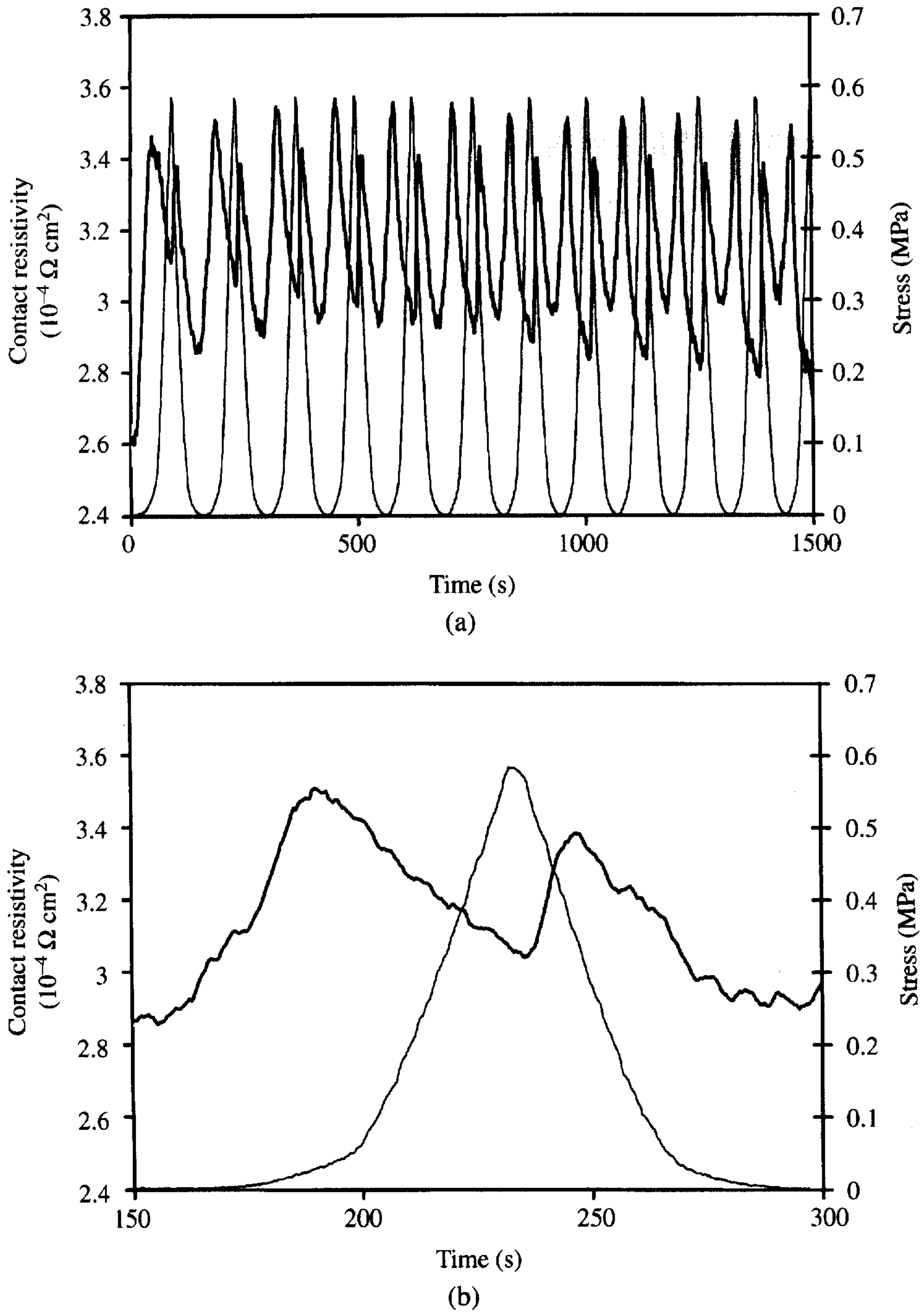


Figure 7. Contact resistivity *vs.* time during stress cycling of the soldered joint at an amplitude of 0.58 MPa. (a) Multiple cycles. (b) One of the cycles in an expanded view. Thick curve, resistivity; thin curve, stress.

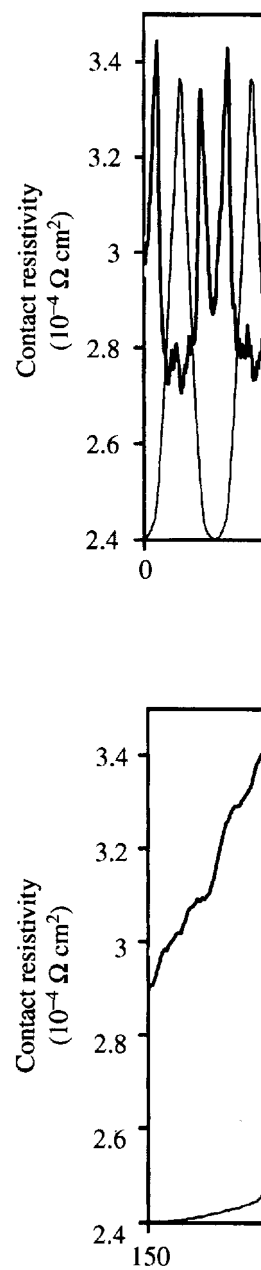


Figure 8. Contact resistivi
0.87 MPa. (a) Multiple cyc
thin curve, stress.

