



# The friction behavior of IG-110 nuclear graphite during continuous heating under a helium atmosphere

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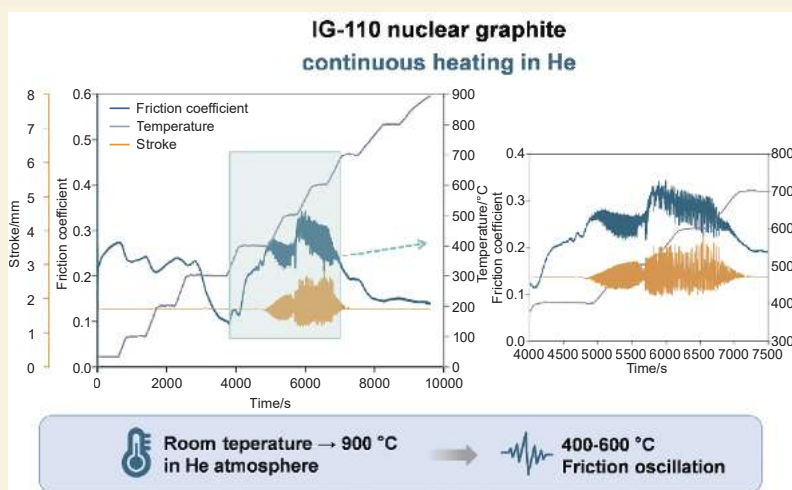
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**Abstract:** The friction and wear characteristics of nuclear graphite when one piece rubs against another profoundly impact the design of graphite moderated nuclear reactors. We investigated the friction and wear behavior of IG-110 nuclear graphite at different temperatures in a helium atmosphere, focusing on the adhesive wear mechanisms. Experiments were conducted from room temperature to 900 °C at intervals of 100 °C and showed that the coefficient of friction initially decreased and then increased, fluctuated, and finally stabilized at a value that was notably lower than that initially observed.

Adhesive wear occurred mainly in the temperature range of approximately 400 to 600 °C, and this triggered the rapid fluctuations in the friction coefficient, thus becoming more pronounced under increased loads. The adhesive wear is associated with changes in the graphite surface at high temperatures which result in intermittent adhesion and detachment during sliding.

**Key words:** Nuclear graphite; Friction and wear characteristics; Adhesive wear mechanisms; Friction coefficient; Oscillations



## 1 Introduction

Graphite, due to its unique structure, exhibits low friction and excellent lubrication properties, making its tribological performance a subject of considerable interest in various critical fields<sup>[1–3]</sup>. Additionally, graphite possesses exceptional properties such as high-temperature resistance, radiation tolerance, neutron deceleration capability, and a small neutron absorption cross-section, playing a significant role in nuclear engineering<sup>[4–5]</sup>. In high-temperature gas-cooled reactors (HTGRs), nuclear graphite is a critical structural material in the reactor core. During reactor operation, relative motion and friction may occur at the interfaces between graphite components as well as between graphite components and control rods. There-

fore, studying the friction and wear properties of nuclear graphite at high temperatures is of vital importance for the design and safe operation of nuclear reactors<sup>[6–7]</sup>.

There have been several studies on the behavior and mechanisms of friction and wear in nuclear graphite. Stansfield systematically investigated the friction and wear behavior of various graphite materials in dry helium at 25, 400 and 800 °C, and found that wear decreased significantly at elevated temperatures along

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with a transient friction peak induced by the degassing treatment<sup>[8]</sup>. More recent studies have further investigated the performance of nuclear graphite under conditions simulating reactor environments. Luo Xiaowei et al. investigated the effect of temperature on the frictional properties of IG-11 graphite, used in 10 MW high-temperature gas-cooled reactors, in various atmospheres in 2004 and identified the variation and mechanisms of the friction coefficient of graphite from room temperature up to 400 °C<sup>[9]</sup>. In 2005, they studied the wear mechanisms of IG-11 at different temperatures<sup>[10]</sup>. Li Xinnan and others explored the friction and wear properties of spherical fuel element matrix graphite in HTGRs in helium at different temperatures and loads, analyzing its friction and wear mechanisms<sup>[11]</sup>. He Xiujie et al. studied the wear performance of IG-11 graphite plates and spheres in the HTR-PM reactor<sup>[12]</sup>. Hiruta et al. investigated the wear behavior of IG-11 graphite in helium from room temperature to 750 °C and found that the wear volume exhibited a peak around 200 °C, while also noting that the formation and adhesion of flake-like debris at elevated temperatures affected the apparent wear rate<sup>[13]</sup>. Vergari et al. studied the tribological behavior of nuclear graphite in an argon atmosphere and reported that thoroughly degassed graphite at 600 °C showed lower friction coefficients and wear rates than at room temperature<sup>[14]</sup>. However, the experimental temperatures in these studies are typically focused on low-to-intermediate temperature ranges, or the experiments involve isothermal conditions at specific temperatures. There is a lack of systematic tracking of the dynamic evolution of graphite's frictional behavior during continuous heating from room temperature to high temperatures.

Unlike many previous studies that mainly focused on friction behavior at discrete temperatures or under isothermal conditions, this work investigates the continuous evolution of friction behavior during heating from room temperature to 900 °C. By capturing the transient variation of the friction coefficient during the temperature ramping process, this study aims to identify the temperature-dependent transition in the

tribological behavior of graphite and clarify the possible contribution of adhesive wear in the intermediate temperature range.

