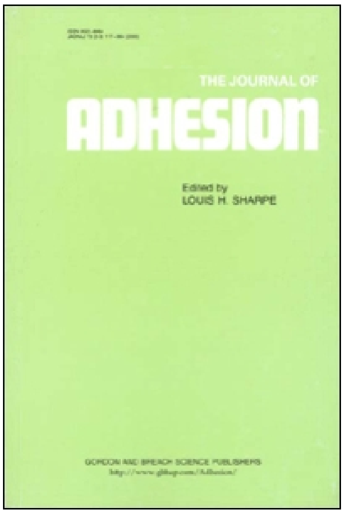

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The Contact Adhesion of Self-Adhesive Strain Gauges

R. H. Norman[a]; W. C. Wake[a]
[a] Rubber and Plastics Research Association Shawbury, Shrewsbury, England

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The Contact Adhesion of Self-Adhesive Strain Gauges

R. H. NORMAN AND W. C. WAKE
Rubber and Plastics Research Association
Shawbury, Shrewsbury, England

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ABSTRACT

Thin pieces of flexible polymers may be adhered to rigid substrates merely by pressing the two surfaces into intimate contact. The peel strength of the bond is poor, but the shear strength can be sufficiently high for strain gauge operation. This paper offers an explanation for the adhesion which can account quantitatively for the behaviour of various materials. Frictional phenomena, resulting from a normal force produced by the surface tension of a surface film, can explain why a gauge with a PVC body does not slip. With other polymers, other liquids or electrostatic effects may be of importance. Any surface "fluid" film of sufficiently high viscosity that viscous effects are important will behave as an integral part of the elastomer.

INTRODUCTION

THERE ARE numerous occasions when thin pieces of flexible plastic or rubber are pressed into intimate contact with a smooth, clean rigid surface such as metal or glass and in which, although the film is easily removable by peeling, considerable adhesion to the film surface is exhibited. Technically the most important concerns the self adhesive strain gauges developed at the Royal Aircraft Establishment, Farnborough [1, 2]. Strain gauges, attached to the metal substrate by adhesive, were introduced in the early 1940's; they are usable once only. A comprehensive strain gauge survey of a structure with such gauges is frequently difficult whereas the self-adhesive strain gauge can be used as an easily movable probe to explore structurally interesting areas before fastening the conventional type of strain gauge for more extended use.

Explanations advanced to explain the existence of adhesion under these conditions depended on a hypothetical film of moisture or other liquid acting as an adhesive, but no convincing discussion of the phenomenon is known to the authors. This paper attempts to remedy this by offering explanations to cover the very diverse known facts and to show that these explanations are quantitatively reasonable in accounting for the behaviour of these strain gauges.

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EXTENT OF THE PHENOMENA

To describe the general phenomenon we have used the expression given in the title, namely, Contact Adhesion although it is unfortunate that 'Contact Adhesives' is a description used for adhesives which, when substantially free of solvent, will fuse together even though apparently dry and non-adhesive to other surfaces. Such adhesives are also known as 'Impact Adhesives'. In the present context the term 'contact adhesion' is intended to convey the essential fact that the bond is formed solely by placing the surfaces firmly into contact without any glue, adhesive or even surface preparation other than the removal of superficial dirt. Such adhesion between a thin polymer film and a metal surface is characterized by a low peel strength but high shear strength and there is no observable slip over long periods of time under conditions which apply to strain gauge usage.

Contact adhesion seems to be demonstrable between any elastomer and any polished substrate. The following polymers and substrates have been tried [1]: Polymers; Plasticised PVC; films formed from dried natural rubber latex (vulcanised and unvulcanised latex both behaving equally well); neoprene, Viton, polyurethane and silicone rubbers (all vulcanised). The only limitation seems to be the modulus of the elastomeric or PVC material which should not exceed about 70 kgf. cm^{-2}. Substrates; Polished metals; anodised aluminium, glass; polymethylmethacrylate; polyester sheet; polyethylene; polytetrafluorethylene.

It has sometimes been found advantageous to wash elastomer and substrate surface with water and to dry before making contact. Such conditions are likely to leave adsorbed moisture films but such water may not be essential to preservation of the bond since a silicone rubber-aluminium system retains its shear strength after prolonged heating at 200°C.

PLASTICISED POLYVINYLCHLORIDE

We start our examination of this problem from a consideration of plasticised PVC because this is the material commonly used for strain gauges; it is known to be a two phase system and one of the authors [3] has worked extensively on its frictional properties.