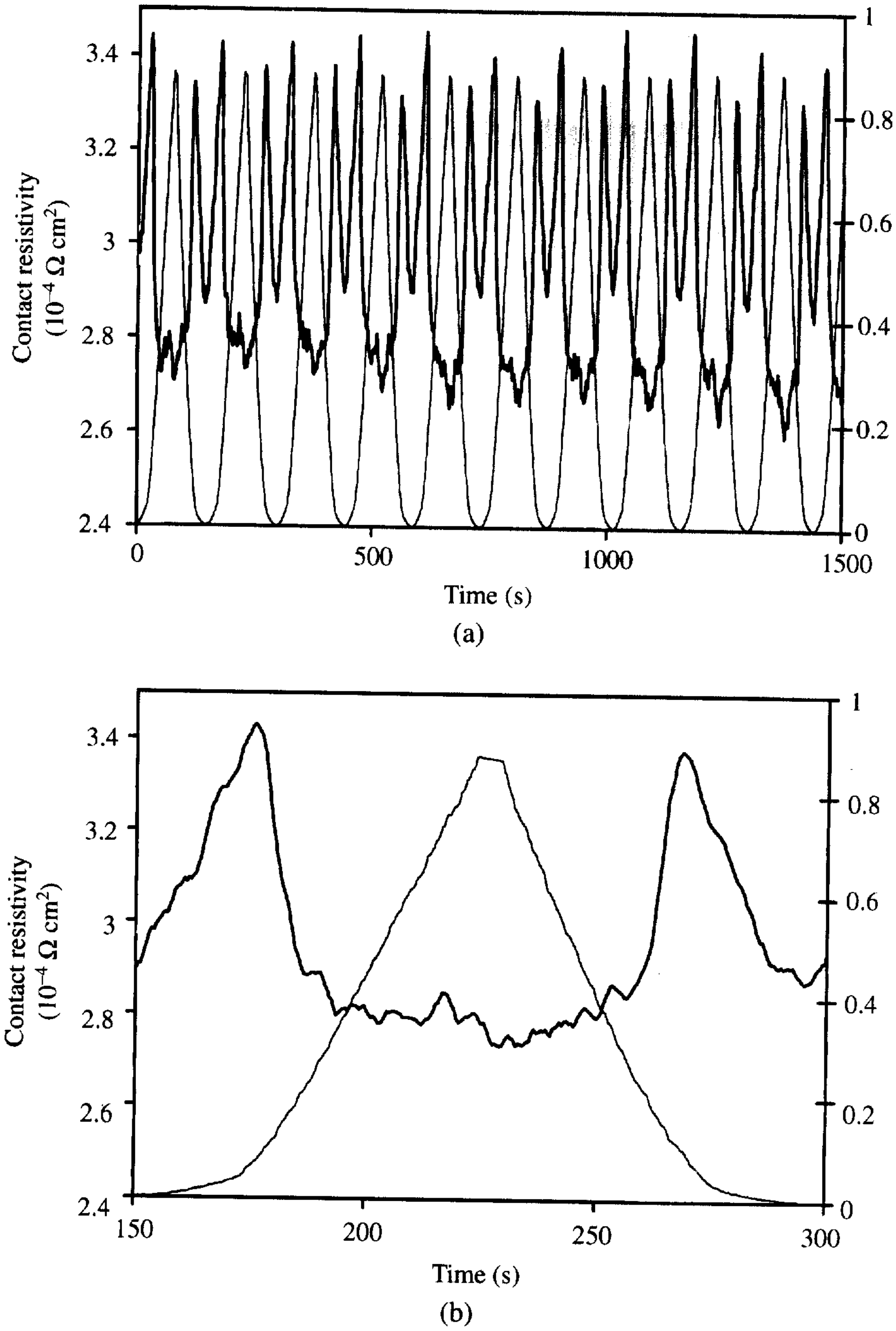


Figure 8. Contact resistivity *vs.* time during stress cycling of the soldered joint at an amplitude of 0.87 MPa. (a) Multiple cycles. (b) One of the cycles in an expanded view. Thick curve, resistivity; thin curve, stress.

