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Reinforcing cross-tension strength of adhesively bonded joints using metallic solder balls

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ABSTRACT

With the broader utilization of adhesive bonding in the automotive industry for structural lightweight applications, hybrid joining methods such as weld or rivet-bonding are being employed to complement the strength of adhesive-only joints. In this paper, a novel method to significantly improve the energy absorption of adhesive bonds by the addition of solder balls was developed and experimentally verified. Numerical analysis predicted a maximum increase of cross-tension strength and energy absorption by 25% and 80%, respectively. Our experimental study exhibited the same trend and achieved a maximum increase of strength and energy absorption of 17.5% and 40%, respectively. Microscopy indicated the presence of a thin adhesive layer between the solder balls and substrate after bonding which is believed to limit the full theoretical potential of the solder-adhesive bond strength. Effects of volume fraction of solder balls, and pre-tightening of the solder-adhesive joint prior to curing on the mechanical performance of solder-adhesive bonds were investigated. Additional work is ongoing to explore avenues to achieve the full potential of solder adhesives.

1. Introduction

Adhesive bonding has the advantages of good fatigue performance, vibration absorption [1], corrosion resistance [2], and high lap-shear strength [3] and is therefore widely used in the automotive industry [4]. However, when compared with other joining methods such as spot welding or self-piecing riveting (SPR), adhesive has relatively poor peel and cross-tension performance. As shown by our results in Fig. 1, when compared to SPR of the same substrate material, adhesive bonding has a higher lap-shear peak force and fracture displacement but very low peak force and energy absorption in the T-peel and cross-tension test. This limits the application of adhesive bonding and drives the application of hybrid methods such as weld bonding or rivet bonding.

In order to improve the peel/cross-tension performance of the adhesive layer, a hybrid approach which combines fusion or mechanical spot joining processes with adhesive bonding is commonly applied, especially for the joining of dissimilar metals [5]. Such examples include weld bonding, i.e., the combination of resistance spot welding and adhesive bonding [6–8], and rivet bonding, i.e., the combination of self-piercing riveting and adhesive bonding [9–11]. Hybrid bonding techniques in [9–11] exhibit more advantages in joint performance, but those processes are very costly for the rivets and equipment investment. Moreover, when riveting high strength steels over 800 MPa or brittle materials, such as magnesium alloys or casting aluminum, those hybrid bonding techniques are faced with great challenges. Thus, it is very necessary to develop alternatives. Furthermore, the introduction of the rivets in rivet bonding increases mass and cost for each individual rivet as well as the susceptibility for issues related to sealing and corrosion. For weld bonding, the introduction of extensive heat will decompose and degrade the adhesive surrounding the weld zone [12], leaving an unprotected region adjacent to the weld.

Improving bond performance of the base adhesive itself is a straightforward path of improving the strength of bonded joints. Since chemical modification of the base adhesive is typically treated as proprietary information by the adhesive suppliers, an alternative path for adhesive customers is the addition of particles composed of materials having greater strength than the adhesive itself such as glass/carbon fibers [13–15], polymer particles [16,17]

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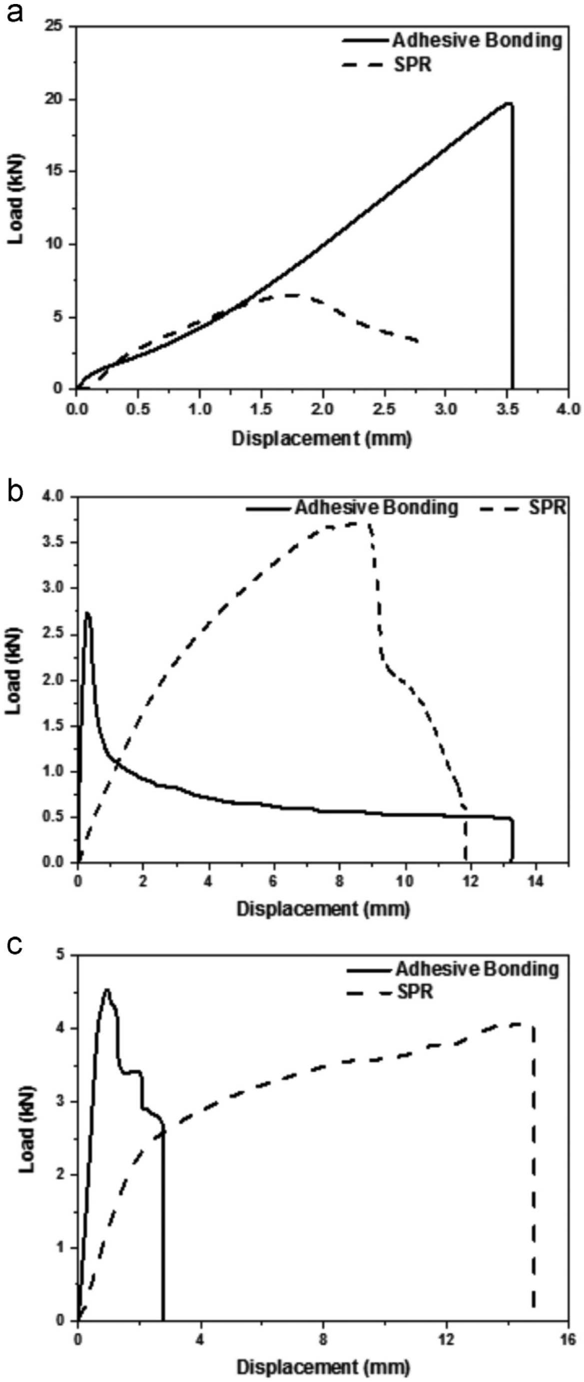

