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THE PRINCIPLES OF ADHESION

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A MAJOR part of dental practice is the treatment of localised lesions in teeth and the replacement of lost tissue with restorative materials. As stated by Skinner and Phillips (1967), the lack of adhesion of most of them to the structure of the prepared tooth presents a serious problem; it causes seepage of deleterious agents along the interface between the restoration and the tooth (Nelsen *et al*, 1952). Fig. 1.

Micro-leakage of saliva, acid and bacteria has been demonstrated by various techniques: radioactive tracers, (Going *et al*, 1960; Petersen *et al*, 1966), dye penetration (Holliger, 1967; McLean and Kramer, 1952), and penetration of bacteria (Rose *et al*, 1961; Kraus and Kraus, 1951).

It leads to the breakdown of the marginal areas of the filling with resultant secondary caries along the interface between the restoration and the tooth structure. It is likely that certain phenomena such as post-operative sensitivity and pulp pathology are associated with the leakage pattern (Phillips, 1967). In many instances where the filling material has been blamed for the pulp pathology, it has been shown conclusively that it is not so; it is the gross leakage around the filling that does the damage (Phillips, 1961). This leakage could be eliminated by a restorative material or film capable of forming a strong adhesive bond with enamel and dentine that would survive under oral conditions (Buonocore, 1963). Fig. 2.

Research programmes aimed at the development of such a material are under way. If successful, it will replace many of those in use today and will change the method of cavity preparation. It could also be used to bond orthodontic attachments directly to enamel surfaces (Retief and Dreyer, 1967; Mizrahi and Smith, 1969) or to coat the entire tooth surface thus forming an impermeable barrier to the caries process (Gwinnett and Buonocore, 1965; Roydhouse, 1968).

The stage has not yet been reached where an adhesive can readily be synthesised for a particular purpose because, in spite of advanced technology, many of the principles underlying the mechanism of adhesion remain unknown.

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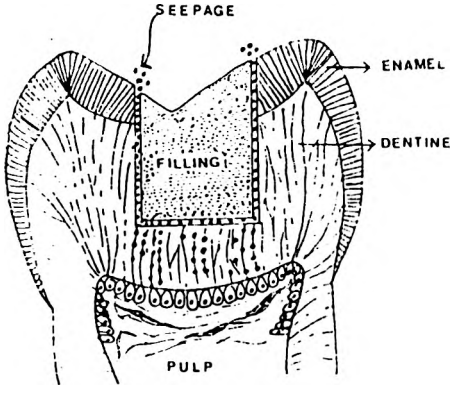


FIG. 1: Marginal leakage at the restoration/tooth interface.

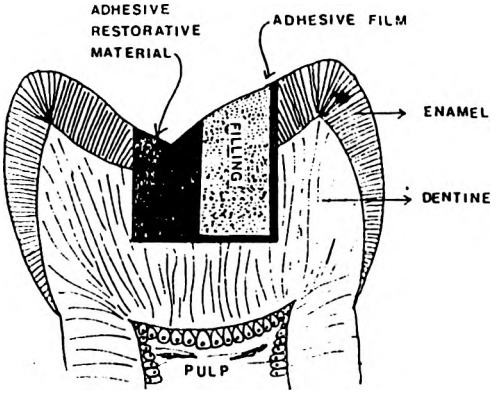


FIG. 2: Elimination of microleakage by adhesive film or adhesive restorative material.

THE NATURE OF ADHESION

Adhesion is defined as the molecular attraction exerted between the surfaces of bodies in contact or the attraction between molecules at an interface. This force is called adhesion when unlike molecules are attracted and cohesion when molecules of the same kind are attracted. The material added to produce the adhesion is known as the adhesive and that to which it is applied is called the adherend. The interface is the zone between the interacting substances.

The molecular forces involved in adhesion may be divided into chemical and physical attractive forces. The former include electrovalent, covalent and metallic bonds and constitute the primary bonds; the latter arise from van der Waal's forces and hydrogen bonding and constitute the secondary bonds.

Chemical or primary forces	1. Electrovalent or ionic bond	
	2. Covalent bond:	a. nonpolar
		b. polar
	3. Metallic bond.	
Physical or secondary forces	1. van der Waal's forces.	
		a. Keesom forces—orientation effect.
		b. Debye forces—induction effect.
		c. London forces—dispersion effect.
	2. Hydrogen bond.	

