Interface in Mechanically Fastened Polymer Joint, Studied by Contact Electrical Resistance Measurement

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A polymer-polymer joint obtained by mechanical fastening at a compressive stress of 5% (or less) of the 1% offset yield strength of the polymer (nylon-6) was found to exhibit irreversible decrease in the contact electrical resistance upon repeated fastening (loading) and unfastening (unloading). The decrease occurred after up to 10 cycles of fastening and unfastening, although the decrease diminished with cycling. It is primarily due to local plastic deformation of the matrix. Moreover, the stress required for the resistance to reach its minimum in a cycle decreased with cycling, owing to softening of the matrix.

INTRODUCTION

Mechanical fastening is one of the most common methods of joining. It involves the application of a force to the components to be jointed. Examples of fasteners are rivets, bolts, screws and nuts. Fasteners as well as components are most commonly made of metals, such as steel. However, polymers are increasingly used for both fasteners and components, due to their moldability, low density and corrosion resistance.

Both experimental and numerical studies have previously been made on adhesively bonded polymer composite joints subjected to compressive, tensile and shear loading in static and cyclic conditions (1–5) for the purpose of understanding the damage progression and failure mechanism. Experimental methods previously used for such joint studies were mainly either mechanical or optical. Electrical methods have not been previously used for polymeric joint studies.

In an earlier paper, we studied the interface in mechanically fastened steel joint by contact electrical resistance measurement and unexpectedly found that the steel-steel joint exhibits irreversible change upon repeated fastening (loading) and unfastening (unloading), even though the compressive stress is just 7% (or less) of the yield strength (6). The effect is primarily due to local plastic deformation. In this paper, we have extended the work from metal to polymer by studying a polymer-polymer joint through contact electrical resistance measurement during repeated compressive loading.

Because of the electrically insulating behavior of conventional polymers and the need for an electrical resistance, this work used a polymer that contained continuous carbon fibers in a direction parallel to the plane of the joint. The carbon fibers cause the composite to be electrical conducting in the fiber direction, as well as the through-thickness direction, because the fibers, though said to be unidirectional, are not all straight and parallel and there is some degree of contact between adjacent fibers in the composite in spite of the presence of the matrix (7). Owing to the direction of the fibers, the mechanical properties of the composite in the through-thickness direction is dominated by the polymer matrix, as desired for studying a mechanically fastened polymer-polymer joint.

The objectives of this work are to investigate the effect of repeated fastening and unfastening on a polymer-polymer joint interface and to compare the behavior of the polymer-polymer joint interface and to compare the behavior of the polymer-polymer joint of this work with that of the steel-steel joint of our previous work.

EXPERIMENTAL METHODS

The thermoplastic polymer was a nylon-6 (PA) in the form of unidirectional carbon-fiber (CF) prepreg supplied by Quadrax Corp. (Portsmouth, Rhode Island; QNC 4162). The fibers were 34-700 from Grafil, Inc. (Sacramento, California). The fiber diameter was 6.9 μm. The fiber weight fraction in the prepreg was 62%.

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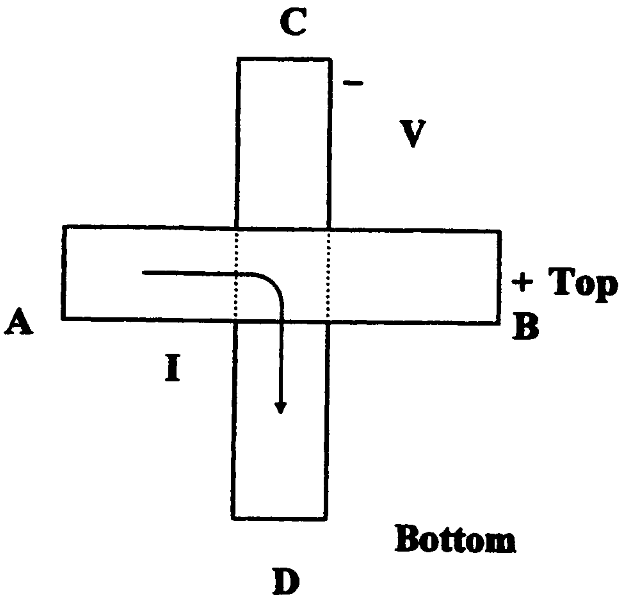

Fig. 1. Polymer joint test configuration.

