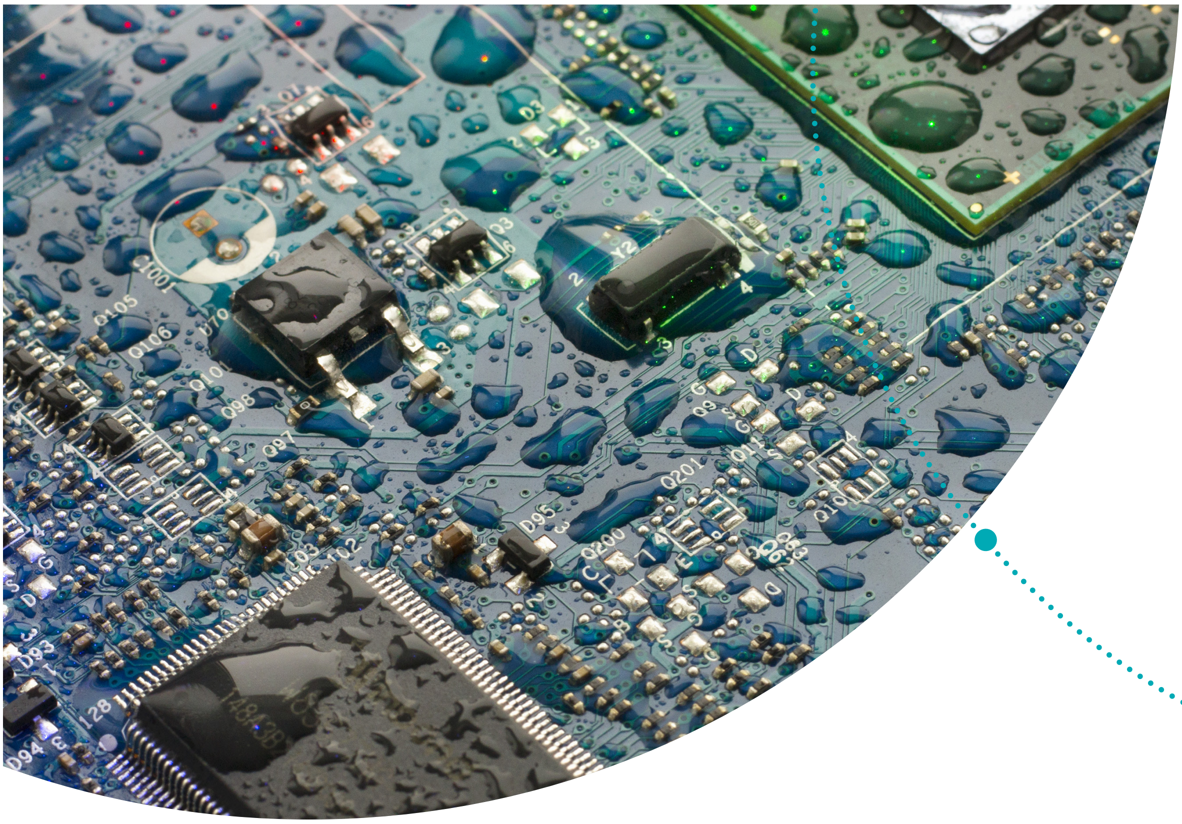

The Science of Bonding

Understanding the Interaction Between Adhesive Chemistry, Processing and Substrate Surfaces to Achieve Optimal Bonding Performance

Written by Dave Dworak & Doug Katze of Dymax
& Giles Dillingham of Brighton Science

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Abstract

Modern electronics manufacturing is driven by ongoing and increasingly sophisticated component miniaturization, along with rising demands for greater functionality and reliability. At the same time, manufacturers must boost throughput while reducing costs. As a result, advanced adhesives have become an essential solution for addressing many of these challenges in modern electronics assembly. Yet despite rapid advances in adhesive chemistry, dispensing systems, and curing technologies, adhesion failures persist, often not due to the adhesive itself, but to the condition of the surface it must bond to.

To better understand the factors that govern bonding success, Dymax partnered with Brighton Science to study how substrate type, adhesive chemistry, and surface preparation methods influence adhesion reliability. Four adhesives commonly used in electronics manufacturing (UV-curable acrylate, UV-curable epoxy, 1K silicone, and 2K epoxy) were evaluated on two widely used substrates (polycarbonate and FR-4). Lap shear test specimens were prepared using different surface treatments (as-received, isopropyl alcohol (IPA) wiping, and plasma treatment) prior to bonding.

Lap shear testing demonstrated that adhesion performance cannot be assured by adhesive chemistry or process controls alone. Achieving durable bonds require surfaces that are properly prepared and sufficiently activated for adhesion. The study revealed the value of assessing surface energy as a predictor of bond success and illustrated how water contact angle measurement can provide a practical, repeatable method for verifying that surfaces are ready for bonding.

Together, these insights offer manufacturers actionable strategies to improve bond performance, reduce rework and scrap, and ensure long-term adhesion reliability across demanding applications, from automotive and aerospace electronics to medical and industrial systems.

Three Pillars of Reliable Adhesion

Reliable bonding depends on three critical variables working together in synergy (Figure 1). If any one of these pillars are weak or inconsistent, the overall bond performance is compromised.

1. **Adhesive Chemistry –** Adhesive performance begins with formulation. Polymers, such as acrylics, epoxies, and silicones, are blended with fillers, crosslinkers, and other additives to tune properties for strength, toughness, flexibility, cure speed, and environmental resistance.

2. **Process Controls –** Even the most advanced adhesive cannot perform as intended without proper processing. Correct storage, handling, mixing (for two-component systems), dispensing, and curing are all critical to achieving full polymerization and consistent bond strength.

3. **Substrate Surface Energy –** The condition of the bonding surface plays a critical role in an adhesive's ability to wet the substrate and form a durable bond. Low surface energy, often caused by contaminants, oxidation, and manufacturing residues, impedes wetting and can significantly reduce bond performance.