## 2 Experiment

### 2.1 Apparatus

The friction experiments conducted in a high-temperature helium atmosphere were dynamic friction tests. For these experiments, the SRV-5 multifunctional friction and wear testing machine, manufactured by Optimol in Germany, was employed. This device is capable of switching between reciprocating and rotational motion modes. It can conduct several typical tests, such as ball/disc, pin/disc, and disc/disc friction pairs in reciprocating motion, facilitating point, line, and surface contact. Its main technical specifications include a load range of 1 N to 2500 N, a frequency range from 1 to 500 Hz, a temperature range from −35 to 1000 °C, and a maximum stroke of 5 mm. In the SRV friction test system, a resistive heater integrated with the lower sample holder heats the sample, with temperature monitored by a thermocouple. High purity helium gas is introduced into the sample area through stainless steel tubing at a controlled flow rate of 1 L/min, creating a helium atmosphere within the chamber (Fig. 1).



Fig. 1 SRV friction testing system

### 2.2 Samples

IG-110 nuclear graphite was selected as the test material because it is a representative nuclear graphite grade with extensive research background for high-temperature gas-cooled reactor applications. Graphite-graphite friction pairs were selected, utilizing a disc/disc configuration to achieve surface contact. Both the upper and lower samples were made of IG-110 nuclear graphite. Fig. 2a shows the upper sample with a conical groove on its surface for gripping and

reciprocating motion; Fig. 2b displays the lower sample, which is disc-shaped. No pre-degassing treatment was performed before the friction tests. The samples were directly tested under a helium atmosphere after surface preparation.

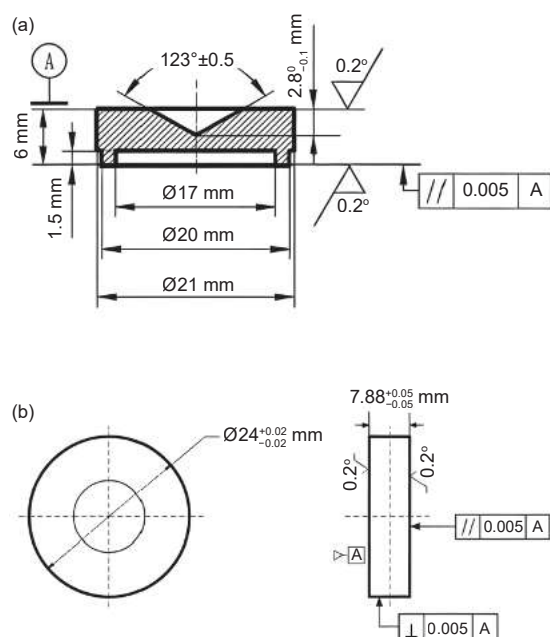


Fig. 2 Schematic representations of the sample dimensions: (a) The upper IG-110 graphite sample; (b) the lower IG-110 graphite sample. All dimensions are in mm unless otherwise specified; surface roughness is in  $\mu\text{m}$

### 2.3 Conditions

In this experiment, the atmosphere was helium, with loads of 87 N (1 MPa) and 174 N (2 MPa). The applied loads were determined according to the target nominal contact stress conditions. Contact stresses of 1 and 2 MPa were selected, and the corresponding loads were calculated based on the nominal contact area, resulting in applied loads of 87 and 174 N. The contact mode between the upper and lower samples was surface contact. The lower sample was fixed, while the upper sample was reciprocated by the clamp above, with a stroke of 1.7 mm and a frequency of 3 Hz, resulting in a relative speed of approximately 1 cm/s between the friction pairs. There was no lubrication between the friction pairs. The experiment employed a continuous heating method, with temperatures starting at room temperature and increasing to 100, 200, 300, 400, 500, 600, 700, 800 and 900 °C, with each temperature maintained for 10 min.

### 2.4 Data processing and morphology characterization

The software component of the SRV-5 friction testing system can set and adjust test parameters, control and monitor the friction testing process, and read, record, and process the test results. During the testing process, the software records real-time data on friction coefficient, temperature, load and stroke, presenting the data in graphical form to yield accurate and reliable experimental results.

Relationship curves between the friction coefficient, reciprocating stroke, temperature, and time were plotted. As the sample temperature changes, the system requires a certain period to achieve thermal equilibrium. Therefore, the last 60 s of the friction coefficient at each temperature stage was selected as the sample to calculate the average friction coefficient and standard deviation at that temperature.

To investigate the adhesive wear mechanism, the experiment was halted and cooled down when the adhesive wear characteristics became apparent at 400 °C. Subsequently, a Scanning Electron Microscope (SEM) was used to observe and analyze the surface morphology of the upper and lower samples after friction, to explore the surface morphology changes and wear mechanisms of nuclear graphite materials during the friction process.

To investigate the microstructural characteristics of wear surfaces, specimens tested at room temperature and 400 °C were selected for Transmission Electron Microscope (TEM) characterization, with representative wear-track regions shown in Fig. 3. As depicted in Fig. 4, focused ion beam (FIB) technology was used to prepare cross-sectional TEM samples of the wear grooves, with the axial direction of the TEM samples perpendicular to the groove direction.

