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Polymer–Aluminum Lightweight Multi-Material Joints Bonded with Mixed Adhesive †

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Abstract: Considering the challenges faced when joining multi-materials where welding is not possible, such as with polymers and metal, adhesives can be used to bond them. In this study, two chemically different adhesives, namely epoxy and silicone, were used to bond PVC/Al. Infrared spectra of a mixed adhesive revealed the presence of overlapping peaks with PVC, namely $–CH_2$, $–CH_3$ around 2800–3000 cm^{-1} and $Si–CH_3$ at 1260 cm^{-1}. Mechanical testing on single-lap shear specimens of PVC/Al prepared using mixed adhesive showed the enhancement in the adhesive strength was ~5 times higher compared to the adhesive strength of PVC/Al joints made with only silicone adhesive.

Keywords: polymer–aluminum joints; polyvinyl chloride (PVC); aluminum (Al); mixed adhesive; single-lap shear strength (SLS)

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1. Introduction

The development of the aerospace and automobile industries requires lightweight materials with high reliability and good dimensional stability, and thus promotes the application of polymers such as polyvinyl chloride (PVC) and light metal materials, such as aluminum (Al) alloys [1–4]. Compared with conventional mechanical joining approaches, such as welding, bolting and riveting, adhesive bonding stands out for several reasons, including its uniform stress distribution, low weight and good bondability of multi-material systems [5–8]. Bonding multi-material systems such as polymers to lightweight metals increases the efficiency in weight reduction in automotive and transportation structures, and hence improves overall fuel efficiency. For example, Pantelakis and Tserpes [9] discussed the development and challenges of adhesive bonding technology for composite materials in aircraft structures, proposing a numerical design method for bonding polymer materials to an Al alloy. Wang et al. [10] studied the influence of bonding parameters, namely adhesive types, surface treatment, substrate shape and bonding area on the improvement of the mechanical strengths. Pitta et al. [11] demonstrated a three-times-higher strength for metal–polymer systems when bonded adhesively compared to riveted counterparts. All these studies show that joint strengths and weight reduction can be improved using adhesives for assembling polymers to metals. However, the durability of the joint is determined by the strengths of the interfacial bonds between the polymer surface and the adhesive. Appropriate surface treatment is known to have a significant impact on improving the interfacial bonds between the treated polymer surface, such as PVC, and the adhesives [12–14]. Joining PVC with a metal using an adhesive is challenging as polymers have inherently very low surface energies, unfavorable for adhesion with adhesives. In addition to surface treatment, the selection of the right adhesive chemistry also plays a significant role for its compatibility with the polymer surface chemistry.

In the present work, we investigate the adhesion properties of two dissimilar materials, PVC and Al, adhesively bonded with a mixed adhesive chemistry by combining two different adhesive types, namely epoxy and silicone. The chemical compatibility of the mixed adhesive with the PVC substrate as well as Al and the improvements in the mechanical strengths of the bonded joints are presented.

2. Materials and Methods

The commercially available 1.5-mm-thick AA 6061-T6 Al flat sheet from Russel Metals Inc. (Mississauga, ON, Canada) and the 6.35-mm-thick PVC Type 1 plastic from McMaster-Carr (Elmhurst, IL, USA) were utilized as substrates. Commercially available silicone adhesive (SI 595) and epoxy adhesive (loctite EA E-20HP), provided by Henkel Inc. (Düsseldorf, Germany), were used to bond the substrates. These two adhesives were mixed in equal volume proportions at an ambient temperature and pressure. Single-lap shear (SLS) specimens of PVC bonded to Al were prepared according to the ASTM D1002 standard [15]. The geometrical and topographic characteristics of surfaces of PVC and Al were analyzed using an optical microscopy (Nikon Eclipse, El Segundo, CA, USA) and MicroX-AM-100 HR 3D surface profilometer, respectively. The chemical composition of mixed adhesive was studied using attenuated total reflectance Fourier-transform infrared (ATR-FTIR) spectroscopy. The SLS strength of the PVC/Al bonded joints were determined using an INSTRON 8801 mechanical testing unit.

3. Results and Discussion

Figure 1 presents the optical images and corresponding 3D profile images of the roughness for the as-received PVC and Al substrates, in which Figure 1a,c are for the PVC surface and Figure 1b,d for the Al surface, respectively. These topographic images show that both substrate surfaces presented naturally rough surface profiles in their as-received state. The presence of crests (peaks) and troughs (valleys) in the surfaces provided certain microroughness: 0.34 ± 0.13 µm for the PVC and 0.61 ± 0.21 µm for the Al.