The principle of the explanation is simple. Surface tension forces associated with the liquid phase draw the film close to the metal surface so that contact exists between asperities of the substrate surface (assumed here to be a polished metal) and the solid phase of the PVC. This contact corresponds to a frictional contact produced by a normal force equivalent to the surface tension force. The coefficient of friction for various plasticiser contents is known, the normal force can be calculated and hence the force extending

Table 1.

	As given	*Symbol*	*Metric units*
Size of strain gauge	2½ × 2 × 0.028 cm	l × w × t	
Cross section of strain element	0.1 × 0.00128 cm	W × T	
Gauge length of element	1 cm	L	
Young's modulus of element	600,000 psi	E_s	4.1×10^4 kgf.cm^{-2}
Young's modulus of gauge body	600 psi	E	41 kgf.cm^{-2}
Average separation of surfaces in nominal contact (vide infra)	10^{-5} cm	d	
Maximum strain	0.008	e	

the PVC film and the shear across the interface can be calculated. The dimensions and physical properties in Table 1 refer to a specific case of a known strain gauge [3] or are typical for the materials employed.

Calculation of Shear Stresses:

There are two components of retractive force, one due to the polymer and the other due to the strain element. Because we assume the absence of an adhesive layer, we cannot use conventional formulae to calculate the shear stress distribution. Instead, we use the simplified model that the interface of 0.5 cm length at each end of the gauge body is uniformly stressed in shear and the remaining 1.5 cm of the gauge body, including the whole of the strain element, is stressed only in tension. This model accords with the known distribution of stress in surface coatings [5] except that the edge shear stress should be taken as exponential instead of square.

Tensile force in gauge body $= eEwt = 1.8 \times 10^{-2}$ kgf.

Force contributed by strain element $= eE_sWT = 4.2 \times 10^{-2}$ kgf. The total force is, say, 60 gf. and hence the shear stress at the interface is 60 gf.cm^{-2} (because the assumption above implies stress is borne over two areas of 0.5×2 cm which are effectively in series; hence each area bears the full stress).

In fact, the much greater stiffness of the strain element embedded in the strain body will give rise to shearing stresses within the body which ought to be considered in a rigorous analysis. It will also give rise to a larger shear stress at parts of the interface. The maximum this will reach will depend on the dissipation of stress within the body of the gauge but it will be less than that calculated from the modulus of the strain element alone, probably considerably less because of the spreading effect of about 0.005 inch (0.01 cm) of PVC beneath the element. The transmission of strain through a soft elastic layer to the sensitive element of a strain gauge is considered rigorously in an appendix to Ref. 1.

Mechanisms to Support Shear Stress:

The explanation given in outline above involves real contact between the polymer and asperities on the surface of the metal. This is the explanation given for frictional phenomena. Asperities and polymer interact under the action of the normal force caused by the surface tension of a plasticiser film and this plays the same role as the normal force in ordinary measurements of friction. Additionally, this surface tension normal force is enhanced by an electrostatic force which does not seem to have been considered in discussions on the behaviour of strain gauges. The questions which need to be answered are:

1. If a shear stress of the magnitude calculated is to be sustained, what true area of contact must exist in the form of junctions between PVC and the asperities of the metal?
2. Is the estimate of contact area reasonable in the light of evidence from frictional experiments?
3. What is the magnitude of the normal force due to the surface tension of the plasticiser and is it sufficient to provide adequate areas of true contact?
4. What is the magnitude of any electrostatic force and is it essential to invoke its aid?

1. Area of True Contact:

When two surfaces are placed in contact they make real contact only at asperities on the surfaces [6]. Short range surface forces, molecular or atomic forces, produce bonds which are usually strong enough to hold when the surfaces are displaced with respect to one another. Failure then occurs within the body of one of the materials, tearing the asperity out from the bulk substrate. If a force is applied normal to the surface, further contacts are formed and local stresses set up. The force required to separate the surfaces normal to their plane is largely provided by elastic recovery of these "built-in" stresses and hence the external force necessary is usually very low. However, the *tangential* (or frictional) force will be high.

To provide a shear stress, S, of 60 gf.cm^{-2}, the area of real contact, A, is at least S/S_0 where S_0 is the shear strength of the weaker material, in this case the plasticised PVC. This shear strength will be similar to the tensile strength as ordinarily measured, which for the soft flexible material containing about 100 parts of plasticiser to 100 of resin is about 70 kgf.cm^{-2}. This gives an area of real contact of at least 8.6×10^{-4}cm^2 for each cm^2 of geometric area. This area is small and people working on frictional problems would expect a larger figure.

