We are IntechOpen, the world’s leading publisher of Open Access books
Built by scientists, for scientists

4,200 Open access books available
116,000 International authors and editors
125M Downloads

154 Countries delivered to
TOP 1% Our authors are among the most cited scientists
12.2% Contributors from top 500 universities

WEB OF SCIENCE™
Selection of our books indexed in the Book Citation Index in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com
High-performance Self-lubricating Ceramic Composites with Laminated-graded Structure

Yongsheng Zhang, Yunfeng Su, Yuan Fang, Yae Qi and Litian Hu

Abstract

High-performance ceramic composites are potential candidates for the application of wear-resistant components because of their excellent properties. Nevertheless, many problems, such as high friction coefficient of ceramic material and poor mechanical properties of ceramic-matrix self-lubricating composites, limit a wider range of applications of these composites in tribological areas. Therefore, improving high-toughness ceramic-matrix self-lubricating materials for practical applications is significant. This study proposes a new design for ceramic self-lubricating composites to overcome the conflict between their mechanical and tribological properties. Complying with the design principle of bionic and graded composites, two kinds of self-lubricating ceramic composites with laminated-graded structure were prepared, and their mechanical and tribological properties were studied. The results show that this newly developed ceramic composite has achieved satisfactory strength and tribological properties compared with the traditional ceramic self-lubricating composites. The bending strength reached the same level as the properties of general monolithic ceramics. In the temperature range of 25-800 °C, the friction coefficient of composites was less than 0.55, which was about half of that of monolithic ceramics.

Keywords: Functionally graded material, Laminated structures, Ceramic, High temperature, Self-lubricating

1. Introduction

Ceramic materials are promising candidates for wear-resistant components owing to their excellent properties such as high strength and resistance to corrosion and oxidation stability at high temperature. Nevertheless, both the high coefficient of friction of this kind of material under dry sliding and the brittleness of ceramic-matrix itself limit its practical application in
tribological areas. Generally, incorporating solid lubricants (SLs) in ceramic matrixes solves the friction problems, which can reach a positive effect. Moreover, compound lubricants can exhibit excellent self-lubricating abilities in a wide range of temperatures because the lubricants can promote the formation of well-covered lubricating films on the surfaces of ceramics that can work effectively under different temperature [1-3]. Unfortunately, subsequent studies have shown that these composites are homogenous in terms of mechanical and tribological properties. Thus, the strength of ceramics and the lubrication of SLs cannot be fully utilized. Because the continuity of ceramic phases is destroyed by the layered structural SL phase, the mechanical property of this type of material is reduced [4,5]. In these situations, it is necessary to develop a high-strength and high-toughness self-lubricating ceramic composites.

Lamination is one of the new strategies being used to enhance the mechanical properties of ceramics. The ideas of laminated composites inspired from natural biomaterials, such as shells and teeth, are made of layered architectures combining materials with different properties. During the past decade, there are large amounts of layered ceramic composites that have been fabricated and studied [6-8]. These kinds of materials have non-catastrophic fracture behavior and damage tolerance, which exhibit much higher fracture toughness and work of fracture in them than in monolithic ceramics. Moreover, the unique configurations of the layered material allow design flexibility. Therefore, the combination of the laminated design of ceramic materials and self-lubricating ceramic composites with excellent lubricating property is a promising way to achieve the integration of mechanical and tribological properties [9-12].

For laminated self-lubricating ceramic composites, interfacial residual stress between the adjacent layers may have an important effect on their mechanical properties. Any modification or change of the interfacial structure and composition will be a determining factor in the strength of the interfacial bond and will eventually affect the toughness, strength, and fracture behavior of laminated composites [13]. Therefore, a reasonable residual stress between the adjacent layers is essential to improve the mechanical properties. Previous studies have shown that the graded design of the materials is an effective method to eliminate the interface stress of dissimilar material system [14-16]. This design concept of functionally graded materials (FGMs) was first raised by Japanese scientists in 1987 as reported in reference [14]. That is, components with different properties or structures disperse by a gradient change along with one direction instead of a homogeneous manner. Thus, the composite can exhibit different properties that are mutually exclusive at the same time, and the gradient change can eliminate the interface between components. This new-style and non-uniform composite realized the integration of structure and function, making it to have a wider prospect of application in extreme conditions.

