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MINI REVIEW

A Perspective for the Collective Friction and Wear of Tungsten Alloy Balls

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ABSTRACT

The granular flow spallation target is one of the important candidates for Accelerator-Driven Subcritical Transmutation Device. However, this type of target will be faced with many important problems, one of which is the collective friction and wear of granules in the target loop. As granular flow spallation target material, tungsten alloy balls have excellent comprehensive properties. This paper introduces some important problems in the research of the collective friction and wear of granules, as well as some obtained preliminary research results of tungsten alloy balls about collective friction and wear. At last, a perspective for the collective friction and wear of tungsten alloy balls for future research has been provided, especially the dependence of the formation of new layer on experimental conditions and the collective friction and wear behavior under irradiation conditions. It is hoped that more researchers will participate in this research field and more new discoveries to look forward to in the future.

KEYWORDS

Granular flow spallation target, collective friction and wear, tungsten alloy ball.

INTRODUCTION

Granular matter widely exists in nature and industrial production. So far, considerable studies have been done [**1-2**], such as granule packing and granular flow. However, little research has been done on the friction and wear generated during granular flow which can cause mass loss, modification of surfaces, and even changes in overall properties of the granules. Particularly, when the granular matter is used as a functional material and flows in a closed system for a long time, it is extremely important to study friction and wear of granules.

"Accelerator-Driven Subcritical Transmutation Device (for short ADS)" is an advanced clean nuclear energy system, which can effectively resolve the bottleneck problem of nuclear waste disposal in the development of nuclear energy [**3-5**]. The new concept granular flow spallation target is considered as one of the important candidate target types for ADS [**6**]. Spallation target will be faced with the severe service environment in a long term, including high temperature, strong irradiation and so on. In the light of the excellent neutronics properties and mechanical properties [**7-9**], high density tungsten-based alloy balls with Φ1mm have been considered as one of the important candidates for granular flow spallation target [**10**]. However, numerous target balls circulating in the spallation target loop will cause strong friction and wear, which will affect the service life of the target balls and the operation stability of the spallation target device.

Challenges for studying collective friction and wear

However, many difficulties will be met when we set out to evaluate friction and wear properties of granules. There are several important factors that are needed to be taken into account.

First, the number of target balls is large, more than one billion. Second, their collective movements are complicated, including sparse flow, dense flow and intermediate transition states. Third, the wear and friction forms are diverse, including rolling, sliding, collision and impact. Fourth, the contact forces between balls are mainly impact force and shear force which are constantly changing in the magnitude, direction, and form during the collective movement. These factors greatly complicate the investigation of the specific wear mechanism. The regular friction and wear experiments are unavailable to evaluate the friction and wear behavior caused by the collective motion of a large number of alloy balls.

Therefore, it is necessary to design special equipment according to the characteristics of granular flow to study the friction and wear behavior of granules' collective movement.

Introduction of preliminary results

By using the self-developed granular collective friction and wear experimental device [**11**], Pang *et. al*. [**12**] have made a study of collective friction and wear behavior of W-Ni-Fe alloy balls under the state of dense flow at 250 ℃. The experimental time was over 3000 h, and helium gas was chosen as the protective atmosphere.

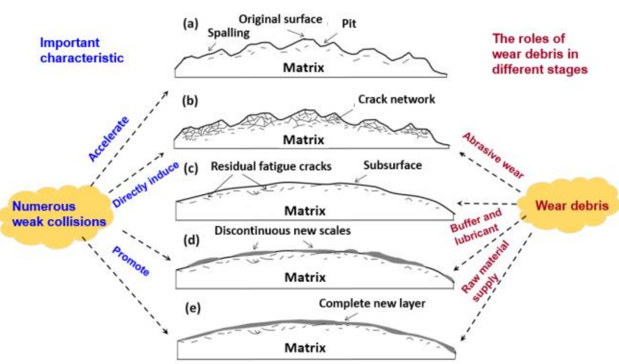

Fig. 1. Schematic illustration process of wear evolution of tungsten alloy balls [12] (middle), roles of wear debris (right) and roles of numerous weak collisions (left). (a) The profile of the friction surface of the ball at the initial stage. (b) The development of crack network. (c) The exposed subsurface layer after the crushed layer falling off. (d) Discontinuous new scales formed on the surface of the ball. (e) The formation of a complete new layer resulting from connection and growth of scales.

It is found that the mass loss ratio of the target balls increases firstly and then decreases a little, experiencing six different stages, with a maximum of about 0.32 wt% during the whole process. The wear evolution process of tungsten alloy balls has been revealed, as shown in **Fig. 1**. In the initial stage, fatigue wear is dominant, and then the micro-crack network on the surface of the ball begins to sprout and develops into a crushed layer. After the crushed layer falls off, the sub-surface begins to wear. Finally, a self-assembled new layer with a structure of amorphous surrounding nanocrystallines is formed on the ball surface. In the new layer, nanocrystallines phase and amorphous phase coexist. This peculiar structure can effectively inhibit the generation of dislocations and propagation of cracks, and possesses an ability of large elastic strain limit and excellent strength and good corrosion/wear resistance [**13**], so that it is useful for improving the wear resistance of the ball surface.

