Adhesion in Paints and Coatings

By SpecialChem
Adhesion is an essential aspect in paints and coatings industry. This property ensures that the coating (or paint film) remains adhered to the surface as long as possible especially under aggressive conditions. There exist several theories to describe phenomenon of adhesion.

However, no single theory explains adhesion in a general, comprehensive way. Some theories are more applicable for certain substrates and applications; other theories are more appropriate for different circumstances.

The most common theories of adhesion are based on:

- Adsorption theory
- Mechanical interlocking
- Electrostatics (electronic) theory
- Diffusion theory

But before discussing these theories in detail, first check out what is adhesion and key factors on which this property depends...

What is Adhesion?

Adhesion of a coating is defined as the resistance of the coating to be removed from the substrate

The single most important requirement for most coatings and inks is that the system adheres strongly, and for a long time, to the substrate after film formation has completed. The adhesion between the surfaces is then dependent on two properties of the material:

- Adhesion – the bonding strength of the adhesive to the substrate surface
- Cohesion – the strength of the bond between adhesive particles
Adhesion is related to:

- The substrate-coating interface
- The composition
- The film formation of the system must be such that this interface becomes as strong as possible

The binder, or resin, in paint formulation is the non-volatile film-forming component. It ensures adhesion to the substrate and cohesion within the paint film. Hence, type of binder influences film formation, film strength and other properties (physical or chemical).

Now that you have a fundamental understanding of what adhesion is, let’s talk about different theories governing this property...

Theories of Adhesion

The main theories are:

- **Adsorption Theory** – By a force of attraction between the surface molecules and the adherends at their interfaces i.e. intermolecular forces
- **Chemisorption Theory** – It is an extension of adsorption theory in which adhesion happens when chemical bonds are formed across the interface
- **Mechanical Interlocking** – Molecule interlocking around irregularities on the surfaces/substrate
- **Electrostatics (electronic) Theory** – Electrons are transferred from one surface to the other to build up dissimilar charges, exerting a force of attraction
- **Diffusion Theory** – By the adhesion of polymeric materials to the inter-penetration of chains at the interface

**Adsorption Theory**

This theory states that two materials will adhere due to the attractive forces that exist between the molecules of two materials. The surface forces that develop usually designated as secondary or van der Waals force. For these forces to develop, the paint molecules must make intimate, molecular contact with the substrate surface. In addition, acid-base interactions and hydrogen bonds may also contribute to intrinsic adhesion forces.

To obtain good adsorption, it is important to establish continuous contact between paint film and the adherend such that van der Waals interaction or the acid-base interaction or both take place. This can be achieved by phenomenon called “Wetting”.

Complete, spontaneous wetting occurs when Contact angle = 0°, or the material spreads uniformly over a substrate to form a thin layer. Wetting is favored when:

- The substrate's surface tension, better known as the critical surface energy, C, is high
- The surface tension of the wetting liquid is low
**Chemisorption Theory**

The chemical bonding mechanism suggests that primary chemical bonds may form across the interface. Chemical bonds are strong and make a significant contribution to the intrinsic adhesion in some cases. **Adhesion promoters** work according to chemisorption theory.

These additives are functionalized on one end to react with the substrate and on the other end to react with coating.

**Mechanical Interlocking**

At one time, adhesion was thought to occur only by the paint flowing and filling micro-cavities on the substrate. When the paint film hardens, the substrates are held together mechanically. The surface of a substrate is never truly smooth but consists of a maze of peaks and valleys.

According to the mechanical theory of adhesion, in order to function properly, the paint film must:

- Penetrate the cavities on the surface
- Displace the trapped air at the interface
- Lock-on mechanically to the substrate

**One way that surface roughness aids in adhesion is by increasing the total contact area between the paint and the adherend**

If the interfacial or intermolecular attraction is the basis for adhesion, increasing the actual area of contact will increase the total energy of surface interaction by a proportional amount. Thus, the mechanical theory generally teaches that roughening of surfaces is beneficial because it:

- Gives "teeth" to the substrate (mechanical interlocking), and
- Increases the total effective area over which the forces of adhesion can develop.

However, roughening is only effective if the coating wets the surface well.

Get the clues to improve the adhesion of your inks, lacquers ... on metal substrates by better characterizing surfaces with a smart combination of AES, SIMS, XPS...[Learn More](#)
Electrostatic Theory

The electrostatic theory states that electrostatic forces are formed at the coating-adherend interface. These forces account for resistance to separation. This theory gathers support from the fact that electrical discharges have been noticed when a coating is peeled from a substrate.

Electrostatic adhesion is regarded as a dominant factor in biological cell adhesion and particle adhesion.

Diffusion Theory

The fundamental concept of the diffusion theory is that adhesion arises through the inter-diffusion of molecules in the coating and adherend. The diffusion theory is primarily applicable when both the coating and adherend are polymeric, having compatible long-chain molecules capable of movement. Solvent or heat welding of thermoplastic substrates is considered to be due to diffusion of molecules.

*The electrostatic and diffusion theories of adhesion are generally not regarded as highly as the other theories in general bonding practice. However, there are certain applications where these are very important and help explain why bonds form.*

Adhesion Bond Failure

Weak-Boundary-Layer Theory

According to the weak-boundary-layer theory, when bond failure seems to be at the interface, usually a cohesive rupture of a weak boundary layer is the real event. This theory largely suggests that true interfacial failure seldom occurs.