Based on the above background, the authors prepared high-performance structural/lubricating-functional integration ceramic composites using the design of graded laminated structure [4,17,18]. This design is conductive to the combination of mechanical and tribological properties while retaining all the advantages of these materials. The aim of this chapter is to illustrate the design, fabrication, and properties of alumina and zirconia self-lubricating composites with laminated-graded structure and to provide guidance for the optimum design of these materials.
2. Design, fabrication, and properties of laminated ceramic composites

2.1. Design and fabrication of laminated composites

Figure 1 illustrates the schematic and the design concept of laminated composites. The thickness of the A layer and B layer are \(d_1\) and \(d_2\), respectively, where the A layer is the \(\text{Al}_2\text{O}_3\) or \(\text{ZrO}_2\)-\(\text{Al}_2\text{O}_3\) and the B layer is \(\text{Al}_2\text{O}_3\)-\(\text{ZrO}_2\) or \(\text{ZrO}_2\). Commercially available \(\text{Al}_2\text{O}_3\), \(\text{ZrO}_2\), \(\text{Y}_2\text{O}_3\), CuO, and TiO\(_2\) were used in this study. The material was manufactured using the following steps [17-20]: (1) ball-milling of powder, (2) sequential stacking of layers in steel mold, and (3) hot-pressing in graphite mold. Hot-pressing was performed at 1350-1400 °C and 25 MPa using graphite die in an argon atmosphere for 100-120 minutes. Monolithic \(\text{Al}_2\text{O}_3\) and \(\text{ZrO}_2\) with sintering aids were also sintered at same condition as comparisons. The microstructures of the composites were observed using scanning electron microscopy (JSM-5600LV). The sintered specimens were sliced into test bars for bending strength and work of fracture.

![Figure 1. Schematic of laminated composite structure.](image)

An example of the microstructure of the \(\text{ZrO}_2\)(3Y)-\(\text{Al}_2\text{O}_3\)/\(\text{ZrO}_2\)(3Y)-laminated composites is shown in Figure 2, where the dark layer is the \(\text{ZrO}_2\)(3Y)-\(\text{Al}_2\text{O}_3\) layer and the light layer is the \(\text{ZrO}_2\)(3Y) layer. The multilayer structure with a relatively straight interface can be observed without clear delamination. It can also be seen from Figure 2 that the \(\text{ZrO}_2\)(3Y)-\(\text{Al}_2\text{O}_3\) layer and \(\text{ZrO}_2\)(3Y) layer have the same thickness of approximately 160 μm.

2.2. The mechanical properties of laminated composites

The geometric parameters of the layered structure are the key factors for the optimal design of laminated composites. These parameters mainly include the layer numbers and thickness ratio of the two layers. The mechanical properties of \(\text{Al}_2\text{O}_3/\text{Al}_2\text{O}_3-10\text{wt.\% ZrO}_2\)(3Y)-laminated composites with different layer numbers are shown in Figure 3 [19,20]. As shown in Figure 3, a relatively large number of layers are likely to improve the mechanical properties of the materials. When the number of layers is 41, the bending strength and work of fracture of materials reach the maximum value. The relationship between the mechanical properties and
layer thickness ratio is displayed in Figure 4 [19,20]. One can see that the layer thickness ratio also has an enormous effect on the mechanical properties of laminated composites. The bending strength and work of fracture of all of the laminated materials are higher than that of the monolithic materials and decrease with the increase of the layer thickness ratio. When the layer thickness ratio is 1:1 and the thickness of each layer is 80 μm, the bending strength and work of fracture of the Al\(_2\)O\(_3\)/Al\(_2\)O\(_3\)-ZrO\(_2\) (3Y) laminated composites could reach to 740 MPa and 3892 J m\(^{-2}\), respectively [19,20].

![Figure 2. SEM photograph of profile of laminated composites.](image)

In addition, the compositions of the two layers also have significant effects on the mechanical properties of the laminate composites. The bending strength and work of fracture of Al\(_2\)O\(_3\)/Al\(_2\)O\(_3\)-ZrO\(_2\) (3Y)-laminated composites with different content of ZrO\(_2\) (3Y) in Al\(_2\)O\(_3\)-ZrO\(_2\) (3Y)
layers are shown in Figure 5 [19,20]. As can be seen from the figure, with the increase of the content of ZrO$_2$(3Y), first, the bending strength and work of fracture of the material increase and then they decrease gradually. When the mass content of ZrO$_2$(3Y) is 10%, both bending strength and work of fracture reach the optimal value. This is mainly because the variation of content of ZrO$_2$(3Y) in Al$_2$O$_3$-ZrO$_2$(3Y) layers causes significant changes in the residual stresses between adjacent layers and the contribution of phase transformation toughening to the crack propagation energy of the materials, thus realizing the optimization of the materials [19,20].
ZrO$_2$(3Y)-Al$_2$O$_3$ layers is 15%, the bending strength and work of fracture of the ZrO$_2$(3Y)-Al$_2$O$_3$/ZrO$_2$(3Y)-laminated composite reach to 968 MPa and 3751 J m$^{-2}$, respectively (Fig. 6a and b).

