Research on high temperature friction performance of carbon fiber composite materials

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Carbon fiber composites have a wide range of applications in body lightweighting due to their light weight, large friction coefficient and excellent mechanical properties. In the forming of body parts and subsequent operation, the composites have high requirements of available high temperature lubrication and wear resistance, therefore, this paper investigates the friction behavior of carbon fiber composites in different laying directions and temperatures, and studies the high temperature friction and wear mechanism through the friction coefficients obtained and the observation of friction morphology under the microscope. The results show that the friction coefficient of carbon fiber composites increases from 0.53 to 0.83 and 1.15 when the laying direction of carbon fiber composites is changed from 0º to 45º and 90º, respectively, during friction at room temperature. the confinement effect formed by the interconnection of resin and fibers at room temperature makes the fibers fracture transversally during the friction process and the fracture is disordered, which results in a large friction coefficient during sliding friction in the perpendicular direction of the fibers, and the friction coefficient of the carbon fiber composites is larger during sliding friction in the vertical fiber direction at 160ºC. The coefficient of friction of carbon fiber composites decreases with the increase of laying angle from 0º to 45º and 90º, i.e., from 0.54 to 0.25 and 0.22, respectively. The resin is easy to detach from the fibers due to the good softening and fluidity at high temperatures, the flow of resin plays a lubricating role in the friction interface, which reduces the coefficient of friction and the detachment of the fibers from the resin leads to easy fiber fracture, and the radial fracture of the fibers supports the friction head. The fiber plays a supporting role for the friction head, increasing the coefficient of friction when sliding friction in parallel fiber direction.

Keywords: Car body lightweight; Carbon fiber composites; High temperature friction; Friction coefficient; Wear mechanism.

1. Introduction

Vehicle body lightweighting refers to reducing the weight of the vehicle body in the process of automobile design and manufacturing by adopting lightweight materials, innovative design methods and advanced manufacturing technologies, so as to improve fuel economy, reduce carbon emissions, and enhance vehicle performance and safety. Composite materials have a wide range of application prospects in the field of body lightweight, mainly due to the fact that composite materials have lightweight, high strength, high stiffness, corrosion resistance and other characteristics, which can effectively meet the needs of automotive lightweight [1]. The wide application of high-strength steel hot

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stamping materials and processes has promoted the exploration of new materials for bodywork research and application [2]. Carbon Fiber Reinforced Plastics (CFRP) consists of carbon fibers and resin matrix, which has excellent properties such as light weight, high strength, high thermal conductivity, low thermal expansion and chemical radiation resistance. In the automotive field, carbon fiber composites can be used to make body parts, driveline components, interior trim, etc. to reduce the weight of the body. Therefore, it is very meaningful to study the friction of CFRP during the molding process. The coefficient of friction reflects the friction behavior between the contacting pairs to a certain extent, and an accurate coefficient of friction (COF) can provide more accurate results for numerical simulation and guidance for industrial production.

At different temperatures, the resin fluidity and viscosity in the composites change, and the wear mechanism also changes. Yu et al [3] investigated the high-temperature friction properties of pyrolytic carbon modified carbon fiber mat reinforced polyimide composites (PI-C/CF), and found that the wear mechanisms were interlocking mechanism, adhesive and abrasive wear at room temperature, while they changed to adhesive wear, abrasive wear and oxidative wear at high temperatures. In addition, factors such as sliding speed [4,5] and load [6] also affect the tribological properties of friction materials.

Therefore, in this paper, the friction behavior of the friction vice composed of CFRP prepreg and steel was investigated by using standard high temperature friction tester UMT-Tribolab at different laying directions and temperatures, the friction coefficients were measured, and the wear micromorphology of CFRP was observed under different conditions to analyze and study the friction wear mechanism.

2. Friction experiment

The CFRP prepreg used in the experiment is a unidirectional epoxy resin-based carbon fiber prepreg produced by a composite material company in China, which is used to prepare the lower friction pair in the friction experiment. Three layers of CFRP at 0º, 45º and 90º (0º direction is defined as the friction direction, i.e., the length direction of the aluminum alloy block) were laid on the 6061 aluminum alloy block. The three prepared friction sub-systems are shown in Fig. 1, which shows the specimens with 0º, 45º and 90º layers of CFRP, in that order.

The high-temperature friction tester used was the UMT-Tribolab from Bruker, whose measurement principle is shown in Figure 2. Instead of the molds, the upper friction pair was made of pins made of H13 steel with the dimensions shown in Fig. 3a. In the experiment, the lower friction pair needs to be supported by a certain thickness, so the method of laying CFRP on 6061 aluminum alloy on a certain thickness is used to fabricate the lower friction pair, the dimensions of which are shown in Fig. 3b (thickness of 9 mm). The above dimensions are the standard and recommended configuration for this friction tester. The normal loading force range of this equipment is 1 mN-2000 N. The model for this friction experiment is Pin on plate.

