Study on the Friction and Wear Performance of Lightly Loaded Reciprocating Carbon/Aramid-Based Composites

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The preparation methods of T300 carbon cloth- and aramid cloth-reinforced epoxy resin and cyanate ester were proposed, and four kinds of composite samples were obtained. The friction coefficient and wear rate under different test times and loads were obtained using a reciprocating pin-disk tribology tester. The tribology pairs included pins or sliding blocks made from different metals (45 steel and brass) and the disk samples of the composites. The test results showed that the friction coefficients of the T300 carbon cloth- (T300/4211 and T300/BS-4) and aramid cloth- (aramid/4211 and aramid/BS-4) reinforced epoxy resin or cyanate ester changed from 0.09 to 0.3 and were low under dry friction conditions. Under 75N, aramid/BS-4 coupled with 45 steel pins was the lowest friction coefficient, which was 0.09. In particular, the friction coefficient and wear rate of the composite-reinforced cyanate ester were the lowest, which meant that this composite may be more suitable for use under lightly loaded and reciprocating running conditions in space engineering. By comparing the surface morphologies of composites before and after the test, the wear mechanism of the composites was discussed and the lower friction coefficient and wear rate may originate from the abrasive wear effects occurring between the tribology pairs. The research results have important engineering significance for guiding the use of composites in the deployable mechanisms used in space engineering.

1. Introduction

To improve the effective bearing capacity and reduce the occupied space in the spacecraft, the oncoming large-diameter deployment mechanism needs to be folded into a closed state and then expands when it works in space. Figure 1 shows the motion diagram of the space deployment mechanisms.

Because of the mechanism’s weight, the base is generally made of high-performance metal, which is considered due to the self-lubricating property of copper and the high strength property of steel, and the unfolded parts can be replaced by nonmetal to reduce the weight of the mechanism. Hence, in practical space engineering, to simultaneously meet large volume, lightweight, and high flexibility deployment mechanism requirements, advanced materials have been studied, different composites have been introduced [1], and increasing numbers of composites have been gradually adopted [2, 3]. Due to their advantages of lightweight, high specific strength, high specific modulus, better design, and resistance, carbon/aramid-based composites have been developed and applied to space engineering [4].

Many researchers have carried out related research on carbon/aramid-based composites. For example, Cai et al. [5] studied the effect of the aspect ratios of aramid fibers on the mechanical and tribological behaviors of friction materials and found that the 10 vol% aramid pulp in composites was an optimum volume fraction for improving the friction and wear behaviors. Ahmadijokani et al. [6] studied the tribological properties of four different volume contents of carbon fiber-reinforced phenolic resin. Yin et al. [7] found that different carbon fiber reinforcements had an effect on the friction and wear properties of resin-based friction materials and that the resin-based friction material...
reinforced with 4 wt% carbon fiber had the best friction and wear performance. The above research results indicate that different composite preparation methods or compositions result in large differences in the friction, wear, and mechanical properties of materials.

Researchers have paid increasing attention to the application adaptability of different materials for space engineering, and in particular, it is also very important to study friction and wear performances [8–10]. To make the material better match the application conditions, the friction and wear test of the material under the specific working conditions has become a basic step in relevant research. To determine the friction and wear performance of materials used for space components, Zhang et al. [8, 9] used a ball-on-disk testing machine to analyze the tribological properties of coatings, which improved the characteristics of the metal, Jia et al. [10] studied the dry friction and wear characteristics of impregnated graphite in a corrosive environment. These research methods provide an important experimental basis for the acquisition of the friction and wear properties of composites and will guide the experimental design in this paper.

Thus, in this paper, to apply the new carbon/aramid-based composites to space deployment mechanisms, the methods used to prepare composites tested are proposed, and the friction and wear performance of the different composites and metal pairs under different reciprocating conditions are studied. The friction coefficient and wear rate of four composites (T300/4211, T300/BS-4, aramid/4211, and aramid/BS-4) coupled with two metals (steel and brass) at room temperature will be obtained. The wear mechanism of the tribology pairs is discussed by comparing the morphology of the composites before and after the test. The results will provide an important reference for the preparation and testing of carbon/aramid-based composites for space deployment mechanisms.

