Overview of Polymer-Aluminum Adhesion: Dry vs. Wet Processing Techniques

Ihab S. Hasan[1]
1,College of Engineering University of Kerbala, Karbala, Iraq
ihab.sh@s.uokerbala.edu.iq

Emad Q. Hussein [2]
2,College of Engineering University of Kerbala, Karbala, Iraq
emad.dujaily@uokerbala.edu.iq

Amira Mohammed Ali Hussain [3]
3,Iraqi Engineering Union – Karbala .; yoouoo313@gmail.com

ABSTRACT

Achieving optimal adhesion between polymers and aluminum is paramount for diverse engineering applications, and several techniques have been explored to realize this. This review elucidates the various methodologies employed, dividing them into dry and wet processing techniques. Dry processing emphasizes controlled surface modifications but can be capital-intensive, while wet processing, though economically viable, sometimes requires potentially hazardous chemicals. Central to both techniques is the goal of augmenting the aluminum's bonding surface by inducing micro-level roughness. Moreover, polymers with inherent carbonyl groups have shown promising spontaneous adhesion to the alumina layer of aluminum, offering a robust interface without the necessity for exhaustive surface treatments. While such treatments can bolster interface strength, their indispensability varies based on the specific polymer-aluminum pairing. Decisions regarding surface treatment methodologies should be judiciously made, considering the specific application and polymer in use. give me a sutable keywords

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1. Introduction

In the expansive domain of material science and engineering, the pursuit to merge distinct classes of materials has always driven innovation. Among these, the union of polymers and metals, specifically aluminum, presents an intriguing juxtaposition. Here, we are looking at the synergy between the malleability and lightweight nature of aluminum and the diverse characteristics of polymers, which range from elasticity to impressive thermal resistivity. Their combined potential offers groundbreaking solutions across various industries, from aerospace to consumer electronics.

However, this marriage is not without challenges. At the heart of achieving a seamless blend lies the issue of adhesion. How do we ensure that these materials, with their distinct molecular structures and properties, bond in a manner that extracts maximum utility from both? Aluminum, despite its many advantages, presents a smooth, non-porous surface that may not readily bond with many polymers. On the flip side, polymers, given their vast structural diversity, can sometimes be too inert or incompatible with metallic surfaces.

The evolving landscape of manufacturing and design demands materials that aren't just functional but are also sustainable, cost-effective, and adaptable to diverse applications. As a result, enhancing the interfacial bond between aluminum and polymers isn't just a matter of academic interest; it's an industry imperative. This comprehensive review seeks to navigate the various paths explored in this endeavor. From intricate surface treatments and processing techniques to the discovery of inherent bonding mechanisms, we aim to provide a holistic understanding of where we stand and the promising horizons ahead in the realm of polymer-aluminum adhesion.

2. Aluminum-Thermoplastic Synergies in Engineering Applications

Aluminum stands out as a material of choice in numerous applications owing to its affordability, light weight, and weldable characteristics. These traits make it particularly conducive to high-frequency manufacturing processes. On the other hand, thermoplastics bring forward the capacity to generate intricate part geometries within a singular process step, most notably via methods such as injection molding. This method bypasses the requisite joining stages inherent in conventional metal shaping. Moreover, thermoplastics possess inherent thermal and electrical insulating properties, rendering them useful in providing insulation to aluminum structures.

When discussing composite materials, those incorporating polymeric matrices bolstered by either glass or carbon fibers also merit attention. These can potentially be integrated with aluminum. Short-fiber polymers, fortified by such reinforcements, can be maneuvered using the high-frequency methods akin to their unfortified counterparts. This facilitates the crafting of intricate components, with the added boon of enhanced rigidity and tensile strength.

A notable application spotlighting the convergence of these materials pertains to automotive body panels. Aluminum has been identified as a pragmatic alternative for weight mitigation purposes. Its ductility, however, renders it susceptible to superficial indentations, often resulting from minor collisions with hailstones or road debris. While these indentations might not compromise the vehicle's structural integrity, they're aesthetically unappealing. In contrast, polymer-fortified composites exhibit heightened resilience against such surface indentations, often to the extent that the inflicted damage remains imperceptible to the unaided eye. In such contexts, an exterior composite layer can safeguard the pristine appearance of aluminum panels. Simultaneously, an underlying aluminum layer can serve dual purposes: economizing the panel and affording feasible welding junctions. This dual-layered design philosophy ensures the seamless integration of these hybrid panels within prevailing production frameworks.