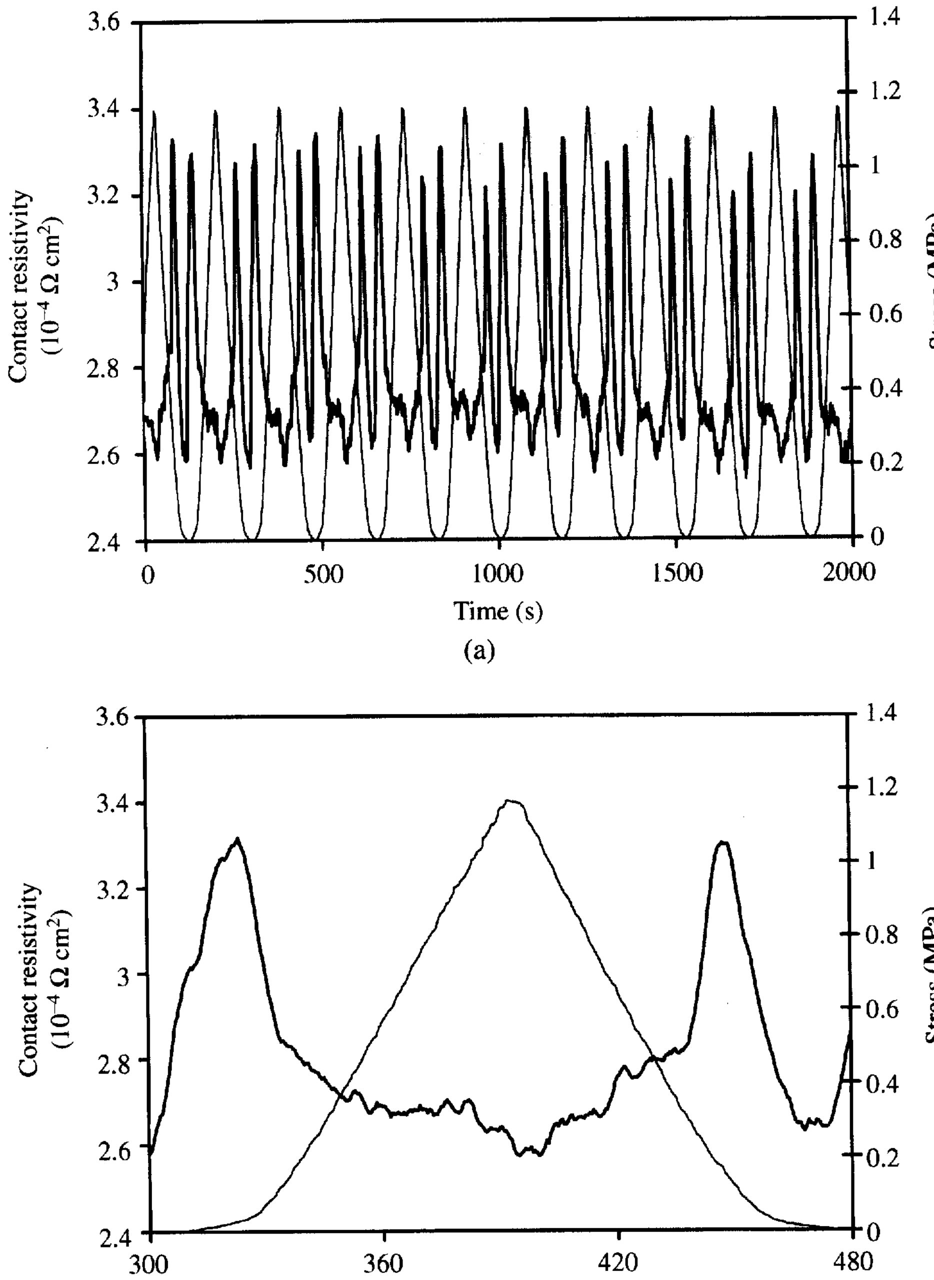


Figure 9. Contact resistivity *vs.* time during stress cycling of the soldered joint at an amplitude of 1.16 MPa. (a) Multiple cycles. (b) One of the cycles in an expanded view. Thick curve, resistivity; thin curve, stress.

