Study on the mechanical properties of single lap joints of carbon fiber/hot stamped high strength steel plates

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Automotive parts for lightweight requirements continue to rise, modern body lightweight materials are moving toward the trend of multiple materials composite use. Carbon fiber/hot stamped metal composite panels with lightweight and high strength, excellent corrosion resistance, fatigue resistance and other advantages have attracted wide attention. Gluing technology is an important joining technology, but the mechanical properties of carbon fiber/hot stamped metal sheet with glued single lap structure are still lack of effective research. Therefore, this study focuses on the effects of acrylate adhesive and polyurethane adhesive on the joints of dissimilar materials in terms of mechanical characteristics. Carbon fiber (CFRP) and hot stamped boron steel (22MnB5) are selected as the base material, and acrylate adhesive and polyurethane adhesive are used as the bonding agent to analyze the load displacement curves of the glued joints through shear experiments, and analyze the different mechanical performance of the glued joints by the three dimensions of shear strength, energy absorption, and stiffness of joints; observe the damage surface and the damage surface of the glued single lap joints. The mechanical properties were analyzed by three dimensions: shear strength, energy absorption and joint stiffness. The micro-morphology of the damaged surface was observed to analyze the effect of the two different adhesives on the joint structure. The results show that: the damage of acrylate adhesive in carbon fiber/hot stamped steel single-lap adhesive joint is CFRP interlayer damage; polyurethane adhesive in carbon fiber/hot stamped steel single-lap adhesive joint has cohesion damage and adhesive/steel interface damage; acrylate adhesive has a more positive effect on the improvement of the mechanical properties of carbon fiber/hot stamped steel single-lap adhesive joints.

Keywords: High-strength steel; Composites; Adhesive-lap joints; Mechanical property testing; Lightweighting.

1. Introduction

In today's automobile manufacturing industry, there is a growing demand for lightweighting technology, which not only helps to improve fuel efficiency but also reduces environmental pollution. In this context, carbon fiber and hot stamped high strength steel (e.g., 22MnB5) have attracted much attention due to their lightweight and high strength properties. Carbon fiber not only provides excellent strength and stiffness, but also good fatigue resistance and corrosion resistance, while hot stamped high-strength steel is widely used in critical parts of car bodies due to its excellent mechanical properties and cost-effectiveness. In this study, these two materials are fabricated into a single lap joint structure with the aim of investigating their relevant mechanical properties.

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The commonly used joining techniques in current research include mechanical riveting and welding, which often fail to achieve the desired joining strength without compromising the original properties of the materials. Therefore, this study chooses to apply the joining process of glued joints with the aim of investigating the mechanical properties of glued single lap structures.

Zhou et al [1] investigated the mechanical properties of carbon fiber single lap joint structure by using epoxy resin as a binder, and the ultimate failure load of the specimen with a lap length of 20 mm reached up to 4.97 KN.In contrast, Liu et al [2] utilized graphene oxide (GO) for the modification, and under the same experimental conditions, due to the chemical connection between the epoxy resin/carbon fiber structure and graphene oxide, the graphene oxide The interlaminar shear strength of GO-CF/EP composites with a content of 0.05% was increased from 59.7 MPa for CF/EP composites to 70.2 MPa. Therefore, it can be seen that the chemical structure of the adhesive itself has a certain influence on the mechanical properties of the glued structures. There are many researches on the process parameters of adhesive bonding, and in this study, two common adhesives, polyurethane (PU for short) and acrylic ester (acrylic ester for short), were selected for comparative analysis, aiming at exploring the different action mechanisms of the two for the overlap structure, and illustrating that the different structures of adhesives have different action mechanisms for adhesive bonding and different studies on its mechanical properties. The research of the adhesive structure is different.

In this study, acrylate and polyurethane were used as the adhesive between carbon fiber and hot stamped high-strength steel to make CFRP/AE/steel and CFRP/PU/steel single-lap joint structures. The mechanical properties were investigated through shear experiments, aiming to deeply analyze the performance of this lap joint structure under the action of different adhesives, as well as the influence mechanism of different adhesives on the overall mechanical properties of the joint.

