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Review
Joints obtained by soldering, adhesion, autohesion and fastening, studied by electrical resistance measurement

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Joints obtained by soldering, adhesion, autohesion and fastening and involving metals, polymer-matrix composites and concrete, as studied by electrical resistance measurement, are reviewed. The measurement was conducted during bonding, debonding, fastening and/or unfastening, and involved either measuring the contact resistance of the joint interface or measuring the apparent volume resistance of a member of the joint.

1. Introduction

Joining is one of the key processes in manufacturing and repair. It can be achieved by welding, diffusion bonding (autohesion in the case of polymers), soldering, brazing, adhesion, fastening, or other methods. Fusion welding involves relatively high temperatures and the heat associated with fusion welding tends to affect negatively the microstructure and properties of the materials outside the weld pool. In contrast, diffusion bonding, soldering, brazing, adhesion and fastening involve lower temperatures and hence less side effects. Soldering and brazing are similar in concept, as both involve the melting of an alloy which acts as the joining medium; the difference between soldering and brazing lies mainly in that brazing involves higher melting temperatures than soldering. This paper addresses soldering, adhesion, autohesion and fastening, which represent the four main types of joining methods other than welding.

Joints can be evaluated destructively by mechanical testing which involves debonding. However, it is preferred to use nondestructive methods, such as modulus (dynamic mechanical), acoustic and electrical measurements. Electrical measurements, especially under the Direct Current (DC) condition, are attractive, due to the short response time and equipment simplicity. However, electrical measurements are not commonly used for joint evaluation. This paper reviews the use of electrical measurements for the study of joints.

A requirement for the feasibility of electrical measurements for joint evaluation is that the components being joined are not electrical insulators. Thus, joints involving metals, cement (concrete) and conductor filled polymers are suitable.

A joint can be studied during bonding for the purpose of understanding the bonding process, and during debonding for the purpose of understanding the debonding process. Study of the joint after bonding and before debonding provides information on the structure and properties of the joint, but does not give much information on the processes of bonding and debonding. Study of the joint after debonding provides information on the aftermath of the failure, but gives limited information on the process of debonding. Knowledge of the process of bonding is valuable for guiding the choice of process conditions (e.g., temperature, pressure, time, etc.) for bonding. Knowledge of the process of debonding is valuable for the choice of bonding and use conditions for avoiding debonding, as the bonding and use conditions affect the joint quality, thereby affecting the propensity for debonding.

Electrical measurements can be carried out in real time during bonding and debonding on the same specimen. In contrast, microscopy and destructive mechanical testing cannot. Thus, electrical measurements are quite powerful for joint studies.

For a joint obtained by fastening, bonding and debonding do not occur. Nevertheless, the joint may be repeatedly fastened and unfastened. The effects of fastening stress and of prior fastening and unfastening on the joint are of practical importance. They may be studied by electrical measurements that are carried out in real time during fastening and unfastening.

The method of electrical resistance measurement for joint evaluation most commonly involves measurement of the contact electrical resistivity of the joint interface. The contact resistivity is given by the product of the contact resistance and the joint area; it is a quantity that is independent of the joint area. Degradation of the joint causes the contact resistivity to increase. A less common method involves measuring the apparent volume resistance of a component while the component

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(A) is joined to another component (B). When B is less conducting than A, but is not insulating, degradation of the joint causes the apparent volume resistance of A to increase. Both of these methods are illustrated in this paper, which is a review that includes joints obtained by soldering, adhesion, autohesion and fastening.

2. Joints by soldering

Electrical and mechanical connections using solder (e.g., tin-lead) as the joining medium are widely used, in spite of the environmental problems associated with solder use and the thermal fatigue problem associated with soldered joints. Intuition suggests that a debonded joint is bad electrically, but recent work has shown that the contact resistivity of a soldered joint essentially does not change upon debonding, but only upon physical separation [1, 2].