2. Support for Estimate of Contact Area from Friction Experiments:

Lavrent'ev [7] investigated the coefficient of friction of vulcanised rubber against steel for a range of loads. Extrapolating the results to zero normal load and comparing it with very high normal loads indeed, he deduced a contact area for zero load of 3×10^{-2} cm^2 and claimed that "physically this is determined by molecular forces between specimen and surface."

3. Magnitude of Normal Force due to Surface Tension:

If two surfaces are separated a small distance d by a liquid which makes zero contact angle with the surfaces, the pressure inside the liquid is reduced by surface tension effects. This gives a pressure difference of $2\gamma/d$ forcing the plates together. γ is the surface tension of the liquid. If the distance is that of closest approach, the gap being maintained only by the asperities of the two surfaces, the pressure difference ($d = 10^{-5}$ cm; $\gamma = 30$ dynes.cm^{-1}) is about 6 kgf.cm^{-2}. This arises from a negative pressure in the liquid which may not, in fact, be sustained and it can be argued that a maximum of about 1 kgf.cm^{-2} is all that would be realised with zero pressure inside the liquid boundary.

The normal pressure thus obtained can be used with the total shearing force (60 gf.cm^{-2}) to give a notional coefficient of friction of 0.06. Since this is somewhat lower than observed values this is acceptable. The coefficient of friction, it will be recalled, is the *limiting* value of the ratio of tangential to normal force.

4. Magnitude of Electrostatic Forces:

There is accumulating evidence that electrostatic forces may be involved in adhesion between conductors and semiconductors. In this context a polymer, such as PVC, normally regarded as an insulator, is here regarded as a semiconductor with a particularly high potential gap between the valency levels and the conduction levels. Calculations made by Russian workers [8] give very large values for the normal force, values which would exceed the strength of the polymer. Presumably such forces apply at only those points where actual molecular contact occurs as at asperities in contact. The actual charge density on either surface at very small distances of separation cannot be assessed but it must be assumed that real measurable attraction exists over the distances which have been postulated as separated by liquid. It is, therefore, not possible to put a figure on the contribution from this source but it is believed to exist.

Conclusions for PVC:

A well-plasticised PVC, soft and flexible enough to be used for gauge work but not containing so much plasticiser that it will visibly 'sweat', will contain 50 to 55% plasticiser and will show a coefficient of friction against steel [3] of, say, 0.8. It has been shown that a gauge which can stand a strain of up to 0.008 before giving electrical signs of slipping must have an interfacial shear strength of at least 60 gf.cm^{-2}. Frictional considerations would therefore require a normal pressure of at least 75 gf.cm^{-2}. This force is well within any estimate of the pressure arising from surface tension effects to which must be added pressures dye to electrostatic force.

An alternative approach considers only the true area of contact with asperities which would be required to ensure the shear strength. This area comes out at about 10^{-3}cm^2 for each cm^2 and is smaller than would be expected. Such an area of true contact could be maintained without superposed normal forces provided the polymer was soft and smooth enough to lie easily to the surface. The extremely low peeling force with high shearing force is expected from an asperity fusion effect. These calculations show that there is no difficulty or mystery about the contact adhesion of plasticised PVC and smooth metals.

OTHER POLYMERS AND SUBSTRATES

The task of explaining contact adhesion is particularly easy with PVC because its structure is known to involve a microphase system with a surface which has the essential properties of a liquid. Such adhesion is independent of the nature of the substrate provided it is rigid and smooth. Other polymers and substrates require further consideration.

If electrostatic forces are absent or insufficient, some other mechanism must be invoked to generate a normal force sufficient to maintain asperity contact or to dissipate or neutralize residual stresses around points of fusion of asperities. It will be realised that the pressure of applying the polymer to the surface will be sufficient to cause adhesion at the asperities where true contact occurs but these are mainly broken by elastically stored stresses when the applying pressure is removed. Some mechanism must exist to neutralize these elastic stresses, either permanently or until they have relaxed by flow processes within the bulk of the polymer film.

The question really resolves around the presence of liquid films on polymers or the existence of surface structures which simulate liquid properties and therefore may be said to exhibit a surface tension and wet other surfaces with which they are placed in contact.

