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Effect of laser ablation treatment on corrosion resistance of adhesive-bonded Al alloy joints

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ABSTRACT

Laser ablation treatment modifies the chemical property (i.e. increased surface oxide layer) and topography (i.e. rough surface microstructures) of Al alloy substrates, and both aspects are considered as contributing factors to the corrosion resistance of adhesive-bonded joints. To analyze the effects of modified chemical property and topography on corrosion resistance of adhesive-bonded Al alloy joints, the laser ablation treatments were applied to Al alloy with/without argon shielding gas and in different power levels. Results show that although the increased surface oxide layer resulting from laser ablation treatment greatly improves the corrosion resistance of Al alloy substrate, it has negligible effect on corrosion resistance of adhesive-bonded Al alloy joints. Nevertheless, the modified surface topography has a significant effect on corrosion resistance of adhesive-bonded Al alloy joints. The bonding interfaces of joints fabricated from Al alloy substrates with relatively smooth surface topography are continuously broken by salt solution with the extension of corrosion exposure time, which changes the failure mode from cohesive to adhesive failure. The rough surface topography prevents the diffusion of salt solution through the Al/adhesive bonding interface and consequently protects Al alloy from being corroded, which results in better corrosion resistance of adhesive-bonded Al alloy joints.

1. Introduction

Al alloy with low density is more and more used in the automotive industry. Adhesive bonding is increasingly applied to Al alloys as well as other materials in automotive manufacturing duo to advantages of uniform load distribution, improved joint stiffness and capability of joining dissimilar materials [1–3]. To achieve superior adhesive performance, many surface pretreatment methods have been widely adopted for adherends. Among these methods, laser ablation treatment is demonstrated to be very effective. Recent research shows that laser ablation treatment increases the surface oxide layer and creates rough surface topography on adherends, which are responsible for improved adhesive bonding performance of joints, especially corrosion resistance [4]. However, the improving mechanisms of laser ablation treatment on corrosion resistance are still not quite clear. To further explore the improving mechanisms, the effects of modified chemical property and topography on the corrosion resistance of adhesive-bonded joints should be well understood.

During the whole life cycle of vehicle, the environmental aging of adhesive-bonded components is an important concern. Previous studies reveal that the declined strength of adhesive-bonded joints is mostly related to water absorption [5–15] and surface corrosion of adherends [16–23] after environment exposure. After water absorption, the mechanical performance of adhesive would decline since of plasticization, swelling and hydrolysis [5,6,10]. Many researchers have dedicated to analytical, experimental and numerical studies on the water diffusion and absorption rates in adhesive-bonded joints, which were applied to predicting the residual adhesive bonding strength of exposed joints. Armstrong et al. [7] found that for a given type of surface preparation and adhesive chemistry, the durability of adhesive-bonded joints depended on the permeability of the adhesive towards water. Wahab et al. [9] studied the diffusion of moisture in adhesively bonded composite joints under hot-humid environmental exposure, and built a tentative link between fatigue threshold and water concentration at the site of failure initiation, which could be used to predict the strength of joints subjected to moisture-induced degradation. Bordes et al. [13] investigated the long-term behavior of adhesively bonded steel joints aged in sea water. A coupled diffusion-mechanical property analysis approach had been used to examine the long-term response of aged structures and predict the failure behavior of aged joints, which was based on a diffusion model and an experimentally determined relationship between the content of absorbed water and the loss of adhesive property. Ameli et al. [14] proposed an exposure index (EI) that is defined as the time integral of water concentration in joints, and they

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successfully predicted the fracture toughness of closed double cantilever beam (DCB) adhesive joints from calculated EIs by referring to fracture toughness data from open-faced DCB specimens degraded to various EI levels. In addition, the environmental corrosion solution would cause the hydration of surface oxide layer on metallic adherends, which results in weakening and failure of the oxide layer and a decreased adhesion between adhesive and adherend [17,19,20]. Kinloch et al. [17] found that the role of the interphase was crucial in determining the durability of adhesive joints, the failure in adhesive/oxide interphase contributed to the poor durability of joints. Doyle et al. [20] studied the degradation of adhesive-bonded aluminum joints in water-based environments (de-ionized water, urea solution and simulated ocean water), and they concluded that the degradation was a result of water plasticizing the resin and lowering the Tg followed by enhanced water ingress and corrosion of the aluminum substrate. Zhang et al. [21] investigated the hygrothermal degradation of adhesive-bonded AA6111-T4-DP590 joints, the corrosion of steel with zinc coatings at 80 °C and 90% R.H. acted to weaken the interface between adhesive/zinc oxide layer and reduced joint strength significantly. Zheng et al. [22] focused on the effect of hot-humid exposure on the static strength of adhesive-bonded aluminum alloys. Test results showed that the hot-humid exposure led to a significant decrease in joint strength and changed failure modes from mixed to adhesive failure, which was primarily attributed to the corrosion of aluminum substrate. To improve the durability of adhesive-bonded joints under enviromental exposure, surface pretreatment methods are always used to modify the surface condition of adherends. Previous studies have already proved that laser ablation treatment is able to improve the adhesive strength of joints before exposure [24–33], but there are very few reports on durability in literature. Baburaj et al. [24] found the increased strength of titanium alloy by laser surface modification was mainly related to the following three aspects: (1) increased adhesive bonding area, (2) mechanical interlocking formed by micro-columnar array structure, (3) improved wettability of adherend by surface chemistry modification. Alfano et al. [27] improved the adhesive bonding strength of steel/Al joints by laser surface textures. They attributed the improving mechanism of steel joints to mechanical interlock at the interface of steel/expoxy resin. However, the surface chemistry (surface oxide layer), rather than mechanical interlock, was more likely to explain for the increased strength of adhesive-bonded Al joints. Rotella et al. [30] reported that laser ablation treatment improved the shear and peel strength of adhesive-bonded steel joints before and after corrosive environment exposure.