A reciprocating motion mode was selected with a speed of 0.5 HZ, i.e., 10 mm/s, and a single stroke of 10 mm. 1 N was used as the loading force, and the temperatures of the experiments were room temperature (about 20º C) and 160 ºC. For the high-temperature experiments, the specimen and the friction head were placed in a small heated oven. The specimens were placed on a specimen stage and their positions were fixed by two pins. For the high-temperature test, the specimens were heated directly to the test temperature and held for 5 min before the friction test was performed. Half of the final loading force was applied for 10 s, and then the full loading force was applied for 600 s. The morphology of the friction surfaces was observed using an environmental scanning electron microscope (ESEM, FEI/QUANTA 200) after the friction experiments were completed for all specimens.

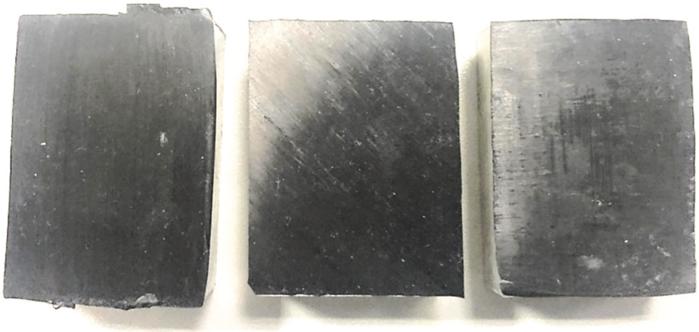

Fig. 1 Friction sub under CFRP for friction experiments (surface is CFRP material)

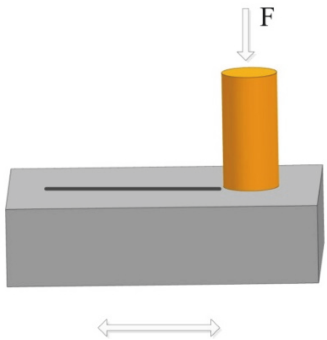

Fig. 2 Measurement principle of UMT-Tribolab high temperature friction tester

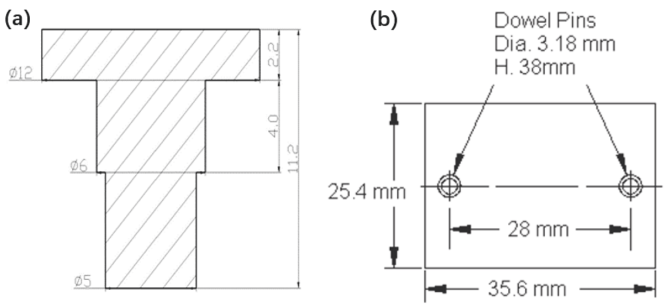

Fig. 3 Dimensions of the friction pair: (a) upper friction pair dimensions; (b) lower friction pair dimensions

3. Test results and discussion

3.1. *Friction at room temperature*

Figure 4a illustrates the coefficients of friction at ambient temperature for various stacking orientations and applied loads, whereas Figure 4b presents the mean friction coefficients corresponding to the respective scenarios. The findings indicate a gradual increase in the friction coefficient as the stacking orientation of CFRP transitions from 0º to 45º and 90º, and a concurrent rise in the friction coefficient with an escalation in the normal load from 1N to 5N. The overall frictional process can be segmented into two phases: the initiation phase and the phase of relative stabilization.

When subjected to an identical load, the fibers in the CFRP aligned in the 0º direction run parallel to the direction of friction, resulting in minimal resistance to surpassing static friction for motion initiation. Consequently, the fluctuation in the friction coefficient during the onset phase is minimal, ranging from approximately 0.7 to 0.5.

Conversely, the variation in the initial segment of the friction coefficient for the CFRP sample aligned in the 45º direction is more pronounced, fluctuating from around 2.5 to approximately 0.7. This is primarily attributed to the oblique orientation of the fibers, which heightens the impediment to motion. The twisted and fractured nature of the inclined fibers at the friction point, as depicted in Figures 5b and 5e, is the primary factor contributing to the increased friction.

In the case of CFRP laid in the 90º direction, the fibers perpendicular to the motion direction experience breakage, subsequent accumulation, and eventual delamination and flattening, as illustrated in Figure 5c (Figure 5f). Consequently, there is a sharp rise in frictional resistance prior to the breakage and accumulation of fibers, followed by a rapid decline post this phase.