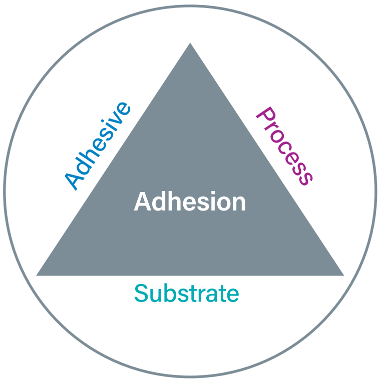


Figure 1. Three pillars of reliable adhesive bonding

While advances in adhesive chemistry and processing have made the first two pillars easier to optimize, substrate surface variability remains the most persistent cause of inconsistent adhesion and often the most overlooked. Understanding and managing substrate surface energy is therefore essential to achieving reliable, high-performance bonds. Only with an understanding of all three pillars and carefully aligning and managing them will one be able to optimize adhesive bonding.

The following is a more in-depth look at each pillar:

Pillar 1: Adhesive Chemistry

Adhesives today are used in electronic assemblies and applications to address many needs beyond bonding such as providing a method to absorb stress from substrate CTE mismatches, providing thermal conductivity, electrical conductivity, or flame retardancy. Adhesive formulations have evolved into an advanced science delivering the end-user with one's specific, desired product properties. In addition to these advanced product properties, adhesives can be formulated to enhance adhesion targeting specific substrates. It is important to seek the guidance of the adhesive manufacturer to properly select the adhesive for a particular application.

Chemical formulation, including polymer architecture, cross-link density, and additive selection, plays a central role in adhesive performance. These factors govern curing speed, viscosity, rheology, strength, toughness, and flexibility. Additives, such as adhesion promoters, coupling agents, fillers and diluents, can further enhance compatibility with difficult-to-bond substrates. Together, these formulation choices influence how effectively an adhesive wets and conforms to surface topography.

Yet even the most advanced formulation cannot completely compensate for an adhesive that was stored, dispensed or cured incorrectly or applied to poorly prepared, low-energy surfaces. While formulation allows chemists to tailor adhesives for specific needs, proper handling and processing of the adhesive and proper substrate conditioning remains essential for achieving consistent, long-term bond reliability.

Pillar 2: Process & Application Controls

The proper handling and processing of adhesives is critical to the ultimate performance of the adhesive. This includes receiving the adhesive from shipping, storage, thawing and mixing if required, management of pot life, dispensing and curing. Each one of these steps impacts the performance of the adhesive and should be optimized according to the adhesive manufacturer's guidelines.

One-component (1K), heat-curing adhesives typically need to be shipped in dry ice and stored frozen while 2-component (2K) adhesives mostly are room-temperature stable. Adhesives which were stored frozen require a thawing step before use. Proper thawing technique is required to avoid introducing air voids into the adhesive. Also, as soon as the adhesive is removed from the freezer, careful accounting of time is required to track adhesive pot life. UV-curable adhesives are unique in that they are 1K adhesives but mostly are room temperature stable and do not require frozen storage. UV-curable adhesives also typically have an unlimited pot life so no need to track time when in use.

2K adhesives require a mixing step to blend the two parts in the appropriate ratio prior to use. The adhesive manufacturer will provide the mix ratio of the 2 components, and it is critical that this mix ratio is properly achieved. Typically mixing each component separately to address filler settling then mixing the 2 components together is required.

The adhesive needs to be dispensed and cured, again according to the adhesive manufacturer's guidelines. Heat or room temperature exposure are common methods to achieve cure, typically from 30 minutes to 24 hours sometimes. UV light curing adhesives will cure in seconds.

Each one of these steps is important to properly process the adhesive. It is important to follow the adhesive manufacturer's guidelines and optimize the manufacturing process. In conjunction with the other 2 pillars, this will ensure the best opportunity for a successful bond.

Pillar 3: Substrate Surface Condition

While pillars 1 and 2 are critical components to achieving a successful bond, they are mostly well understood and optimized. Pillar 3 and understanding the impact the substrate surface condition has on the adhesive bond is many times overlooked. The root cause of many adhesive failures is related to the substrate and poor conditioning of the substrate surface.

Following are insights into the substrate surface energy, which is the key property determining the readiness of a substrate to bond with adhesive, as well as practical methods to measure surface energy.

Surface Energy Principles and How to Measure It

Atoms and molecules at a substrate's surface exist in a higher-energy, more reactive state than those within the bulk material. This property, known as surface energy, determines how readily the surface interacts with other materials. In practical terms, it governs whether a liquid, such as water, an adhesive, a coating, or ink, will spread out (wet) or bead up on the surface.

For an adhesive to bond effectively, it must wet the substrate by spreading out to make intimate surface contact. Whether wetting occurs depends on the balance of interfacial energies between the liquid, the solid, and the surrounding air. Each interface (liquid-solid, liquid-air, and solid-air) has an associated energy, and the system as a whole naturally seeks a more stable, lower-energy state. If spreading reduces the total interfacial energy, then the liquid wets the surface. If spreading would increase the total energy, then the liquid retracts and beads up.

Water contact angle measurement is a practical method for evaluating surface energy (Figure 2). By placing a small water droplet on a surface and measuring the angle at the liquid-solid-air interface, engineers can quickly assess surface condition and bond readiness. Water is particularly useful for this test because its high polarity and sensitivity to surface chemistry correlate well with adhesion performance.

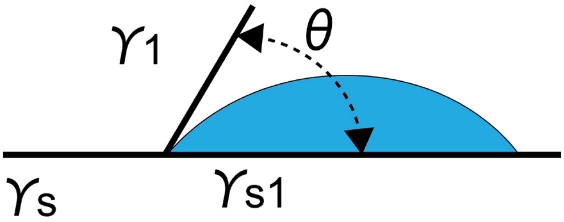


Figure 2. Contact Angle (Θ) is determined by the balance of interfacial energies: liquid surface tension γl, solid surface energy γs, and the remaining interfacial energy γsl

Low-Energy Surfaces

Polymeric substrates such as untreated polyethylene, polypropylene, or polytetrafluoroethylene (PTFE) have inherently low surface energy due to their chemically inert structures. Since water is more strongly attracted to itself than to these surfaces, droplets remain nearly spherical, producing high contact angles (typically 70-90°). These low-energy surfaces exhibit poor wettability and limit adhesive flow, resulting in weak and unreliable bonds. To improve adhesion, these surfaces can be modified using plasma, corona discharge, or flame treatments, or by applying chemical primers — all of which increase surface reactivity and promote improved wetting.