2. Preparation of Carbon/Aramid-Based Composites

2.1. Preparation of T300/4211 and Aramid/4211 Composites. The steps used to prepare the T300/4211 and aramid/4211 composites are shown as follows:

(1) Configuration of 4211 resin: stir 648 phenolic epoxy resin and boron trifluoride-ethylamine complex in a ratio of 100:3, and then, place them in a vacuum drying oven at 80°C for vacuum degassing.

(2) Preparation of prepreg: put the treated carbon cloth or aramid cloth into the prepared resin, and then continuously extrude on an 80°C rubber mixer roll to remove the internal bubbles in the cloth and fully immerse the cloth in the resin. Finally, freeze the prepared prepreg to avoid curing.

(3) Moulding of the composite: clean the mould and apply the release agent. Preheat it in the tablet press. Cut the prepreg to the appropriate size in the mould, and edit the control program. Moulding conditions: first, heat the tablet press to 145°C for 1 hour under no pressure to fully gel the resin, and then, raise the pressure to 10 MPa and keep it at that pressure. Then, raise the temperature to 170°C for 2 hours. Finally, cool to room temperature and remove the prepreg.

2.2. Preparation of T300/BS-4 and Aramid/BS-4 Composites. The steps used to prepare the T300/BS-4 and aramid/BS-4 composites are shown as follows:

(1) Configuration of BS-4 resin: BS-4 cyanate ester is prepared with a certain ratio of cyanate resin and epoxy resin.

(2) Preparation of prepreg: put the treated carbon cloth or aramid cloth into the prepared resin, and then continuously extrude on an 80°C rubber mixer roll to remove the internal bubbles in the cloth and fully immerse the cloth in the resin. Finally, freeze the prepared prepreg to avoid curing.

(3) Moulding of the composite: clean the mould, and apply the release agent. Preheat it in the tablet press. Cut the prepreg to the appropriate size in the mould, and edit the control program. Moulding conditions: first, heat the tablet press to 130°C for 1 hour under no pressure to fully gel the resin, and then raise the temperature to 170°C; the pressure increases with increasing temperature. Keep it at 170°C for 2 hours; the total pressure is 10 MPa. Then, raise the temperature to 180°C for 2 hours to ensure the complete curing of the prepreg. Finally, cool to room temperature, and remove the prepreg.

2.3. Analysis of the Initial Morphologies of Composites Tested. The surfaces of the composites after preparation were investigated with scanning electron microscopy (SEM, TM4000PLUS) operated at 2000× magnification and an applied voltage of 5 kV. The pictures of specimens are shown in Figure 2. The morphologies of composites tested are shown in Figure 3. Surface defects are formed in the composites. As shown in Figures 3(a) and 3(b), it can be clearly seen that composite T300/4211 contains the most defects, and composite aramid/4211 contains fewer defects than composite T300/4211. The adhesive force might be weaker between the carbon fibers and 4211 resin due to the adhesive force of the reinforced BS-4 resin composites is in the following ascending order: T300/BS-4 < aramid/4211 < T300/BS-4 < aramid/BS-4.
2.4. Physical and Mechanical Properties of Composites Tested. The density and hardness of the composite materials were measured. Flexural and compressive strengths were evaluated according to Chinese standards GB/T1449-2005 and GB/T1448-2005, respectively. All the mechanical tests were performed at room temperature.

Table 1 summarizes the density, flexural strength, compressive strength, and hardness of the composites. The hardness of the composites does not vary substantially for each composite. For the same material, the flexural strength is higher than the compressive strength. Because of the addition of fibers, the flexural strength of composites increases. Thus, the compressive strength is usually lower than flexural strength. With reinforcing the same resin, the flexural strength of aramid fiber-reinforced BS-4 is approximately 15% higher than that of carbon fiber-reinforced BS-4 resin. For the same fiber, the flexural strength of aramid fiber-reinforced BS-4 resin is 24% higher than that of fiber-reinforced 4211 resin. This is due to the interfacial adhesion between the fibers and the resin [11]. The compressive strength of the fiber composites is mostly determined by the interfacial adhesion between the fibers and the resin. The functional material surface performance tester, and testing the friction and wear properties will change abruptly [14]. The relative motion of the deployment mechanism is reciprocating. According to several investigations, the reciprocating parameters of the expandable mechanism and the range of test parameters are obtained. The expandable velocity $V$ of a space expandable mechanism is from 0.01 to 0.06 m·s$^{-1}$, and the pressure $P$ range of reciprocating contact between the joints during expansion is from 4 to 9 MPa; thus, the range of the PV value used for the friction and wear tests is from 0.04 to 0.54 MPa·m·s$^{-1}$. In order to study the tribological properties of composite materials, the PV values of the tests should be within the range of the PV values of the actual working conditions. The friction and wear tests conditions are designed in this paper; the range of the applied load is from 50 to 100 N, and the reciprocating velocity is defined as 0.33 m·s$^{-1}$. Meanwhile, the load and reciprocating velocity are constant in each special test process. Hence, in the whole test, the PV value ranges from 0.2 to 0.42 MPa·m·s$^{-1}$. The test is a dry friction test performed at room temperature. Table 2 summarizes the combinations of the different composites and the experimental conditions.