Fig. 1 [2] shows the shear stress and contact resistivity obtained simultaneously for acid washed copper wire (1 mm diameter) embedded in solder (eutectin tin-lead) to a length of 2.5 mm. The shear stress increases due to debonding. The maximum shear stress corresponds to the shear bond strength (11 MPa, Fig. 1). The initial contact resistivity is 10^{-5} $\Omega \cdot \text{cm}^2$; the absolute value cannot be accurately measured due to its small value, so the increase in contact resistivity is shown in Fig. 1. At the completion of debonding, the shear stress drops abruptly due to the pull-out of the wire from the solder, but the contact resistivity hardly changes. The contact resistivity rises abruptly when the pull-out is almost complete.

3. Joints by adhesion

3.1. Joints involving silver-epoxy and copper

Conductor filled polymer, such as silver particle filled epoxy (abbreviated silver-epoxy) [2–6], are increasingly used to replace solder as the joining medium in electronic packaging. A conductor filled polymer is a composite material in which the matrix (polymer) is non-conducting and the conductivity of the composite is derived from that of the filler. In contrast, a solder is a metal alloy, the entirety of which is conducting. Moreover, a conductor filled polymer is much less conducting than a solder. In addition, joining with solders involves heating, but joining with conductor filled polymers may or may not involve heating. These differences between a conductor filled polymer and a solder suggest differences between joints made using these two media.

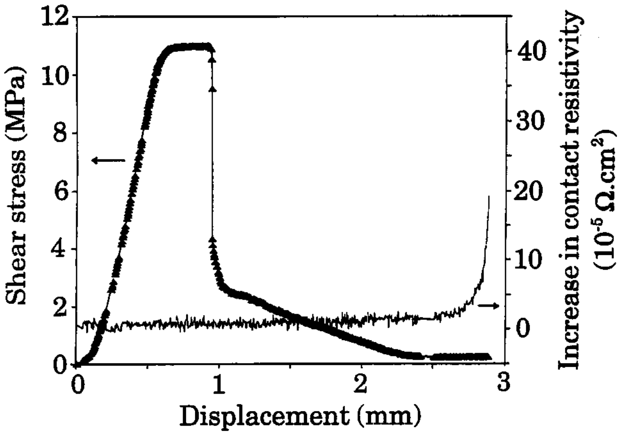


Figure 1 Variation of contact electrical resistivity and shear stress with displacement during pull-out of acid washed copper wire from solder.

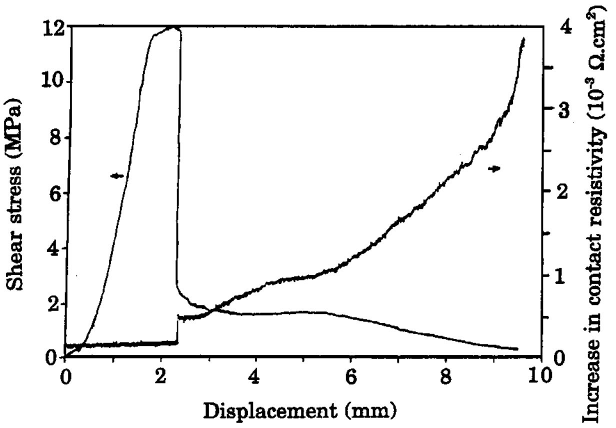


Figure 2 Variation of contact electrical resistivity and shear stress with displacement during pull-out of acetone washed copper wire from silver-epoxy.

Fig. 2 [2] shows data corresponding to those of Fig. 1 but for acetone washed copper wire and silver-epoxy. The embedment length is 9.0 mm. The shear bond strength is 12 MPa. The initial contact resistivity is 2×10^{-4} $\Omega \cdot \text{cm}^2$. At the completion of debonding, the shear stress drops abruptly, while the contact resistivity jumps up. The jump is in contrast to the absence of a jump in the case of the soldered joints (Fig. 1).