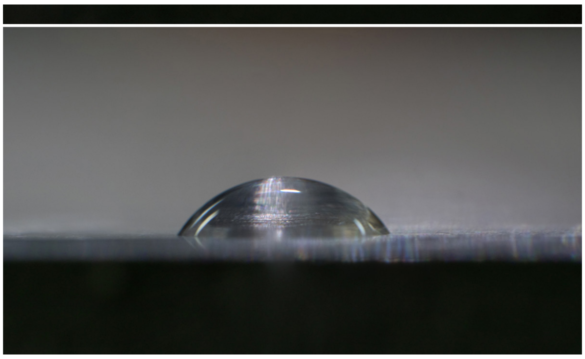


Figure 3. Low-energy surface (liquid beads up, indicating poor adhesion)

High-Energy Surfaces

When a water droplet is placed on a high-energy surface, such as freshly cleaned metal, ceramic, glass, or a substrate, the droplet is more strongly attracted to the surface than to itself and spreads out, producing a low contact angle (typically <50°). This behavior reflects strong molecular attraction between the liquid and solid and indicates excellent wettability. In practical terms, good wettability allows the adhesive to make intimate surface contact, flow into microscopic surface features, and establish strong chemical and mechanical bonds.

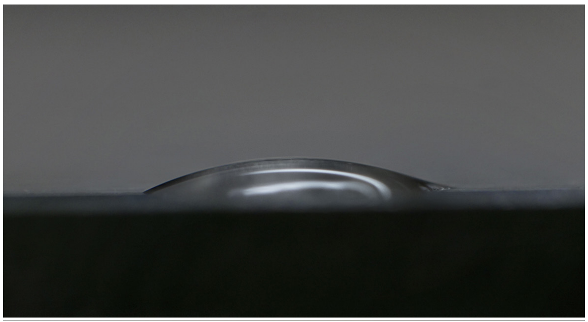


Figure 4. High-energy surface (liquid spreads out, indicating good adhesion)

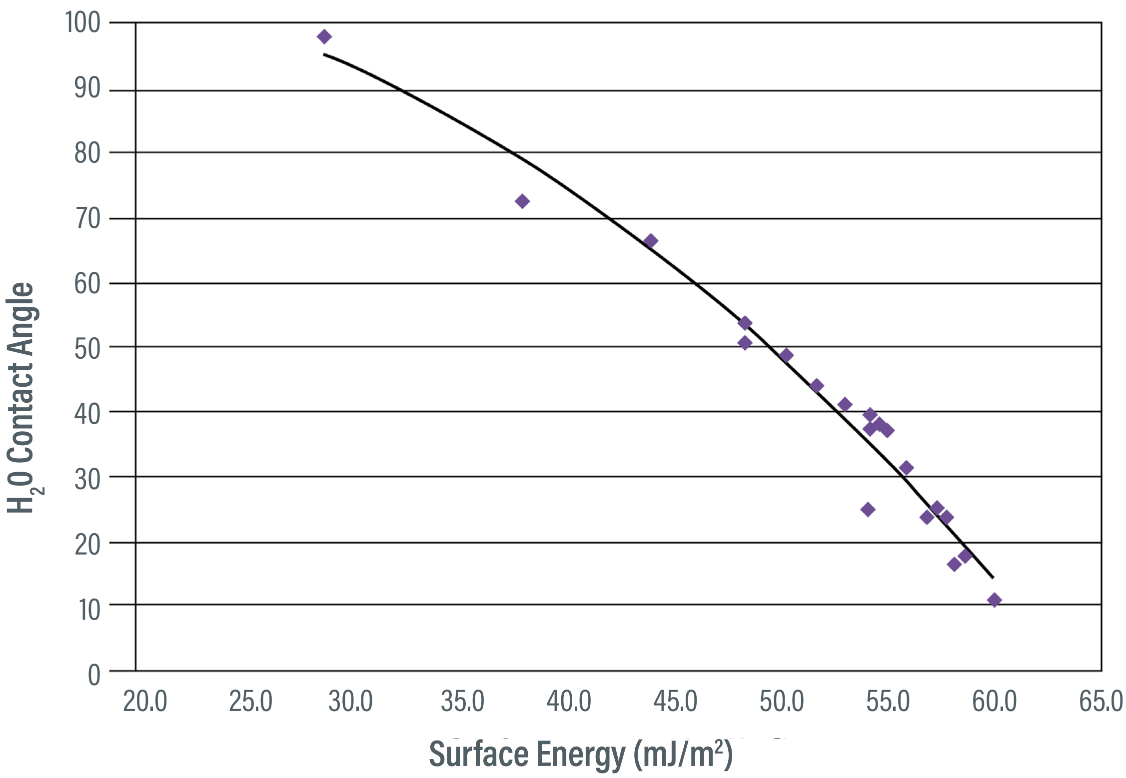
Moderate-Energy Surfaces

Moderate-energy surfaces exhibit limited attraction to water and other liquids, sufficient for partial wetting, but not strong enough to fully overcome a droplet's cohesive forces. Consequently, adhesives may show inconsistent or marginal performance on these surfaces unless additional surface preparation is performed.

Graphical Correlation Between Surface Energy and Water Contact Angle

Graph 1 shows the inverse relationship between water contact angle and surface energy. High surface energy produces low contact angles, indicating that a liquid can spread out and wet the surface effectively. Conversely, low surface energy results in high contact angles, where liquids bead up and wetting is poor. The rate and extent of surface energy decay depend largely on the material's initial surface energy. High-energy surfaces, such as freshly cleaned metals or glass, degrade quickly because their strong reactivity accelerates oxidation and contaminant adsorption. Low-energy surfaces like untreated polyethylene or polypropylene change far more slowly and may show minimal measurable decay.

Graph 1. Surface Energy vs. Water Contact Angle



Fundamentals of Surface Chemistry

Although mechanical bonding, created when an adhesive wets and flows into microscopic surface features, contributes to bond strength, adhesion primarily originates from chemical interactions between the adhesive and the substrate at the molecular level.

In hard materials such as metals and glass, atoms are arranged in tightly bound, well-ordered lattice structures. At the surface however, the structure is incomplete because exposed atoms lack bonding partners. As a result, these materials naturally have high surface energy and interact strongly with their surroundings. This high surface reactivity makes metals susceptible to oxidation, which can impede adhesion. When the oxide layer is removed through cleaning processes such as grit blasting, the freshly exposed high-energy surface can readily form strong, reliable adhesive bonds.