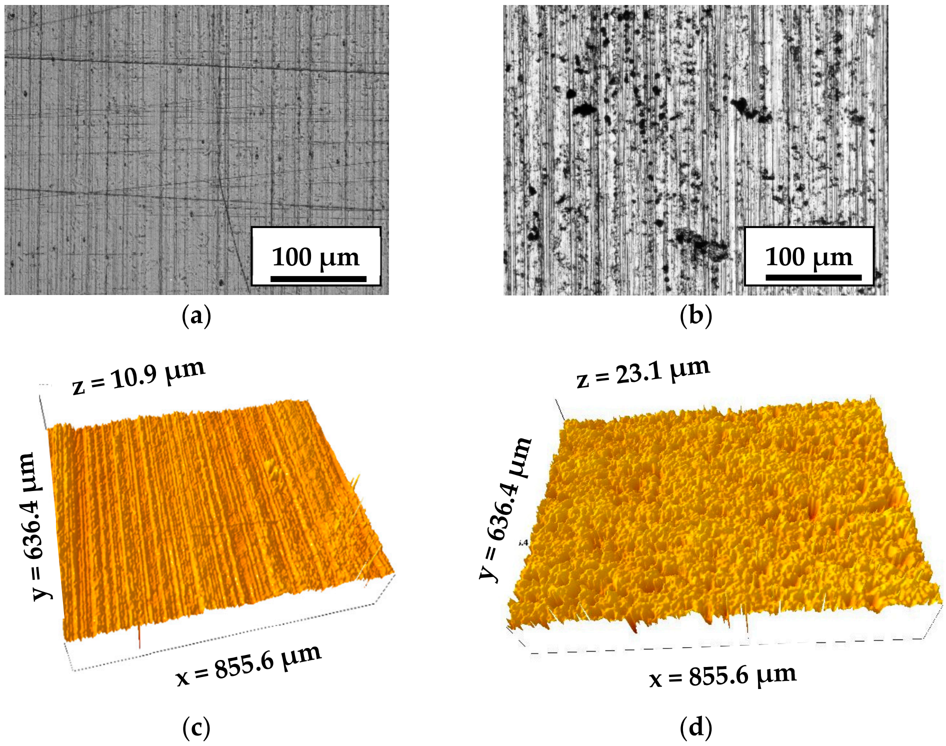

Figure 1. Optical images of as-received (**a**) PVC and (**b**) Al and their corresponding 3D profile images of the roughness in (**c**,**d**).

Figure 2 shows the digital images of droplets of water on the surfaces of the as-received PVC and Al substrates. The water drop placed on the surface of the PVC substrate provides a water contact angle of ~96°. On the other hand, the water contact angle on the surface of the Al substrate was found to be ~68°. The higher water contact angle on the PVC substrate is attributed to the lower surface energies of the PVC as compared with that of the Al.

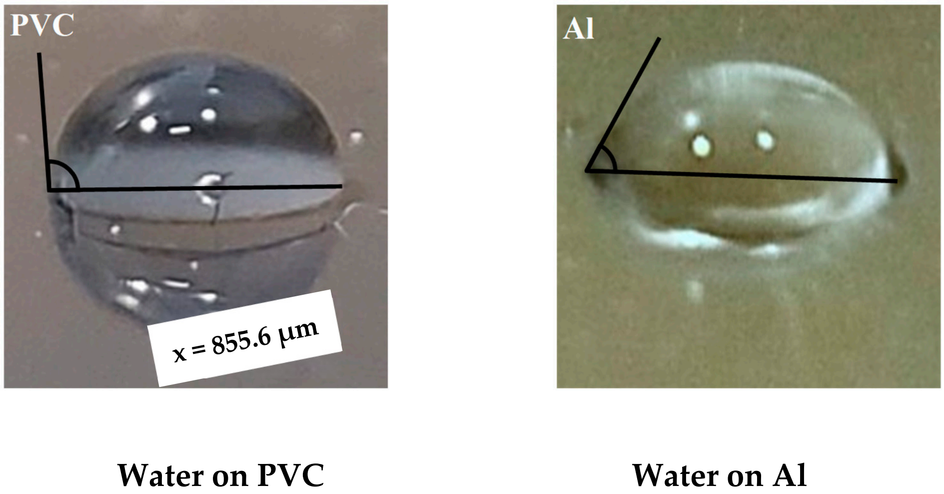

Figure 2. Digital image of a water droplet on the PVC and Al substrate surfaces showing the water contact angles.