Silver-epoxy joints to copper abruptly increase in contact resistivity upon completion of debonding, whereas soldered joints to copper essentially do not change in contact resistivity upon completion of debonding, due to the lower ductility of silver-epoxy than solder. The contact resistivity before debonding is higher for silver-epoxy than solder. Cleansing of the copper surface is essential for silver-epoxy, but not essential for solder. Acetone washing of the copper surface helps silver-epoxy joints, but has little effect on soldered joints. Acid washing helps soldered joints more than acetone washing, but helps silver-epoxy joints to the same extent as acetone washing [2].

3.2. Joints involving composite and concrete

Continuous fiber polymer-matrix composites are increasingly used to retrofit concrete structures, particularly columns [7–20]. The retrofit involves wrapping a fiber sheet around a concrete column or placing a sheet on the surface of a concrete structure, such that the fiber sheet is adhered to the underlying concrete by using a polymer, most commonly epoxy. This method is effective for the repair of even quite badly damaged concrete structures. Although the fibers and polymer are very expensive compared to concrete, the alternative of tearing down and rebuilding the concrete structure is often even more expensive than the composite retrofit. Both glass fibers and carbon fibers are used for the composite retrofit. Glass fibers are advantageous for their relatively low cost, but carbon fibers are advantageous for their high tensile modulus.

The effectiveness of a composite retrofit depends on the quality of the bond between the composite and the underlying concrete, as good bonding is necessary for load transfer. Peel testing for bond quality evaluation is destructive [21]. Nondestructive methods to evaluate the bond quality are valuable. They include acoustic methods, which are not sensitive to small amount of debonding or bond degradation [22], and dynamic mechanical testing [23]. Electrical resistance measurement was used for nondestructive evaluation of the interface between concrete and its carbon fiber composite retrofit [24]. The method is effective for studying the effects of temperature and debonding stress on the interface. The concept behind the method is that bond degradation causes the electrical contact between the carbon fiber composite retrofit and the underlying concrete to degrade. Since concrete is electrically more conducting than air, the presence of an air pocket at the interface causes the measured apparent volume resistance of the composite retrofit in a direction in the plane of the interface to increase. Hence, bond degradation is accompanied by an increase in the apparent resistance of the composite retrofit. Although the polymer matrix (epoxy) is electrically insulating, the presence of a thin layer of epoxy at the interface is unable to electrically isolate the composite retrofit from the underlying concrete.

The apparent resistance of the retrofit in the fiber direction is increased by bond degradation, whether the degradation is due to heat or stress. The degradation is reversible. Irreversible disturbance in the fiber arrangement occurs slightly as thermal or load cycling occurs, as indicated by the resistance decreasing cycle by cycle [7].

4. Joints by autohesion

4.1. Bonding

Joining methods for polymers and polymer-matrix composites include autohesion, which is relevant to the self-healing of polymers. Diffusion bonding (or autohesion) involves interdiffusion between the adjoining materials in the solid state. In contrast, fusion bonding involves melting. Due to the relatively low temperatures of diffusion bonding compared to fusion bonding, diffusion bonding does not suffer from the undesirable side effects that typically occur in fusion bonding, such as degradation and crosslinking of the polymer matrix. Although the diffusion bonding of metals has been widely studied [24–28], relatively little study has been conducted on the autohesion of polymers [29–45]. Because of the increased segment mobility above the glass transition temperature (T_g), thermoplastics are able to undergo interdiffusion above T_g.

Diffusion, as a thermally activated process, takes time. In other words, how long diffusion takes depends on the temperature. In order for diffusion bonding or autohesion to be conducted properly, the kinetics of the process needs to be known.