## 3 Results and discussion

### 3.1 Variations in the coefficient of friction under different conditions

The frictional behavior of IG-110/IG-110 nuclear graphite pairs under a helium atmosphere was studied under loads of 87 N (1 MPa) and 174 N (2 MPa)

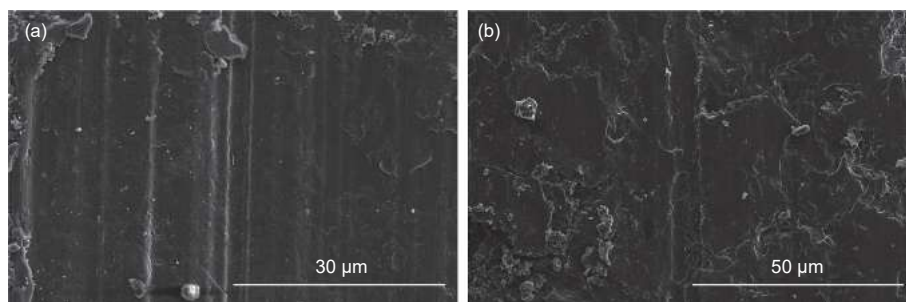


Fig. 3 SEM images of the wear tracks at (a) room temperature and (b) 400 °C

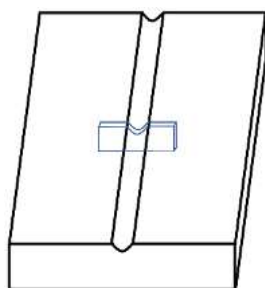


Fig. 4 Schematic of FIB sectioning

Fig. 5(a, b). The coefficient of friction (CoF) of these pairs exhibits a distinct temperature-dependent variation. Specifically, in the temperature range from room temperature to 300, the CoF fluctuates between 0.2 and 0.3. A notable decrease in CoF to approximately 0.1 is observed around 300 °C. Subsequently, between 300 and 400 °C, the CoF begins to increase, returning to its initial value before the decrease. In the range of 400 to 600 °C, the CoF exhibits oscillations, with values varying between 0.2 and 0.3. Upon further temperature elevation beyond 700 °C, the oscillatory behavior ceases, and a continual decrease in the CoF is observed. At 800 °C, the CoF stabilizes around 0.1.

At temperatures between 400 and 600 °C, the CoF is extremely unstable, displaying behavior markedly different from that at other temperatures, indicating a distinct wear mechanism in this temperature range. Fig. 5(c, d) show the relationship between CoF and time in the temperature range of approximately 400 to 600 °C. In this temperature interval, not only does the CoF exhibit rapid oscillations, but the stroke also fails to maintain a constant value, presenting a state of rapid fluctuation. The rapid fluctuation of friction coefficient suggests unstable interfacial interactions during sliding.

With increased load, the oscillation phenomena in the CoF due to adhesive wear become more pronounced. Fig. 5(c, d) respectively represent the frictional behavior of the nuclear graphite pairs under loads of 87 N (1 MPa) and 174 N (2 MPa), showing the variation curves of the CoF during friction testing. Fig. 5(e, f) also display a significant increase in the standard deviation of the CoF in the temperature range of 400 to 600 °C. Although similar trends in CoF variation are observed under different loads, certain differences remain. Specifically, at a load of 87 N (1 MPa), the CoF begins to decline at 400 °C, with rapid oscillations occurring in the temperature range of 400 to 600 °C. The amplitude of these oscillations is  $\sim 0.02$ , with a maximum standard deviation of 0.005, and a stroke variation of about 0.01 mm. In contrast, at an increased load of 174 N (2 MPa), the CoF starts decreasing at a lower temperature range ( $\sim 300$  °C) and exhibits more pronounced oscillations between 400 and 600 °C. The amplitude of these oscillations increases to 0.06, with a maximum standard deviation of 0.027, and a stroke variation of up to 1.56 mm. This indicates that with increasing load, the decrease in the CoF of the IG-110 nuclear graphite pair occurs earlier and with a greater magnitude. Additionally, the oscillatory phenomena in both CoF and travel variation are observed in the temperature range of 400 to 600 °C under different loads, but the amplitude of these oscillations increases with the load, meaning that the rapid oscillations in both CoF and travel become more pronounced.