As shown in Tables 2–4, the number of experimental designs described in the paper is 28. Three parallel tests were carried out for each group to minimize the error.

3. Test Equipment and Design

3.1. Test Equipment. The test equipment is a CFT-I multifunctional material surface performance tester, and schematics of the instrument and wear measuring instrument are shown in Figure 4. During the test, reciprocating motion components are selected to simulate the reciprocating motion of the deployment mechanism used in space engineering.

The friction coefficient is obtained directly by the above instrument, and the wear rate $W$ (mm$^3$·N$^{-1}$·m$^{-1}$) is obtained by equation (1). The formula used to calculate the wear rate $W$ (mm$^3$·N$^{-1}$·m$^{-1}$) is as follows:

$$ W = \frac{\Delta V}{F \cdot L}, $$

where $\Delta V$ is the wear volume loss (mm$^3$), $F$ is the load (N), and $L$ is the sliding distance (m), which is the product of time ($s$, which is the time of the friction test run) and reciprocating velocity (m/s, which is the product of the reciprocating length and the reciprocating speed divided by 30000). The reciprocating length and the reciprocating speed are shown in Table 2. The wear volume loss $\Delta V$ is calculated according to the following formula:

$$ \Delta V = D \times B \times H, $$

where $D$ is the wear scar width (mm), $B$ is the wear scar length (mm), and $H$ is the wear scar depth (mm). The width, length, and depth are obtained directly by displacement sensor 17 in Figure 4.

3.2. Design of Experiments. Table 3 summarizes the size and identity of composites tested. The properties and parameters of the three metal materials coupled with composites tested are summarized in Table 4.

For most metal materials participating in matching, as the PV value, which is the product of Pressure and Velocity, increases, the material wear increases, and the friction coefficient decreases. Moreover, as the PV value increases, the friction and wear properties will change abruptly [14]. The relative motion of the deployment mechanism is reciprocating. According to several investigations, the reciprocating parameters of the expandable mechanism and the range of test parameters are obtained. The expandable velocity $V$ of a space expandable mechanism is from 0.01 to 0.06 m·s$^{-1}$, and the pressure $P$ range of reciprocating contact between the joints during expansion is from 4 to 9 MPa; thus, the range of the PV value used for the friction and wear tests is from 0.04 to 0.54 MPa·m·s$^{-1}$. In order to study the tribological properties of composite materials, the PV values of the tests should be within the range of the PV values of the actual working conditions. The friction and wear test conditions are designed in this paper; the range of the applied load is from 50 to 100 N, and the reciprocating velocity is defined as 0.33 m·s$^{-1}$. Meanwhile, the load and reciprocating velocity are constant in each special test process. Hence, in the whole test, the PV value ranges from 0.2 to 0.42 MPa·m·s$^{-1}$. The test is a dry friction test performed at room temperature. Table 2 summarizes the combinations of the different composites and the experimental conditions.

As shown in Tables 2–4, the number of experimental designs described in the paper is 28. Three parallel tests were carried out for each group to minimize the error.

4. Results and Discussion

4.1. Test Results Obtained with 45 Steel Pin. Figure 5 shows the friction coefficients of the four composites coupled with 45 steel pins (B-1) under three kinds of loads and dry friction conditions.