The study of the kinetics requires monitoring the process as it occurs. A real-time monitoring technique is obviously preferable to a traditional method that requires periodic interruption and cooling of the specimen. However, real-time monitoring is experimentally difficult compared with interrupted monitoring. The method described here is ideal for thermoplastic prepregs containing continuous carbon fibers, since the carbon fibers are conductive. Two carbon-fiber thermoplastic prepreg plies are placed together to form a joint. The electrical contact resistance of this joint is measured during autohesion. As autohesion occurs, the fibers in the plies undergoing joining come closer together, thus resulting in a decrease in the contact resistance. Hence, with the measurement of this resistance in real time, the autohesion process was monitored as a function of time at different selected bonding temperatures for Nylon-6 and polyphenylenesulfide (PPS), both thermoplastics [45]. Arrhenius plots of a characteristic resistance decrease versus temperature allow determination of the activation energy for the process. This method can possibly be used for monitoring of bonding of unfilled thermoplastics if a few carbon fibers are strategically placed.

4.2. Debonding

Engineering thermoplastics can be bonded together by autohesion above the glass transition temperature but below the melting temperature, or fusion welding (i.e., melting and subsequent solidification). Both methods involve heating and subsequent cooling. During cooling, the thermoplastic goes from a soft solid state (in the case of autohesion) or a liquid state (in the case of fusion welding) to a stiff state. If the thermoplastic members to be joined are anisotropic (as in the case of each member being reinforced with fibers) and the fiber orientation in the two members is not the same, the thermal expansion (actually contraction) mismatch at the bonding plane will cause thermal stress to build up during cooling. This thermal stress is detrimental to the quality of the adhesive bond formed between the two members.

Two scenarios can lead to the absence of bonding after cooling. One scenario is the absence of bond formation at the high temperature during welding, due to insufficient time or temperature. The other scenario is the presence of bonding at the high temperature, but the occurrence of debonding during subsequent cooling due to thermal stress. The cause of the absence of bonding is different in the two scenarios. In any given situation, the cause of the debonded joint must be understood if the absence of bonding after cooling is to be avoided.

The propensity for mutual diffusion in thermoplastic polymers increases with temperature. The contact at the interface across which interdiffusion takes place also plays a role. An intimate interface, as obtained by application of pressure to compress the two members together, also facilitates diffusion. Thus, the quality of the joint improves with increasing temperature and increasing pressure in the high temperature period of welding. The poorer is the quality of the joint attained at a high temperature, the greater is the likelihood that thermal stress built up during subsequent cooling will be sufficient to cause debonding. Hence, merely having bonding achieved at the high temperature in welding is not enough. The bond achieved must be of sufficient quality to withstand the abuse of thermal stress during subsequent cooling.

The quality of a joint is conventionally tested destructively by mechanical methods or nondestructively by ultrasonic methods [46, 47]. This testing is performed at room temperature after the joint has been cooled from the high temperature used in welding. As a result, the testing does not allow distinction between the two scenarios described above. The use of a nondestructive method, namely contact electrical resistance measurement, to monitor joint quality in real time during the high temperature period of welding and also during subsequent cooling has been shown [48]. The resistance increases by up to 600% upon debonding. The resistance increase is much greater than the resistance decrease during prior bonding. Debonding occurs during cooling when the pressure or temperature during prior bonding is not sufficiently high.