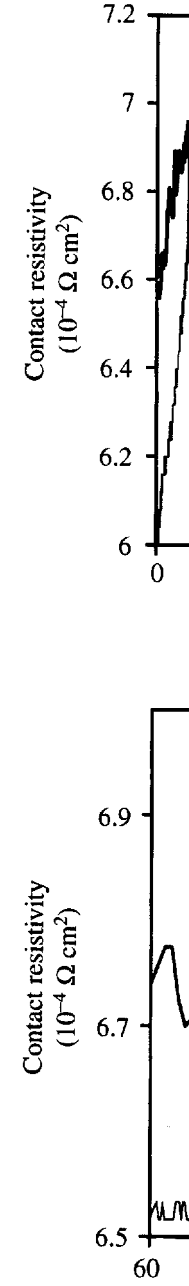


Figure 10. Conta
amplitude of 0.009
curve, resistivity; th

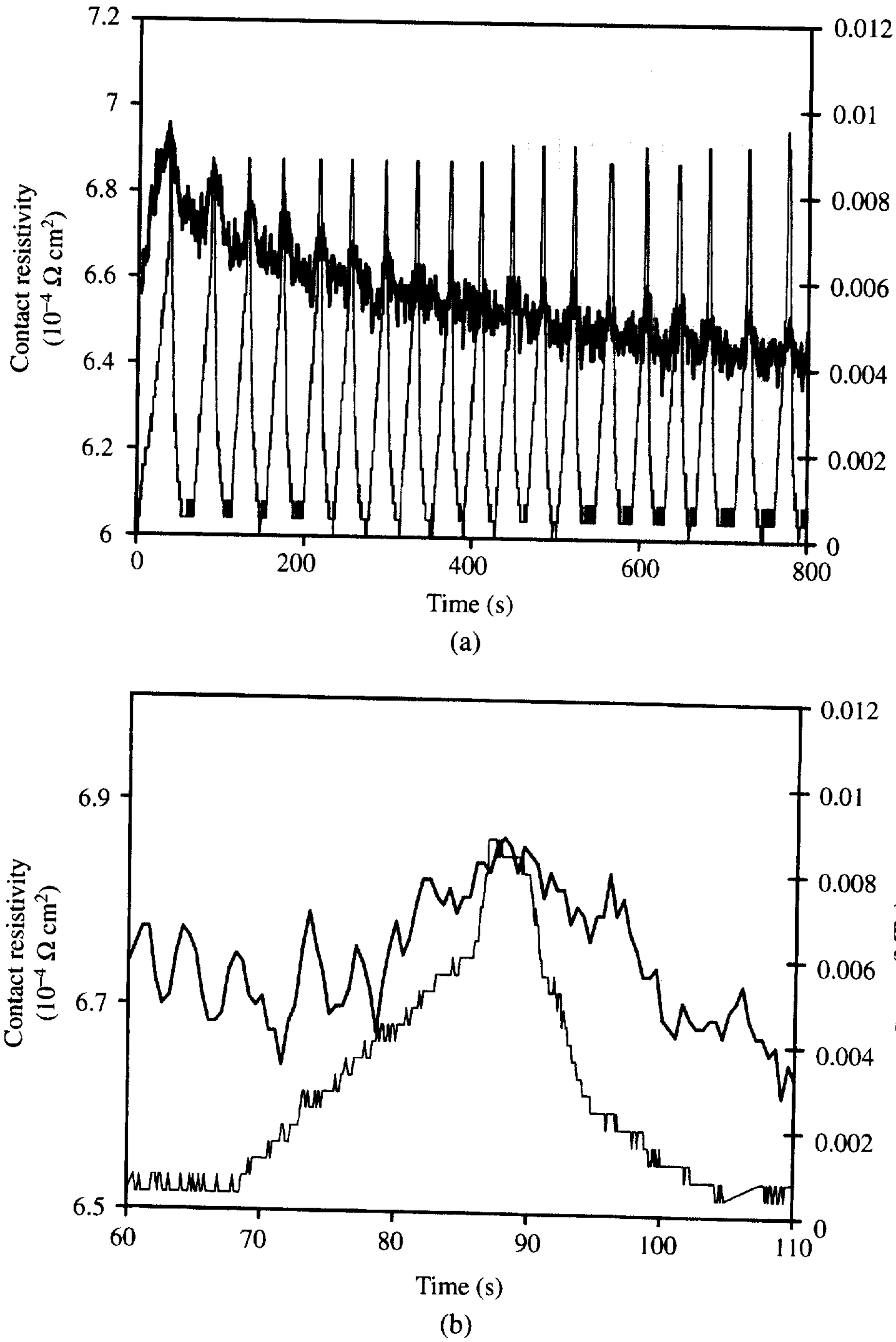


Figure 10. Contact resistivity *vs.* time during stress cycling of the adhesive joint at the initial amplitude of 0.009 MPa. (a) Multiple cycles. (b) One of the cycles in an expanded view. Thick curve, resistivity; thin curve, stress.

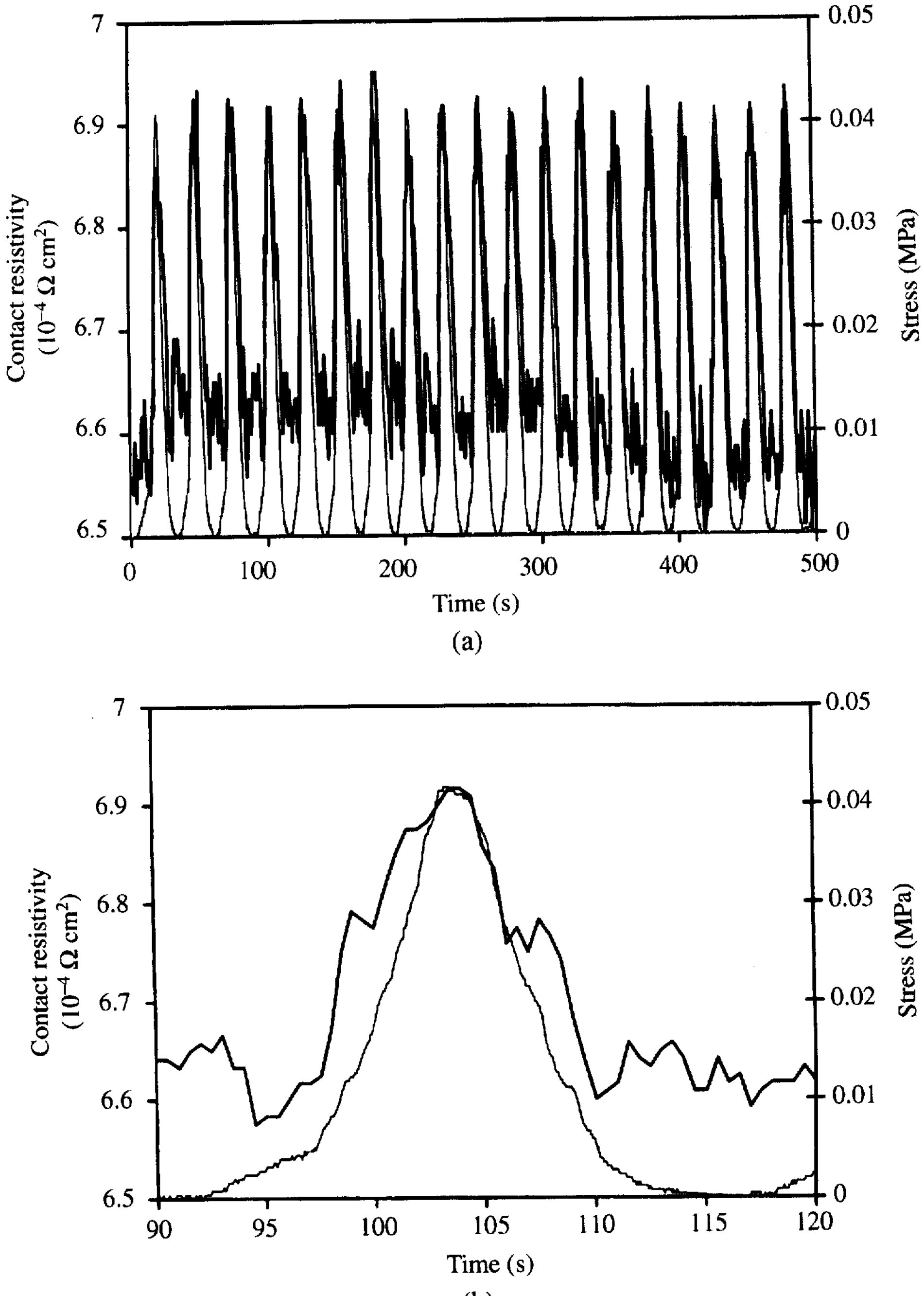


Figure 11. Contact resistivity *vs.* time during stress cycling of the adhesive joint at the initial amplitude of 0.04 MPa. (a) Multiple cycles. (b) One of the cycles in an expanded view. Thick curve, resistivity; thin curve, stress.