### 3.2 Microscopic morphology and wear mechanisms

Based on the friction behavior and wear morpho-

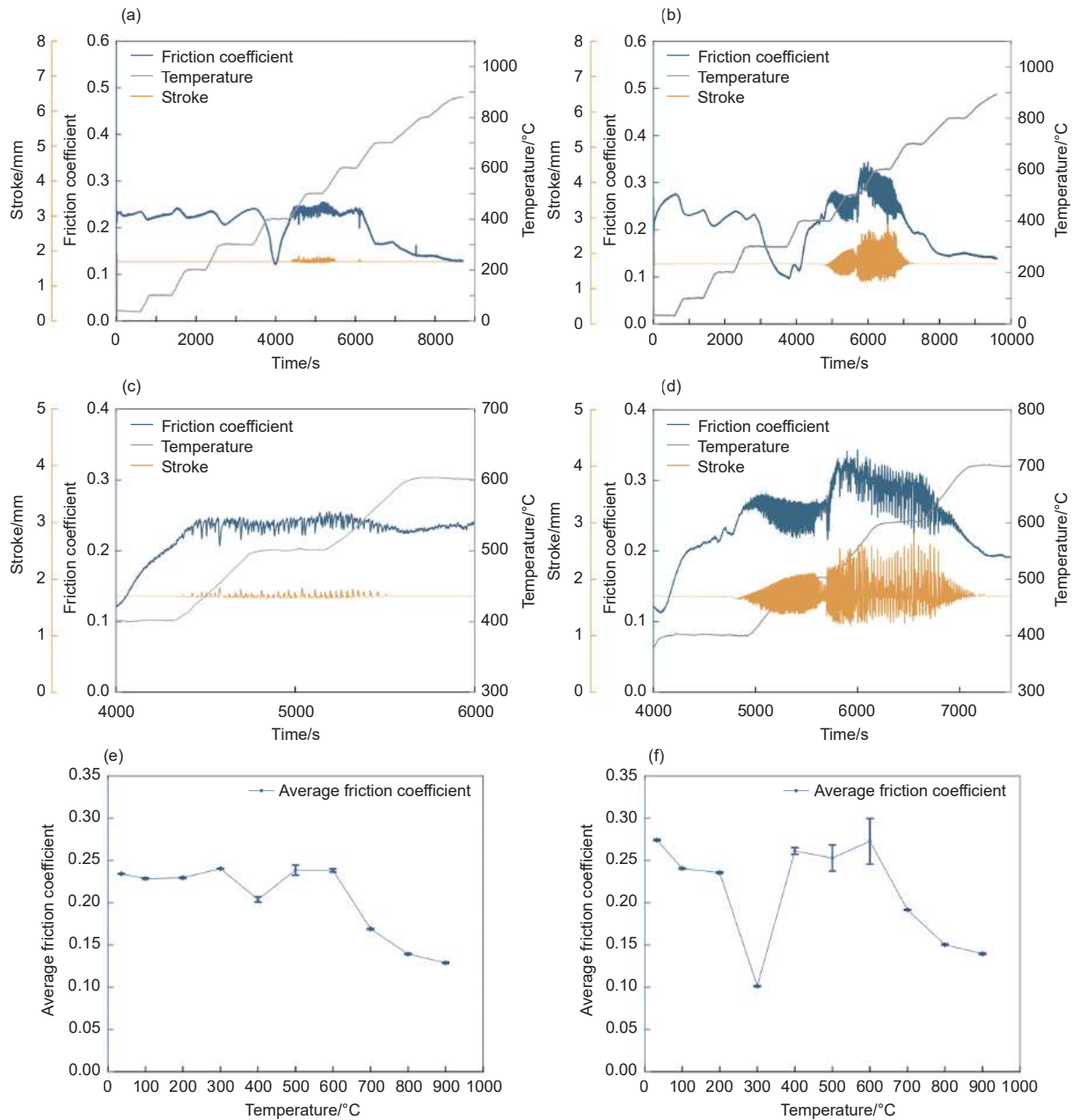


Fig. 5 The variations in the coefficient of friction and temperature over time under (a) 87 N or (b) 174 N. The relationship curves between the coefficient of friction, reciprocating stroke, and temperature in the range of 400 to 600 °C under (c) 87 N or (d) 174 N. The variation in the mean and standard deviation of the coefficient of friction as a function of temperature under (e) 87 N or (f) 174 N

logy under different loads, the samples tested at 174 N were selected for further SEM and TEM characterization. Although wear features were observed under both 87 and 174 N conditions, those at 174 N were more pronounced, facilitating more detailed observation and analysis of the wear mechanisms.

Fig. 6 displays SEM images of the worn surface morphology of the upper sample after applying a load of 174 N (2 MPa) under a helium atmosphere on nuclear graphite IG-110, at room temperature and at

400 °C. From Fig. 6(a-d), it can be inferred that at room temperature, the friction surface appears relatively flat and bright, with distinct scratches aligned in the direction of sliding. Additionally, fine wear debris and spalling pits are present on the friction surface. Moreover, shallow grooves with a regular shape, parallel to the scratches, can also be observed on the surface. These grooves are formed due to the sliding of hard abrasive particles across the surface, indicating that the wear mechanism at room temperature is ab-

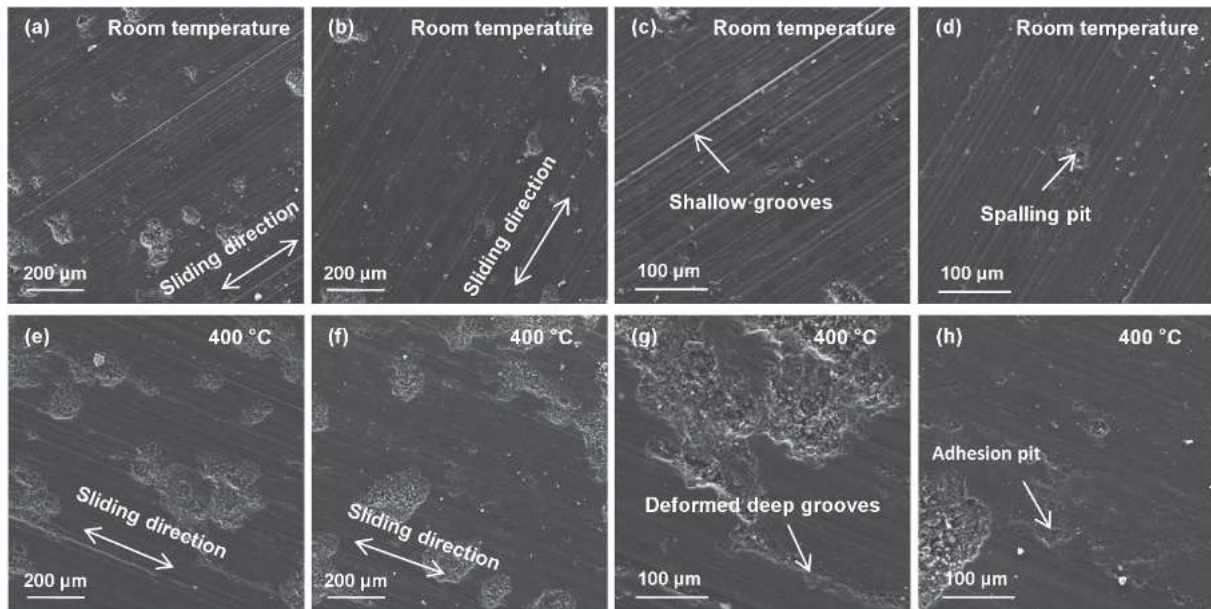


Fig. 6 SEM images of the wear surface morphology of the upper sample of graphite under a load of 174 N: (a, b) at room temperature (200X); (c, d) at room temperature (500X); (e, f) at 400 °C (200X); (g, h) at 400 °C (500X)

rasive wear<sup>[15]</sup>.