Polymeric substrate surfaces behave very differently. Their organic molecular structures exhibit far less intrinsic surface reactivity than inorganic materials, and their long, flexible polymer chains tend to move and reorient to minimize surface energy. Reactive groups may rotate inward or even diffuse beneath the surface, leaving a top layer dominated by low-energy loops and chain ends that interact weakly with adhesives. As a result, adhesives often struggle to bond to polymeric substrate surfaces without additional surface treatment.

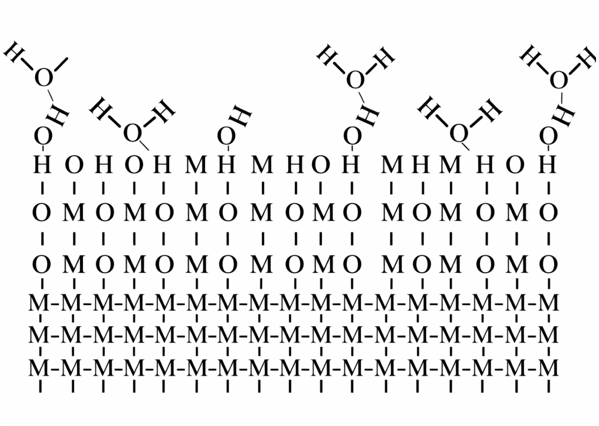


Figure 5. Chemical structure of an air-exposed metal surface composed of high-energy oxide and hydroxide groups along with small amounts of adsorbed water

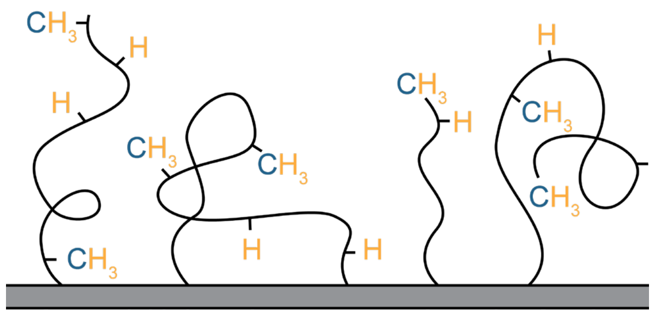


Figure 6. Illustration of a low-energy polymer surface composed of non-reactive hydrocarbon molecules

Polymers Vary in Reactivity

Not all polymeric substrate surfaces exhibit the same bonding potential. Polar polymers, such as polycarbonate and polyamides (nylons) contain functional groups like hydroxyls and amides that create permanent dipoles. These increase surface energy and improve wetting, enabling stronger interactions with adhesives and other liquids. In contrast, non-polar, chemically inert polymers such as untreated polyethylene, polypropylene, or PTFE, lack these functional groups, resulting in low-energy surfaces that inherently resist bonding.

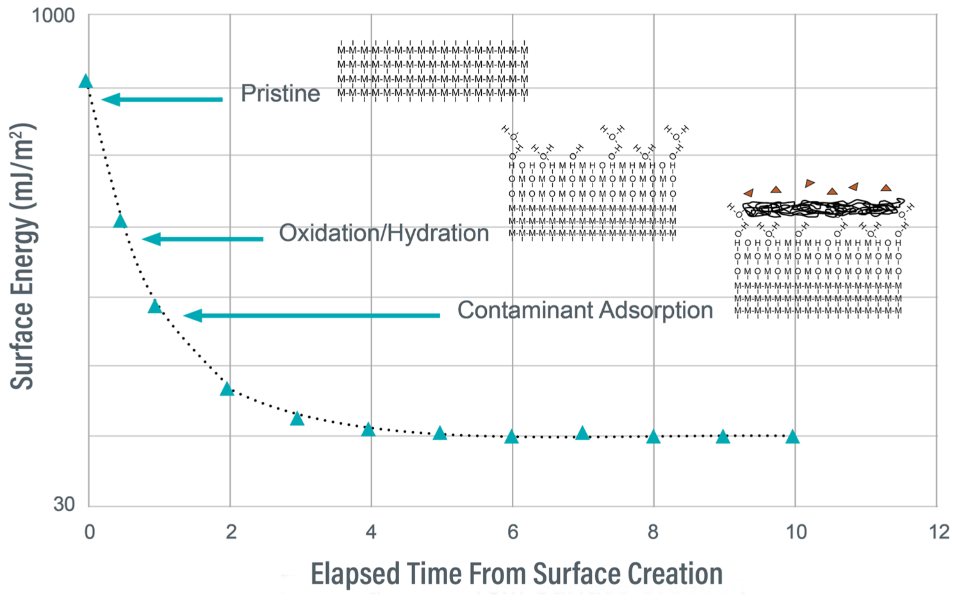
Time-Driven Decay of Surface Energy

Because surface atoms are highly reactive, they constantly interact with their environment. As a result, surface energy decreases during storage and handling as water vapor, hydrocarbons, and other contaminants adsorb onto the surface. Metals oxidize rapidly, often unevenly, introducing variability in bond performance and highlighting the need for tightly controlled processing windows. Activated polymers treated by plasma, flame, or corona show similar decline as newly formed polar groups migrate or reorient into the bulk. This time-dependent loss of surface energy can significantly reduce wettability and bond strength.

The rate and extent of surface energy decay depend largely on the material's initial surface energy. High-energy surfaces, such as freshly cleaned metals or glass, degrade quickly because their strong reactivity accelerates oxidation and contaminant adsorption. Low-energy surfaces like untreated polyethylene or polypropylene change far more slowly and may show minimal measurable decay.

Graph 2 shows the exponential decline in surface energy over time for freshly cleaned metal. Immediately after cleaning, the surface reacts rapidly with oxygen and water vapor to form a thin oxide layer, followed by slower adsorption of airborne hydrocarbons. Glass undergoes similar degradation as moisture and environmental chemicals react with its surface to form a silica film or alkali-rich layer. To maximize bond strength, adhesives or coatings should be applied promptly after surface preparation, before these changes compromise wetting and adhesion.

Graph 2. Surface energy decay of a freshly cleaned metal (no time scale is included because reaction rates depend on the environment)



Using Contact Angle to Monitor Surface Energy Changes

Water contact angle is highly sensitive to small changes in surface energy. Even slight contamination or oxidation from surface aging can increase the angle, signaling reduced wettability and a higher risk of bond failure. Because such shifts can affect whether an adhesive forms a durable bond or fails prematurely, contact angle measurement serves as both a convenient diagnostic tool and an essential process-control method for verifying surface readiness and predicting adhesion performance.