As shown in Figure 5(a), it is apparent that, under the 50 N dry friction condition, the friction coefficient of composite aramid/BS-4 coupled with 45 steel pins is the lowest, and the value is approximately 0.12. The friction coefficient of composite T300/4211 is the highest, followed by that of aramid/4211 and T300/BS-4.

As shown in Figure 5(b), under the 75 N dry friction condition with 45 steel pins, the friction coefficient of composite aramid/BS-4 is lowest, and the value is approximately 0.1. The friction coefficients of composites T300/4211 and aramid/4211 are higher than those of composites T300/BS-4 and aramid/BS-4.
It can be seen from Figure 5(c) that, under the 100 N dry friction condition, the composite with the lowest friction coefficient coupled with 45 steel pins is aramid/BS-4, and its value is 0.11. The friction coefficients of composites T300/4211 and aramid/4211 are higher than those of composites T300/BS-4 and aramid/BS-4.

In conclusion, the friction coefficient of the reinforced BS-4 cyanate ester composites is lower than that of the reinforced 4211 resin composites, and the friction coefficient of aramid fiber-reinforced BS-4 cyanate ester is the lowest. Under a lower load, the time it takes to reach a stable friction coefficient is shorter than the time it takes under a higher load. Meanwhile, the friction coefficient of the composites generally decreases with increasing load. A common explanation is that the friction of polymer composites with respect to load follows equation $\mu = kN^{n-1}$ (where $\mu$ is the friction coefficient, $N$ is the load, and the $k$ and $n$ are constants, with $2/3 < n < 1$, which depends on the strength of the interactions between elastic and plastic deformation) [15].

The wear rate of the composites coupled with 45 steel pins under different loads is shown in Figure 6. From Figure 6, in the stable stage, with the increase in load, the wear rate of composite T300/4211 increases. When the load acting on composites aramid/4211 and T300/BS-4 is 75 N, the wear rate is the lowest. The composite with the lowest wear rate under three kinds of forces is aramid/BS-4. When the load is 50 N or 75 N, the wear rate of aramid/BS-4 in the stable stage is very low (less than $1 \times 10^{-7} \text{mm}^3\text{N}^{-1}\text{m}^{-1}$) and can be ignored. In the same system of resin composites, the wear rate of composites reinforced with aramid fibers is lower than that of composites reinforced with carbon fibers. This may be because aramid fibers have a stronger bond to the resin than carbon fibers [16]. Hence, the wear rate of aramid fiber composites is lower than that of carbon fiber composites. As Wan et al. [17] reported, for the wear rate of the composites, the higher the bond strength is, the lower the wear rate is, and vice versa.

### 4.2. Test Results Obtained with Brass Pins and Sliding Blocks.

Figure 7 displays the friction coefficients of the four composites coupled with the pair of brass pins (B-2) and brass sliding blocks (B-3) under different loads and dry friction conditions.

As shown in Figure 7(a), under the 50 N dry friction condition, the friction coefficient of composite T300/BS-4 coupled with brass pins is lowest, and its value is approximately 0.13. The friction coefficient of the aramid/4211 composite is the highest. The friction coefficient of aramid/BS-4 is slightly higher than that of T300/BS-4, but lower than that of T300/4211 and aramid/4211.
As shown in Figure 7(b), under a load of 75N and dry friction conditions, the friction coefficient of T300/BS-4 is the lowest, and its value is also 0.13. The friction coefficient of aramid/BS-4 is the highest. The friction coefficient of aramid/4211 is slightly higher than that of T300/BS-4, but lower than that of composites T300/4211 and aramid/BS-4.

As shown in Figure 7(c), under a load of 100N and dry friction conditions, the friction coefficient of composite T300/BS-4 is the lowest, and its value is approximately 0.14. The friction coefficient of aramid/4211 is the highest.

In conclusion, under the three different loads, the friction coefficient of the carbon fiber-reinforced BS-4 cy-anate ester composite coupled with B-2 is the lowest. This can be attributed to the fact that the carbon fibers prevent the oxidation of copper during friction testing [18], and copper has good self-lubricating capabilities. During friction testing, the carbon fibers protect copper from oxidation. Therefore, when the metal pair is the brass pins, composite T300/BS-4 achieves the lowest friction coefficient.