In real-world scenarios, direct interfacing between the polymer and core aluminum is uncommon. Typically, the polymer interacts with an aluminum oxide (alumina) layer. This oxide sheath spontaneously forms on aluminum surfaces upon oxygen exposure. Hence, any hybrid material fabrication in non-controlled environments predominantly entails the polymer's interaction with the aluminum's oxide layer.

3. Enhancing Aluminum Surface for Optimal Adhesion

Optimal adhesion between metals and thermoplastics is often crucial for various material pairings and applications. To achieve this, the metal surface typically undergoes specific pretreatments. These pretreatments can be broadly bifurcated into two methods: dry adhesion and wet adhesion. Dry adhesion leverages mechanical means, like laser machining and abrasive blasting, while wet adhesion employs chemical procedures, including chemical etching and anodization. Both strategies aim at amplifying the metal's surface area to enhance bonding potential.

Dry Processing Techniques

A significant advantage of dry processing is its tendency to eschew chemical etchants, making it a greener alternative. However, a potential downside includes the need for substantial capital, especially if there's a demand for consistent, structured outputs.

Ramani et al [1]–[3] delved into experiments evaluating the influence of multiple processing parameters on the adhesion strength between sand-blasted metals and injection overmolded polymers. Their analysis spotlighted the paramount importance of metal substrate temperature. Absence of pre-heating rendered bonding ineffective, attributable to the polymer's rapid cooling, which impeded its intimate contact with the metal substrate.

In a similar vein, Enami et al [4] studied how laser-induced surface ruggedness affected the bond strength when aluminum was overmolded with polybutylene terephthalate (PBT). Their findings suggested superior adhesion with a larger count of smaller dimples on the aluminum surface. Further, enhanced surface irregularities within these dimples were associated with better adhesion. Under optimal processing parameters, they achieved adhesive shear strengths surpassing the inherent shear strength of the polymer. This underscores the significance of evenly spaced interaction sites between the polymer and aluminum, emphasizing that an intentionally designed surface profile is instrumental for realizing a robust polymer-aluminum bond.

Another noteworthy study by Taki et al [5] leveraged laser ablation to engineer a microgrid on aluminum before overmolding it with materials like acrylonitrile butadiene styrene (ABS), polystyrene (PS), and glass-filled PBT. Compared to particle ablation, laser ablation crafted deeper surface structures, which seemed to enhance the bond strength between the polymer overmold and aluminum. Nonetheless, the efficacy of this process was contingent on the polymer's ability to permeate the microgrid—this was particularly challenging at lower substrate temperatures. When the substrate temperature was optimized to facilitate polymer infiltration prior to its cooling, the interface witnessed the formation of potent bonds.

Wet Processing Techniques

While wet processing often comes with the advantage of lower equipment costs, the utilization of certain chemicals, especially in etching processes, presents environmental and health concerns. These chemicals may mandate specialized disposal methods given their potential harm to humans and ecosystems.

Case Studies and Research Highlights

Fabrin et al [6] employed an acid-alkaline pretreatment on aluminum bars to achieve a porous surface texture. They then proceeded to overmold the bars with TPE without any pre-heating of the aluminum. Their results pointed out an intriguing behavior: thicker aluminum, particularly more than 0.5mm, acted akin to a heat sink. This phenomenon led to rapid cooling of the overmolded TPE upon its encounter with the aluminum, hindering the material's full penetration into the porous structure of the metal and subsequently, weaker bonding interfaces.

Yin et al [6] took a different approach, utilizing an electrochemical anodization technique on their aluminum sheets. The outcome was an alumina-coated surface, punctuated with nanopores. These minuscule pores facilitated mechanical interlocking when PBT was overmolded onto the aluminum. A noteworthy observation was that aluminum sheets subjected to higher voltage treatments had more expansive nanopores, bolstering the bond strength. However, as nanopore dimensions shrank from 14.3nm to 7.8nm, the polymer melt struggled to infuse these nanopores effectively.

In a preceding investigation by the same team [7], they solely deployed chemical treatment on aluminum before overlaying with PBT. Although they managed to achieve larger pores compared to their electrochemical methods, the resultant alumina coating on the aluminum surface was inconsistent. The team posited that this irregular coating, with micropores only manifesting in the alumina regions, led to a bond that was less robust than what they observed with electrochemical treatments.

Lastly, Yusof et al [8] determined that anodizing aluminum markedly improved its bond strength when interfaced with PET, outperforming non-anodized counterparts. Additionally, they deduced that the bond's resilience was further augmented with a surge in the interfacial temperature. Such conditions enhanced the infiltration of the PET within the intricate surface topography of the aluminum.