From Fig. 6(e-h), it is observed that at 400 °C, the scratches on the friction surface become shallower, which is attributed to the localized plastic deformation of the graphite surface. Concurrently, adhesive wear results in material transfer and tearing, continuously removing material from the protrusions on the specimen surface, thereby reducing the local surface roughness (Fig. 7). Numerous pits formed by adhesive wear are observed. In addition, irregularly shaped, wider, and unevenly edged deep grooves appear on the friction surface. These grooves may be formed by the accumulation of a large amount of wear debris in the recesses of the graphite surface during the adhesive wear process. With higher magnification SEM images at 400 °C (Fig. 8a), partial areas of the friction surface exhibit flake-like peeling or fracture phenomena, and Fig. 8b reveals traces of large graphite material on the verge of detachment. Due to tearing in the adhesive regions, graphite detachment occurs, forming flat pits on the friction surface, with the detached material potentially adhering to the lower specimen surface. These pits are irregular in shape with uneven edges, and some cracks can also be observed at the bottom and edges of the flat pits. The irregular grooves are primarily connected to the pits, suggest-

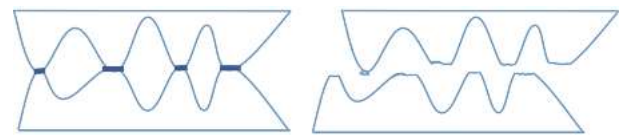


Fig. 7 Adhesive wear mechanism

ing that these grooves were also formed by tearing during the reciprocating sliding process. The morphological features observed at 400 °C, including material transfer pits, tearing ridges, and adhesive debris, indicate material removal resulting from localized adhesion and subsequent shear, which is distinct from purely fatigue-dominated wear. These observations indicate that the wear mechanism at elevated temperatures is predominantly adhesive wear.

Fig. 9 displays SEM images of the worn surface morphology of the lower sample of the nuclear graphite IG-110 pair under a helium atmosphere at room temperature and 400 °C, following the application of a 174 N (2 MPa) load. Fig. 9a shows the non-friction area of the lower surface, characterized by its rough texture. Fig. 9(b-d) depict the regions where constant friction occurs between the upper and lower surfaces of the friction pair. Due to the roughness and irregularity of the lower surface, numerous micro-protrusions exist, leading to contact occurring only between these micro-protrusions, thereby forming the effect-

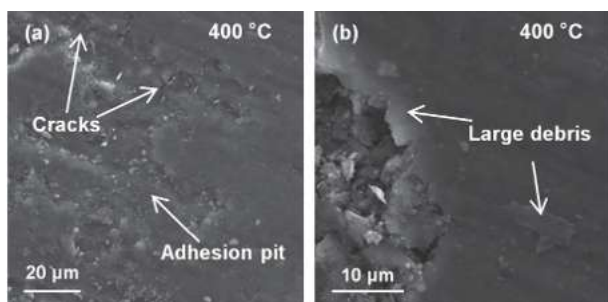


Fig. 8 High-magnification SEM images of the wear surface morphology of the upper graphite sample under a load of 174 N: (a) 2000X; (b) 5000X

ive contact area. With ongoing friction, these micro-protrusions gradually become flattened, resulting in a relatively smooth surface. On these flattened areas, scratches are present along the sliding direction. Comparing the surface morphologies between ambient temperature and 400 °C, it is evident that surface scratches are more pronounced under ambient temperature conditions. Observation from Fig. 9b reveals that at room temperature, the surface bears many parallel scratches and several shallow grooves, where the more prominent grooves are formed by larger abrasive particles sliding across the friction surface. Fig. 9c demonstrates that at 400 °C, the scratches on the flattened surface become less distinct, but the surface exhibits some deep grooves with deformed edges. From the higher magnification image in Fig. 9d, adhesion pits and cracks on the friction surface at high temperatures are clearly visible. These observations are consistent with the previous descriptions concerning the upper sample. Summarizing the above observations, it can be concluded that the wear mechanism at room temperature is predominantly abrasive wear, while at 400 °C, the mechanism is primarily adhesive wear.

### 3.3 TEM analysis

Fig. 10(a-d) present HRTEM images of the scratch edge regions. As observed, an obvious amorphous layer forms in the shallow surface area near the scratch, within which nanometer-scale grain structures are dispersed. During the formation of the scratch, hard particles (or rough peaks on the material surface) are pressed into the material's surface layer under normal loading. Subsequently, during the sliding friction process, these hard particles shear the material through cutting action, which significantly impacts the material's structure, leading to the formation of the amorphous layer.

Fig. 11 displays the TEM images of the scratch bottom from the surface to the interior of the sample at room temperature. The specific regions and directions selected for observation are clearly indicated by arrows in Fig. 10. Specifically, Fig. 11(a-d) show HRTEM images, revealing the microstructural characteristics of the scratch bottom at different depths. Fig. 11(e-h) correspond to the electron diffraction patterns for further analysis of the crystal orientations in these regions. It can be observed that the surface layer exhibits typical amorphous features, while the material gradually transitions to a crystalline structure with increasing depth. These observations suggest that the amorphization is mainly confined to the shallow surface region, while the deeper region maintains relatively intact crystalline characteristics due to the reduced influence of shear stress and frictional heat.

