Preparation of chameleon coatings for space and ambient environments

C.C. Baker⁠, R.R. Chromik, K.J. Wahl, J.J. Hu, A.A. Voevodin

North Carolina State University, Department of Physics, Raleigh, NC 27695, United States
U.S. Air Force Research Laboratory, Materials and Manufacturing Directorate, Wright Patterson Air Force Base, OH 45433, United States
U.S. Naval Research Laboratory, Code 6176, Tribology Section, Washington, DC 20375, United States

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Abstract

Tribological coatings of yttria-stabilized zirconia (YSZ), Au, diamond like carbon (DLC) and MoS₂ were synthesized using magnetron assisted pulsed laser deposition. The coatings were synthesized in four-component and three-component combinations that included YSZ/Au/DLC/MoS₂, YSZ/Au/MoS₂, and YSZ/Au/DLC. A range of coating compositions was studied to explore coating optimization for low friction in varying environments (dry, humid and high temperature). For four-component YSZ/Au/DLC/MoS₂ coatings, the optimal compositions for friction adaptation between dry nitrogen and humid air included relatively high concentrations of the soft phase, Au (>20 at.%), and low amounts of the hard phases, DLC and YSZ. Ex situ Raman spectroscopy analysis indicates that friction adaptation involves a combination of both lubricating species, MoS₂ and carbon, where transitions of DLC to graphitic-carbon and amorphous MoS₂ to its hexagonal phase occur after cycling between both room temperature humid air and dry nitrogen. In large carbon concentrations (>30 at.%), the DLC component was found to be detrimental for friction in dry nitrogen and humid air, but promoted a longer coating wear life at 500 °C. The three-component coating of YSZ/Au/MoS₂ performed well in both dry nitrogen and humid air, suggesting a synergism between Au and MoS₂, where carbon was not necessary for lubrication in humid air.

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1. Introduction

One current challenge in tribological coatings research is to obtain coatings with low coefficients of friction (c.o.f.) in varying environmental conditions. This is especially important for aerospace applications. Satellites that are designed for hard vacuum in space are also exposed to moisture during launch as well as extreme temperature fluctuations. Solid lubricants that impart low friction behavior in one environment do not generally perform well in another. For example, dichalcogenides like WS₂ and MoS₂, can provide low friction in vacuum conditions, but do not work well in high humidity environments by themselves [1,2]. Similarly, graphite can provide low friction in humid air but not in vacuum. For such applications a composite coating that can adapt itself to provide good friction and wear performance in multiple environments is desirable.

We have previously reported on adaptive “chameleon” nanocomposite coatings where excellent tribological properties are achieved in varying environments [3–10]. These coatings have a combination of solid lubricant components that give low coefficients of friction in both humid environments and in vacuum or dry nitrogen (simulating space environments). The coatings also have nanocrystalline oxide phases that impart high hardness and wear resistance. A nanocomposite system of particular interest includes yttria-stabilized zirconia (YSZ), diamond like carbon (DLC), and MoS₂. This coating system provided good friction properties in dry and humid conditions and survived up to 10,000 cycles at elevated temperatures [10]. The addition of Au was found to be essential for lowering the coefficient of friction at high temperatures and extending the coating lifetime [10].
Previously, four-component coatings were studied over a relatively small range of compositions [10]. Here we report a study on the properties of a four-component system in a broader range of compositions, maintaining MoS\textsubscript{2} around 14–18% while varying Au, YSZ and DLC contents. We also report on the three-component systems YSZ/Au/MoS\textsubscript{2} and YSZ/Au/DLC in order to examine the role of both MoS\textsubscript{2} and carbon for lubrication in this particular coating system. Measurements of the friction coefficient during humidity cycling and separate high temperature experiments were used to determine which coatings were good candidates for aerospace applications.

2. Experimental details

YSZ/Au/DLC/MoS\textsubscript{2}, YSZ/Au/MoS\textsubscript{2}, and YSZ/Au/DLC coatings were prepared in a vacuum chamber using magnetron assisted pulsed laser deposition (MSPLD) [11]. The chamber was initially pumped down to a base pressure of $7 \times 10^{-6}$ Pa or less. The samples were grown on various mirror-polished 24.5 mm diameter substrates including 440C steel, 52100 steel, M50 steel, (001) silicon, and Inconel 718. The substrates were cleaned in an acetone bath for 30 min prior to mounting in the chamber, where they were cleaned with energetic argon $\leq -800$ V and Ti ions at $\leq -650$ V. During deposition, substrates were biased at $-150$ V with respect to ground and heated to either 150 °C or 300 °C. The purpose of the increase in deposition temperature was to promote coating crystallization.