Figure 3 shows the ATR-FTIR spectra of the mixed adhesives of the epoxy and silicone as well as of the PVC and Al substrate surfaces. The Al surface showed no IR absorptions, except for a small band at around ~950 cm^{-1} due to the possibility of the presence of an ultrathin oxide layer. However, the PVC substrate displayed multiple strong characteristic IR bands, such as 600 cm^{-1} (C–Cl stretching) and a broad absorption peak at 1425 cm^{-1} corresponding to $–CH_2$ bending, typical of PVC surfaces [16]. Small bands of $–CH_2$ and $–CH_3$ between 2800–3000 cm^{-1} were also observed [16]. Upon analyzing the epoxy-silicone adhesive mixture, overlapping peaks with PVC, namely (i) $–CH_2$, $–CH_3$ around 2800–3000 cm^{-1}, (ii) $Si–CH_3$ at 1260 cm^{-1} were observed. The presence of a characteristic Si–O–Si stretching mode at ∼1050 cm^{-1} and bending modes at 800 cm^{-1} were also observed, confirming the components from the silicone in the mixed adhesive. The presence of these components effectively enhanced the bonding with the Al substrate due to their chemical affinity to PVC that has an inherently low-surface-energy chemical structure.

The presence of Si components in the mixed adhesive shows promise for enhancing bonding with the mixed adhesive compared with those bonded with silicone individually. Further mechanical tests were carried out on the PVC/Al adhesive joints prepared using the pure silicone adhesive and mixed adhesive. The SLS strength of the PVC/Al bonded joints with pure silicone were found to be 0.43 MPa, while the joint strength using the mixed adhesive increased to 2.21 MPa, showing 413% enhancement. This behavior can be attributable to the affinity of low-surface-energy PVC to silicone. The results show that the mixing of epoxy with silicone at an equal proportion provides an increment in the joint strengths, with the mixed adhesive having excellent compatibility with PVC/Al.

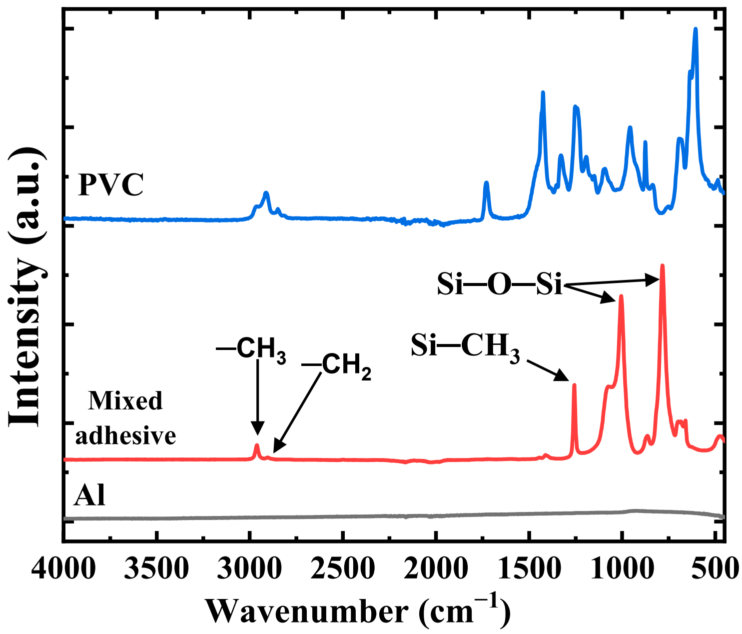

Figure 3. ATR-FTIR spectra of mixed adhesive of epoxy and silicone, PVC and Al surfaces.

4. Conclusions

A simple modification of the adhesive chemistry by combining epoxy and silicone resulted in a significant enhancement of the interfacial joint strength between the mixed adhesive and PVC when bonded with aluminum. The ATR-FTIR analysis presented the presence of overlapping –CH_2, –CH_3 and Si–CH_3 functional groups, which shows the chemical affinity of the mixed-adhesive molecules over the PVC surface. A maximum shear strength of ~2.2 MPa was obtained with 413% enhancement using the mixed adhesive compared to the joints prepared with the pure silicone adhesive. Further work is in progress to obtain an in-depth understanding of using and optimizing adhesive mixture proportions.