Figure 6. Mechanical properties of ZrO$_2$(3Y)-Al$_2$O$_3$/ZrO$_2$(3Y)-laminated composites and monolithic ceramic.

3. Graded structure and tribology design for optimal lubricating properties in laminated ceramic composites

3.1. Design and preparation of laminated-graded self-lubricating ceramic composites

From the results above, it can be concluded that the layered structure design is a good strategy to enhance the mechanical properties of monolithic ceramics, which can efficiently improve the bending strength and work of fracture. Nevertheless, the friction and wear rate of these materials under dry sliding conditions are still high. To overcome this problem, the laminated-graded structure self-lubricating ceramic composites were designed. Figure 7 shows the schematic of self-lubricating ceramic composites with laminated-graded structure, where $d_1=d_2$, the A layer is the Al$_2$O$_3$ or ZrO$_2$-Al$_2$O$_3$, and the B layer is Al$_2$O$_3$-ZrO$_2$ or ZrO$_2$. The center area is composed of laminated composites that are similar to that of in the section 2, which provides high strength for the whole material. The content of SLs is graded, increased from center to two sides, and finally reaches a fixed value on the surface to ensure the excellent lubricating function of the materials. In this study, each couple of ZrO$_2$(3Y)-Al$_2$O$_3$ and ZrO$_2$(3Y) or Al$_2$O$_3$ and Al$_2$O$_3$-ZrO$_2$ has the same SL content. The SL content of each couple $f(x)$ is determined by the following equation [18]:

$$f(x) = (x/m)^p \times f(s)$$  \hspace{1cm} (1)

Where $x$ is the number of the couple, $m$ is the total number of the couples in the gradient area, $p$ is the gradient exponent, and $f(s)$ is the content of SLs in surface layers. Commercially
available Al₂O₃, ZrO₂, Y₂O₃, CuO, TiO₂, and SLs (graphite+CaF₂+BaSO₄ and graphite+CaF₂ in
two kinds of laminated-graded structure self-lubricating ceramic composites, respectively) were used. Experimental details for preparation and characterization are described in these references [17, 18].

Figure 7: Schematic of the laminated-graded structure self-lubricating composites.

3.2. The mechanical and tribological properties of traditional self-lubricating ceramic composites

For comparison, the mechanical and tribological properties of traditional self-lubricating ceramic composites were first conducted. Figure 8 shows the microstructure of two kinds of traditional self-lubricating ceramic composites. It can be seen that there are lots of tiny pores in the sintered samples. There is no doubt that these defects will greatly degenerate the mechanical properties of the materials. The mechanical properties of two kinds of traditional self-lubricating ceramic composites (Al₂O₃-graphite and Al₂O₃-LaF₃ composites) are given in Figure 9. It can be seen clearly that the bending strength and work of fracture decrease rapidly with the increase of the content of SLs. For the Al₂O₃-LaF₃ composites, when the volume content of lubricants increase to 40%, the bending strength and work of fracture reduced to as low as 67 MPa and 44 J m⁻², which were 6.3 and 2.9 times lower than those of monolithic Al₂O₃ ceramic. Therefore, the traditional self-lubricating ceramic composites exhibit poor mechanical properties mainly because of the lots of SLs that destroyed the continuity of ceramic matrix. The ceramic composites may exhibit good lubricating properties when proper amounts of lubricants were added [1,4]. Nevertheless, this kind of ceramics possesses poor anti-destructive and reliability, which is the key obstacle to its practical application. Therefore, as mentioned
earlier, improving high-strength and high-toughness ceramic-matrix self-lubricating materials for practical applications is significant.

Figure 8. SEM micrographs of fracture surface of traditional Al\textsubscript{2}O\textsubscript{3}-graphite (a) and Al\textsubscript{2}O\textsubscript{3}-LaF\textsubscript{3} (b) self-lubricating ceramic composites.

Figure 9. Mechanical properties of Al\textsubscript{2}O\textsubscript{3}-graphite (a) and Al\textsubscript{2}O\textsubscript{3}-LaF\textsubscript{3} (b) self-lubricating composites.