Sectioned targets were used for laser ablation with quarter circles of YSZ (ZrO\textsubscript{2}–5 wt.% Y\textsubscript{2}O\textsubscript{3}), MoS\textsubscript{2}, and graphite, while Au was deposited using magnetron sputtering. For the four-component coatings, the target consisted of two quarter sections of YSZ, one quarter section of MoS\textsubscript{2}, and one quarter section of carbon. For the three-component coatings the target consisted of two quarter sections of YSZ and one half section of either carbon or MoS\textsubscript{2}. Laser ablation was performed with a KrF laser operated with radiation of 248 nm, 800 mJ in pulsed mode with 25 ns wide pulses, and a repetition rate of 40 Hz. Magnetron sputtering was performed with a Au target at powers of 3–6 W/cm\textsuperscript{2}. Composition control was achieved by varying the magnetron power to obtain between 10% and 35% Au to the coatings. Depositions were performed in an Ar atmosphere. A filtered vacuum arc system was used to both clean the substrates and deposit a Ti transition layer between the substrate and coating. This is effective in providing good coating adhesion and film stress reduction [12]. A schematic of the deposition chamber with the vacuum arc system is given in Fig. 1. Here a Ti cathode was evaporated with 125 A current, generating a Ti plasma. Titanium ions were guided by an electromagnetic field around a 90° turn to filter out droplets from reaching the substrates. For cleaning, the substrates were biased at $\leq -650$ V and bombarded with Ti ions from the arc source. The bias was then reduced stepwise to that of the growth bias, $-150$ V, and a Ti/YSZ/C/MoS\textsubscript{2} transition layer was produced by gradually increasing the laser repetition rate to the YSZ/C/MoS\textsubscript{2} ablation target during deposition with the arc source. Finally, for sample deposition, the arc source was shut off, and the magnetron was turned on for deposition of Au. The Ti layer is generally $\sim 100$ nm thick and the graded layer is $\sim 300$ nm thick. The coatings were generally $\sim 1–2$ µm thick.

Chemical analysis of the coatings was investigated with a Surface Science Instruments M probe X-ray photoelectron spectrometer (XPS) using Al k\textalpha\textsubscript{2} radiation at 1487 eV. Prior to analysis the samples were sputter cleaned for 60 s with 1000 eV Ar\textsuperscript{+} ions. Coating compositions were calculated using intensity factors from area analysis of C 1s, O 1s, Zr 3d doublet, Au 4f doublet, Mo 3d doublet, S 2p doublet, and Y 3d doublet peaks. Coating microstructure was analyzed with X-ray diffraction (XRD) using a Rigaku diffractometer and Cu k\textalpha\textsubscript{α} radiation in the 2θ–2θ mode. High resolution transmission electron microscopy (HRTEM) and selected area diffraction (SAD) were performed on a Philips CM200 microscope to identify phases present in the coatings. Micro-Raman spectroscopy was performed on a Renishaw Ramascope 2000 equipped with a 514.5 nm laser. Raman shift scattering was recorded from 200 to 2000 cm\textsuperscript{-1}.

Friction coefficient was measured using ball on disc tribometers with a 1 N load applied to M50 steel balls (radius=3.175 mm) and a sliding rate of 0.4 m/s. The Hertzian contact stress was estimated to be $\approx 0.43$ GPa for steel vs. steel. The tests were run during cycling in air at 40% relative humidity (RH), and nitrogen at $<1$% RH. High temperature tests (in air at 500 °C) used a Si\textsubscript{3}N\textsubscript{4} ball (radius=3.175 mm) loaded to 1 N and sliding speed of 0.2 m/s.

Nanoindentation was performed using a Hysitron Ubi scanning indenter. Indentations were conducted on sections of wear tracks that had been run for 100 cycles. These areas were used because there was minimal wear and the surface was smoother than the as-prepared coating. An exception was the YSZ/Au/DLC coating, which was much smoother than the other coatings; indentation experiments on this coating were done on the as-prepared sample. Indentation load functions consisted of loading at 0.2 mN/s to either 1.0 mN or 2.0 mN maximum load, a hold segment of 2 s, followed by unloading at 0.2 mN/s. The load function with 2.0 mN maximum load
resulted in depths of penetration on the order of 120 nm, or approximately 5–15% of the total coating thickness. Arrays of indents were spaced 5 μm apart and were followed by post-indentation imaging using the scanning capability of the indenter system. Indents found to be near coating defects or obvious track damage or debris were discarded from each dataset. Average hardness and modulus values reported here were calculated from at least 30 indents, all analyzed using the standard Oliver and Pharr method[13]. The indenter tip was a diamond Berkovich with a nominal tip radius of 100 nm. Calibration of the tip area function was conducted on a fused silica specimen.