4. Inherent Adhesion Dynamics between Aluminum and Thermoplastics

Natural Adhesion Mechanisms

While the merits of surface treatments to amplify adhesion between thermoplastics and metals are undeniable, not all applications demand such rigorous bonding. Interestingly, certain thermoplastics might innately covalently bond to metal surfaces, obviating the need for preparatory surface treatments.

Liu et al [9] shed light on an intriguing phenomenon. Polymers possessing carbonyl groups—such as PA, polyethylene terephthalate (PET), polycarbonate (PC), and polymethylmethacrylate (PMMA)—appear to have the inherent capability to establish covalent bonds with metal atoms, specifically within the oxide layers enveloping metal surfaces. Their research notably highlighted the spontaneous genesis of an Al-O-C bond, formed between the carbonyl constituent in PA6,6 and the alumina layer.

Building on this understanding, subsequent research endeavors have seamlessly amalgamated PA6 with metal sheets, employing friction lap welding [10]. This specific technique harnesses a rotating instrument, exerting downward pressure, to generate heat through friction. Such localized thermal conditions render the materials malleable, promoting their interaction at the boundary and subsequently leading to bond formation. Delving deeper into the nuances of this technique, Liu et al [10] discerned that an optimal bond between aluminum and PA6 was attained under certain conditions: a heightened tool rotation speed and diminished transverse speed. Essentially, under circumstances where friction-induced temperatures peaked.

However, a recurrent challenge emerged. Like many thermal methodologies for metal-polymer amalgamation, bubble formation within the thermoplastic became prevalent. This is attributed to localized, extreme temperature-induced degradation[8], [11]–[13]. Astonishingly, despite the presence of these bubbles, robust bonds could still be established. Some research even suggests that the bond's resilience might be bolstered by these very bubbles[12]. However, this is a double-edged sword, as the polymer's life expectancy could potentially diminish owing to such degradation. Consequently, the paramount importance of meticulously calibrating processing conditions to curtail excessive degradation cannot be overstated.

5. Summary of Polymer-Aluminum Adhesion Strategies

Enhancing the adhesion between polymers and alumina can be achieved through a variety of methods related to aluminum surface preparations. These methods broadly fall into two categories: dry and wet processing techniques.

Dry vs. Wet Processing

Each of these methods has its own set of benefits and challenges. Dry processing allows for meticulous control over local surfaces, but it can be capital-intensive. Conversely, wet processing may not demand significant upfront investments; however, it often entails the use of chemicals that pose risks to both the environment and human health. Notably, regardless of the technique employed, the fundamental principle for bond enhancement remains consistent. Both strategies focus on augmenting the available aluminum bonding surface by introducing micro-level surface roughness.

Surface Considerations

For optimal adhesion, it's crucial to ensure that this roughness is uniformly distributed across the aluminum substrate. Processing parameters need careful calibration to guarantee the polymer remains in a melted state sufficiently long, enabling it to form a close bond with the aluminum. Moreover, if the generated surface roughness on the aluminum translates to overly diminutive pores, polymers might face challenges permeating these pores, even under ideal processing circumstances.

Inherent Adhesion Properties

Certain polymers, especially those integrated with carbonyl groups, demonstrate an innate ability to bind with aluminum atoms present in the alumina surface layer. This spontaneous bonding culminates in a robust interface, bypassing the need for intricate and potentially costly aluminum surface treatments. While surface treatments can elevate the interface's strength, they may not always be imperative. The choice of whether or not to employ a specific surface treatment should be application-centric and hinge upon the specific polymer intended to be amalgamated with aluminum.

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BIOGRAPHIES

Emad Q. Hussein was born in Karbala, in 1962. He received Ph.D. Degree in aircraft design from Mechanical Engineering Department, University of Technology, Iraq, in 2006. He is current with the College of Engineering, University of Kerbala. He is specialist in fluid structure interaction and CFD dynamic mesh. He has published more than 37 articles.

Ihab Sh. Hasan was born in Baghdad in 1995. He received a B.sc degree in General Mechanical Engineering from Karbala University in 2019., he works as an employee in Alezza Co. specializes in contract management In addition, he was a mechanical designer.

Amira M. Hussain She received a B.sc degree in Civil Engineering, As a principal civil engineer in Karbala, She led the engineering team, overseeing significant infrastructure projects. Her role was pivotal in enhancing the region's urban and public utilities development, ensuring quality and efficiency.