Comparison of Adhesive Curing Technologies

Different adhesive chemistries possess distinct curing mechanisms that influence how they interact with surfaces. Understanding these differences is important to achieving reliable adhesion.

- **UV-curable acrylates and epoxies** — These adhesives cure rapidly on demand, supporting high-throughput manufacturing with minimal thermal stress on components. Their adhesion, however, is highly dependent on surface preparation. Even slight contamination can significantly reduce bond strength. When paired with clean, high-energy substrates, UV-curable adhesives form strong, reliable bonds very quickly.
- **Two-part (2K) epoxies** — These adhesives cure through chemical crosslinking, creating strong bonds with excellent thermal and chemical resistance. Most conventional formulations require clean, well-prepared surfaces to ensure reliable adhesion. However, some specialized 2K systems are engineered to tolerate modest variations in surface cleanliness and surface energy. Their chemistry allows them to absorb and displace small amounts of moisture and contaminants during curing.
- **Silicone adhesives and sealants** — Silicones feature a flexible siloxane backbone that provides exceptional elasticity, thermal stability, and environmental durability. While they adhere to many substrates, their ultimate bond strength is limited by their low surface energy and low cohesive strength, making them best suited for applications requiring high flexibility. Silicones are highly sensitive to surface contamination. Even thin films of oil, mold-release agents, or residue can inhibit wetting and compromise adhesion, making surface cleanliness critical.

The Dymax / Brighton Science Study

Taking into consideration all the nuances and interactions with substrate surfaces and adhesives previously discussed, Dymax, a global manufacturer of advanced adhesives and coatings, partnered with Brighton Science, a leader in surface intelligence technologies, to conduct a structured investigation to quantify how substrate surface energy and water contact angle correlate with adhesive performance.

Experimental Setup

Adhesive Systems Tested

Four adhesives commonly used in electronics manufacturing were tested:

1. UV-curable acrylate – single-component, translucent, acrylated urethane chemistry
2. UV-curable epoxy – single-component, opaque, epoxy-based chemistry
3. RTV silicone – single-component, room-temperature-vulcanizing, silicone-based chemistry
4. 2K epoxy – two-component, room-temperature-curing, epoxy-based chemistry

Substrates Included in the Study

Two substrates frequently used in electronics manufacturing were evaluated:

1. Polycarbonate (PC)
2. FR-4 glass fiber reinforced epoxy laminate

Surface Preparation Techniques

The following techniques were used to prepare substrates for bonding:

1. As-received (no treatment)
2. Isopropyl alcohol (IPA) solvent wipes by Kimtech™
3. Plasma treatment (bonded within minutes of treatment)
4. Aged plasma treatment (bonded after 24 hours of storage)

Surface Energy Evaluation

Surface energy was assessed using water contact angle measurements taken prior to adhesive application. Multiple independent point-to-point measurements were taken for each test condition to verify consistency across the surface.

Quantifying Adhesive Strength

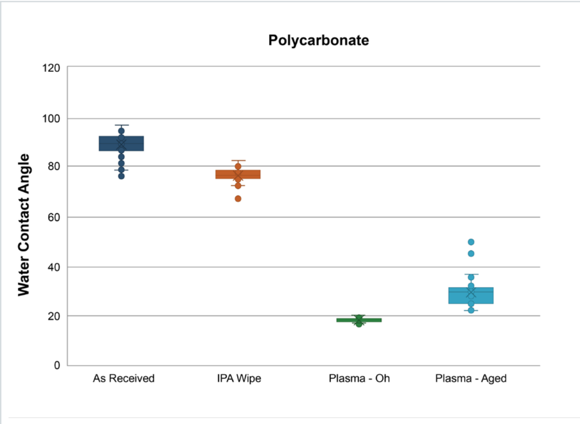
Single-lap joint specimens were prepared by bonding PC to FR-4 for each combination of surface preparation method and adhesive system. All samples were tested according to ASTM D1002, the standard tensile test method for determining shear strength of adhesively bonded joints. Five replicates were produced for each test condition.

Experimental Results

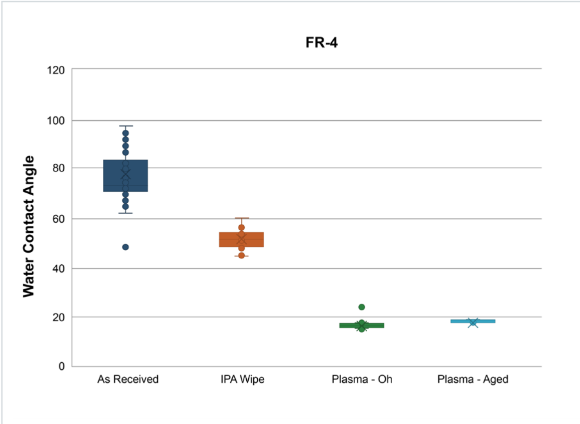
Contact Angle Characterization

Graphs 3 and 4 present water contact angle measurements for PC and FR-4 across different surface preparation methods. The spread within each data group reflects the variability in contact angle for that condition, making it easy to compare the uniformity and consistency of surface energy across the substrate.