Table 1 Parameters of polyurethane and acrylate

Type No.	Ingredients	Mixing ratio (main agent: curing agent)	Strength (24°C)
DP6310NS	Semi-rigid polyurethane (PE)	1:1	25MPa
MA805	Acrylic ester (AE)	10:1	18.6~20.7MPa

2. CFRP/AE/steel and CFRP/PU/steel prototyping process

In this study, carbon fiber reinforced polymer (CFRP) and hot stamped boron steel (22MnB5) were used as the base materials, and acrylate and polyurethane were used as the adhesives to make single lap joint samples. The sample making process is as follows: in the first step, carbon fiber plates and steel plates were cut with reference to the standard GBT33334-2016; in the second step, single lap joint specimens were made. After bonding, all samples were placed at room temperature for 24 hours to fully cure the structural adhesive. During the curing process, the samples were placed under pressure, and long-tailed clamps were selected to pressurize the samples according to the standard gluing area to ensure that there were no air bubbles and other potential defects between the contact surfaces. The molded specimens are shown in Figures 1-3. After curing was completed, the samples were inspected for size and appearance, and some samples with obvious defects were discarded to ensure that all samples met the experimental requirements.

Table 2 List of material specifications and related parameters

Material type	Sizes （mm）	Treatment	Lap length （mm）	Thickness of adhesive layer （mm）
Hot stamped boron steel（22MnB5）	100 x 25 x 1.5	Sanding and cleaning	12.5	0.2
Carbon fiber board （CFRP）	100 x 25 x 1.5	Sanding and cleaning	12.5	0.2
Acrylate adhesive (AE)	-	Evenly spread on contact surface	-	0.2
polyurethane glue （PU）	-	Evenly spread on contact surface	-	0.2

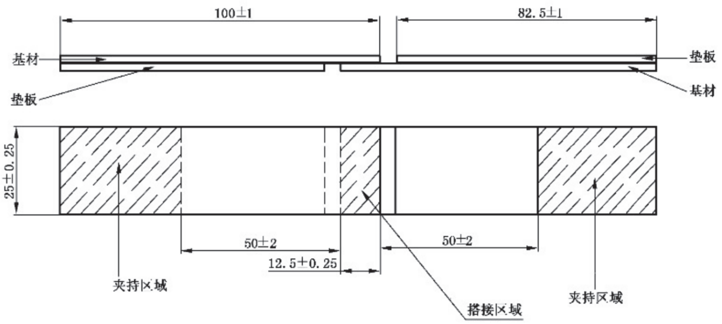


Fig. 1 Schematic diagram of specimen dimensions

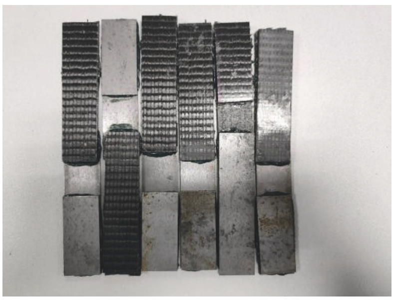


Fig. 2 CFRP/AE/steel specimen

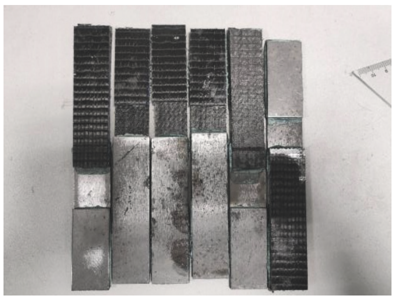


Fig. 3 CFRP/PU/steel specimen

3. Shear test program

As in Fig. 4, the prepared joint samples were fixed in the fixture of the testing machine, ensuring that the lap part of the samples was facing the shear direction of the fixture. The shear load was gradually increased at a constant rate (1 mm/min) through the control system of the AG-IC 100kN Material High Temperature Persistence Tester. Load and displacement data were continuously recorded throughout the shearing process. When the joint sample shows obvious failure (such as adhesive layer peeling or material fracture), stop the experiment and record the maximum load and corresponding displacement values at this time.

Fig. 4 Shear test loading device

4. Results and Analysis

4.1. *Shear strength (τ)*

Calculation formula: $\tau = P_{max}/A$

where P_{max} is the maximum load when the joint fails, A is the lap area.

The shear experiments tested the displacement and load of the carbon fiber/hot pressed steel sheet single lap joints glued using two adhesives, acrylate and polyurethane, are shown in Figs. 4 and 5, and their ultimate load data are shown in Table 3.The ultimate load data show that the CFRP/AE/steel has an ultimate load of 6.46 KN, and according to the formula for shear strength calculation, its shear strength is obtained as 15.73 MPa; the CFRP/PU /steel has an ultimate load of 5.88 KN and a shear strength of 13.27 MPa. AE performs better in the CFRP/steel lap structure, compared to PU, in terms of ultimate load, it improves by nearly 10% and shear strength by 18.5%.