Fig. 12(a-d) present HRTEM images of the groove edge region. Observations indicate that no distinct amorphous layer is formed in the shallow sur-

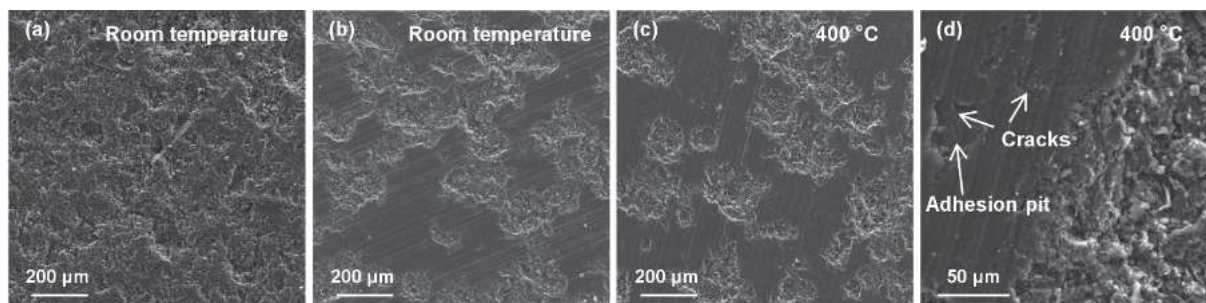


Fig. 9 SEM images of the wear surface morphology of the lower sample of graphite under a load of 174 N: (a) Non-friction area (200X); (b) Friction area at room temperature (200X); (c) Friction area at 400 °C (200X); (d) Friction area at 400 °C (1000X)

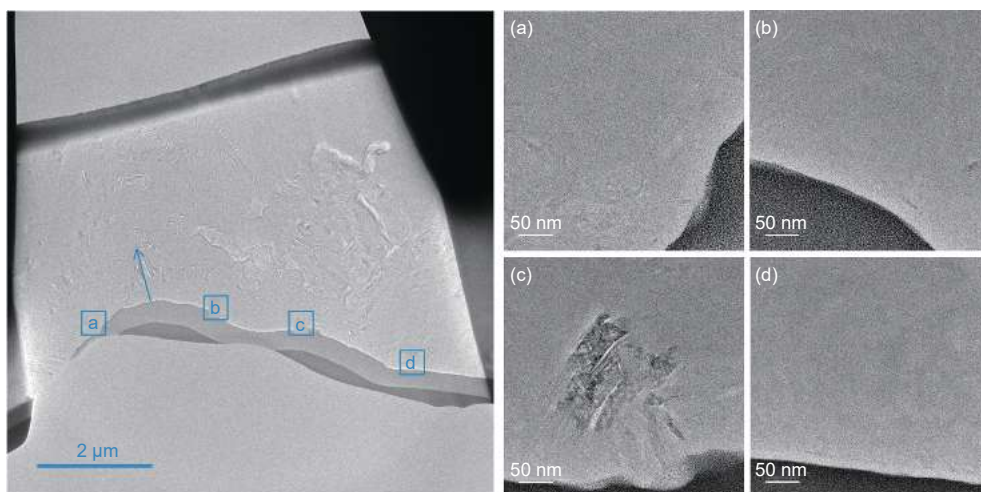


Fig. 10 TEM images of the scratch cross-section at room temperature: (a-d) HRTEM images of the scratch edge

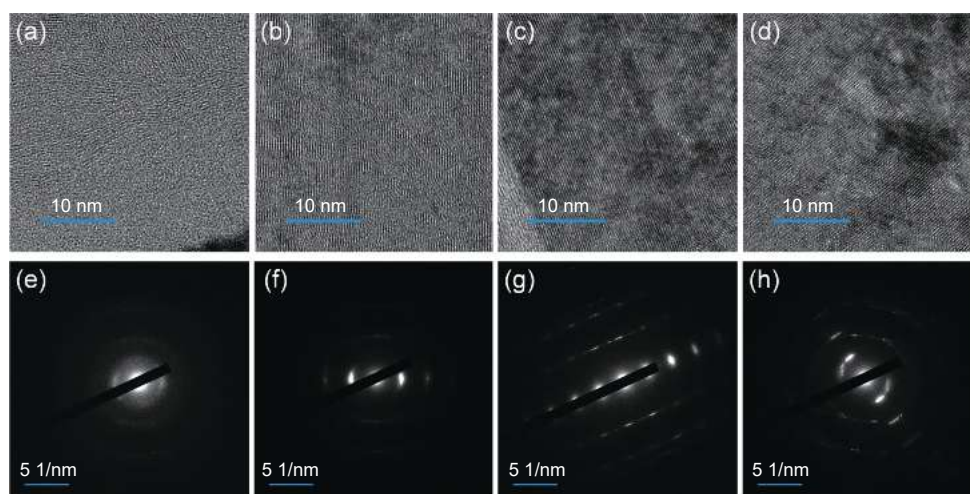


Fig. 11 TEM images of the scratch bottom of the sample at room temperature, from the surface to the interior: (a-d) HRTEM images; (e-h) The corresponding electron diffraction patterns

face layer near the groove. Instead, a complex structural feature is observed, which significantly differs from the amorphous layer structure formed at room temperature, confirming the role of temperature in regulating the wear mechanism. Fig. 13(e-h) show TEM images of the groove bottom region from the surface to the interior under 400 °C conditions. The specific areas and directions of the images are indicated by arrows in Fig. 12. Specifically, Fig. 13(a-d) present HRTEM images, while Fig. 13(e-h) display the corresponding electron diffraction patterns. The TEM observations reveal that the examined region maintains clear crystalline characteristics under 400 °C conditions. The relatively preserved subsurface structure beneath the groove is consistent with a wear process involving limited subsurface structural

damage, which supports the proposed interpretation of adhesive wear behavior at elevated temperatures. During adhesive wear, the formation of irregular grooves results from tearing in the adhesive contact region under reciprocating sliding. The adhesive-tearing process leads to material detachment and removal, forming adhesive pits and grooves on the surface. Material loss primarily occurs above the groove, while the structure beneath the groove remains intact, preserving its crystalline form. This is fundamentally different from the abrasive wear mechanism at room temperature: in abrasive wear, hard particles scratch the material surface, often damaging the structure beneath the scratch. Although both abrasive wear and adhesive wear mechanisms result in surface damage, they differ significantly in terms of the damage mech-