Graph 3. Polycarbonate contact angles by surface preparation method



Graph 4. FR-4 contact angles by surface preparation method



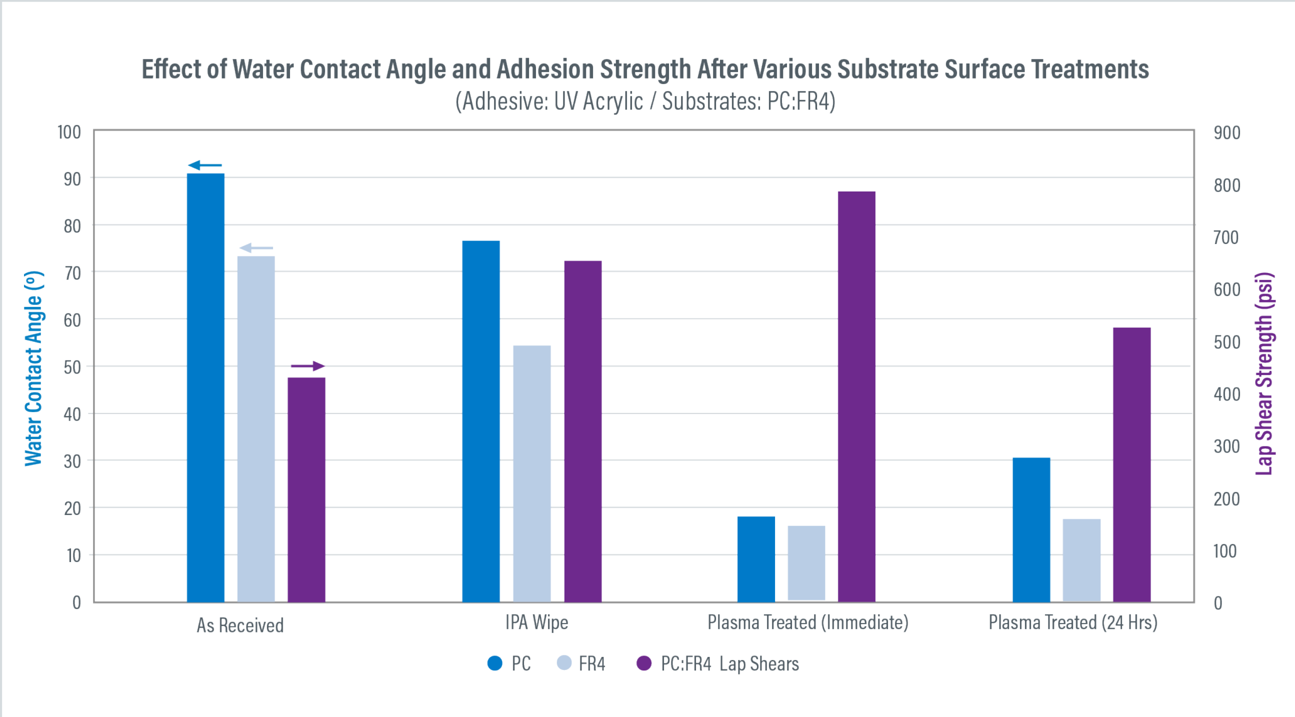
Key Findings: Water Contact Angle Assessment

- **As-received surfaces** showed the highest contact angles (around 80°) with significant point-to-point variability, reflecting inconsistent levels of contamination from handling and storage. These elevated values suggest a high likelihood of poor adhesion.
- **IPA wiping** produced a measurable reduction in contact angles across both substrates, indicating that IPA-soluble contaminants were removed. However, contact angles were still high (above 50°) suggesting that IPA cleaning alone may not be sufficient to achieve strong adhesion.
- **Plasma treatment** generated the largest decreases in contact angle compared to untreated specimens, falling below 20o for both polycarbonate and FR-4. These low values indicate a surface highly favorable for bonding.
- **Aged plasma treatment** displayed a noticeable increase in contact angle, demonstrating that plasma-activated surfaces quickly react with the environment and lose surface energy during storage.

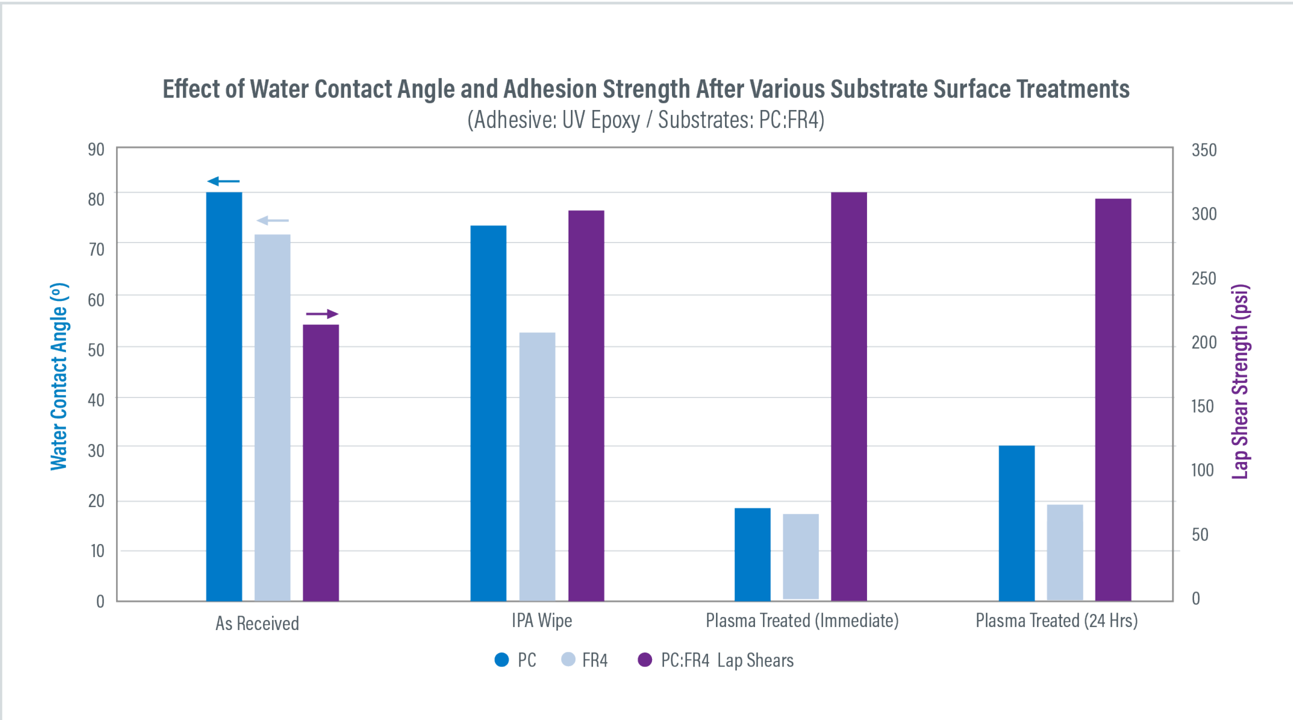
Contact Angle and Bond Strength by Adhesive System and Surface Preparation Method

Graphs 5-8 show how water contact angle correlates with lap shear strength for polycarbonate bonded to FR-4 across all adhesive systems and surface preparation methods. Graph 9 consolidates these results, comparing lap shear strength across all adhesives and surface conditions tested.