In most cases, coating defects result from a cohesive failure of a weak boundary layer. Weak boundary layers can originate from the paint, the adherend, the environment, or a combination of any of the three.

Weak boundary layers can occur on the paint film or adherend if an impurity concentrates near the bonding surface and forms a weak attachment to the substrate.

*When the failure occurs, it is the weak boundary layer that fails, although failure may seem to occur at the paint-adherend interface*

In addition to external contamination, examples of weak boundary layers are:

- Corrosion or oxide layers on metal surfaces
- Low molecular weight constituents (e.g., release agents, plasticizers) on polymeric surfaces
Weak boundary layers must be removed by physical or chemical means so that there is no weak link in the film formation that would contribute to premature coating adhesion failure.

Complete, spontaneous wetting occurs when Contact angle = 0°, or the material spreads uniformly over a substrate to form a thin layer. Wetting is favored when the substrate’s surface tension, better known as the critical surface energy, \( C \), is high and the surface tension of the wetting liquid, is low.

**Adhesive** (which is failure at the interface)

**Cohesive** (which is failure within the adhesive)

**Interfacial** (which is failure because of something specific (e.g. hydrolysis) at the interface)

**Substrate** (which is failure within the substrate)

**Near-interface** (which suggests that the adherend and adhesive are affecting each other locally)

**Dissipative** (which is failure after (large) absorption of energy within the adhesive system)

Source: *Adhesion Science: Principles & Practice*, Professor Steven Abbott
Factors that Influence the Adhesion

There are several factors which influence the adhesion between paint film and substrate.

- One of the obvious causes for adhesion failures are poor substrate cleaning. The failure happens when soils not completely removed from the substrate prevent the coating from properly bonding to the substrate surface.
- Adhesion failure also depends on surface profile. E.g. Smooth surfaces do not hold coatings very well.
- Another reason could be inappropriate wetting of coating on the substrate to provide surface bond and proper adhesion.
- Insufficient crosslinking or uncured coating and even over-curing of coatings can lead to poor adhesion of the coating to the substrate surface.

Some of the adhesion related coating failure mechanisms are:

- **Blistering** – Blistering may occur when a coated object is immersed in water. Blisters are dome-shaped defects that appear on surface. Blistering is caused by:
  - Water-soluble materials within or under the coating that exert pressures stronger than both the adhesion and the internal cohesion of the coating.
  - Rapid drying of coatings on the heated surface or when applied in sun. This happens when the pressure exerted by solvent vapor when becomes larger than the adhesion of paint.
  - Chemical exposure often leads to blisters especially in the presence of volatile acids.

- **Peeling** - Peeling is the reduction in bond strength of the paint film due to contamination or incompatibility of coats.
- **Flaking** - Flaking is the result of adhesion failure, causing the paint to become separated from the substrate.
- **Undercutting** - Undercutting is another type of adhesion failure that involves the corrosion buildup under coating.
Ways to Achieve Better Adhesion

The following factors have a predominant importance to improve adhesion:

- Wetting of the surface
- Surface treatment
- Structure of the materials to be bonded

Further a variety of additives also impact physical/mechanical properties which can in turn can improve or worsen coating adhesion. For example:

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<th>Additive</th>
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| Adhesion promoters  | • Help improve adhesion  
|                     | • Have has an affinity for the substrate and the applied coating and form a permanent and strong bonding                                   |
| Plasticizers        | • Can soften binders used in ink and coatings, improving their flexibility  
|                     | • The increased flexibility enhances coating’s resistance to the mechanical impact force during coating process and hence minimize any potential failure |
| Solvents            | • Are volatile component which reduce the viscosity of binder  
|                     | • Increases drying time of coating to minimize formation of blisters and hence, avoid adhesion failure                                   |
| Pigments & extender | • Impart physical properties such as hardness and water resistance                                                                        |
| Wetting agents      | • Surfactants based on polysiloxanes, fluoro-based surfactants and special wetting agents overcome local differences in surface tension or wet the substrate surface to improve adhesion |
On the other hand, additives that have a specific chemical structure can worsen adhesion.

Test Methods to Evaluate Adhesion

There exist several methods which can be used to determine how well a coating is bonded to the substrate – allowing it to perform well. While employing any test method it is important to note if the bond failure was adhesive (failure at the coating / substrate interface) or cohesive (failure within the coating film or the substrate).

The primary methods used to test paint adhesion include:

Cross-Cut Test

**ASTM D3359 - Standard Test Methods for Rating Adhesion by Tape Test**

These test methods cover procedures for assessing the adhesion of coating films to metallic substrates by applying and removing pressure-sensitive tape over cuts made in the film.

This test method is similar in content (but not technically equivalent) to ISO 2409.

(Source: BYK)
Scrape Test


This test method can help you determine the adhesion of organic coatings such as paint, varnish, and lacquer when applied to smooth, flat (planar) panel surfaces.

The materials under test are applied to a smooth substrate at a uniform thickness. After drying the adhesion is determined by pushing the panels beneath a rounded stylus or loop that is loaded in increasing amounts until the coating is removed from the substrate surface.

Pull-Off Test


This test method covers a procedure for evaluating the pull-off strength (commonly referred to as adhesion) of a coating on rigid substrates such as metal, concrete or wood.

The method assesses the adhesion of either one or multiple coatings on a smooth surface by applying tensile stress (rather than shear stress measured in the previous two tests) from a dolly to the surface. The load is slowly increased until the dolly along with the adhesive layers is removed. It is equivalent to ISO 4624 standard.