The glass transition temperature (T_g) was 40–60°C and the melting temperature (T_m) was 220°C for the nylon-6 matrix. The prepreg thickness was 250 μm. Two rectangular strips of prepreg with length about 72 mm and width between 8.2 and 11.1 mm were allowed to overlap at 90° to form a rectangular junction (8.2–10.4 mm × 9.5–11.1 mm), as illustrated in *Fig. 1*. The junction was the joint under study. Uniaxial compression at a displacement rate of 0.5 mm/min (corresponding to the application of a fastening load) was applied at the junction in the direction perpendicular to the junction, using a screw-action mechanical testing system (Sintech 2/D, Sintech, Research Triangle Park, N.C.), while the contact electrical resistance of the junction was measured. A DC current was applied from A to D, so that the current traveled down the junction from the top prepreg to the bottom prepreg. Meanwhile the voltage was measured between B and C using a Keithley 2002 multimeter; this voltage was the voltage across the junction between the top and bottom prepregs. The use of two current probes (A and D) and two voltage probes (B and C) corresponds to the four-probe method of resistance measurement.

This paper includes a comparison of the results of this work on polymer joint with those of Ref. 6 on low carbon steel joint. Unless stated otherwise, all results are for polymer joint.

RESULTS AND DISCUSSION

Figure 2 shows the variation in resistance and stress during cyclic compressive loading at a stress amplitude of 0.8 MPa. In every cycle, the resistance