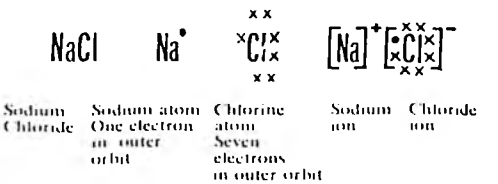
The Chemical Forces.

These are intramolecular attractive forces.

(1) *Electrovalent or Ionic Bond.*

The bond is formed by the electron transfer from the valency orbit of one atom to the valency orbit of another atom. This transfer results in the formation of positively- and negatively-charged ions, and the attractive forces arise from the electrostatic attraction between these ions.

This type of bond is found in sodium chloride. The outer valency electron of the sodium atom is transferred to the chlorine atom which already has seven outer valency electrons, and positively-charged sodium ions and negatively-charged chloride ions are formed. In a sodium chloride crystal the ions are held together by electrostatic attraction.



The force of attraction is given by:

$$F = \frac{9^+ \cdot 9^-}{r^2}$$

where 9^+ and 9^- are the charges of the ions.

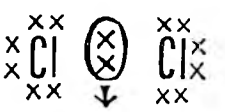
r = the distance between the ions.

Although the typical ionic bond only appears in ion-crystals, similar forces appear in any system containing ions.

(2) *Covalent Bond.*

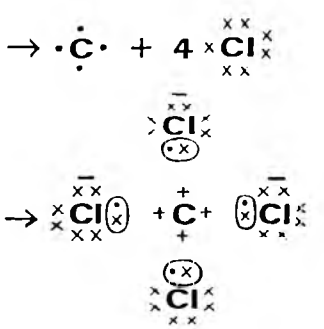
This is formed by the sharing of electrons of the valency orbits, and a shared pair of electrons constitute a covalent bond.

A purely covalent or non-polar bond is formed by the equal sharing of electron pairs by similar atoms, for example Cl_2 (Parker and Taylor, 1966).



Such a bond has no ionic character.

If the electron pairs are shared by dissimilar atoms, that is, those which have different degrees of electro-negativity, they will be displaced closer towards the more electro-negative atom. The bond or bonds between the atoms will have a partly ionic character; and they will have a polar characteristic due to the unequal sharing of the electron pairs.



The shared pairs of electrons, ·×, are displaced towards the more electro-negative chlorine atoms which thus are given a negative charge and the carbon atom a positive charge.

The ionic character of polar covalent bonds varies as it is dependent on the electro-negativity of the atoms between which the bonds are formed. The estimated ionic character of some single bonds is:

Bond	*Approximate ionic character* %
C - C	0
C - H	4
C - Cl	10
C - F	44

Covalent bonds are commonly found in organic compounds.

A dipole results whenever a covalent bond is formed by the unequal sharing of the electron pairs that go to make up the bonds. The shared electron pair is displaced towards the most electro-negative atom and the degree of electron displacement is reflected by the dipole moment.

The electric dipole moment

$$\mu = ql$$

where q = the magnitude of the charges separated.

l = the distance separating the charges.

Permanent dipoles are found in polar organic compounds and are of considerable importance in adhesion.

(3) *Metallic Bond.*

The free valence electrons of metals can move about the metal space lattice to form an electron cloud. The movement of these electrons is responsible for some of the properties of metals such as the conduction of electricity; and the movement of the free valence electrons leads to a regular array of positive ion cores being found in the crystal. The electron clouds and the positive ion cores provide the forces of attraction which bond the metal atoms together. The surface of metals will have some free electron deficient sites available for bonding.

The Physical Forces.

These are intermolecular attractive forces.

(1) *Van der Waal's forces.*

According to Eley (1961), these forces of molecular attraction are due to three main factors: the Keesom, Debye and London forces.

(a) *The Keesom forces—orientation effect.*

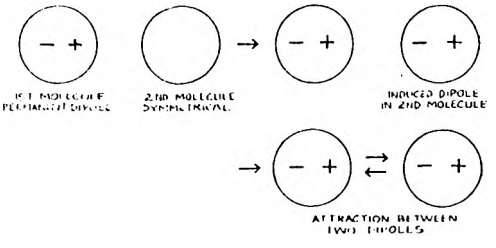
These result from the interaction of permanent dipoles in neighbouring molecules of polar compounds. If in a bimolecular reaction the two dipoles are free to rotate they will take up a head-to-tail or lowest energy configuration as here shown:



A typical molecule in a liquid will have 10 - 12 molecules in its immediate vicinity, all interacting with one another. Except for molecules of very low polarity, the rotation of the dipoles will certainly not be free and the problem of the relative orientation of dipoles in a liquid is a very difficult one (Good 1967).