Table 3 Shear strength related data

Type of glued structure	Specimen number	Pmax (KN)	$A(mm^2)$	τ(MPa)
CFRP/AE/Steel	1-1	6.33	399.58	15.84
	1-2	6.02	426.98	14.09
	1-3	7.03	406.85	17.27
	average value	6.46	411.14	15.73
CFRP/PU/Steel	2-1	6.08	429.50	14.15
	2-2	5.96	491.50	12.13
	2-3	5.61	414.00	13.54
	average value	5.88	445.00	13.27

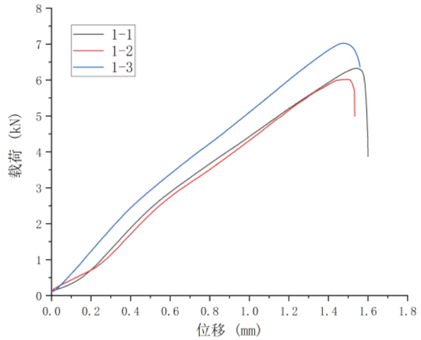


Fig. 5 CFRP/AE/steel load-displacement curve

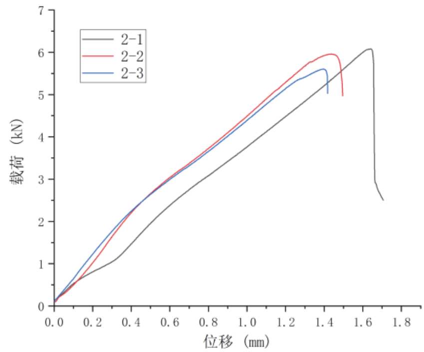


Fig. 6 CFRP/PU/steel load-displacement curve

4.2. *Energy absorption (U) and joint stiffness (K)*

Energy absorption (U) is calculated as the area under the entire load-displacement curve:

$$U = \int_0^{d_{fail}} Pd$$

where is the displacement of the joint at failure and P is the corresponding load.

Joint stiffness (K), calculated as the slope during the elastic phase: K=ΔP/Δd

where ΔP and Δd are increments of load and displacement, respectively, limited to the linear elastic range.

The data related to energy absorption and stiffness were obtained from Fig. 4 and Fig. 5 and are shown in Table 4.

Table 4 Data related to energy absorption and joint stiffness

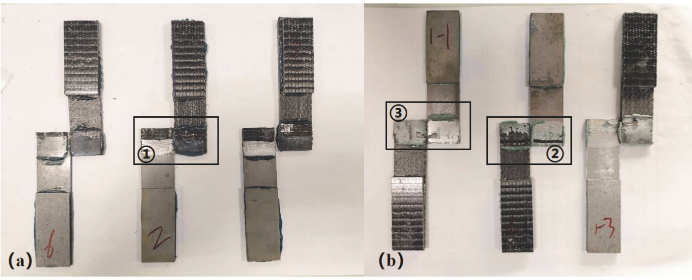
Type of glued structure	Specimen number	P_{fail}(KN)	d_{fail}(mm)	U(J)	K(N/m)
CFRP/AE/Steel	1-1	6.33	1.54	5.20	3.80
	1-2	6.02	1.50	4.84	4.04
	1-3	7.03	1.47	5.84	4.36
	average value	6.46	1.50	5.29	4.07
CFRP/PU/Steel	2-1	6.08	1.63	5.12	3.67
	2-2	5.96	1.44	4.78	3.92
	2-3	5.61	1.40	4.51	3.60
	average value	5.88	1.49	4.80	3.73

The energy absorption of CFRP/AE/steel and CFRP/PU/steel was 5.29 J and 4.80 J respectively, with the former showing an increase of 10.2% compared to the latter. The energy absorption of a material is the amount of energy it can absorb when it is subjected to an external force or energy impact's/AE/steel has a higher energy absorption index, which indicates its superior strength and durability. The stiffness of CFRP/AE/steel and CFPA/PU/steel is 4.07N/m and 3.73N/m, respectively. Stiffness is the ability of a material or structure to resist elastic deformation when subjected to a force, and it is the ability of a material or structure to resist elastic deformation when subjected to a force, and it is the ability of a material or structure to resist elastic deformation when subjected to a force. Stiffness refers to the ability of a material or structure to resist elastic deformation when subjected to a force, and is a characterization of the degree of difficulty of elastic deformation of a material or structure. The single-lap structure with AE as the adhesive shows better resistance to elastic deformation, with an increase of 9.1% compared with PU.