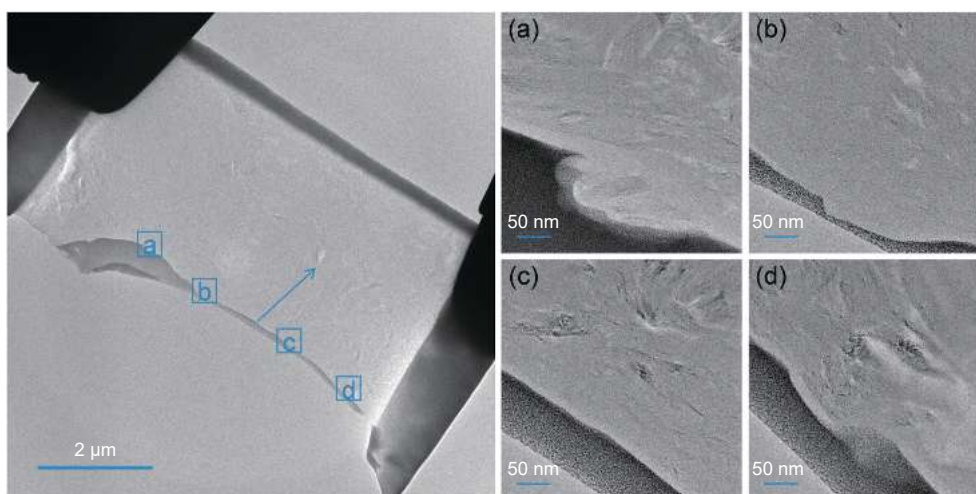


Fig. 12 TEM images of the groove cross-section at high temperature: (a-d) show HRTEM images of the groove edge

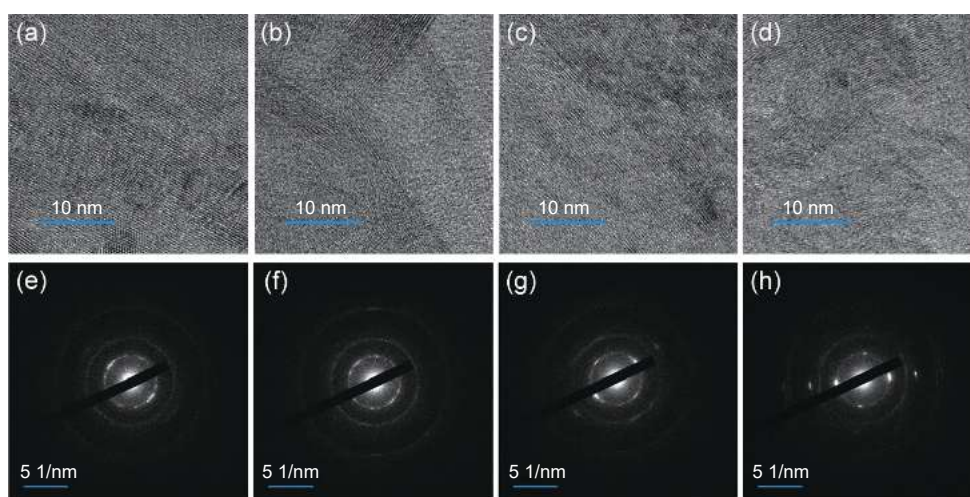


Fig. 13 TEM images of the scratch bottom of the sample at 400 °C, from the surface to the interior: (a-d) show HRTEM images; (e-h) display the corresponding electron diffraction patterns

anisms, extent of damage, and their impact on the deeper structures.

It should be noted that the present TEM analysis mainly provides qualitative information on the structural evolution of the worn regions. Quantitative evaluation of lattice spacing variation, amorphous layer thickness, and crystallographic orientation requires further systematic characterization.

### 3.4 Wear behavior of IG-110 nuclear graphite during continuous heating

Previous studies have reported temperature-dependent friction transitions in nuclear graphite. The different temperature ranges reported may be related to variations in graphite grades, testing atmospheres, temperature control methods, and evaluation parameters. For example, Hiruta et al. reported a variation in

wear volume around 200 °C, whereas the present study observed a transition in friction coefficient mainly between 300 and 400 °C during continuous heating. The difference may result from the different indicators used for evaluation, as wear evolution and friction evolution do not necessarily occur at the same temperature range. Stansfield et al. attributed transient friction changes to surface desorption processes. The friction variation observed near 300 °C in the present study may be related to similar surface evolution during heating; however, the specific contribution of desorption requires further characterization.

Under a continuous heating regime in the helium environment, the evolution of the friction and wear behavior of nuclear graphite is a dynamic process, which can be divided into 3 stages.

The first stage occurs from room temperature to 300 °C, where the friction coefficient remains relatively stable at 0.2–0.3. The stable friction behavior may be related to the presence of adsorbed species on the graphite surface, which can influence the interfacial interaction during sliding.

The second stage occurs between 300 and 600 °C, corresponding to a transition from stable friction behavior to unstable friction dominated by adhesive interactions. The decrease of CoF near 300 °C may be associated with the gradual evolution of the surface state during heating. With further temperature increase, significant friction oscillations appear between 400 and 600 °C, which may result from the repeated formation and fracture of adhesive junctions under the combined effects of temperature-dependent surface evolution, interfacial interactions, and mechanical deformation.