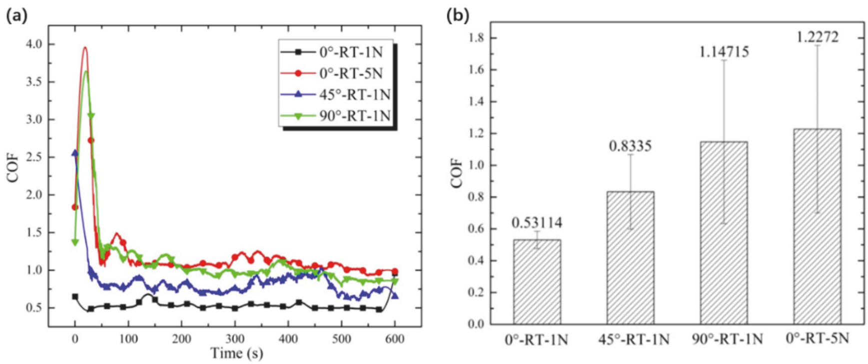

Fig. 4 (a) Friction coefficients at room temperature for different lay-up directions and loading loads; (b) Average friction coefficient statistics at room temperature

Throughout the phase of frictional stabilization, the friction coefficient escalates from 0.53 to 0.83 and 1.15 as the stacking orientation of CFRP transitions from 0º to 45º and 90º, respectively. Notably, the load was only increased for CFRP aligned at 0º, as the fibers in the CFRP laid at 90º fractured and accumulated at a 1N load, leading to a higher friction coefficient.

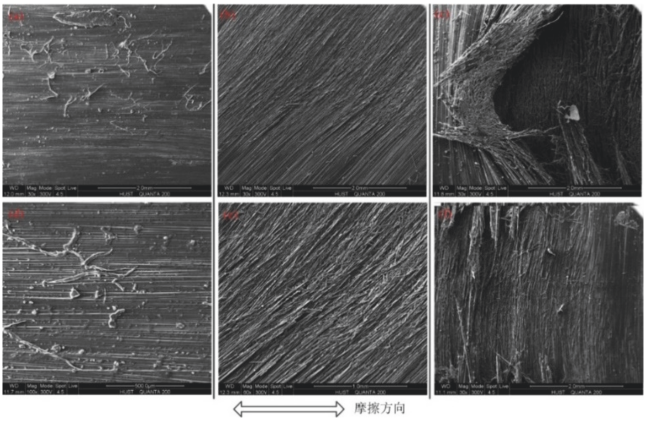

Fig. 5 Friction surface topography at room temperature (loading force 1N): (a) (d) 0º; (b) (e) 45º; (c) (f) 90º

3.2. *Friction test in high temperature environment*

Figure 6a illustrates the coefficients of friction for various layup orientations at a temperature of 160ºC. The friction coefficient of Carbon Fiber Reinforced Polymer (CFRP) aligned in the 0º orientation is relatively higher, prompting a replicated experiment as shown in Fig. 6b. The results demonstrate similarity, with a slight variance in the average friction coefficients of merely 3.3%, confirming the reliability of the experimental results.

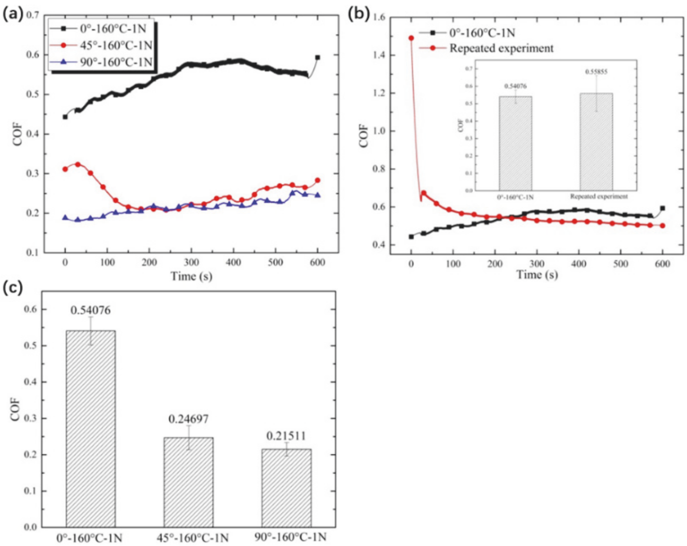

Fig. 6 (a) Friction coefficient under different layup directions at 160ºC; (b) Repeated experiment of friction coefficient for 0º layup; (c) Average friction coefficient under different layup directions after 160ºC friction

When the resin is exposed to a brief period of 160ºC, its fluidity surpasses that at room temperature, leading to a lubricating effect that decreases the coefficient of friction. This results in relatively similar outcomes for CFRP aligned in the 45º and 90º orientations, although a slightly lower friction coefficient is observed for the 90º orientation. Thus, the friction coefficient of CFRP at 160ºC decreases as the laying angle increases from 0º to 45º and 90º (Fig. 6c), i.e., from 0.54 to 0.25 and 0.22, respectively.