4.3. *Failure analysis*

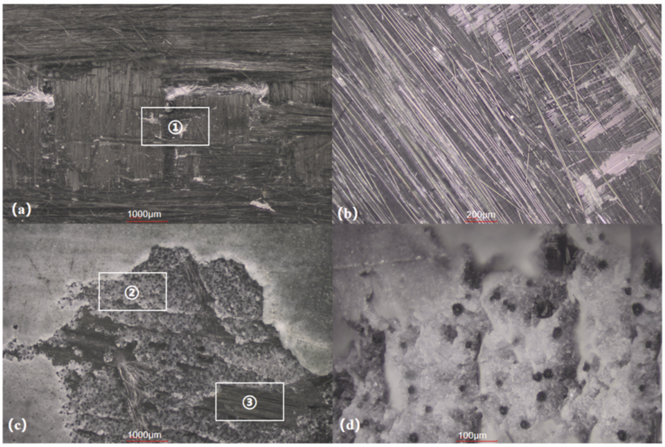
In this study, the damage interface morphology was characterized using an ultra-depth-of-field microscope. As shown in Fig. 6 Fig. 7, some carbon fibers of CFRP/AE/steel were torn in the glued joint region, and the damage of the adherend (CFRP) occurred, i.e., CERP interlayer damage. When the damage mode is CFRP interlaminar damage, the joint has strong shear strength; CFRP/PU/steel in the glued joint region presents a mixed damage of PU/steel interface damage and adhesive cohesion damage. When the mixed damage of cohesive interface appears, it indicates that the strength of the bond is comparable to the cohesive strength of the adhesive itself. The comparison of the two forms of damage shows that the bonding effect of AE is better.

Since the chemical structure of acrylate is CH2=CH-COOR, and the chemical structure of polyurethane is NH- (CH2)6-NH-CO-O- (CH2)4-O-CO-NH- (CH2)6-NH2, the two structures are different, and therefore, in terms of chemistry, the mechanism of action of acrylate and polyurethane is not the same. Under the action of the initiator, the double bond of acrylate will undergo a ring-opening reaction to form free radicals, which in turn triggers a polymerization reaction between the monomers. The polymerization reaction makes the adhesive molecules form a cross-linked structure, thus enhancing the mechanical properties and durability of the adhesive. Polyurethane is a polymer compound containing isocyano (-NCO) and carbamate (-NH-COO-), so polyurethane adhesives show a high degree of activity and polarity. Therefore, the bonding properties of both binders are excellent. However, polyurethane produces a cross-linking structure by reaction during the curing process, resulting in a tight intermolecular arrangement, and therefore volume shrinkage occurs, leading to poor bond strength. The volume contraction will lead to easy to produce internal stress in the adhesive layer, resulting in stress concentration, so as to cause cracking of the adhesive layer or joint damage, directly affecting the service life of the glued joint. In contrast, acrylate has a higher bond strength and shows better operational performance, the requirements for the bonding interface and the group ratio are not strict, and even can be glued on the oil surface, so it shows a certain advantage in CFRP/steel glued joint structure.



PS:
①CFRP is destroyed and remains on the steel surface
②PU adhesive breaks irregularly and CFRP surface are damaged
③Steel/Glue interface is damaged

Fig. 7 Specimen damage forms (a) CFRP/AE/steel CFRP interlayer damage (b) CFRP/PU/steel cohesive interface mixed damage.



PS:
①CFRP interface failure②PU glue cohesion destruction
③Continuous undemaged layers of carbon fiber

Fig. 8 Observation of damage forms under super depth-of-field microscope (a) CFRP/AE/steel damage form magnified 50 times (b) CFRP/AE/steel damage form magnified 500 times (c) CFRP/PU/steel damage form magnified 50 times (d) CFRP/PU/steel damage form magnified 500 times.

5. Conclusion

In this study, the mechanical properties of CFRP/steel single lap joints were obtained by shear test after being glued with different adhesives, and the different mechanical properties were analyzed in three dimensions: shear strength, energy absorption and joint stiffness, and the effects of different mechanisms of acrylate and polyurethane on the mechanical properties of the lap joints were investigated in conjunction with the analysis of the failures and mechanisms. The following conclusions were obtained in this study:

(1) In this study, CFRP/AE/steel and CFRP/PU/steel single lap joint specimens were designed to compare and analyze the joint properties of acrylate adhesive and polyurethane adhesive, and the shear strengths of the CFRP/AE/steel and CFRP/PU/steel single lap joint specimens were 6.46 KN and 5.88 KN, respectively; the energy absorptions were 5.29 J and 4.80 J; and the stiffness was 4.07 N/m and 3.0 N/m respectively. 4.07N/m and 3.73N/m, respectively.

(2) In this study, microscopic observation of CFRP/AE/steel and CFRP/PU/steel single-lap glued joints was carried out, and it was found that in CFRP/AE/steel structure, the CFRP interlayer damage form was presented, and in CFRP/PU/steel structure, the PU cohesive damage and PU/steel interfacial damage form were presented.

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