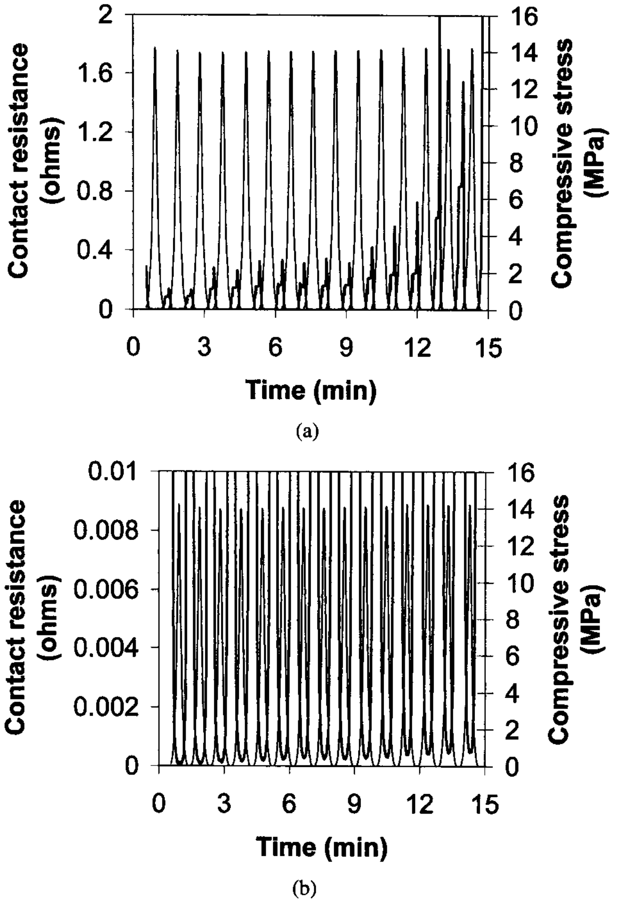
Adhesive joint formation between thermoplastic adherends typically involves heating to temperatures above the melting temperature (T_m) of the thermoplastic. During heating to the desired elevated temperature, time is spent in the range between the glass transition temperature (T_g) and the T_m. The dependence of the bond quality on the heating rate, heating time, and pressure was investigated through measurement of the contact resistance between adherends in the form of carbon fiber reinforced PPS [49]. A long heating time below the melting temperature (T_m) is detrimental to subsequent PPS adhesive joint development above T_m. This is due to curing reactions below T_m and consequent reduced mass flow response above T_m. A high heating rate (small heating time) enhances the bonding more than a high pressure.

5. Joints by fastening

5.1. Joints involving steels

Mechanical fastening involves the application of a force to the components to be joined, so as to prevent the components from separating in service [50]. During repair, maintenance or other operations, unfastening may be needed. Hence, repeated fastening and unfastening may be necessary. By design, the stresses encountered by the components and fasteners are below the corresponding yield stresses, so that no plastic deformation occurs. However, the local stress at the asperities at the interface can exceed the yield stress, thereby resulting in local plastic deformation, as shown for carbon steel fastened joints at a compressive stress of just 7% or less of the yield stress [51]. The plastic deformation results in changes in the joint interfaces. This means that the joint interface depends on the extent of prior fastening and unfastening. The joint interface affects the mechanical and corrosion behavior of the joint. This problem is thus of practical importance.

Stainless steel differs from carbon steel in the presence of passive film [52–68]. The passive film is important to the corrosion resistance of stainless steel. The effect of repeated fastening and unfastening on the passive film is of concern.



(a)

(b)

Figure 3 Variation of contact resistance (thick curve) and stress (thin curve) during cyclic compression of stainless steel on stainless steel at a stress amplitude of 14 MPa.

Fig. 3 [69] shows the variation in resistance and displacement during cyclic compressive loading of stainless steel on stainless steel at a stress amplitude of 14 MPa. In every cycle, the resistance decreases as the compressive stress increases, such that the maximum stress corresponds to the minimum resistance and the minimum stress corresponds to the maximum resistance (Fig. 3a).

The maximum resistance (in the unloaded condition) of every cycle increases upon stress cycling, such that the increase is not significant until after 13 cycles (Fig. 3a). The increase is due to the damage of the passive film and the consequent surface oxidation. The minimum resistance (at the maximum stress) of every cycle increases slightly upon cycling (Fig. 3b), probably due to strain hardening.

The higher the stress amplitude, the fewer is the number of stress cycles for passive film damage to start. At the lowest stress amplitude of 3.5 MPa, passive film damage was not observed up to 30 cycles.

Comparison of the results on stainless steel and on carbon steel shows that the carbon steel joint is dominated by effects associated with plastic deformation whereas the stainless steel joint is dominated by effects associated with passive film damage. The effect of the passive film is absent in the carbon steel joint, as expected from the absence of a passive film on carbon steel. The effects of plastic deformation and strain hardening at asperities are much larger for carbon steel than stainless steel, as expected from the lower yield stress of carbon steel.