3. Results

3.1. Preparation, chemistry, structure and mechanical properties

Eight different coating compositions were studied and are listed in Table 1. The coatings are classified as “high Au” and “low Au”. The high Au coatings had 23–34 at.% Au, and the low Au coatings had 10–14 at.% Au as determined by XPS. Note that among the high Au coatings are the three-component coatings YSZ/Au/MoS2 and YSZ/Au/DLC.

XPS results were examined in more detail to determine the chemical state of the various elements in the coatings. The C 1s peak was found at binding energies of 284.5 eV for all coatings which is consistent for C–C bonds with no evidence for carbide formation. The Zr 3d5/2 peak was consistent with ZrO2 which has a binding energy of 182.4 eV, and the Au doublet was consistent with literature values for metallic Au. The sulfur 2p doublet had a binding energy of 161–163 eV, consistent with a sulfide. However, we note that the Mo 3d5/2 peak was found at 228–228.3 eV indicating that Mo exists with a stoichiometry as MoSx with x < 2. This may be a result of preferential sputtering of the sulfur during sample cleaning in the XPS chamber[14].

A HRTEM image corresponding to a low Au sample ((YSZ)0.33(Au)0.14(MoS2)0.15(C)0.36) is shown in Fig. 2 along with a selected area electron diffraction pattern. The image shows dark regions composed of Au nanocrystals in an amorphous matrix. The interplanar spacing is highlighted and also indicates Au. From these HRTEM studies only Au was found to exist in nanocrystalline form, and carbon, YSZ, and

<table>
<thead>
<tr>
<th>Sample composition</th>
<th>Growth T (°C)</th>
<th>Hardness (GPa)</th>
<th>Reduced modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Au</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(YSZ)0.34(Au)0.24(MoS2)0.17(C)0.24</td>
<td>150</td>
<td>3.0±0.4</td>
<td>66±7</td>
</tr>
<tr>
<td>(YSZ)0.31(Au)0.31(MoS2)0.16(C)0.11</td>
<td>300</td>
<td>3.9±0.2</td>
<td>90±4</td>
</tr>
<tr>
<td>(YSZ)0.33(Au)0.34(MoS2)0.14(C)0.17</td>
<td>150</td>
<td>3.2±0.3</td>
<td>91±8</td>
</tr>
<tr>
<td>(YSZ)0.41(Au)0.23(MoS2)0.35</td>
<td>150</td>
<td>3.4±0.5</td>
<td>74±4</td>
</tr>
<tr>
<td>(YSZ)0.39(Au)0.28(C)0.31</td>
<td>150</td>
<td>7.0±1.0</td>
<td>110±10</td>
</tr>
<tr>
<td>Low Au</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(YSZ)0.33(Au)0.14(MoS2)0.15(C)0.36</td>
<td>150</td>
<td>4.8±0.3</td>
<td>105±9</td>
</tr>
<tr>
<td>(YSZ)0.45(Au)0.10(MoS2)0.14(C)0.30</td>
<td>150</td>
<td>6.3±0.8</td>
<td>121±12</td>
</tr>
<tr>
<td>(YSZ)0.39(Au)0.10(MoS2)0.14(C)0.11</td>
<td>300</td>
<td>5.2±0.7</td>
<td>133±11</td>
</tr>
</tbody>
</table>
MoS₂ exist in a mostly amorphous state within the region examined. In the SAD pattern rings are indexed to Au.

XRD results for two samples are presented in Fig. 3. The patterns correspond to a high Au sample ((YSZ)₀.₄₂(Au)₀.₃₁(MoS₂)₀.₁₆(C)₀.₁₁) and a low Au sample ((YSZ)₀.₅₉(Au)₀.₁₀(MoS₂)₀.₁₈(C)₀.₁₁). Broad peaks corresponding to Au are evident for both coatings. For the low Au sample with 59% YSZ the (111) ZrO₂ peak is evident at $2\theta \approx 30^\circ$, which gives a close match to the P4m2 tetragonal symmetry with lattice parameters $a=0.512$ nm and $c=0.525$ nm [15,16]. This sample represents the maximum in YSZ obtained for all coatings in this study. All other samples showed no diffraction peak for YSZ and thus these elements were part of the amorphous matrix, consistent with prior studies of YSZ/Au nanocomposites [9,17]. Note that a small peak for metallic molybdenum is also evident. This may be the result of occasional Mo droplets from the PLD process [10].