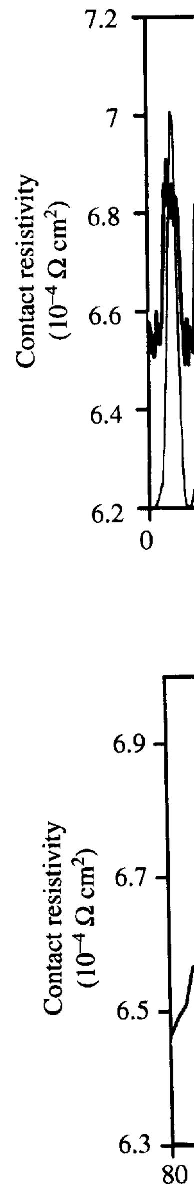


Figure 12. Contact
amplitude of 0.08 MP
curve, resistivity; thin

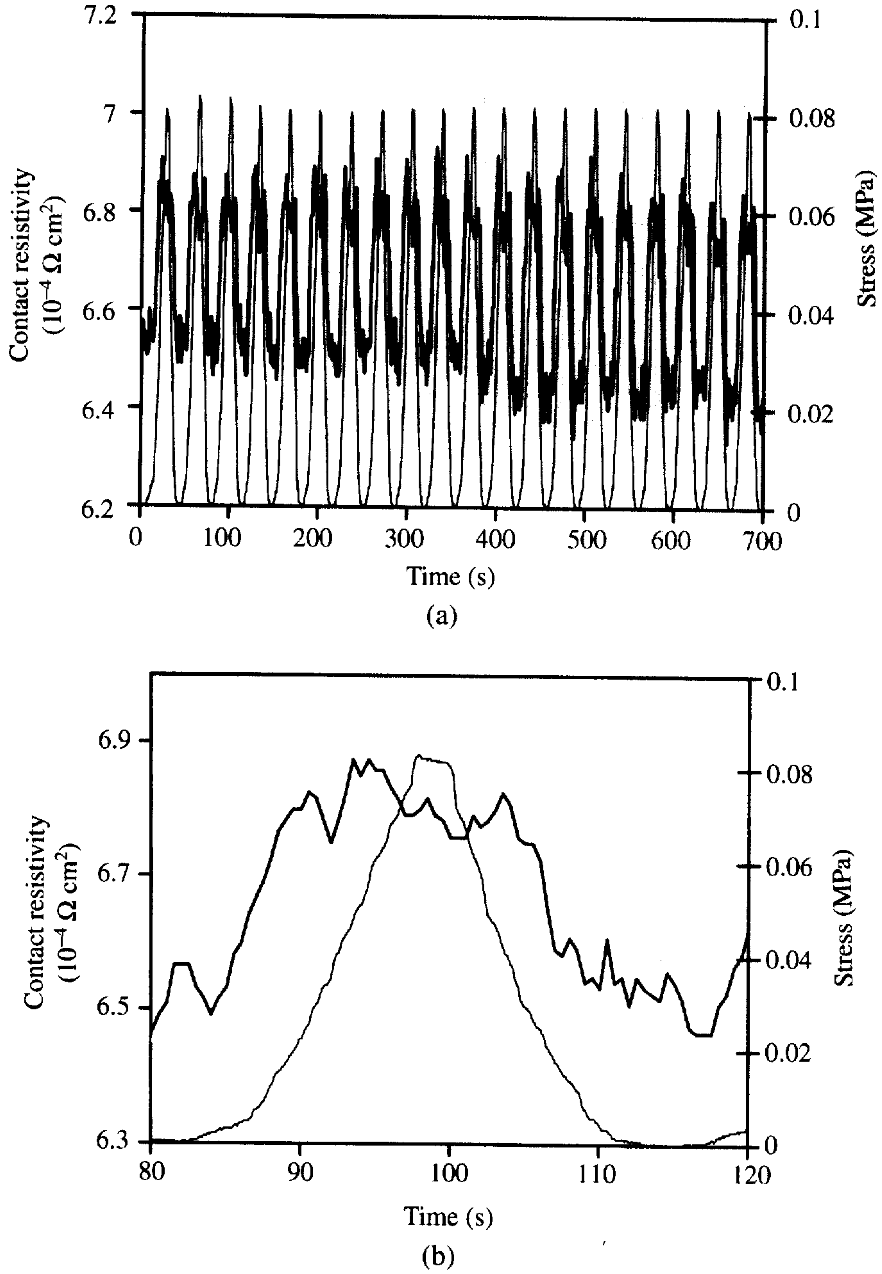
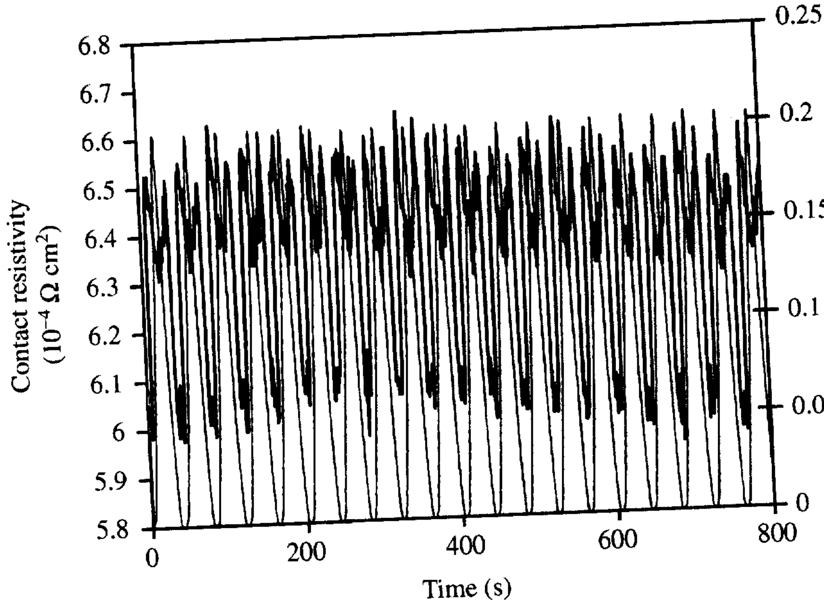
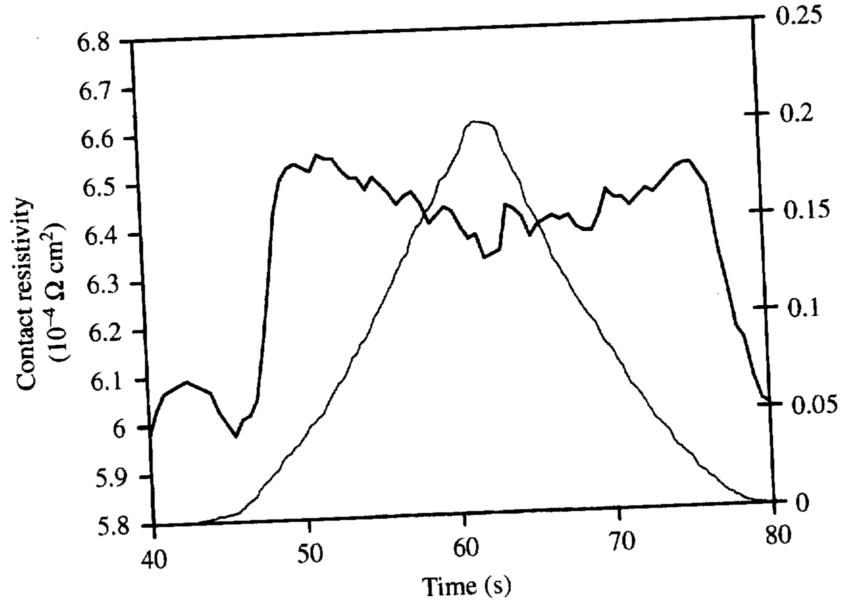