(b) *Debye forces—induction effect.*

These arise from the induction effect that takes into account the influence of the dipole moment in a molecule which induces an additional dipole moment in a neighbouring molecule; that is to say, they result from the interaction of a permanent dipole with a bond system capable of being polarized. A dipole in a molecule may provide the electrical field to polarize a neighbouring symmetrical molecule. Once a dipole moment has been induced, the two molecules attract each other.



The Keesom and Debye forces both depend on the existence of permanent dipole moments in molecules and there-

fore play no part in a medium consisting of non-polar molecules.

(c) *London forces—dispersion effect.*

These are not dependent on the existence of permanent dipoles. Slight displacement of the electrons or nuclei in an atom or molecule is constantly occurring; it is instantaneous and at random, and results in the formation of a dipole which at any one instant induces another dipole in a neighbouring molecule.

The Keesom and London forces are by far the most important in adhesion.

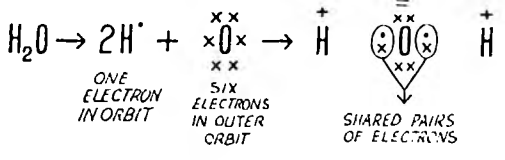
(2) *Hydrogen Bond.*

This can be regarded as a special type of dipole—dipole interaction. According to Good (1967) it calls for two conditions:

(a) A highly electro-negative atom such as F, O or Cl, or strongly electro-negative groups like -CN with a hydrogen atom attached.

(b) Another highly electro-negative atom which may or may not be in a molecule of the same species as the first atom or group, to be in the vicinity. For example the water molecule, H_2O, does not exist as such but as $(H_2O)_3$ where the three associated molecules are held together by hydrogen bonds.

The primary intramolecular bonds between the hydrogen and the oxygen within the water molecule is of the covalent type: the bonds are formed by electron sharing.



As the two shared pairs of electrons will be orientated much closer to the strongly electro-negative oxygen atom, the electron density around the oxygen nucleus will be much greater than around the hydrogen one (proton). Consequently the hydrogen portions of the water molecule are positive in relation to the oxygen portion. When a single water molecule intermingles with other water molecules, its positive hydrogen parts are attracted

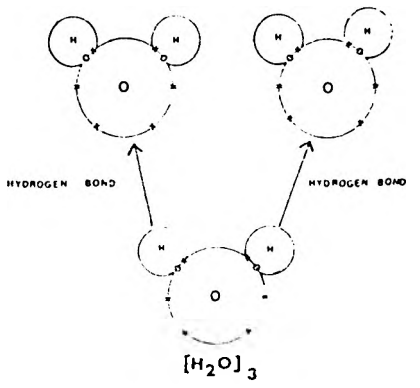


FIG. 3: Hydrogen bonding in the associated water molecule.

to the negative oxygen portions of neighbouring molecules and two hydrogen bonds, which are inter-molecular attractive forces, are established. Fig. 3.

The physical forces of attraction result in the physical adsorption of the adhesive on the adherend; the adsorption is a rapid and reversible process and requires no activation energy as the molecules remain chemically intact on the surface. In all three types of physical interaction, Keesom, Debye and London, there is the same marked dependence on separation between the interacting molecules—a dependence on the inverse sixth power of the distance. The London or dispersion effect is universal and operates whenever two molecules, atoms or ions are in close contact. The London forces are sufficiently strong so that good adhesive performance should be observed no matter what the chemical nature of the two phases in contact, provided that enough intimate intermolecular contact is achieved at the interface.

Chemisorption is preceded by physical adsorption. In the former the interaction with the surface is much more specific than is the case of the latter. The adsorbed molecules are held to the surface by bonds which may be covalent, ionic or metallic. The rate of chemisorption may be slow because an activation energy is required before the adsorption process can take place. The nature of the adherend will have a profound effect on the rate of the reaction. Chemisorption gives rise to very strong attractive forces and once established is not easily reversed.