As shown in Figure 7(d), under the 100N load and dry friction conditions with brass sliding blocks, the friction coefficient of aramid/4211 is the lowest. The difference in the contact types between the samples and the brass sliding block or the brass pin has an important effect on the friction and wear performance. The contact between the sliding block and the composites is face-to-face contact, while that between the brass pin and the composites is line-to-face contact. Hence, the composite with the lowest friction coefficient would change. This can be attributed to the shear strength of composites decreasing with increasing temperature, which led

![Figure 3: Morphologies of the four composites: (a) T300/4211. (b) Aramid/4211. (c) T300/BS-4. (d) Aramid/BS-4.](a) (b) (c) (d)

| Table 1: Physical and mechanical properties of composites tested. |
|---------------------------------------------------------------|
| Properties | T300/4211 | Aramid/4211 | T300/BS-4 | Aramid/BS-4 |
| Density (g/cm³) | 1.63 | 1.65 | 1.61 | 1.63 |
| Hardness (shore D) | 81.7 | 84.04 | 82.1 | 84.7 |
| Flexural strength (MPa) | 956 | 974 | 1051 | 1210 |
| Compressive strength (MPa) | 850 | 887 | 890 | 943 |
to the decrease in friction coefficient. As presented in Sections 2.1 and 2.2 for the fabrication of the composites, the moulding temperature of the fiber-reinforced 4211 resin is lower than that of the fiber-reinforced BS-4 resin. Therefore, the fiber-reinforced 4211 resin is more sensitive than the fiber-reinforced BS-4 resin, and the surface temperature of the composites paired with brass sliding blocks is higher than that of the composites paired with brass pins.

Figure 8 presents the wear rates of the composites paired with brass pins and brass sliding blocks. As shown in Figure 8, the wear rates of the four composites coupled with the brass pin metal pair increase with the increase in the load. When the load is 50 N, the wear rate of composite aramid/4211 is so low that it can be ignored. Under loads of 75 N and 100 N, the order of the wear rates of four composites from low to high is aramid/4211, aramid/BS-4, T300/BS-4, and T300/4211. This proves that aramid fibers have a stronger bond to the resin than carbon fibers. The wear rate of composite aramid/BS-4 coupled with brass sliding blocks under a load of 100 N is too low to be ignored. In addition, the wear rate of composite T300/BS-4 is the highest, which indicates that this composite is not an optimal tribological pairing material when brass is used to make good heat conduction parts in space engineering.
Figure 5: Friction coefficients of the composites coupled with 45 steel pins with (a) 50 N, (b) 75 N, and (c) 100 N loads.

Figure 6: Wear rate of the composites coupled with the 45 steel metal pair under different loads.
4.3. Discussion of Wear and Friction Mechanisms. As shown in the above test results, when the pairs are made by 45 steel pins, brass pins, and brass sliding blocks, the composites with the lowest friction coefficients are aramid/BS-4, T300/BS-4, and aramid/4211, respectively. Metallographic microscopic imaging (GX41) is performed to observe the worn surfaces of the composites after finishing all the tests to determine the wear mechanism. The microscopic morphologies of the composites paired with different metals are shown in Figures 9–11. Thus, the wear mechanism of the composites is discussed by analyzing the surface morphologies.

The microscopic morphologies of composite aramid/BS-4 paired with 45 steel pins (B-1) are provided in Figure 9. The reciprocating running condition of the pair can produce cyclic contact on the surface of the composites. Hence, due to cyclic contact stress, the resin base on the surface may fall off, exposing the fiber to the contact face. Obviously, clear furrows and well-defined scrapes are shown on the surface of the composites. Therefore, the friction and contact type of composite aramid/BS-4 paired with the 45 steel pins is mainly abrasive wear. According to the experimental phenomenon in the test process, the main reason for this friction is the fatigue spalling of the microconvex bodies from the surface of the composites. The spalled microconvex bodies are tiny particles because of cyclic stress, and these tiny particles reciprocate between the contact surfaces and then induce the defined furrows and abrasions. The fine debris on the worn surface temporarily acted as three body abrasives,
which contributed to the increase in the friction coefficient and wear rate [5].

Figure 10 displays the microscopic morphologies of composite T300/BS-4 paired with brass pins (B-2). Under the three loads, the surface’s resin base falls off, exposing fibers to the contact surface. Thus, the surface of the composite has obvious furrows and scrapes. In particular, under a lower load, relatively few fibers of composite T300/BS-4 are exposed to the surface. The friction and wear mechanisms of composite T300/BS-4 paired with the brass pin are mainly abrasive wear.