Nanoindentation measurements of the hardness and modulus of the low and high Au coatings revealed distinct differences between the two coating sets (see Table 1). The high Au YSZ/Au/DLC/MoS₂ coatings were found to have moduli of about 70–90 GPa and hardness values between 3 and 4 GPa. The YSZ/Au/MoS₂ coating had similar mechanical properties to the four-component high Au coatings. The YSZ/Au/DLC coating was much harder and stiffer than the other high Au coatings. This coating was more similar in mechanical properties to the low Au coatings, which were found to have moduli of roughly 100–130 GPa and hardness values of 5–6 GPa.

3.2. Tribological properties

3.2.1. Four-component coatings

In Table 2 we present the average friction coefficient results for all coatings. The values were determined after 10,000 sliding cycles in humid air and dry nitrogen. The table also gives values for the friction and cycles to failure in air at 500 °C for several coatings. Coating failure and friction spiking are also indicated with letters a and b respectively.

From all of the coatings studied, the four-component coatings with high Au content had the lowest and most stable friction. On the other hand, low Au coatings with either high carbon or high YSZ content were found to have friction spikes and in one case an extended run-in stage at high friction ($\mu \sim 0.4$). Spiking and extended run-in occurred in dry nitrogen for the coating with 36 at.% carbon and low Au. Spiking also occurred in humid air for two coatings with high YSZ content ($\geq 45\%$) and low Au. Examples of two coatings showing

<table>
<thead>
<tr>
<th>Sample composition</th>
<th>Thickness</th>
<th>c.o.f. humid air</th>
<th>c.o.f. dry nitrogen</th>
<th>c.o.f. air 500 °C</th>
<th>Cycles to failure 500 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Au</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(YSZ)₀.₃₄(Au)₀.₂₄(MoS₂)₀.₁₇(C)₀.₂₄</td>
<td>2.67</td>
<td>0.1–0.13</td>
<td>0.02</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>(YSZ)₀.₄₂(Au)₀.₃₁(MoS₂)₀.₁₆(C)₀.₁₁</td>
<td>1.73</td>
<td>0.1–0.11</td>
<td>0.03–0.04</td>
<td>0.2–0.3</td>
<td>700</td>
</tr>
<tr>
<td>(YSZ)₀.₃₃(Au)₀.₄₃(MoS₂)₀.₁₄(C)₀.₁₇</td>
<td>1.45</td>
<td>0.1–0.11</td>
<td>0.02–0.03</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>(YSZ)₀.₄₁(Au)₀.₂₃(MoS₂)₀.₁₅</td>
<td>3.01</td>
<td>0.1</td>
<td>0.01–0.02</td>
<td>0.1–0.3</td>
<td>1200</td>
</tr>
<tr>
<td>(YSZ)₀.₃₉(Au)₀.₂₈(C)₀.₃₁</td>
<td>1.19</td>
<td>a</td>
<td>0.15</td>
<td>1800</td>
<td></td>
</tr>
<tr>
<td>Low Au</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(YSZ)₀.₃₃(Au)₀.₁₄(MoS₂)₀.₁₃(C)₀.₃₆</td>
<td>1.65</td>
<td>0.1–0.13</td>
<td>0.05(^b)</td>
<td>0.1–0.25</td>
<td>6200</td>
</tr>
<tr>
<td>(YSZ)₀.₄₅(Au)₀.₁₀(MoS₂)₀.₁₄(C)₀.₃₀</td>
<td>2.15</td>
<td>0.1(^b)</td>
<td>0.05</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>(YSZ)₀.₅₉(Au)₀.₁₀(MoS₂)₀.₁₄(C)₀.₁₁</td>
<td>–</td>
<td>0.1(^b)</td>
<td>0.05</td>
<td>0.15–0.25</td>
<td>1500</td>
</tr>
</tbody>
</table>

\(^a\) Indicates coating failure before 10,000 sliding cycles.
\(^b\) Indicates friction spikes.