SURFACE PHENOMENA

(1) *Surface Contact.*

Adhesion, depending essentially on the forces of molecular attraction at the interface, exists only at short distances of separation, in the order of one or two Ångström units. If solid surfaces are naturally smooth on an atomic scale they will adhere spontaneously when brought together without an intermediate layer of adhesive. Fig. 4(a). An example of the adhesive force uniting atomically smooth surfaces is the bond between mica sheets. The strength of this adhesion is about 14,000 lbs/sq. inch, as strong as the mica itself (Buonocore 1963). A film of oxide or organic contamination only one molecule thick will greatly decrease the adhesion of solids.

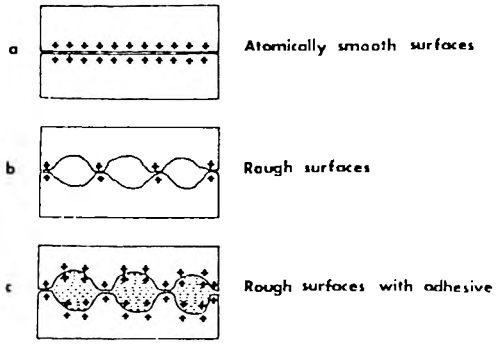


FIG. 4: (a) Adhesion between atomically smooth surfaces.
(b) Adhesion between rough surfaces.
(c) Adhesion with adhesive between rough surfaces.

In practice it is impossible to obtain such atomically smooth surfaces; those to be bonded are very rough at an atomic level. If such rough surfaces are brought into contact the molecular forces of attraction will operate only where the tips of the asperities on the surfaces meet. Fig. 4(b). These widely spaced attractive forces are so small that poor adhesion will result. The actual area of contact is generally a small fraction of the apparent one.

In practice the small separation necessary for adhesion is almost always obtained by introducing a liquid adhesive between solid surfaces; its function is to adapt itself to the irregularities of the surfaces to be bonded thereby establishing close contact with them. The molecular forces of attraction between the solid surfaces operating at the tip of the asperities will be supplemented by those between the adhesive and the adherend at the interfaces. Fig. 4(c). It is not only necessary to obtain molecular closeness but also to maintain it. For this reason a liquid adhesive that solidifies is used: one with a volatile component which sets when it evaporates, or one whose molecules can be made to polymerise or cross-link with each other by means of heat, catalysts or reactive hardeners.

(2) *Wetting.*

To produce adequate adhesion the liquid adhesive must flow easily over the entire surface, thereby ensuring the wetting of the adherend surface. The fundamental requirement for good adhesive performance is intimate interfacial contact between the adhesive and its substrate or adherend. When the attractive forces between the molecules of the adherend and the molecules of the adhesive are stronger than the attractive forces between the molecules of the adhesive, wetting will occur.

Huntsberger (1967) uses the term wetting in reference to a process, and a state. The wetting process is described as the establishment of interfacial contact. The wetting state is defined as the number of interfacial contacts between the phases at the interface in relation to the maximum number possible for the system when wetting is complete.

The extent to which an adhesive will wet a surface depends on its viscosity and on the shape of the irregularities on the surface of the adherend (De Bruyne, 1962). If the depressions are of the ink-bottle type with increasing distance between the lateral walls, the adhesive can hardly penetrate. Fig. 5(a). If the pit is

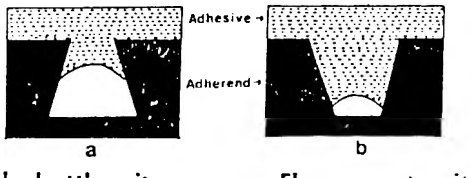


FIG. 5: Types of depressions on adherend surfaces.

shaped like a flower-pot, its penetration is facilitated: and it will cease only when the force of the surface tension pulling the adhesive into the depression is balanced by the pressure of the entrapped air. Fig. 5(b). The process of filling the depression will be slowed down by an increase in viscosity of the adhesive.

(3) *Contact Angle.*

The contact angle, θ, is the one formed between the surface of the adhesive drop and the surface of the adherend upon which it is resting. Fig. 6 gives a diagrammatic scheme for the drop of liquid in equilibrium with the solid surface and the surrounding atmosphere saturated with the liquid vapour.