Figure 11 shows the microscopic morphologies of the composite coupled with the brass sliding block (B-3). The T300/BS-4 resin composite exhibits very serious surface wear, and the serious furrows and scrapes are uniformly distributed on its surface. Meanwhile, the wear of composite aramid/4211 is not serious. The reason for this is that the worn surface of aramid/4211 is covered with many secondary plateaus with the largest sizes. The reason for the formation of secondary plateaus is that the 4211 resin, which easily falls off the surface of aramid/4211 because of the low adhesive force between the fiber and resin, is soft and attaches again to the fiber’s surface with increasing surface temperature, which effectively improves the wear resistance of the composite. As shown in Figure 11, under the same working conditions, the wear rate of composite T300/BS-4 is much higher than that of composite aramid/4211.

The above test results and discussions show that the four kinds of composites presented in this paper have different friction and wear performances. Under the dry friction condition, the friction coefficients of the four composites coupled with the 45 steel pin or brass pin/sliding block and the time they take to reach a stable wear stage are very different, but the reinforced BS-4 cyanate ester composites have better properties. The friction coefficient is lower for the composites paired with the brass sliding block due to its larger contact surface area. Meanwhile, the friction mechanisms of the four composites coupled with the 45 steel pin and brass pin are mainly abrasive wear. However, although the same friction mechanism is observed, the 45 steel is harder than the brass pin, so the microconvex bodies of the brass pin fall off more easily during the running process, and abrasive wear occurs easily on the contact surface. When the metal pair is the brass sliding block, many furrows and scrapes appear on the surface of the composites, but the wear of the aramid/4211 composite is not obvious. The resin that falls off the surface softens and attaches again to the surface fiber to form the secondary plateaus with increasing local temperature, which will effectively improve the wear resistance of the composite.

However, for the applicable spaceflight environment, the friction and wear of carbon/aramid-based composites need to be discussed for their applicability in space engineering. Lv et al. [19] found that the introduction of carbon and aramid fibers reduced the friction coefficient of composites and improved the wear resistance of polyimide after ultraviolet irradiation. Dhieb et al. [20] studied the effect of relative humidity and full immersion in water on the friction, wear, and debonding of unidirectional carbon fibre-reinforced epoxy under reciprocating sliding. The above studies show that the carbon/aramid-based composites have good applicability.
Figure 9: Microscopic morphologies of aramid/BS-4 paired with 45 steel pin under (a) 50 N, (b) 75 N, and (c) 100 N loads and (d) before the test.

Figure 10: Continued.
5. Conclusions

(1) The flexural and compressive strength of aramid/BS-4 is higher than that of the other composites because of the better adhesion between the fibres and resin. The flexural strength of aramid fibre-reinforced BS-4 resin is 24% higher than that of the fibre-reinforced 4211 resin, and the compressive strength of aramid fibre-reinforced BS-4 resin is 6% higher than that of the fibre-reinforced 4211 resin. The flexural strength of aramid fibre-reinforced BS-4 is 15% higher than that of carbon fibre-reinforced BS-4 resin, and the compressive strength of aramid fibre-reinforced BS-4 is 6% higher than that of carbon fibre-reinforced BS-4 resin.

(2) Using a 45 steel pin, the composite with the lowest friction coefficient and wear rate is aramid/BS-4 (with a friction coefficient of 0.09), and the magnitude of the friction coefficient and wear rate of the composites follows the order aramid/BS-4 > T300/BS-4 > aramid/4211 > T300/4211 (except for the wear rate obtained at 50 N). When using the brass pins, the composite with the lowest friction coefficient is T300/BS-4 (with a value of approximately 0.13), and the wear rate of the composites is in the order aramid/4211 < aramid/BS-4 < T300/BS-4 < T300/4211 (except for the wear rate obtained at 50 N).

(3) Using brass sliding blocks, the composite with the lowest friction coefficient is aramid/4211, with a value of approximately 0.1. Using brass sliding blocks, the 4211 resin can form secondary plateaus, which effectively improve the wear resistance of the composite.
Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

Acknowledgments

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