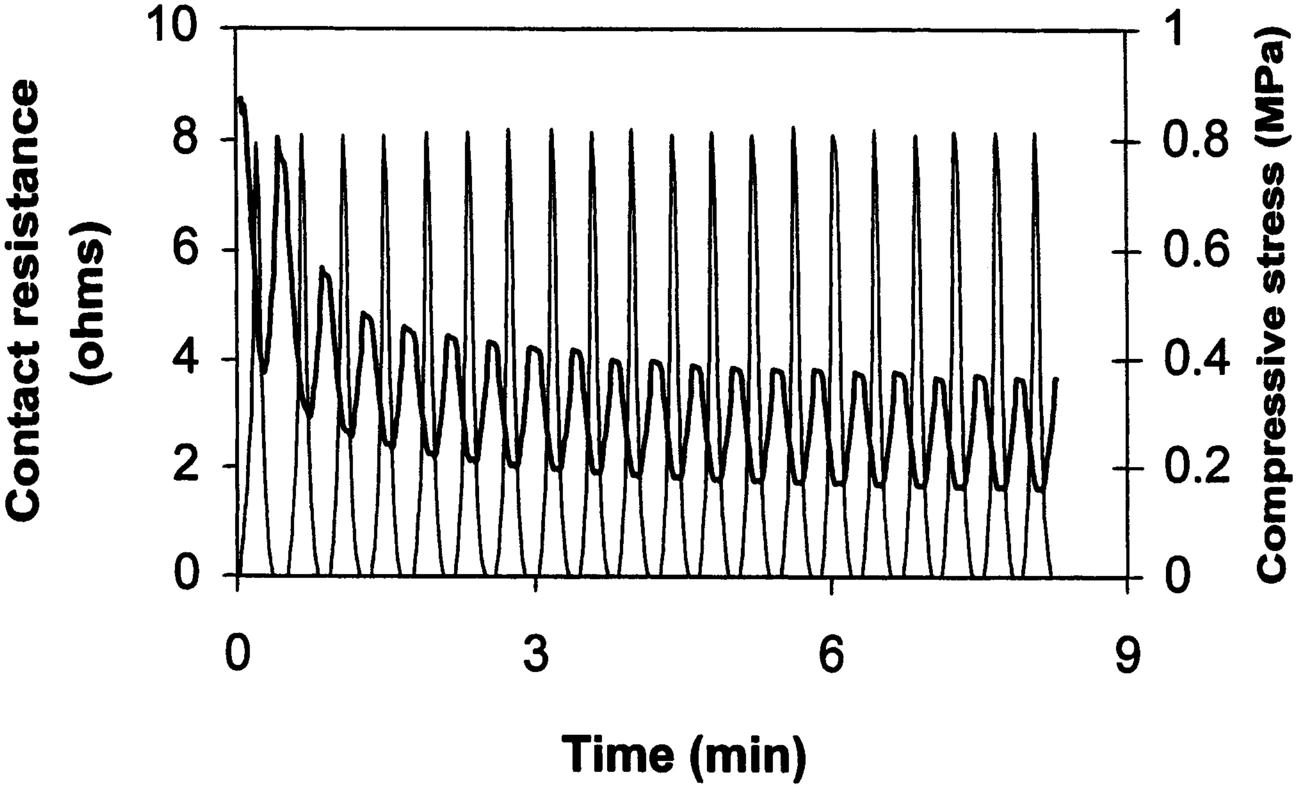

Fig. 2. Variation of contact resistance (thick curve) and stress (thin curve) for polymer joint during cyclic compression at a stress amplitude of 0.8 MPa.

decreased as the compressive stress increased, such that the maximum stress corresponded to the minimum resistance and the minimum stress corresponded to the maximum resistance. The minimum resistance (at the maximum stress) decreased upon cycling; so did the maximum resistance (at the minimum stress). *Figure 3* shows the first seven cycles more clearly. In the first cycle, the minimum in the resistance curve was quite sharp. The sharpness decreased as cycling progressed. This means that the stress required for the resistance to reach the minimum decreased as cycling progressed. Since, during loading, there is no change in the electrical property of the carbon fibers, which are responsible for the electrical conduction, the observed electrical resistance decrease upon loading is due to the increase in the extent of contact between fibers on the two sides of the joint interface. The stress amplitude of 0.8 MPa is much less than the 1% offset yield stress (83 MPa) (8). However, because of the asperities at the interface, the local stress on the asperities was much higher than the applied stress. As a result, plastic deformation occurred at the asperities. Furthermore, the compressive stress probably caused the matrix molecules to orient preferentially in the direction perpendicular to the stress, thereby weakening the mechanical property of the matrix in the stress direction, especially near the interface. This notion is consistent with reports on the decrease of the modulus of nylon-6 under compression (9–15). In other words, the compressive loading softened the matrix in the stress direction more and more as cycling progressed, thus enhancing the extent of contact between fibers on the two sides of the interface and causing the resistance curve to become blunter at its minimum as cycling progressed. The gradual decrease of both the minimum resistance and the maximum resistance in a cycle as cycling progressed is due to the surface of the prepreg becoming flatter (less pointed asperities) with cycling, as the flattening causes the true contact area at the joint to increase. After about ten loading cycles, the resistance leveled off (*Fig. 2*), probably as a result of the limit of the extent of flattening.

The stress amplitude in *Fig. 4* is 4.0 MPa, which is higher than in that in *Fig. 2* and *Fig. 3* (0.8 MPa). The resistance changed similarly at the two stress amplitudes, except that, at the higher stress amplitude, it took fewer cycles for the resistance curve to level off, as expected.

Figure 5 shows the variation in resistance and stress during compressive loading at a stress amplitude of 20.0 MPa for steel joint. For both polymer joint (this work) and steel joint (6), the contact resistance decreased as the stress increased and the contact resistance increased as the stress decreased. There are two main differences in how the resistance changed