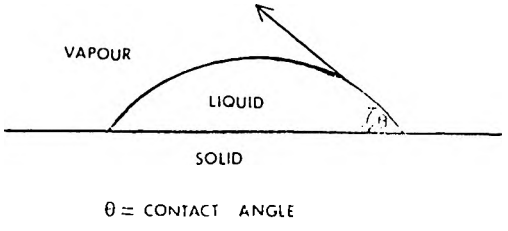


FIG. 6: Contact angle.

The degree of wetting depends on the contact angle at which the adhesive meets the surface of the adherend. It increases as the angle decreases. The contact angle is small if the attraction between the molecules of the adhesive and that of the adherend is greater than the attractive forces between the molecules of the adhesive. If this angle is small the adhesive will wet the adherend surfaces, and the molecular forces of attraction will operate along the entire interface and strong adhesion will result. If it is large the adhesion will be poor. Fig. 7 gives a diagrammatic presentation of the effect of the contact angle on wetting and adhesion.

(4) *Surface Tension.*

The surface tension of the adhesive and the adherend play an important role in adhesion.

In liquids and solids there is a tension in the surface region. A molecule in the bulk of a liquid is surrounded by neighbouring molecules and is attracted equally

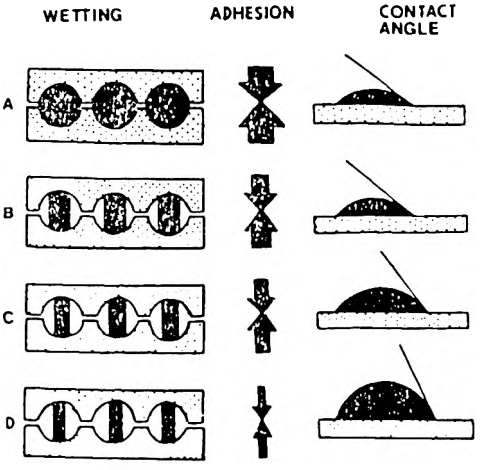


FIG. 7: The effect of the contact angle on wetting and adhesion.

from both sides (Fig. 8). The attractive forces always include the London dispersion forces but additional attractive forces such as dipole interactions or ionic interactions will operate in polar or ionic liquids respectively. A molecule in the surface of a liquid is attracted from below and from the sides but not from above. As a result molecules in the surface are in a one-sided field force pulling them downward in the bulk of the liquid (Fowkes, 1967). The surface tension results from this one sided field force exerted on surface layers. The stronger this force the greater the surface tension. Since the range of these forces is short, most of the tension is in the outer layer of the liquid.

The surface of the liquid may be re-

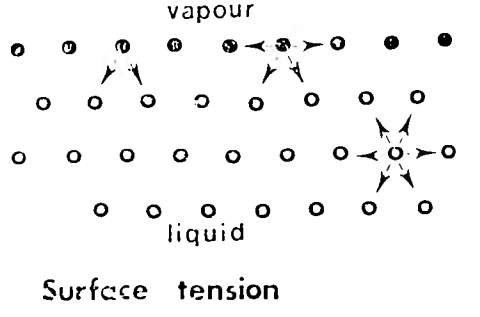


FIG. 8: Molecular forces of attraction in a liquid.

garded as the seat of a special force which acts perpendicular to the surface; and if the section of the surface involved is 1.0 cm long it is called the surface tension and is expressed in dynes/cm.

(5) *Thermodynamic Considerations.*

In 1805 Thomas Young enunciated that the three surface tensions, γ_{SV}°, γ_{SL} and γ_{LV}° existing at the phase boundaries of a drop of liquid at rest on a solid surface must form a system in static equilibrium Fig. 9 (a).

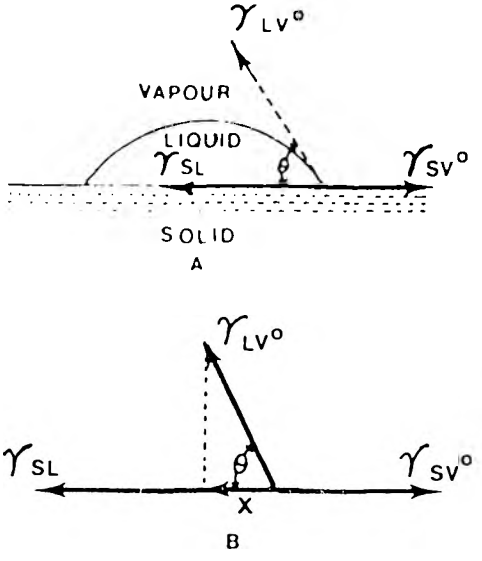


FIG. 9: (a) The surface tensions at the phase boundaries of a liquid at rest on a solid surface.
(b) Resolution of forces at the point where the phases meet.