![Fig. 4. A. Friction coefficient vs. sliding cycles showing friction spikes for coating (YSZ)₀.₃₉(Au)₀.₁₄(MoS₂)₀.₁₃(C)₀.₃₆ tested in humid air. B. Friction coefficient vs. sliding cycles showing extended run-in and friction spikes for sample (YSZ)₀.₃₃(Au)₀.₁₄(MoS₂)₀.₁₅(C)₀.₃₆ tested in dry nitrogen.](image-url)
spiking in humid air and extended run-in and spiking in dry nitrogen are given in Fig. 4A and B respectively.

In tribological testing of the nanocomposites at 500 °C, low friction of $\sim 0.1 - 0.3$ was observed for the coatings tested (Table 2). Coating endurance at this temperature was between 700 and 6200 sliding cycles, with the low Au coatings generally having longer endurance.

In order to simulate an aerospace application, friction tests were performed in varying humidity environments. For these experiments, the friction coefficient was recorded for up to 120,000 sliding cycles while the environment was repeatedly cycled between dry nitrogen at $<1\%$ RH and air at $40\%$ RH. A typical example is given for a four-component coating in Fig. 5, where cycling between the two conditions occurred every 20,000 cycles. The coefficient of friction for an optimal coating was observed to be $\sim 0.02 - 0.03$ in dry nitrogen and $0.1 - 0.15$ in humid air. The coating systems have been found to exhibit these low friction properties from 100,000 to 120,000 cycles depending on coating thickness.

![Fig. 5. Friction coefficient vs. sliding cycles for coating (YSZ)$_{0.33}$(Au)$_{0.34}$ (MoS$_2$)$_{0.14}$C$_{0.17}$ during cycling between dry nitrogen and humid air.](image)

![Fig. 6. Raman spectra for coating (YSZ)$_{0.33}$(Au)$_{0.34}$(MoS$_2$)$_{0.14}$C$_{0.17}$ both as prepared and for a wear track after humidity cycling from dry to humid to dry. Also, the Raman spectrum from a transfer film formed on the steel counterface during the same test.](image)

![Fig. 7. Coefficient of friction vs. sliding cycles for a three-component YSZ/Au/MoS$_2$ coating tested during cycling between dry nitrogen and humid air.](image)

Typical Raman spectra from the as-deposited coating, the wear track surface and the transfer film formed on the ball counterface for sample (YSZ)$_{0.33}$(Au)$_{0.34}$(MoS$_2$)$_{0.14}$C$_{0.17}$ taken after sliding in both environments are given in Fig. 6. Before sliding, only a weak carbon signature was obtained from the coating. After sliding, the wear track and transfer film showed peaks consistent with MoS$_2$ and graphite-like carbon, especially the transfer film. The broad overlapping peaks centered at 1380 and 1530 cm$^{-1}$ correspond to the D and G bands found in graphite-like carbon, while the peaks found in the region between 380 and 410 cm$^{-1}$ correspond to hexagonal MoS$_2$ [18]. With both species found in the spectrum after cycling between the two environments, the friction is likely controlled by both species acting synergistically. We note that in all experiments, the Raman spectra showed no indication of oxide formation in the coatings after environmental cycling. This is not surprising for these experiments where both the oxygen concentration of the coatings and the contact stress were low [19,20].

3.2.2. Three-component coatings

To test the endpoints of the friction behavior as a function of coating composition, coatings were deposited without carbon (YSZ/Au/MoS$_2$) and without MoS$_2$ (YSZ/Au/DLC). Both coatings were cycled in varying environments and the coefficient of friction measured. The YSZ/Au/DLC coating failed immediately in dry nitrogen, where the c.o.f. was 0.4. This coating also failed after only several hundred sliding cycles in humid air as well, with the c.o.f. greater than 0.2. Conversely, the YSZ/Au/MoS$_2$ coating had a friction performance that was comparable to the best YSZ/Au/DLC/MoS$_2$ coatings in this study as well as cycling tests (Fig. 7).

High temperature results for the three-component coatings are also included in Table 2. In this case the friction for both three-component coatings was comparable to the four-component coatings; however, the YSZ/Au/DLC coating had a slightly longer endurance than the YSZ/Au/MoS$_2$ coating.