The third stage occurs above 700 °C, where the friction oscillations disappear and the friction coefficient gradually decreases to  $\sim 0.1$ . Previous studies have suggested that high-temperature tribo-film formation may contribute to the self-lubricating behavior of nuclear graphite. However, the formation of a similar tribo-film was not directly confirmed in the present study due to the lack of specific chemical and structural characterization. The low and stable friction coefficient observed at 800 °C may be associated with temperature-dependent evolution of the graphite interface and possible high-temperature interfacial lubrication effects.

Helium also plays a significant role in influencing the friction coefficient. Under a helium atmosphere, the friction coefficient decreases with increasing temperature. This phenomenon may be related to the evolution of surface structure and interfacial interactions of graphite under elevated-temperature helium conditions. However, the detailed atomic-scale mechanism requires further investigation<sup>[15–18]</sup>.

The frictional surfaces of graphite are inherently rough and uneven, with the actual contact area being confined to the regions of micro-protrusions<sup>[19–21]</sup>. This limited contact is a significant factor contributing to adhesive wear. Under applied loads, these contact re-

gions undergo plastic deformation due to the stress concentrations. A correlation between the plastic deformation of graphite's frictional surfaces and its friction coefficient has been identified: the coefficient is higher when the surface undergoes plastic deformation and lower when no such deformation occurs<sup>[22]</sup>. During the heating process, the graphite surfaces exhibit significantly enhanced interfacial adhesion, which initiates a self-reinforcing cycle: the increased adhesive strength causes strong bonding at asperity contact points, leading to substantial plastic deformation under applied load and shear stress. This deformation further alters the contact interface and generates newly exposed contact regions, which may promote repeated formation of adhesive junctions. This continuous “adhesion–deformation–reinforced adhesion” process may promote the formation and repeated fracture of adhesive junctions. During sliding, these strong junctions impede relative motion between the contacting surfaces, resulting in an elevated friction coefficient. When the accumulated shear stress exceeds the strength of a junction, it may undergo sudden fracture, causing instantaneous separation of the surfaces and a sharp drop in the friction coefficient. As sliding continues, new junctions repeatedly form and subsequently fracture, establishing a recurring “adhesion–shear–reattachment” cycle. Macroscopically, this process manifests as rapid oscillations in the friction coefficient between 0.2 and 0.3 in temperature range of 400 to 600 °C. The wear behavior of nuclear graphite in this temperature range may be influenced by multiple factors, including applied load, temperature-dependent surface evolution, and interfacial interactions. With increasing load, the higher contact stress and more pronounced surface deformation may further intensify this positive feedback loop, resulting in more significant friction oscillations and adhesive interactions. Under the combined influence of these factors, adhesive wear is considered the dominant wear mechanism of nuclear graphite in 400–600 °C.

Further discussion posits that the adhesive wear of nuclear graphite friction pairs might represent a discontinuous process (Fig. 14). During adhesive wear,

the adhesive forces hinder the motion between the friction pairs, necessitating a greater force to achieve relative sliding between these 2 surfaces. As the frictional force increases while the normal force remains constant, the CoF rises. Concurrently, due to the constant driving force and increased resistance to motion, the stroke decreases. When the adhesion at the contact points fractures, the relative sliding between the friction pairs becomes easier, leading to an instantaneous reduction in the friction coefficient and a sudden increase in the stroke. However, due to the complexity of the friction surface and the influence of multiple factors, while other types of wear mechanisms may be involved, the oscillatory behavior does not follow a single pattern or rule.

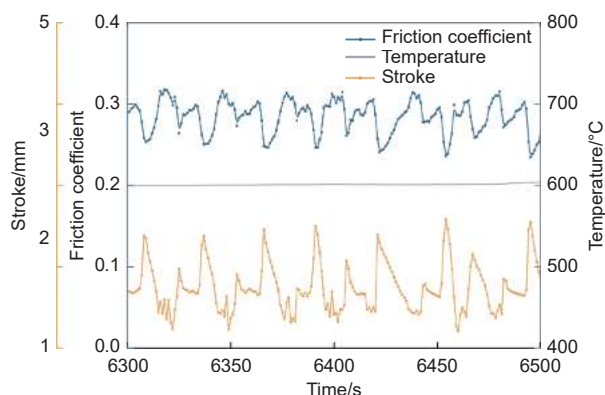


Fig. 14 Enlarged image of the friction coefficient and the oscillation region during the reciprocating stroke under a load of 174 N

## 4 Conclusion

This study elucidates the evolution of friction behavior in IG-110 nuclear graphite under continuous heating conditions under a helium atmosphere. The CoF exhibited distinct temperature-dependent transitions: it remained relatively stable between room temperature and 300 °C, decreased near 300 °C, followed by an increase and pronounced oscillations between 400 and 600 °C. At temperatures above 700 °C, the CoF gradually decreased and stabilized at a low value.

In the high-temperature helium environment, adhesive wear was observed in the self-mated IG-110 graphite pairs mainly in the temperature range of approximately 400 to 600 °C, which was associated with

rapid oscillations in the CoF. The surface deformation of graphite pairs became more pronounced in this temperature range, and the oscillatory friction behavior intensified with increasing load.

These findings provide insights into the friction stability of graphite components used in high-temperature gas-cooled reactors, where graphite structures may experience mechanical contact and relative sliding in helium environments. Understanding the temperature-dependent friction evolution and associated adhesive wear behavior is important for evaluating the contact reliability and wear performance of nuclear graphite components.

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