Where γ_{SV}° = the surface tension of the solid in equilibrium with the vapour.

γ_{LV}° = the surface tension of the liquid in equilibrium with the vapour.

γ_{SL} = the surface tension at the interface between the solid and the liquid.

If we resolve the forces acting along the line of the solid to liquid interface (Fig. 9b) we obtain the following expression:

$$\gamma_{SL} + x = \gamma_{SV}^{\circ} \quad \ldots \quad (1)$$

$$\text{Cos } \theta = \frac{x}{\gamma_{LV}^{\circ}} \text{ where } \theta = \text{contact angle}$$

$$\therefore x = \gamma_{LV}^{\circ} \cos \theta$$

Substitute x in (1)

$$\gamma_{SL} + \gamma_{LV}^{\circ} \cos \theta = \gamma_{SV}^{\circ}$$

$$\text{or } \gamma_{SV}^{\circ} - \gamma_{SL} = \gamma_{LV}^{\circ} \cos \theta \quad \ldots \quad (2)$$

$$\text{and } \cos \theta \quad \frac{\gamma_{SV}^{\circ} - \gamma_{SL}}{\gamma_{LV}^{\circ}} \quad \ldots \quad (3)$$

The cosine of the contact angle formed between a liquid drop and the plane surface of a solid on which the drop is resting has, at equilibrium, a definite relationship to the surface tensions of the liquid and the solid in contact with the saturated vapour.

The free surface energy expressed in ergs/cm^2 is dimensionally the same as the surface tension expressed in dynes/cm. Sumner (1937), using a thermodynamic approach, substituted the specific free energies in the system for the surface tensions and showed that the Young equation (2) could be written:

$$\gamma_{SV}^{\circ} - \gamma_{SL} = \gamma_{LV}^{\circ} \cos \theta \quad \ldots \quad (4)$$

Where γ_{SV}° = the free surface energy of the solid in equilibrium with the vapour.

γ_{SL} = the free surface energy at the solid/liquid interface,

γ_{LV}° = the free surface energy of the liquid in equilibrium with the vapour.

Dupré (1869) showed that W_A, the reversible work of adhesion per unit area of a liquid with a solid (or another liquid), is related to the decrease in free energy when the two surfaces come together to form an interface.

$$W_A = \gamma_S^{\circ} + \gamma_{LV}^{\circ} - \gamma_{SL} \quad \ldots \quad (5)$$

Where γ_S° = the free surface energy of the solid in a vacuum.

It was realized, however, that the solid surface will be covered by adsorbed vapour of the liquid and consequently a new quantity W_A^* was defined (Zisman, 1963). W_A^* is the reversible work of adhesion to pull the liquid off the surface leaving the equilibrium-absorbed film.

$$W_A^* = \gamma_{SV}^{\circ} + \gamma_{LV}^{\circ} - \gamma_{SL} \quad (6)$$

Where γ_{SV}° = the free surface energy of the solid in equilibrium with the vapour.

By eliminating γ_{SL} from equations (4) and (6)

$$W_A^* = \gamma_{LV}^\circ (1 + \cos \theta) \quad .. \quad (7)$$

γ_{LV}° and θ can readily be determined experimentally and W_A^* calculated.

The specific reversible work of cohesion (W_C) of the liquid is calculated by applying equation (7) to a liquid—liquid interface made up of two layers of the same liquid.

$$W_C = 2\gamma_{LV}^\circ \quad (\theta = 0^\circ; \cos \theta = 1) \quad .. \quad (8)$$

In equations (5) and (6) γ_S° and γ_{SV}° refer respectively to the free surface energy of the solid in a vacuum and the free surface energy of the solid immersed in the saturated vapour of the liquid. Thus $\gamma_S^\circ - \gamma_{SV}^\circ$ is the decrease in the surface energy of the solid obtained on immersing it in the saturated vapour of the liquid. The free energy change is presented by f_{SV}° and

$$f_{SV}^\circ = \gamma_S^\circ - \gamma_{SV}^\circ \quad .. \quad .. \quad (9)$$

f_{SV}° is referred to as the equilibrium-spreading coefficient.