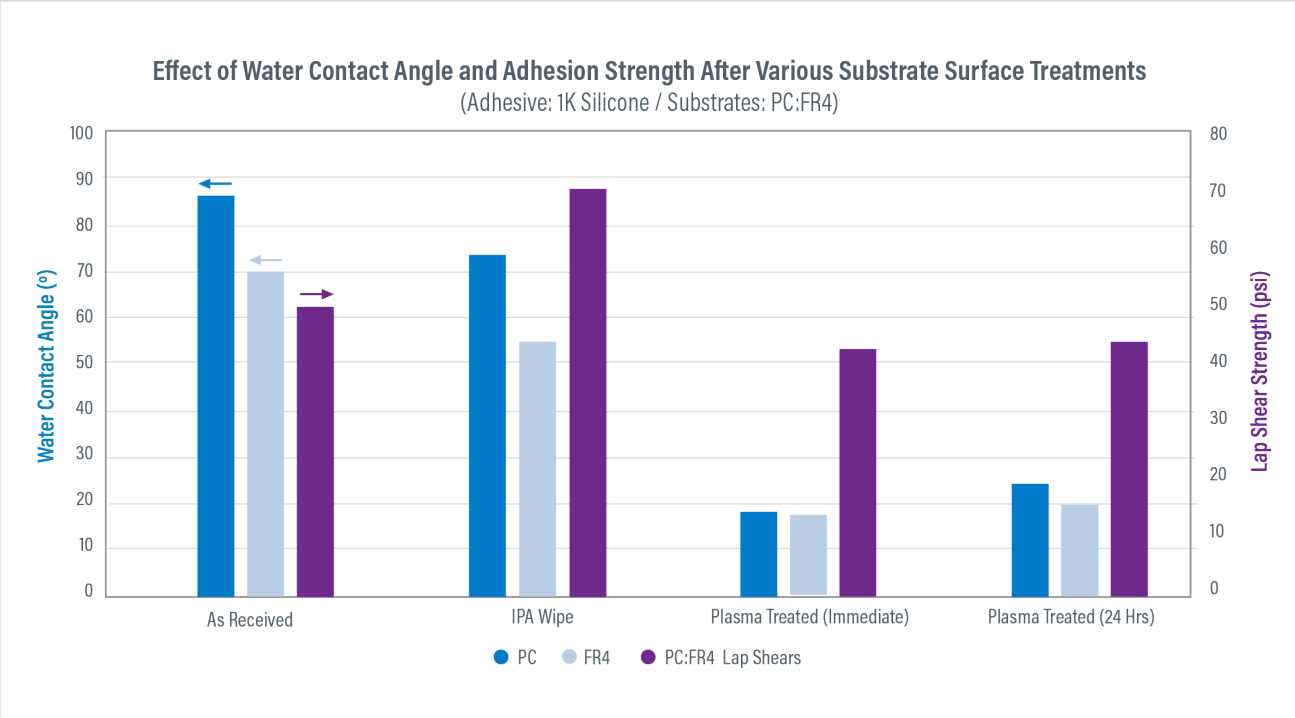
Graph 5. Contact angle (left) and adhesion strength (right) for PC to FR-4 (UV-curable acrylate)



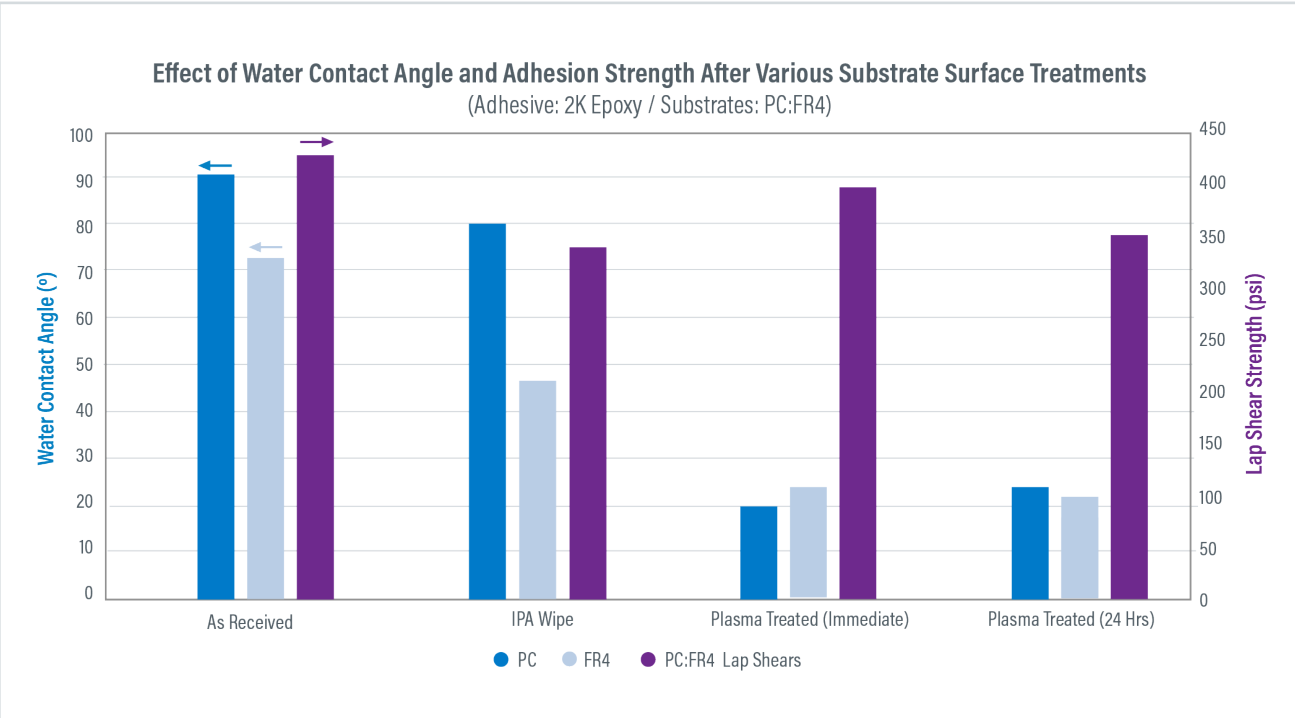
Graph 6. Contact angle (left) and adhesion strength (right) for PC to FR-4 (UV-curable epoxy)