The research [**12**] also reveals the important roles of wear debris and numerous weak collisions during the whole process, as shown in **Fig. 1**. In the early stage, wear debris contributes to the formation of top crushed layer. In the middle stage, it acts as the solid lubricant and buffer layer among spheres, slowing down the friction and wear. And in the later stages, as the raw material, it participates in the formation of self-assembled layers to protect the ball. Numerous weak collisions which are an important characteristic of collective frictional friction, accelerate fatigue wear in the early stage, and directly lead to the formation of crack networks in the middle stage. They eventually promote the formation of the new layer in the later stages.

The research results not only provide an important experimental technical method for the evaluation of friction and wear behavior of the granular spallation target, but also provide an important scientific reference for the evaluation of service life of tungsten alloy balls as target from the perspective of tribology.

Prospective for future research directions

However, what has been discovered so far is merely the tip of the iceberg. We believe that there are still many interesting points in future research. For example, the new layer formed on the surface is proved to be of great interest, because it will play a great role in the later friction and wear behavior of the ball. Although our previous research [**12**] shows that with the interaction force among balls in the range of 0.001 ~ 0.004 N, 3000 hours and the temperature of 250 ^{o}C, the new layer formed on the surface of the sphere can reach about 200 nm thick, we don't think that these are the only experimental conditions for the formation of the new layer.

First, although we have depicted the rough formation mechanism of the new layer, more evidence is needed to deeply understand its formation process in detail, especially during the stage of the sintering process.

Second, what is the evolution of the new layer in longer term experiment? Will it be thickening, wearing away, or reaching a dynamic equilibrium?

Third, what is the influence of the relative velocity of the sphere and the pipeline on the new layer formation? Faster velocity will cause the higher frequency of weak collision, and faster rolling and sliding. So, the faster velocity may favor the formation of the new layer at the beginning. But in the long run, faster velocity will cause to wear it away quicker.

Fourth, the influence of temperature is also very important for the formation of the new layer. There are hardly any new layers formed on the surface of the ball according to our obtained experimental results at room temperature (unpublished). Therefore, high temperature environment is conducive to the formation of the new layer. If the experimental temperature is higher, for instance, 400 ℃, it may promote the formation of the new layer faster. Meanwhile, high temperature will reduce the brittleness of tungsten and increase its ductility, which can inhibit the propagation of surface cracks, slowing down the formation of micro-crack networks. Therefore, the high temperature environment is more likely to reduce the wear of the sphere.

Fifth, can new layers still be formed under conditions of complex flow states, including dense flow, sparse flow, and intermediate states? In the state of sparse flow, the number of collisions is drastically reduced, but the collision is intensified and the interaction force is increased. This will result in strong vibrations and impacts, which cause nano wear debris falling off the surface of the sphere, and the wear debris is the raw material for the formation of the new layer. If there is too much sparse flow in conditions of complex flow states, it may be not conducive to the formation of the new layer. So, whether new layers can form will depend on the proportion of different flow states.

Sixth, with the participation of oxygen under the air atmosphere, what will happen to the collective friction and wear behavior of the balls? This may lead to changes in wear mechanisms, such as oxidative wear. In addition, wear debris is also prone to oxidation reactions to form metal oxides, which will influence the formation of the new layer. Therefore, it is possible that the participation of oxygen may eventually accelerate wear.

Besides the formation of the new layer, there are other interesting points.

Seventh, what are the differences between brittle and ductile materials during the formation of crack networks? Numerous weak collisions are greatly responsible for the formation of crack networks near-surface of spheres. Since the surface of the tungsten alloy ball is almost tungsten material, a brittle material, it is easy to propagate for micro-cracks under numerous weak collisions, forming crack networks. However, if the outer surface of the sphere is a ductile material, the formation of crack networks may be different.

Eighth, what happens to the collective friction and wear behavior under irradiation conditions? As a spallation target material, these tungsten alloy balls will inevitably face strong irradiation. Particle irradiation can generate a large number of defects in material, resulting in changes in microstructure of the material, which are able to drastically affect the friction and wear properties of tungsten alloy balls. However, many difficulties will be faced for studying the collective friction and wear of balls under irradiation conditions. One of the biggest difficulties is how to couple the collective motion of the balls and the particle irradiation, and the corresponding irradiation experimental technology is also needed to develop.

Ninth, what influence will the environmental humidity create? The environment of spallation target is usually dry, so the influence of humidity can be ignored. However, if it is necessary to study the collective friction and wear of balls in other environments in the future, the humidity will be an important factor worthy of careful study. The presence of water vapor, on the one hand, has a certain lubricating effect on reducing wear, on the other hand, is likely to have an impact on the formation of the new layer.

CONCLUSIONS

The collective friction and wear of granular matter is a new field of tribology research. At present, this research field has not received much attention. Here we only take tungsten alloy balls as an example to provide several research directions in the future. It is hoped that more researchers will participate in this research field and more new discoveries to look forward to in the future.

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CONFLICTS OF INTEREST

There are no conflicts to declare.

SUPPORTING INFORMATION

Supporting informations are available online at journal website.

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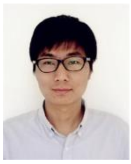

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GRAPHICAL ABSTRACT

Schematic illustration process of wear evolution of tungsten alloy balls (middle), roles of wear debris (right) and roles of numerous weak collisions (left) during the wear process.