From equations (5) and (6) it can be calculated that:

$$W_A - W_A^* = \gamma_S^\circ - \gamma_{SV}^\circ = f_{SV}^\circ \quad .. \quad .. \quad .. \quad (10)$$

It has been shown (Zisman 1963) that f_{SV}° will always have a positive value and hence $W_A > W_A^*$.

Cooper and Nuttal (1915) laid down the conditions for the spreading of a liquid substance on a solid surface.

For spreading to occur $S > 0$

For non-spreading $S < 0$

Where $S = \gamma_S^\circ - (\gamma_{LV}^\circ + \gamma_{SL})$ .. (11)

For an organic liquid spreading on an organic solid surface it can be assumed that γ_{SL} is negligibly small in comparison with γ_{LV}°, therefore:

For spreading to occur $\gamma_S^\circ > \gamma_{LV}^\circ$ (12)

Thus in systems where the specific surface free energy of the liquid is less than that of the solid, spreading should occur.

From equation (7) it is clear that for any system having $\theta = 0^\circ$, i.e. $\cos \theta = 1$,

$$W_A^* \geq 2\gamma_{LV}^\circ \quad .. \quad .. \quad .. \quad (13)$$

This value is much greater than the tensile strength of common adhesives. When the adhesive wets the adherend surface properly ($\theta = 0^\circ$) the tensile strength of the adhesive joint will be considerably more than that of the adhesive. Therefore if the joint fails it will break within the bulk of the adhesive rather than at the adhesive/adherent interface.

(6) The Critical Surface Tension of Wetting — γ_C.

Zisman and his co-workers (Glantz 1969), in their studies of the contact angles between various liquids and different solid surfaces, revealed a rectilinear relationship between the cosine of the contact angle and the surface tension, γ_{LV}°, for each homologous series of organic liquids. The intercept of the extrapolated straight line plot of $\cos \theta$ *vs.* γ_{LV}° with the horizontal line $\cos \theta = 1$ occurs at γ_C (Fig. 10). γ_C is

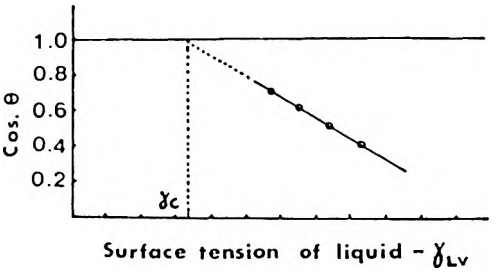


FIG. 10: The critical surface tension of wetting.

called the critical surface tension of wetting of a solid surface for each homologous series of organic liquids. For a liquid to wet a surface completely, the surface tension of the liquid must be lower than γ_C, the critical surface tension of wetting of the adherend.

Even when $\cos \theta$ is plotted against the surface tension for non-homologous liquids, the points on the graph lie close to a straight line or form a narrow rectilinear band; and although the intercept is less precisely defined than is the case with a homologous series of liquids, it is an even more useful parameter because it is characteristic of the solid only. γ_C has been used to study the wettability of a variety of low-energy surfaces.

The surface constitution of solids affects the value of γ_C. Zisman (1961) has observed a parallel and regular increase in γ_C with progressive replacement of fluorine by hydrogen atoms in the surfaces of bulk polymers.

OTHER FACTORS AFFECTING BOND STRENGTH

The manner in which some of the physical and chemical properties of the adhesive and the adherend affect the bond

strength has been described. In addition the external influencing factors have to be considered. These are prevalent when the bond is processed and subsequently when it is subjected to use.

During processing of the bond the way the adhesive is applied is important. It should be at a temperature at which its viscosity provides for adequate spreading on the adherend surface. The setting conditions, pressure and temperature, must be correct for the selected material. In the setting or curing of the adhesive there is shrinkage, which causes residual strain in the bond.

Another significant factor affecting the bond strength is the nature of the adhesive layer: thick ones give weaker joints than thin ones. A number of reasons have been postulated for this observation.