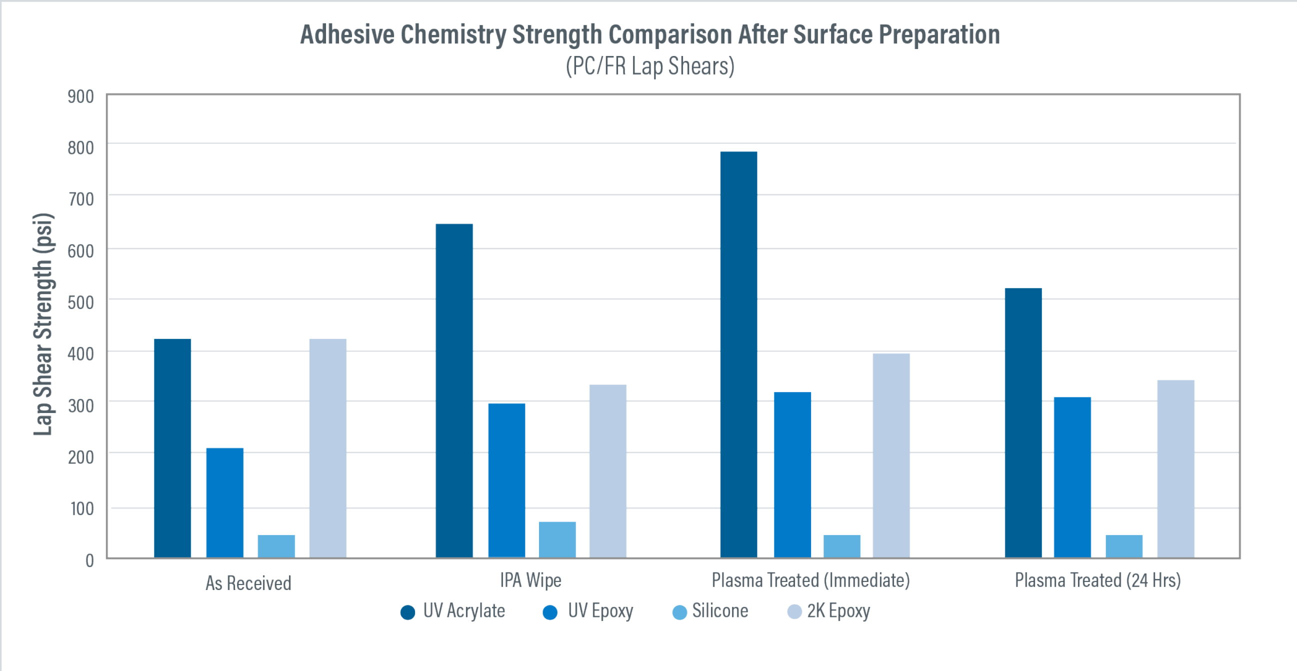
Graph 7. Contact angle (left) and adhesion strength (right) for PC to FR-4 (RTV silicone)



Graph 8. Contact angle (left) and adhesion strength (right) for PC to FR-4 (2K epoxy)



Graph 9. Consolidated Summary - Adhesion strength by surface preparation method



Key Findings: Bond Strength vs. Surface Preparation Technique

- **UV-curable acrylate** showed the most pronounced improvements with surface cleaning, with bond strength increasing in a clear stepwise manner as contact angle decreased. This indicates a strong sensitivity to surface cleanliness. When bonding was delayed 24 hours after plasma treatment, lap shear strength dropped by an average of 33%, confirming the time-dependent decay of surface activation.
- **UV-curable epoxy** demonstrated a similar trend, with bond strength improving as surface energy increased, though the effect was less pronounced than with the acrylate adhesive. Plasma treatment delivered the highest bond strength, but the overall gain was smaller compared to the acrylate system.
- **RTV silicone** showed only modest improvements in bond strength with surface treatments. IPA wiping produced the most noticeable gain, while plasma treatment provided little to no measurable benefit. This behavior reflects silicone's inherently low surface energy and limited cohesive strength, both of which limit the tensile strength of the bond.
- **Two-component epoxy** demonstrated strong lap shear performance across all surface conditions, including the as-received baseline. This suggests the adhesive is not highly dependent on surface activation, likely due to its inherent tolerance for minor surface contamination. Notably, bond strength decreased slightly after cleaning, indicating that surface treatments may have unintentionally reduced surface energy or otherwise altered the substrate in a way that diminished adhesion.

Conclusions and Recommendations

This study demonstrated a strong relationship among the three pillars of adhesion — adhesive chemistry, process control, and surface energy. In particular, it showed a clear correlation between surface energy and bond strength, where lower water contact angles (indicating higher surface energy) consistently produced stronger bonds. Even modest increases in contact angle after only 24 hours of surface aging measurably reduced bond performance, highlighting the value of surface energy assessment as a predictor of bond success.

Water contact angle testing is a practical, repeatable method for verifying that surfaces are ready for bonding and is especially valuable in electronics manufacturing. FR-4 circuit boards may carry solder mask, flux, or other residues that impair adhesion of underfills, conformal coatings, and encapsulants. Polycarbonate components, often bonded to achieve slim form factors, can also lose bond strength when contaminants migrate during assembly. Real-time contact angle measurement provides a fast, quantitative assessment of surface bondability and serves as an early-warning process-control tool for identifying surfaces at risk of poor adhesion before bonding, helping prevent rework, scrap and field failures.

Modern hand-held instruments, make contact angle testing practical even in high-volume production. These devices dispense and analyze micro-droplets of ultra-pure water within seconds, giving operators and quality engineers an immediate way to validate cleaning effectiveness or detect contamination. When contact angle is correlated with mechanical metrics such as lap shear strength, manufacturers can establish quantitative specifications for surface cleanliness and treatment, supporting statistical process controls and more consistent bonding outcomes.

Adhesive manufacturers, can help put these strategies into practice to improve bond performance and ensure long-term adhesion reliability. Backed by decades of formulation and application expertise, adhesive manufacturers can:

- Troubleshoot bonding challenges
- Recommend the most suitable adhesive for the application
- Suggest appropriate surface preparation methods
- Provide detailed processing guidelines and training

By combining data-driven surface characterization with advanced adhesive technologies and expert technical support, electronics manufacturers can achieve reliable, high-performance bonds in demanding applications — from automotive and aerospace electronics to medical and industrial systems — even as devices become smaller, more functional and more complex.

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