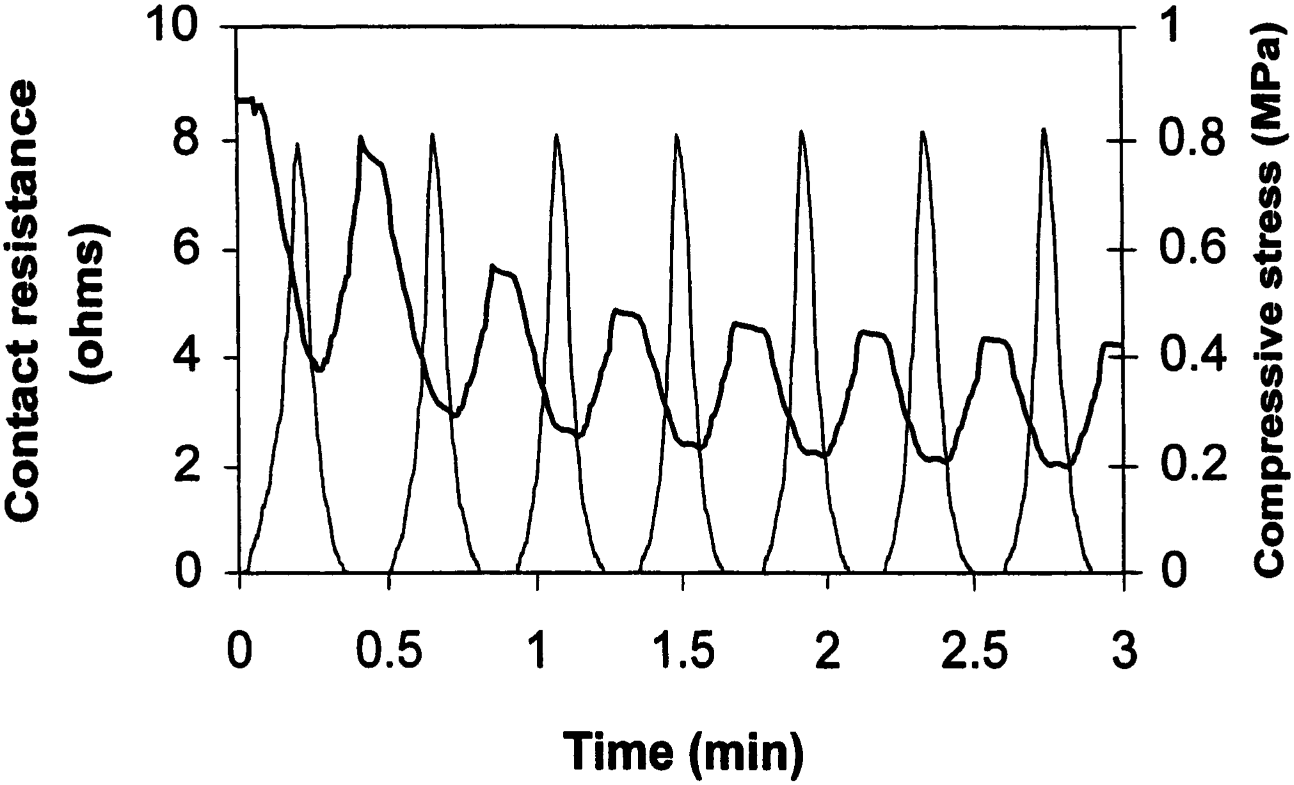

Fig. 3. Variation of contact resistance (thick curve) and stress (thin curve) for polymer joint during cyclic compression at a stress amplitude of 0.8 MPa for the first 7 cycles.

