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Effect of base steels on mechanical behavior of adhesive joints with dissimilar steel substrates

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ABSTRACT

The hybrid steel materials (e.g., advanced high strength steels combined with mild steels) have been increasingly applied in vehicle components to achieve the compromise among mechanical performance, lightweight and material cost. A significant issue related to the bonding of dissimilar steel materials is that the differences in substrate physical properties often lead to bond separation at strength levels far less than the bond strength established by the adhesive manufacturer for the joint with similar substrates. This research studied several important factors influencing the strengths of adhesive-bonded lap shear (LS) and coach-peel (CP) joints. Four types of steel substrates were used to fabricate the unbalanced adhesive joints (dissimilar steels or same steels with different thicknesses). The quasi-static tensile tests of the unbalanced joints were performed. A finite-element model was proposed to characterize the fracture behavior of joints. The effects of substrate properties such as bending stiffness and load-carrying capability of substrates on the joint strength (peak force) and fracture modes were investigated. It was observed that the interfacial fracture is prone to occur on the substrate with the relatively weak yield strength. A cohesive fracture can be produced when the load-carrying capabilities of the two substrates are similar. In order to optimize the load-carrying capability of the unbalanced joint, a design guideline was put forward.

1. Introduction

Automotive manufactures are undergoing increasing pressure to produce safer and more durable vehicles while improving fuel economy and emission standards. Over the years, new and existing materials and joining technologies have been introduced to the automotive industry to achieve the goal of lightweight. Today, advanced high strength steel (AHSS) is one of the most important materials for vehicle structures. AHSS can be combined with the mild steel to obtain the compromise among mechanical performance, lightweight and material cost. Hence, many vehicle producers make use of hybrid steel materials in assemblies at the component or subsystem level. For example, an AHSS B-pillar is joined with a mild steel side frame to achieve weight reduction and acceptable crash-worthiness for side impact protection. However, such a hybrid-material assembly type brings a great challenge to the joining techniques in vehicle bodies. It is difficult to fabricate high-quality joints for the weak (yield strength ≤ 300 MPa)–strong (yield strength > 300 MPa) substrates when the traditional resistance spot welding is utilized. In other words, spattering can occur on the weak substrate (resulting in voids in the weld zone), and undersized welds can be produced on the strong substrate. Since the chemical, physical and mechanical properties of base materials are barely changed in the joining process, adhesive offers unique advantages in joining the unbalanced substrates (dissimilar steels or same steels with different thicknesses). In vehicles, the adhesive is an excellent candidate to be used together with resistance spot welding and self-piercing rivets in the structures with the unbalanced steel substrates.

In order to ensure passenger safety, vehicle design engineers must have sufficient information and knowledge about material mechanical properties before introducing the material to a specific vehicle design. In addition to the base material properties, the mechanical performance of the joints connecting these materials to other parts of the vehicle must also be sufficiently characterized. The mechanical performance of adhesive-bonded steel joints has been studied in many research works using single lap-shear joint [1–6], double lap-shear joint [7], coach-peel joint [8], wedge-peel joint [9], butt joint [10], and component test [11,12]. Karachalios et al. [1,2] performed single lap-shear tests with high-strength steels and low carbon steels. They found that for the high-strength steel adherends, the fracture of the joint is dominated by the adhesive global yielding or the local shear strain

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at the overlap ends; but for the low carbon steel adherends, the fracture mechanism is dictated by the yielding of adherend. Da Silva et al. [3] designed an experimental matrix of single lap-shear joints using Taguchi method, to investigate the factors that could influence the joint strength (including adherend material, geometry, surface treatment and environment). For their test conditions, they concluded that the joint strength increased with the larger overlap length and adherent thickness, and decreased as the bond-line thickness increased. But the main effect is that of the overlap length. De'Nève et al. [6] assessed the mechanical performance of bonded joints with bare steel and zinc electro-coated steel adherents at the temperatures of 40 °C, 55 °C and 75 °C. Their study showed that Zn can migrate into the adhesive, and thus, can help to slightly improve the strength of joints with the Zn-coated adherent. Beevers et al. [8] examined the peel strength of adhesive-bonded low-carbon steel joints by the coach-peel tests. They claimed that the performance of coach-peel joint is critically dependent on the presence of fillets and flange bend radii instead of the base steel strength. Seo et al. [10] assessed the strength of adhesive joint by four points bending, shear and tension butt joints. They summarized that the adhesive shows best performance (for preventing cracking) under the bending load. The adhesive has equivalent performance in both the shear and the tension butt joints. Peroni et al. [11] performed the adhesive-bonded thin-wall component tests, and revealed that the adhesive-bonding can improve the stiffness, fatigue strength and vibration response of the structure.