Upon observing Figure 7d, it becomes evident that the fibers are displaced by the friction head due to irregularities in the fibers when CFRP is aligned at 0º, even though they are parallel to the sliding direction and benefit from resin lubrication. This displacement primarily leads to localized fiber breakage, with the friction head being supported by the fiber length direction, resulting in an increase in the friction force. In the case of CFRP aligned at 45º, small fiber sections are pushed towards the boundary, causing localized fiber breakage at an angle to the sliding direction (highlighted by the red circle in Fig. 7e). This limited support to the friction head leads to a reduction in the friction force and coefficient of friction.

In the case of CFRP aligned at 90º, the isolating and lubricating properties provided by the resin contribute to a decrease in the friction force and coefficient of friction. The resin's isolating and lubricating characteristics at a 90º CFRP orientation lead to minimal friction marks (indicated by red circles in Fig. 7c and Fig. 7f), with fibers experiencing minimal breakage and only sustaining damage. Consequently, the friction force and coefficient of friction decrease significantly compared to alignment at 0º and only slightly decrease compared to the 45º orientation.

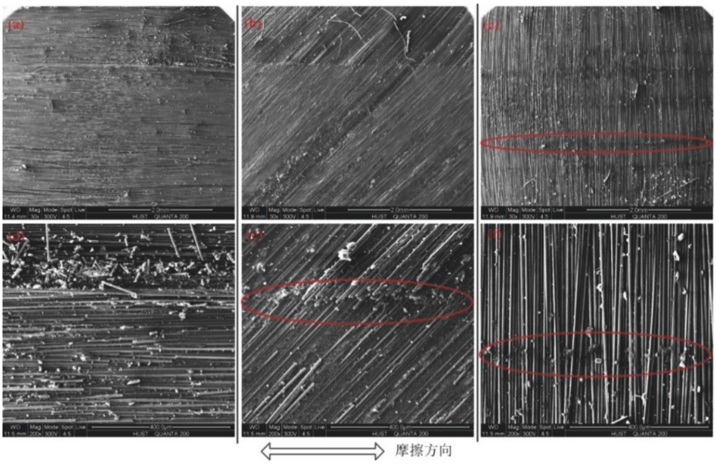

Fig. 7 CFRP surface topography after 160ºC friction: (a) (d) 0º; (b) (e) 45º; (c) (f) 90º

3.3. *Analysis of test results*

At low temperatures, the confinement effect formed by the interaction connection between the resin and the fibers causes the fibers to fracture mainly in the transverse direction during the friction process, and the fracture is messy, resulting in a large coefficient of friction in the sliding friction in the perpendicular direction of the fibers. At high temperatures, the resin due to softening, good mobility, easy to detach from the fiber, on the one hand, the flow of resin to the friction interface to bring lubrication, reduce the coefficient of friction; on the other hand, due to the detachment of the fiber and resin lead to the fiber is easy to be pushed off, the formation of radial fracture of the fiber on the friction head of the support role, increase the coefficient of friction of the parallel fiber direction of friction when sliding friction. On the other hand, 45° laid CFRP can obtain moderate friction coefficient both in high and low temperature condition. Therefore, in terms of overall reduction of coefficient of friction, CFRP should be laid at 45°, which also has a better effect on load bearing. Overall, the coefficient of friction between CFRP and steel is still high, so some protection or lubrication is needed when forming.

4. Summary

The friction behavior of CFRP prepregs in different laying directions and temperatures was investigated using a high temperature friction tester, the friction coefficients were measured, and the friction morphology under microscopic conditions was observed, and an analysis of the test results was given. The specific conclusions are as follows:

At room temperature friction, the coefficient of friction increased from 0.53 to 0.83 and 1.15, respectively, as the laying direction of CFRP was changed from 0° to 45° and 90°; the coefficient of friction increased when the load was increased. The lower temperature at room temperature and the confinement formed by the interactive connection of resin and fiber make the fiber mainly transverse fracture during friction, and the fracture is messy, which leads to a larger friction coefficient during sliding friction in the perpendicular fiber direction.

The coefficient of friction of CFRP at 160°C decreases as the laying angle increases from 0° to 45° and 90°, i.e., from 0.54 to 0.25 and 0.22, respectively, which is the exact opposite of the results of the tests at room temperature. At high temperature, the resin is easy to detach from the fiber due to its softening and good fluidity. On the one hand, the flow of resin brings lubrication to the friction interface and reduces the coefficient of friction; on the other hand, the detachment of the fiber and the resin leads to the fiber being easily "pushed off", which forms a radial fracture of the fiber to the friction head and increases the coefficient of friction when sliding friction is applied in the direction of the parallel fibers. Sliding friction coefficient.

CFRP laid at 45° has a moderate coefficient of friction at both high and low temperatures. Therefore, in terms of the overall reduction of the coefficient of friction, CFRP should be laid at 45°, which also has a better effect on load bearing.

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