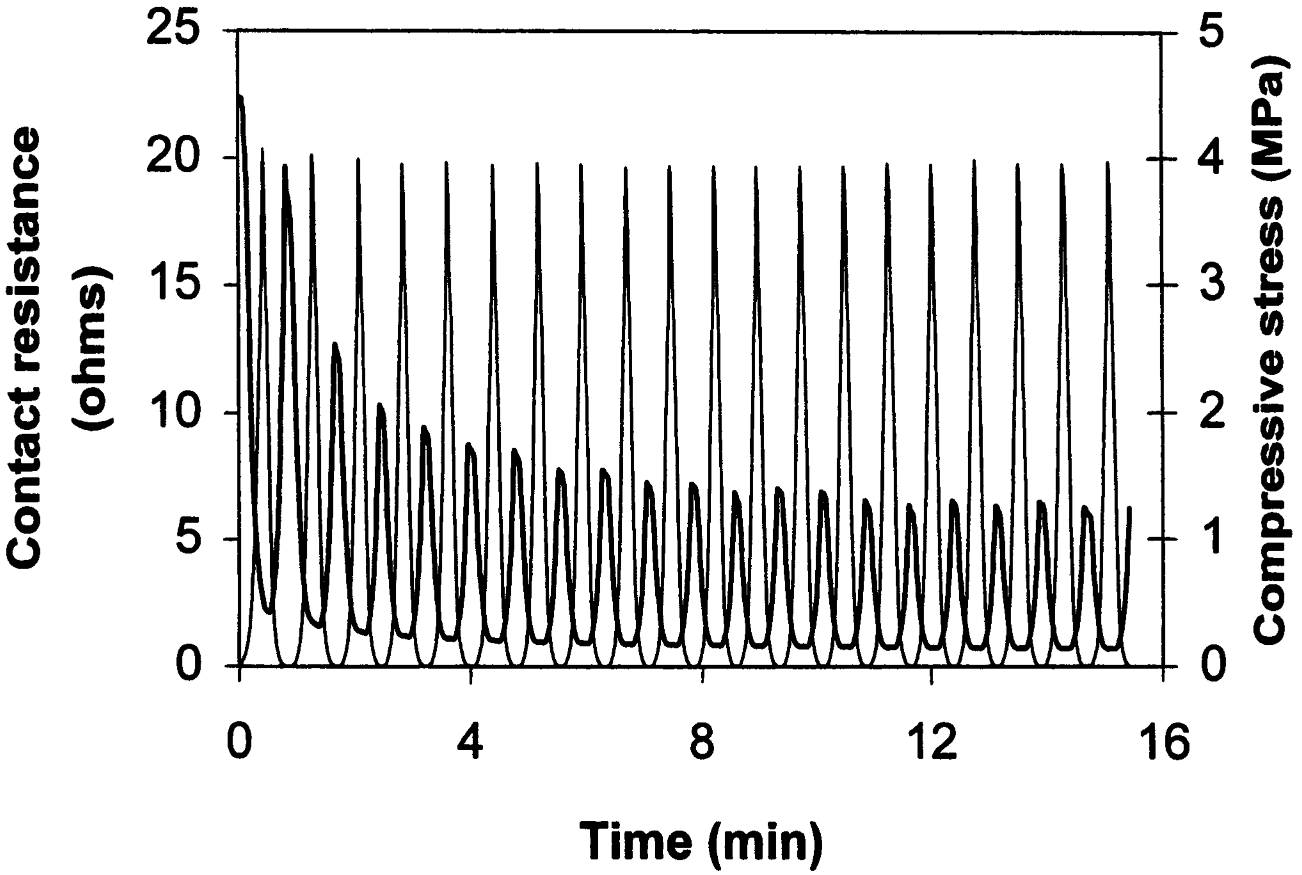

Fig. 4. Variation of contact resistance (thick curve) and stress (thin curve) for polymer joint during cyclic compression at a stress amplitude of 4.0 MPa.

during loading between the polymer joint and steel joint. One is that, for the polymer joint, the resistance curve at its minimum became blunter and blunter as cycling progressed; however, for the steel joint, the resistance curve at its minimum became sharper and sharper as cycling progressed. In both cases the plastic deformation occurred at the interface due to the asperities on the joint surface. However, for the polymer, the stress softened the polymer matrix in the stress direction, probably because of the enhancement of the molecular preferred orientation; for the steel, the stress hardened the surface by work hardening. Another difference is that for the polymer joint, both the minimum resistance and the maximum resistance in a cycle decreased with cycling; but for the steel joint, the minimum resistance increased with the cycling while the maximum resistance decreased. This is because, for the polymer joint, the decrease in the resistance was only the result of the prepregs becoming flatter with cycling, but for the steel joint, the fresh surface created by the local plastic deformation during cycling might be oxidized and/or undergo work hardening, thereby causing the electrical resistivity of the surface region of the steel to increase, despite a similar flattening effect.

CONCLUSION

A polymer-polymer joint obtained by mechanical fastening at a compressive stress equal to 5% (or less) of the 1% offset yield stress of the polymer was studied by measurement of the contact electrical resistance of the joint, which was rendered electrically conducting by the presence of continuous carbon fibers ebedded in the polymer in the direction parallel to the joint interface. The contact resistance decreased upon compressive loading of the joint and increased upon unloading, such that both the minimum resistance (at maximum load) and the maximum resistance (at zero load) decreased as load cycling occurred. The decrease of the minimum and maximum resistances is due to local plastic deformation at the asperities at the joint interface. It persisted for the first few (up to 10) loading cycles; the higher the stress amplitude, the fewer were the cycles in which the decrease occurred. The decrease diminished as cycling progressed. Moreover, the stress required for the resistance to reach its minimum in a cycle decreased as load cycling progressed, owing to the softening of the matrix in the stress direction, probably as a consequence of the molecular orientation enhancement in the matrix.