Fig. 1. Comparison of load–displacement curves of adhesively bonded and SPR joints consisting of 1.6 mm thick DP590 to 1.6 mm thick DP590 substrates and equivalent overlap areas; (a) lap-shear test, (b) coach-peel test and (c) cross-tension test.

or metal/ceramic powders [18–20]. There is an existing body of work in the literature investigating these methods [21,22]. Soon Yoon et al. [15] used several kinds of glass fibers with diameters from 0.12 mm to 0.29 mm in a mat and backfilled it with epoxy to enhance the performance of adhesive at cryogenic temperatures (−150 °C), and the specimens used were double cantilever beam specimens with 12 mm thick aluminum substrates according to ASTM D3433. They found that a volume fraction of glass fiber less than 30% increased the strength as measured by DCB by 40% (from 0.9 kN to about 1.4 kN) and the corresponding fracture toughness increased by 5.3 times under a loading rate of 1.67E^{-2}*1/s by the glass fibers bridging the fracture that propagated. However, the placement of a glass mat backfilled with epoxy is not a realistic solution to typical automotive flanges. Park et al. [17] studied the influence of the addition of 30 nm diameter carbon black particle by up to 3 wt% on the performance of epoxy based adhesive. Their data exhibit an increase of lap-shear strength from approximately 23 to 35 MPa at 1.5 wt% on a glass/epoxy composite substrate with a corresponding increase of adhesive tensile strength and deformation to fracture. Zhai et al. [19] used epoxy adhesive with nano-Al_2O_3 mixture to join steel substrates, and found that the nano-Al_2O_3 helps to form new polar functional groups, leading to the increase of the pull-off strength from 4 to 18 MPa for epoxy resin adhesive on steel substrate through altering the fracture mode from cohesive to partial cohesive/adhesive at an optimum addition of 2 wt% of the nano-Al_2O_3 powders.

It is clear that particle additions can improve adhesive bond strength. Fibers will bridge the crack, thus requiring greater energy to fracture or pull out the fibers. Polymer particles will deform before the crack propagation to absorb energy, and ultimately fracture or debond from the adhesive matrix, thereby increasing the energy necessary for propagation. Oxide powders could improve the performance of the adhesive layer by forming new polar functional groups, which increases the adhesion of the adhesive with the metal substrates. Obviously, as the particles used are small in size compared with the bondline thickness, the added particles in the adhesive layer do not connect both the substrates; thus their contribution to bond performance, especially to peel/cross-tension strength, is limited.

In this paper, a novel type of hybrid adhesive, i.e., “solder reinforced adhesive” [23] was developed by including the substrate/particle interface in addition to the adhesive/particle interface so as to improve the peel/cross-tension performance of adhesively bonded joints. As shown in Fig. 2(a), solder balls are mixed in an adhesive layer between the two substrates. The basis of this method is that the added metallic solder balls are stronger than adhesive itself. Once the solder adhesive is applied and as the temperature rises during the curing process, the solder balls added melt and wet the substrate materials. Simultaneously, the

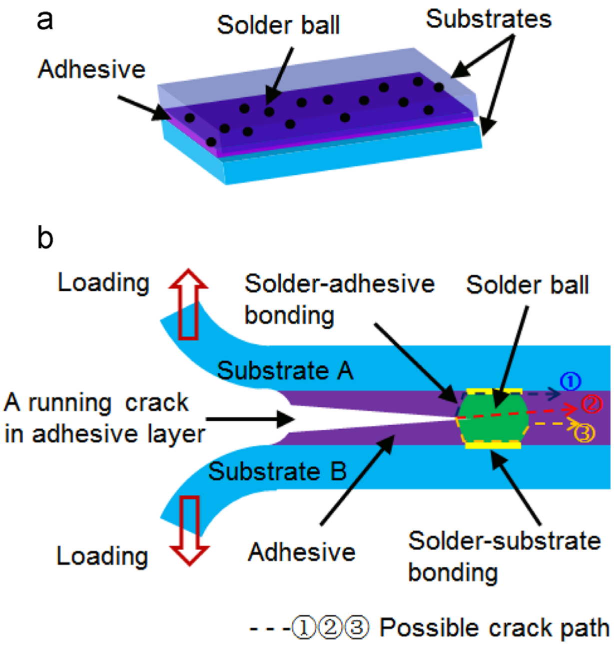

Fig. 2. Schematic of the solder-reinforced adhesive bonding method. (a) Solder balls immerged in the adhesive layer. (b) Theoretical representation of three possible crack propagation paths: solder/substrate interface, through solder ball, and solder/adhesive interface.