Figure 12. Contact resistivity *vs.* time during stress cycling of the adhesive joint at the initial amplitude of 0.08 MPa. (a) Multiple cycles. (b) One of the cycles in an expanded view. Thick curve, resistivity; thin curve, stress.



(a)



(b)

Figure 13. Contact resistivity *vs.* time during stress cycling of the adhesive joint at the initial amplitude of 0.20 MPa. (a) Multiple cycles. (b) One of the cycles in an expanded view. Thick curve, resistivity; thin curve, stress.

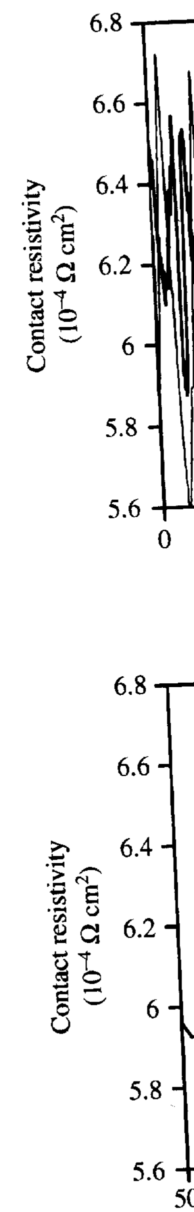


Figure 14. Conta
amplitude of 0.40
curve, resistivity; t

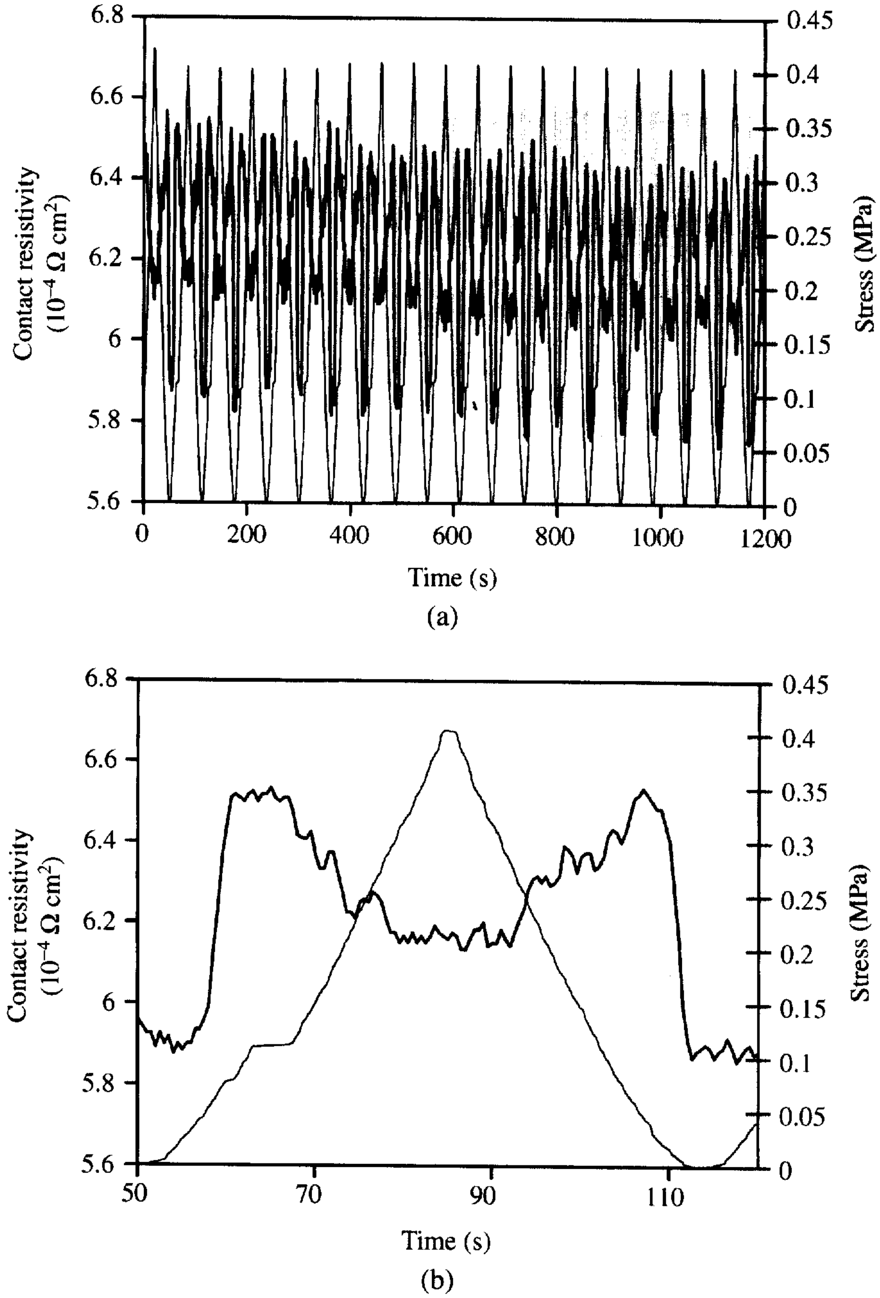