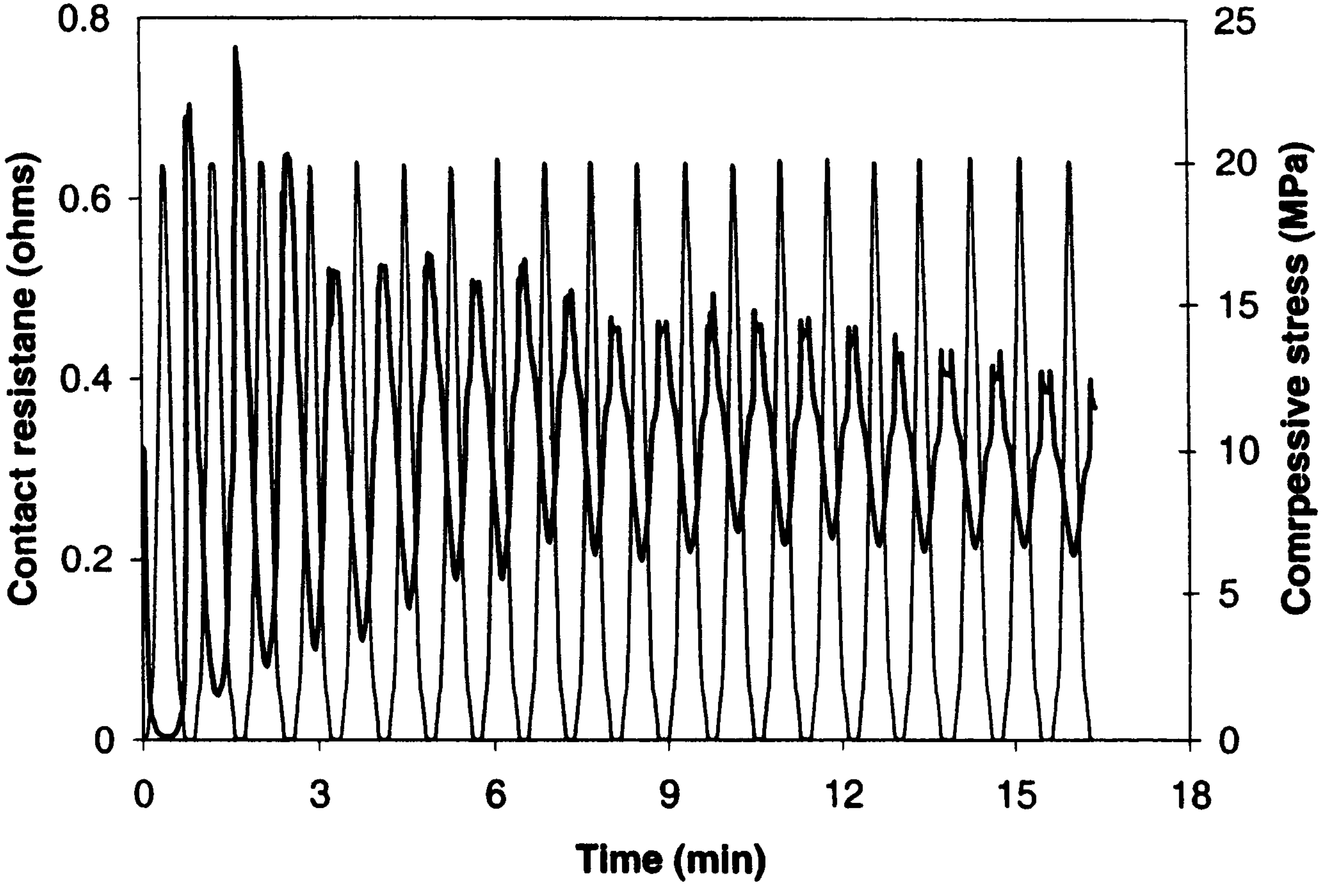

Fig. 5. Variation of contact resistance (thick curve) and stress (thin curve) for steel joint during compression at a stress amplitude of 20.0 MPa.

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