5.2. Joints involving composites

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.

Due to the electrically insulating behavior of conventional polymers and the need for an electrical conductor for the purpose of measuring the contact electrical resistance, a polymer that contained continuous carbon fibers in a direction parallel to the plane of the joint was used [70]. The carbon fibers cause the composite to be electrical conducting in the fiber direction, as well as the through-thickness direction, because there is some degree of contact between adjacent fibers in the composite in spite of the presence of the matrix [71]. Due 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.

Contact resistance measurement was used to investigate the effect of repeated fastening and unfastening on a polymer-polymer joint interface [70]. 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 occurs after up to 10 cycles of fastening and unfastening, although the decrease diminishes with cycling. It is primarily due to local plastic deformation of the matrix at the asperities at the interface. Moreover, the stress required for the resistance to reach its minimum in a cycle decreases with cycling, due to softening of the matrix.

5.3. Joints involving concrete

Many concrete structures involve the direct contact of one cured concrete element with another, such that one element exerts static pressure on the other due to gravity. In addition, dynamic pressure may be exerted by live loads on the structure. An example of such a structure is a bridge involving slabs supported by columns, with dynamic live loads exerted by vehicles traveling on the bridge. Another example is a concrete floor in the form of slabs supported by columns, with live loads exerted by people walking on the floor. The interface between concrete elements that are in pressure contact is of interest, as it affects the integrity and reliability of the assembly. For example, deformation at the interface affects the interfacial structure, which can affect the effectiveness of load transfer between the contacting elements and can affect the durability of the interface to the environment. Moreover, deformation at the interface can affect the dimensional stability of the assembly. Of particular concern is how the interface is affected by dynamic loads.

A mortar-mortar contact was studied under dynamic loading at different compressive stress amplitudes by measuring the contact electrical resistance [72]. Irreversible decrease in the contact resistance upon unloading was observed as load cycling progressed at a low stress amplitude (5 MPa, compared to a value of 64 MPa for the compressive strength of the mortar), due to local plastic deformation at the asperities at the interface. Irreversible increase in the contact resistance at the maximum stress was observed as load cycling progressed, probably due to debris generation; it was more significant at a higher stress amplitude (15 MPa).

6. Discussion

This paper describes electrical methods that are useful for studying joints, whether for the purpose of scientific understanding or for the purpose of practical joint evaluation. The method described for studying solder joints allows correlation of the electrical and mechanical performance of the joint. This correlation is of scientific interest and is potentially useful for nondestructive evaluation of solder joints. The methods described for studying adhesive joints also allow this correlation. In particular, the method for studying adhesive joints involving composite and concrete is practically attractive for nondestructive evaluation of composite retrofits of concrete structures. The methods described for studying joints obtained by autohesion allow scientific understanding and real-time monitoring of the processes of autohesive bonding and debonding. In addition, the method described for studying fastened joints allow observation of the affects of repeated fastening and unfastening, including the effect of loading history on the quality of a fastened joint or a pressure contact. These effects are of practical importance to the use of fastening and pressure contacts.

The electrical methods described in this paper are in general valuable due to their nondestructive nature (which allows real-time monitoring) and equipment simplicity (which allows field application). The applications are relevant to the electronic, automobile, aerospace, construction and other industries.

7. Conclusion

Joints obtained by soldering, adhesion, autohesion and fastening and involving metals, composites and concrete were studied by DC electrical resistance measurement, which was conducted during bonding, debonding, fastening and/or unfastening. The resistance measurement involved either measuring the contact resistance of the joint interface or measuring the apparent volume resistance of a member of the joint. The results provide information on the processes of bonding, debonding, fastening and unfastening, the conditions for attaining good bonding, and the causes of joint degradation.

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