1. In a thin layer there is less chance of flaws occurring which may cause stress concentrations when the joint is subjected to a load (Buonocore, 1963).
2. A thick layer is more likely to become deformed and thus will fracture sooner.
3. There is less shrinkage in a thin layer during polymerization. Further, the swelling of the adhesive due to the absorption of fluid during use, or the effect of a significant difference in the thermal expansion of the adhesive and the adherend are reduced. De Bruyne and Houwink (1951) suggest that these factors produce tangential vectors of force which are proportional to the thickness of the adhesive layer and counteract the molecular forces of attraction between the adherend and adhesive at the interface.

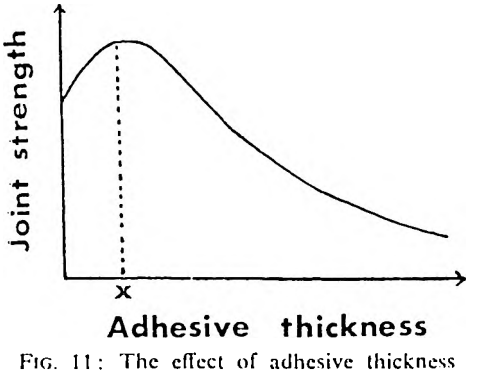


FIG. 11: The effect of adhesive thickness on the joint strength.

The effect of the thickness of the adhesive on the bond strength is presented graphically in Fig. 11. Up to an optimum point, x, the thinner the adhesive layer the stronger is the joint strength. Beyond this, insufficient material is available to cover the whole joint and the bond will fail as a result of joint starvation.

Several factors will affect the bond strength during use: the type of stress to which the joint is exposed; the rate and speed at which the stresses are applied; the temperature changes to which the joint is exposed; and the chemical stresses to which the bond may be subjected (Patrick, 1961).

The effect of certain of these factors can be lessened by the addition of fillers. These are inert inorganic particles which are added to the adhesive to improve some of its physical properties. The improvement in adhesive performance may be obtained by reducing the shrinkage during cure, approximating the coefficient of thermal expansion of the adhesive to that of the adherend, and improving the bulk strength of the adhesive.

ABHESIVES

Abhesives are coatings applied to a solid to greatly decrease or prevent the adhesion to another solid in intimate contact with it. They are commonly employed in moulding or coating operations. Materials employed for this purpose include high molecular weight fatty acids, polydimethylsiloxane and Teflon. A monolayer of the abhesive agent suffices to cause the optimum parting effect. The abhesive coating converts the high-energy solid surface to a low-energy one. This results in the critical surface tension of wetting, γ_c, being markedly reduced. The equilibrium contact angle of any liquid in contact with an abhesive coating will be large; and the greater the difference between the surface tension of the liquid and the critical surface tension of wetting of the abhesive coating the larger it will be. When it becomes large enough the resultant adhesion is so poor that a modest external stress suffices for effective mould release.

SUMMARY

1. Adhesion, depending essentially on the forces of molecular attraction between surfaces, exists only at short distances of separation.
2. In practice the small separation necessary for adhesion is almost always obtained by introducing a liquid adhesive between solid surfaces.
3. To produce molecular closeness the liquid adhesive must wet the adherend surfaces.
4. The degree of wetting depends on the contact angle at which the boundary of the liquid adhesive meets the surface of the adherend. It increases as the contact angle decreases.
5. Surface tension results from the one-sided field force exerted on surface layers of metals and liquids.
6. The contact angle formed between a liquid drop and the plane surface of a solid on which the drop is resting has, at equilibrium, a definite relationship to the surface tension of the liquid and solid.
7. The surface tension is dimensionally the same as the surface-free energy.
8. The force of adhesion or the reversible work necessary to separate a liquid from a solid must be the same as the free energy changes of the system.
9. The force of adhesion can be calculated from experimentally-determined values of cos θ and the surface tension of the liquid, γ_{SV}.
10. For spreading to occur the free surface energy of the liquid must be less than that of the adherend: $\gamma_{SV} > \gamma_{LV}$
11. When the adhesive has wetted the adherend completely, the joint must break by cohesive failure—that is, in the bulk of the adhesive rather than at the adhesive/adherend interface.
12. A liquid will wet a surface completely if the surface tension of the liquid is lower than the critical surface tension of wetting γ_C) of the solid.
13. The thinner the adhesive thickness, the stronger the joint.
14. The critical surface tension of wetting varies with the constitution of the solid surface.
15. Abhesives are materials which are applied as coatings to solid surfaces to decrease or prevent the adhesion of another solid in intimate contact with it.

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