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Conflicts of Interest: The authors declare no conflict of interest.

References

1. Cust'odio, J.; Broughton, J.; Cruz, H. A review of factors influencing the durability of structural bonded timber joints. *Int. J. Adhes. Adhes.* **2009**, *29*, 173–185. [CrossRef]
2. Sankaranarayanan, R.; Hynes, N.R.J. Prospects of joining multi-material structures. *AIP Conf. Proc.* **2018**, *1953*, 130021.
3. Zimmermann, N.; Wang, P.H. A review of failure modes and fracture analysis of aircraft composite materials. *Eng. Fail. Anal.* **2020**, *115*, 104692. [CrossRef]

4. Kumar, P.; Patnaik, A.; Chaudhary, S. A review on application of structural adhesives in concrete and steel–concrete composite and factors influencing the performance of composite connections. *Int. J. Adhes. Adhes.* **2017**, *77*, 1–14. [CrossRef]
5. Wong, D.W.Y.; Zhang, H.; Bilotti, E.; Peijs, T. Interlaminar toughening of woven fabric carbon/epoxy composite laminates using hybrid aramid/phenoxy interleaves. *Compos. Part A Appl. Sci. Manuf.* **2017**, *101*, 151–159. [CrossRef]
6. Antelo, J.; Akhavan-Safar, A.; Carbas, R.J.C.; Marques, E.A.S.; Goyal, R.; da Silva, L.F.M. Replacing welding with adhesive bonding: An industrial case study. *Int. J. Adhes. Adhes.* **2022**, *113*, 103064. [CrossRef]
7. Chang, B.; Shi, Y.; Dong, S. Comparative studies on stresses in weld-bonded, spot-welded and adhesive-bonded joints. *J. Mater. Process Technol.* **1999**, *87*, 230–236. [CrossRef]
8. Saleema, N.; Sarkar, D.K.; Paynter, R.W.; Gallant, D.; Eskandarian, M.A. simple surface treatment and characterization of AA 6061 aluminum alloy surface for adhesive bonding applications. *Appl. Surf. Sci.* **2012**, *261*, 742–748. [CrossRef]
9. Pantelakis, S.; Tserpes, K.I. Adhesive bonding of composite aircraft structures: Challenges and recent developments. *Sci. China Phys. Mech. Astron.* **2014**, *57*, 2–11. [CrossRef]
10. Wang, S.; Shang, X.; Ju, S.; Jiang, D. Progress on research on composite-metal adhesive joints. *Fiber Reinf. Plast./Compos.* **2017**, *44*, 95–100.
11. Pitta, S.; Carles, V.M.; Roure, F.; Crespo, D.; Rojas, J.I. On the static strength of aluminium and carbon fibre aircraft lap joint repairs. *Compos. Struct.* **2018**, *201*, 276–290. [CrossRef]
12. Zhang, Z.; Shan, J.G.; Tan, X.H.; Zhang, J. Effect of anodizing pretreatment on laser joining CFRP to aluminum alloy A6061. *Int. J. Adhes. Adhes.* **2016**, *70*, 142–151. [CrossRef]
13. Xu, Y.W.; Li, H.G.; Shen, Y.Z.; Liu, S.Y.; Wang, W.T.; Tao, J. Improvement of adhesion performance between aluminum alloy sheet and epoxy based on anodizing technique. *Int. J. Adhes. Adhes.* **2016**, *70*, 74–80. [CrossRef]
14. Chen, J.; Du, K.P.; Chen, X.M.; Li, Y.B.; Huang, J.; Wu, Y.T.; Yang, C.L.; Xia, X.C. Influence of surface microstructure on bonding strength of modified polypropylene/aluminum alloy direct adhesion. *Appl. Surf. Sci.* **2019**, *489*, 392–402. [CrossRef]
15. *D1002-10*; Standard Test Method for Apparent Shear Strength of Single-Lap-Joint Adhesively Bonded Metal Specimens by Tension Loading (Metal-to-Metal). ASTM International: West Conshohocken, PA, USA, 2010.
16. Suganya, A.; Shanmugavelayutham, G.; Rodríguez, C.S. Study on structural, morphological and thermal properties of surface modified polyvinylchloride (PVC) film under air, argon and oxygen discharge plasma. *Mater. Res. Express* **2016**, *3*, 095302. [CrossRef]