Figure 14. Contact resistivity *vs.* time during stress cycling of the adhesive joint at the initial amplitude of 0.40 MPa. (a) Multiple cycles. (b) One of the cycles in an expanded view. Thick curve, resistivity; thin curve, stress.

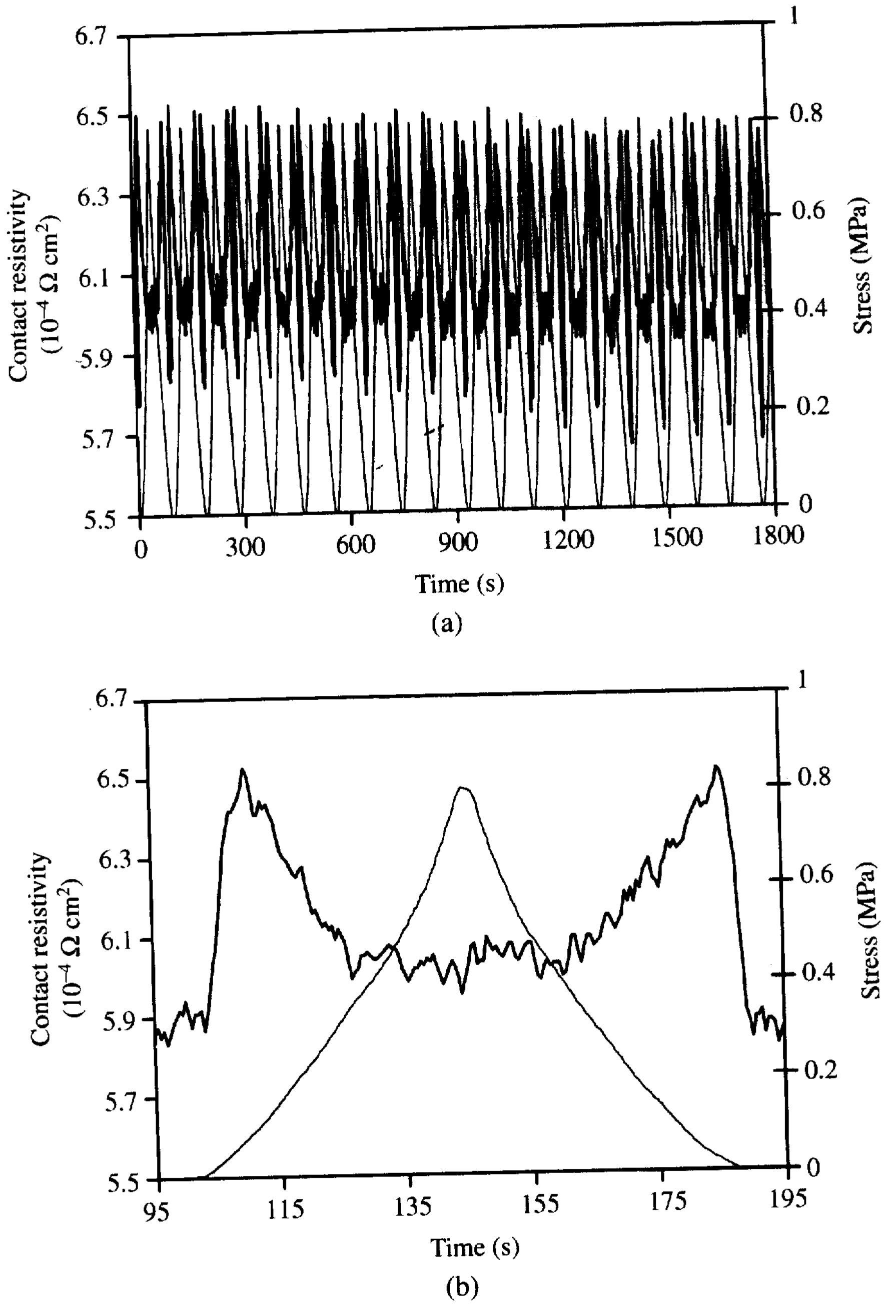


Figure 15. Contact resistivity *vs.* time during stress cycling of the adhesive joint at the initial amplitude of 0.80 MPa. (a) Multiple cycles. (b) One of the cycles in an expanded view. Thick curve, resistivity; thin curve, stress.

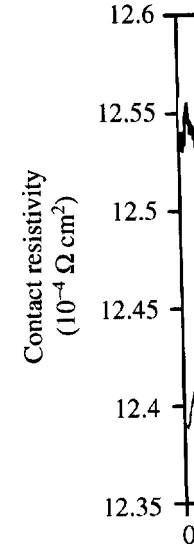


Figure 16. Contact re
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4. DISCUSSION