One-component coatings of either MoS$_2$ or DLC were also tested in both environments to determine their individual tribological performance. As expected, in dry nitrogen MoS$_2$
coatings perform optimally giving friction values of 0.02 for lifetimes well into the millions of sliding cycles. In humid air MoS2 coatings give a friction coefficient of 0.2–0.25 for ~10,000 sliding cycles where failure occurred. In dry nitrogen DLC coatings fail immediately, while in humid air they have a coefficient of friction of ~0.1–0.2.

4. Discussion

The high Au four-component coatings had the best friction performance in cycling between dry nitrogen (c.o.f. = 0.01–0.04), and humid air (c.o.f. = 0.1–0.13). These coatings had moduli of 70–90 GPa and hardness values between 3 and 4 GPa. The low Au coatings were harder, had higher elastic moduli, but exhibited friction spiking. In situ tribometry studies have shown that these spikes are the result of transfer film instabilities initiated by plowing events in the coating [21]. Increasing the Au content of the coatings eliminated the friction spiking and decreased the c.o.f. in dry nitrogen. While the increased Au content decreased hardness and modulus, it also likely decreased fracture toughness, as shown previously [10]. How this impacts friction spiking is not clear, although it is possible that it may have improved transfer film formation and adherence [22]. The improved room temperature performance for high Au content coatings did not translate to better performance at high temperature.

The YSZ/Au/MoS2 coating was found to have nearly identical friction behavior as the optimal four-component coatings in both dry nitrogen and humid air environments. We note that in a prior study, YSZ/MoS2 films without Au showed poor friction performance in air, which was improved by the addition of Au to the matrix [10]. These results are consistent with evidence for a synergistic effect for MoS2 lubrication when Au is present. This is consistent with previous work on Au-doped MoS2 films [23–25], as well as studies showing that metal dopants in MoS2 enhance the tribological performance in both dry [25–29], and humid air [30–32]. Interestingly, the YSZ/Au/MoS2 film from this study outperformed prior similar films in room temperature conditions (both dry and humid environments) [10]. The three-component coating without MoS2 (YSZ/Au/DLC) showed poor friction performance at room temperature conditions. The performance of this coating contrasts previous studies where friction coefficients of 0.25–0.35 were recorded in ambient conditions. The carbon and Au content of the present film (>60%) is far greater than the previous films (~20%) [10], suggesting that the total C and Au content should be limited in this composition range for coatings without MoS2.

In humid air, carbon is generally thought to be the predominant species in the transfer film that imparts low friction, while in dry nitrogen MoS2 is thought to be the most active species determining the friction behavior. Past researchers have reported possible synergistic effects for combinations of graphite/MoS2 [33], polytetrafluoroethylene/MoS2 [34], and for WC/DLC/WS2 systems [6,35–37], where it was shown that these mixtures contributed to improved lubrication and provide longer wear life in humid environments. Our Raman spectra results show that for the four-component YSZ/Au/DLC/MoS2 coatings both species are generally present after cycling between the two environments, similar to that observed by Wu et al. [36]. Thus we find that both the four-component YSZ/Au/DLC/MoS2 and three-component YSZ/Au/MoS2 coatings provided effective lubrication in all three environments tested. For these coatings, the value of carbon in the coatings may lie more in longer wear life at elevated temperatures than for lubrication in humid environments.

Finally, we conclude that although the three-component YSZ/Au/MoS2 performed very well in dry nitrogen and humid air, the four-component YSZ/Au/MoS2/DLC coatings had the broadest range of applicability for lubrication and extended wear life in all environments including high temperature.

5. Summary

Coatings of YSZ/Au/DLC/MoS2, YSZ/Au/MoS2 and YSZ/Au/DLC were synthesized using a hybrid magnetron assisted pulsed laser deposition process. Based on our results, the following summary is made.

5.1. Four-component coatings

The four-component coatings with Au composition > 20 at.% (high Au) performed the best by giving low friction in both dry nitrogen and humid air environments. These coatings had lower moduli and hardness, suggesting that mechanical properties are also a factor in friction cycling performance. Coatings with low Au and with carbon content of ≥ 30 at.% or with YSZ content of ≥ 45 at.% performed poorly in either dry nitrogen or humid air environments. These low Au hard coating samples did however have the greatest cycles to failure in 500 °C air. Upon environmental cycling, Raman analysis showed peaks indicating that both MoS2 and graphite-like carbon were formed in the transfer film, indicating that they work together to lower friction in room temperature environments.

5.2. Three-component coatings

The coatings with MoS2 and no carbon performed optimally in cycling environments of dry nitrogen and humid air. These coatings did not perform as well at high temperatures as coatings with carbon and no MoS2.

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