To understand the improving mechanism of laser ablation treatment on corrosion resistance of adhesive-bonded Al alloy joints, the automotive Al alloy 5052 was used in this study, two experiment groups were designed to investigate the effects of modified surface chemistry and topography by laser ablation treatment on corrosion resistance of adhesive-bonded Al alloy joints under neutral salt spray corrosive environment.

2. Experimental

2.1. Materials

2.0 mm thick Al alloy sheet AA5052 was used as the adhesive bonding substrate. Per the manufacturer's datasheet, the mechanical properties at room temperature and chemical compositions of AA5052 are listed in Table 1 and Table 2, respectively. Dow BETAMATE 1486, a single component, hot-cured epoxy adhesive was used to fabricate adhesive-bonded joints. The curing condition of Dow BETAMATE 1486 is 20 min at 180 °C. Table 3 lists the mechanical properties of the fully cured adhesive at room temperature. The lap-shear joint was used in this study to evaluate the adhesive performance of Al alloy. Fig. 1 shows the dimensions of lap-shear joint fabricated from AA5052 specimens having a size of 25 × 100 mm^2 where the thickness of adhesive layer was controlled as ~0.25 mm by glass beads. All AA5052 specimens were cleaned with alcohol before applying adhesive and laser ablation treatment.

Table 1
Mechanical properties of AA5052.

Material	Yield strength [MPa]	Tensile strength [MPa]	Elongation [%]
AA5052	195	230	13

Table 2
Chemical compositions (wt%) of as-received AA5052.

Element	Al	Mg	Si	Cu	Fe	Mn	Zn	Cr	Other
(wt%)	95.85–96.65	2.2–2.8	0.2	0.1	0.35	0.1	0.1	0.15–0.35	0.15

Table 3
Mechanical properties of fully cured Dow BETAMATE 1486 adhesive.

Adhesive	Elastic modulus [GPa]	Tensile strength [MPa]	Lap-shear strength [MPa]	Elongation [%]
Dow BETAMATE 1486	1.9	38	19	7.3

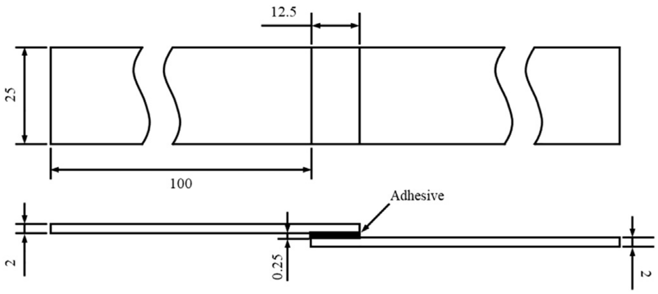

Fig. 1. Illustration of lap-shear joint dimensions (unit in mm).

2.2. Laser ablation treatment

Laser ablation treatments of AA5052 were conducted on a laser machine NC-J-FL-20 W (1064 nm wavelength) with a pulse frequency range from 20 to 80 kHz, a maximum processing speed of 8000 mm/s and a maximum laser average power of 20 W. Laser beam spot is circular with a focal point beam size of 58 μm. To study the effect of increased surface oxide layer on corrosion resistance of adhesive-bonded AA5052 joints, the argon shielding gas was used to protect Al alloy substrate surface from oxidation and prevent the formation of surface oxide layer during laser ablation treatment. The same laser processing parameters as listed in Table 4 were used in laser ablation treatments with and without argon shielding gas, which were hereafter referred to as w-Ar and w/o-Ar, respectively. The average power was set to 19.6 W for the sake of protecting the laser machine. The joints fabricated from AA5052 substrates treated by lasers with and without argon shielding gas were referred to as Ar-19.6 W and Air-19.6 W, respectively.

Table 4
Laser processing parameters.

Pulse frequency [kHz]	Processing speed [mm/s]	Line spacing [mm]	Average power [W]
20	600	0.04	19.6

The relative position of argon shielding gas pipe and Al alloy