All above researchers have characterized the mechanical properties of adhesive-bonded joints by various test methods, and showed that the joint strength depends on coupon size, configuration, loading mode, loading rate and environmental conditions. However, it was noticed that almost all the above studies were carried out with no considerations of the unbalanced substrates. Actually, the main issue concerning engineers in bonding the unbalanced materials is how to incorporate the difference in mechanical properties between two bonded materials to achieve a balance among weight reduction, strength of vehicle body and material cost. Liao et al. [13] revealed that crack initiates at the interface of the adherend with higher Young's modulus in the dissimilar adhesive joint under impact tensile loadings. Seong et al. [14] conducted composite-to-aluminum adhesively bonded lap-shear tests. They concluded that high efficiency would be obtained when the ratio of overlap length to the width of the joint is much lower than 1. Mallick et al. [15] made use of detailed finite-element models to calculate peel, shear and longitudinal stresses in the lap-shear joints between dissimilar materials with modulus ranging from 10 GPa to 207 GPa. They indicated that the maximum peel and shear stresses in the joints occurred at mid-width of the lap ends where the weak substrate extended, and close to the weak substrate surface along the bond thickness direction. Also, the bond between the strong-strong substrates could sustain much higher load than the bond between the weak-strong substrates due to the early yield of the weak substrate. Therefore, it is necessary to understand the roles of the unbalanced substrates during the deformation and fracture of adhesive-bonded joints, and conduct the study with respect to the adhesive of interest and substrates of interest.

In this study, first we selected the steel materials which are commonly used in vehicles, i.e., DP780, DP600, HSLA340 and GMW2 (mild steel) [16] as the substrates. After that, the adhesive-bonded lap-shear and coach-peel joints with the unbalanced substrates were fabricated using the four types of steels with different thicknesses. The static mechanical performances of joints were assessed by the lap-shear and coach-peel tensile tests. A finite-element model was proposed to characterize the fracture behavior of adhesive-bonded joints. The fractures of adhesives in the unbalanced steel joints were analyzed. In order to optimize the load-carrying capability of joints, a design guideline for the adhesive-bonded joints with unbalanced steel substrates was put forward.

2. Testing procedure

2.1. Specimen preparation

Henkel Terokal 5089, a single-part, heat-curing, crash-toughened epoxy structural adhesive was employed throughout this study. The stress–strain curves of the adhesive tested at 23 °C and 50% R.H. under 1×10^{-4}/s is shown in Fig. 1. The curing temperature of the adhesive is between 155 °C and 190 °C. The steel sheets of DP780, DP600, HSLA340 and GMW2 were chosen as the substrates of adhesive-bonded joints. The quasi-static tensile tests of steels were performed according to the ASTM standard [17], to determine the material properties of base steels as shown in Fig. 2. Figs. 3 and 4 show the dimensions of coach-peel (CP), and lap-shear (LS) joints, respectively. The overlap lengths of CP and LS coupons are 25 mm and 15 mm, respectively. The bond-line thickness is 0.25 mm.

To reduce the variation of the joint strength, the fabrication process strictly followed the requirements. Contaminants and oil on the bonding surfaces were first cleaned by 1-1-1 trichloroethane solvent before applying adhesives. Glass beads with a diameter of 0.25 mm were sprinkled evenly on the adhesive layer to control the thickness of the bond-line. All squeezed-out adhesive was scraped off. The bonded CP and LS joints were cured in an oven for 30 min at 180 °C and cooled down at the ambient temperature for 24 h before the tensile tests. The steel types and substrate thicknesses were summarized in a test matrix as listed in Table 1, i.e., 1.6 mm DP780/0.7 mm GMW2 (referred as LS1 and CP1), 1.6 mm DP780/1.2 mm GMW2 (referred as LS2 and CP2), 1.8 mm DP600/1.0 mm HSLA340 (referred as LS3 and CP3), and 1.8 mm DP600/2.1 mm HSLA340 (referred as LS4 and CP4).

2.2. Quasi-static tests

The LS and CP tests to measure the quasi-static strength of joints were carried out by a universal test machine (UTM) at room temperature (23 °C). When performing the LS tests, in order to

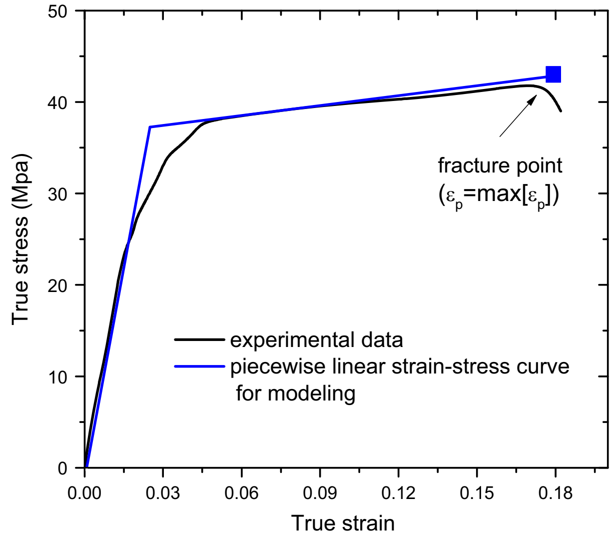

Fig. 1. True strain–true stress curve of adhesive. Maximum effective plastic strain, $max(\varepsilon_P)$, was determined by the fracture point of the tensile test curve. As $\varepsilon_P = max(\varepsilon_P)$, fracture occurs.