Liquid Films on Polymers:

The possibility that liquid films exist on some polymers was first demonstrated by Bikerman [9] who, having postulated the presence of a weakly coherent film on polyethylene, showed that rigorous purification gave a surface to which adhesion was possible. He maintained that material of low molecular weight was present on the surface and accounted for failure to bond to the material. Bikerman's experiments have been confirmed by de Bruyne [10]. This enables an explanation similar to that for PVC to be countenanced for the contact adhesion of polyethylene to smooth surfaces.

The behaviour of thin films of vulcanised rubbers, natural, neoprene and silicone rubber having been cited, is not so simply explained. While the presence of liquid films cannot be ruled out, there is no evidence for them. However, theories of the elastic behaviour of vulcanised rubbers do have consequences which will involve their surface structure. When an elastomer is vulcanised, chemical linkages are established between the long chain molecules. These are achieved by a variety of agents which attack suitably reactive points along the polymer chain. Quantitative interpretation of the elastic behaviour of the crosslinked network has shown the need to correct the equations used to allow for the effect of the parts of chain molecules between their ends and the nearest crosslink. These "loose-ends" as they are called exist in a concentration which can be calculated for the simpler curing systems and must exist on the surface as well as in the bulk of the polymer.

Estimates of the proportion of the polymer which comprise the loose-ends vary from M_c/M (Tobolsky) to 2 M_c/M (Flory) where M_c is the molecular weight between crosslinks and M the initial molecular weight before crosslinking. Estimates for these parameters exist for natural rubber and may be taken as not unreasonable for rubbers generally. These suggest that from 3 to 6% (depending on which of the two expressions is used) of the polymer is involved in the loose-ends. As well as actual chemical crosslinks this estimate for M_c includes entanglements and hence tends to underestimate the true loose-ends. It seems fair, therefore, to accept that 5% of material is involved in loose-ends. The average chain length of this material from the point where the chain joins the network is difficult to assess because of the relative amounts of entanglement and crosslinking but there will obviously be a distribution of lengths averaging about 160 carbon atoms in the case of natural rubber. This material, within the limits of its anchorage, will be more mobile than the normal network and when sufficiently close to the surface will tend, by energetic considerations, to diffuse and lie on the surface giving a surface concentration greater than 5%.

It is suggested that this material provides the equivalent of a liquid layer which wets the substrate and provides by its surface tension the normal force required to maintain asperity contact. The maintenance of the contact bond of a silicone rubber and aluminium substrate after heating at 200°C need, therefore, cause no surprise.

Highly Viscous Films on Polymers:

The film of low molecular weight material on polyethylene is certainly of fairly high viscosity, corresponding, say to a grease. The effective viscosity of the loose-ends of the elastomer network will also be high, since the average molecular weight in the case of natural rubber is about 3000. Impurities in polymers may also be present or low molecular weight material too short to have been included in the network. Such material will tend to bloom to the surface and it is interesting to consider whether a film of finite thickness would be so slow in relaxation because of its high viscosity, that a strain would be communicated to the polymer from the substrate independently of asperity bonding and would not relax noticeably in the 24 hours during which gauges have been known to remain electrically constant in a strained condition. Consider the following conditions:

Maximum rate of contraction (by slip) of the gauge 0.001% per hour. (This means that the gauge will not slip noticeably in 24 hours). As the two ends of the gauge will both slip the maximum permissible rate of slip of one end is

$$\frac{0.5 \times 10^{-5} \times 1.5}{3600} \text{ cm.sec}^{-1}$$

The length of the gauge in tension, 1.5 cm.
The thickness of the film assumed, 10^{-5} cm.

The rate of shear is therefore 2.1×10^{-4} sec^{-1}, and movement would be maintained at this rate with a liquid of viscosity of 2.8×10^{8} poise. This is a viscosity between that of shoemaker's wax and that of pitch and the film will behave as an integral part of the elastomeric material.

CONCLUSIONS

The very low peeling force but relatively high shear strength shown in cases of contact adhesion between thin flexible polymer films and smooth high substrates is typical of adhesion formed by contact of asperities. The maintenance of the contact involves a normal force which can arise by more than one of the possible mechanisms which have been shown to give forces at least of the required threshold magnitude. The picture given agrees closely with that inferred from the known mechanism of friction and its magnitude in these circumstances. The question of the electrostatic component has been left rather vague. Following work by Weaver [11] it may be possible to investigate this by experimenting in the presence of a glow discharge in high vacuum.

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