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damage within the
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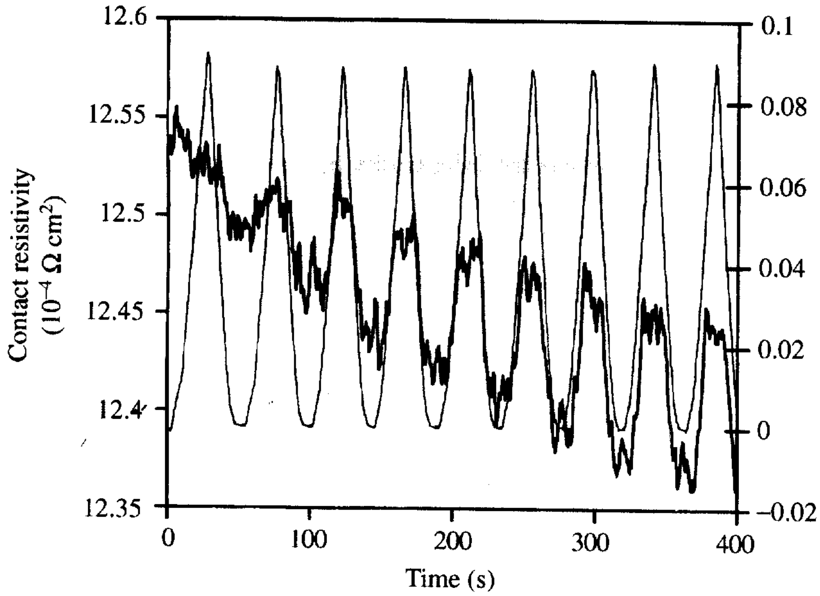

Figure 16. Contact resistivity *vs.* time during stress cycling of the adhesive joint at the initial amplitude of 0.09 MPa. Thick curve, resistivity; thin curve, stress.

slight increase in resistivity near the peak stress of a cycle was not clearly observed, though it was clearly observed in the case of the soldered joint.

4. DISCUSSION

The resistivity increased upon loading beyond about 0.02 MPa (Fig. 2b) in the case of the soldered joint and beyond 0.005 MPa (Fig. 10b) in the case of the adhesive joint. This was almost totally reversible. It cannot be due to elastic deformation of the solder or adhesive, as this would have caused the volume resistance of the solder or adhesive to decrease, thus decreasing the contact resistivity. It is attributed to damage (i.e., a microstructural change) which was almost totally reversible and was more prone to occurring in an adhesive joint than in a soldered joint, due to the brittleness of epoxy. Although the experimental method cannot distinguish between damage within the solder (or adhesive) and that at the interface between copper and solder (or adhesive), it is likely that the damage occurred at the interface, due to the low stress involved.

The irreversible gradual increase of the resistivity baseline in the case of the soldered joint, as observed upon cycling at low stress amplitudes (0.12 and 0.17 MPa), is due to irreversible minor damage. This type of damage was saturated after cycling at the low stress amplitudes, so that no additional damage of this type occurred during subsequent cycling at higher stress amplitudes. In the case of the adhesive joint, the gradual decrease of the resistivity baseline upon stress cycling is probably due to a decrease in the volume electrical resistivity of the adhesive as the proximity between adjacent silver particles in the adhesive increased.

The resistivity drop upon loading beyond a higher level (⩾0.03 MPa) was partially or completely reversible and is attributed to damage diminution (akin to crack closing although the damage does not necessarily involve crack formation). Damage diminution is supported by the previously reported increase in fatigue life upon increasing the dwell time for the compressive stress maximum during tension–compression fatigue testing [15]. In the case of the soldered joint, the resistivity drop may be partly due to elastic deformation of the solder. Plastic deformation can cause an irreversible resistance decrease, but it could not have occurred due to the low stress; the compressive yield strength of the solder is 28 MPa [16]. The slight resistivity increase observed in the soldered joint upon loading beyond about 0.21 MPa is attributed to additional damage at the high stress.

The identification of the type of damage or microstructural change is beyond the scope of this paper. It requires microscopy in real time during loading and unloading, work which is experimentally difficult. Nevertheless, this paper shows that stress has both reversible and irreversible effects on the resistivity, due to both reversible and irreversible microstructural changes. These effects depend on the stress amplitude and the load history, and can involve increase or decrease of the resistivity upon increasing the stress.

The contact resistivity prior to loading was 2.5×10^{-4} and $6.6 \times 10^{-4}\ \Omega\,\mathrm{cm}^2$ for the soldered and adhesive joints, respectively (Figs 2 and 10). Although the volume resistivity of solder is much lower than that of the adhesive, the contact resistivity of the two types of joints is similar. The limited effectiveness of solder is due to the reaction between solder and the copper. This reaction results in copper–tin intermetallic compounds at the solder-copper interface [17–19].

The resistivity effects reported here for the case of compression are much more detailed and more subtle than those previously reported for the case of tension or shear [12, 13]. This is partly due to debonding under tension or shear overshadowing other microstructural effects. In contrast, debonding does not tend to occur under compression (unless the stress is very high), thus allowing more subtle microstructural effects to dominate. The subtle microstructural effects under compression may occur at the solder–copper interface or adhesive–copper interface. That these effects occur at stresses as low as 0.005 MPa means that they can be commonly encountered in the processing and usage of electronic packages.

5. CONCLUSIONS

Compressive stress on a joint (obtained by soldering or by the use of silver epoxy) in the direction perpendicular to the joint area resulted in both reversible and irreversible changes of the DC contact resistivity of the joint. The effects depended on the stress amplitude and the load history. At stress beyond about 0.02 MPa in the case of the soldered joint and beyond 0.005 MPa in the case of the adhesive

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joint, the resistivity increased with almost complete reversibility upon unloading. The slight irreversibility was such that the resistivity at no load increased gradually as stress cycling progressed in the case of the soldered joint, even at the lowest stress amplitude of 0.12 MPa, but the resistivity at no load decreased gradually as stress cycling progressed in the case of the adhesive joint, even at the lowest stress amplitude of 0.009 MPa. At a higher stress ($\geqslant$0.03 MPa) for both soldered and adhesive joints, the resistivity decreased with increasing stress with partial or complete reversibility. At an even higher stress (beyond about 0.21 MPa) in the case of the soldered joint, the resistivity increased slightly.

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