3.3. The performance of laminated-graded structure self-lubricating ceramic composites

Compared to the traditional self-lubricating ceramic composites, laminated-graded structure self-lubricating ceramic composites exhibit excellent mechanical properties. Table 1 describes the bending strength of Al\textsubscript{2}O\textsubscript{3}-laminated-graded structure self-lubricating ceramic composites and of some monolithic self-lubricating ceramic composites. It can be seen from Table 1 that the bending strength of laminated-graded structure self-lubricating ceramic composites are much higher than any one of monolithic materials. The bending strength reached 348 MPa, which is approximately five times higher than that of the traditional monolithic Al\textsubscript{2}O\textsubscript{3}/SL and Al\textsubscript{2}O\textsubscript{3}-ZrO\textsubscript{2}(3Y)/SL ceramics, and which basically approached the properties of general monolithic Al\textsubscript{2}O\textsubscript{3} and Al\textsubscript{2}O\textsubscript{3}-ZrO\textsubscript{2}(3Y) ceramics [17].
Additionally, the gradient exponent $p$ has a remarkable influence on the mechanical properties of laminated-graded structure self-lubricating composites [18]. As shown in Figure 10, the bending strength of the $\text{ZrO}_2$(3Y)-$\text{Al}_2\text{O}_3$/ZrO$_2$(3Y)/SL FGM increased, with the increase of $p$ up to 2.0, and then decreased rapidly when $p$ exceeds 2.0. This phenomenon is caused by the residual stress between the adjacent layers in gradient area. The variation of $p$ causes the change of content of SLs in gradient layers, and then the residual stress that is generated from the thermal mismatch because of the difference in thermal expansion coefficients between the adjacent graded layers (as shown in Figure 11) is influenced. This shows that a reasonable residual stress is essential to adjust the mechanical properties of these materials.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Bending strength (Mpa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{Al}_2\text{O}_3$/10wt.%$\text{ZrO}_2$(3Y)/SL FGMs</td>
<td>348</td>
</tr>
<tr>
<td>$\text{Al}_2\text{O}_3$/SL</td>
<td>68</td>
</tr>
<tr>
<td>$\text{ZrO}_2$(3Y)-$\text{Al}_2\text{O}_3$/SL</td>
<td>69</td>
</tr>
</tbody>
</table>

Table 1. Bending strength of laminated-graded structure self-lubricating ceramic composites [17].

The laminated-graded structure ceramics not only showed excellent mechanical properties, it also maintained good tribological performance. As shown in Figure 12, in the temperature range of 25–800 °C, the friction coefficient of $\text{Al}_2\text{O}_3$ and $\text{ZrO}_2$(3Y) laminated-graded structure composite was less than 0.55, which was approximately half of that of monolithic $\text{Al}_2\text{O}_3$ and $\text{ZrO}_2$ ceramics. The decrease of friction coefficients were achieved by the presence of graphite, CaF$_2$, and BaSO$_4$, which have excellent lubricating property under different temperatures.
Graphite has a good lubricating property at room temperature to 300 °C, and \( \text{CaF}_2 \) at 250 °C to 1000 °C. In addition, \( \text{BaSO}_4 \) also possesses excellent self-lubricating performance over a broad temperature range. During the sliding process, these SLs form the self-lubricating film that is helpful to reduce direct contact between the ceramics and further improved the tribological properties of the materials [17,18].

Figure 11. Variation of the difference value of coefficients of thermal expansion between the adjacent layers with the gradient exponent \( \rho \) [18].

Figure 12. The friction coefficients of two kinds of laminated-graded self-lubricating composites at room temperature to 800 °C.
In conclusion, laminated-graded structure self-lubricating ceramic composites realize the integration of mechanical and tribological properties. Their excellent mechanical and tribological properties indicate that the laminated-graded structure self-lubricating ceramic composites have numerous high-technology applications and promising prospect as structural materials.

Acknowledgements

The authors acknowledge the financial support from the Foundation for National Innovation of Chinese Academy of Sciences (CXJJ-15M059), the Gansu Province Science Foundation for Youths (1107JYA043) and the Youth Innovation Promotion Association CAS (2013272).

Author details

Yongsheng Zhang*, Yunfeng Su, Yuan Fang, Yae Qi and Litian Hu

*Address all correspondence to: zhysh@licp.cas.cn

State Key Laboratory of Solid Lubrication, Lanzhou Institute of Chemical Physics, Chinese Academy of Sciences, Lanzhou, China

References


