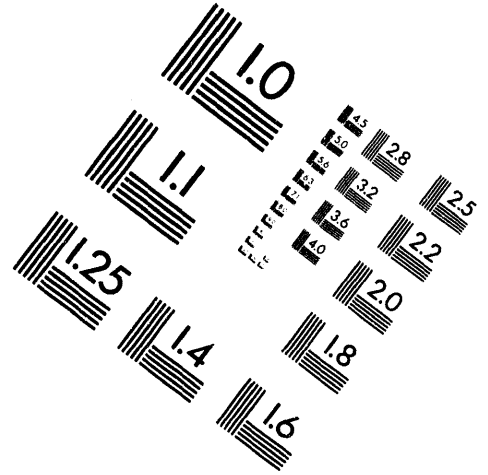
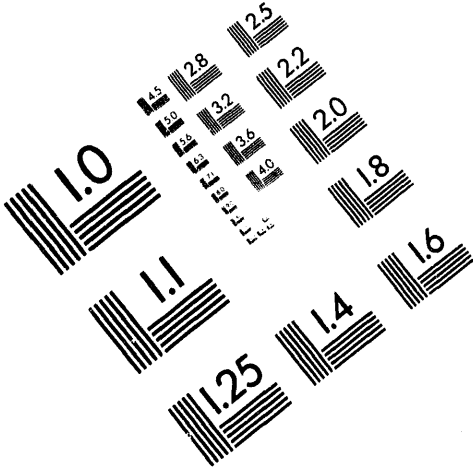




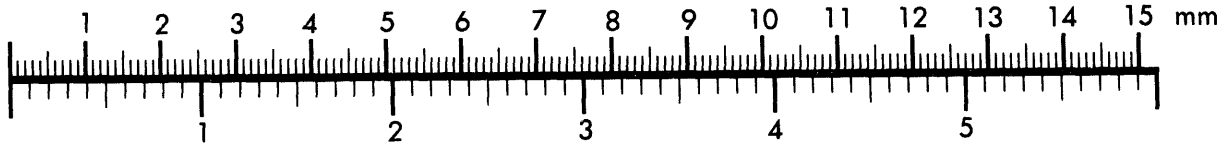
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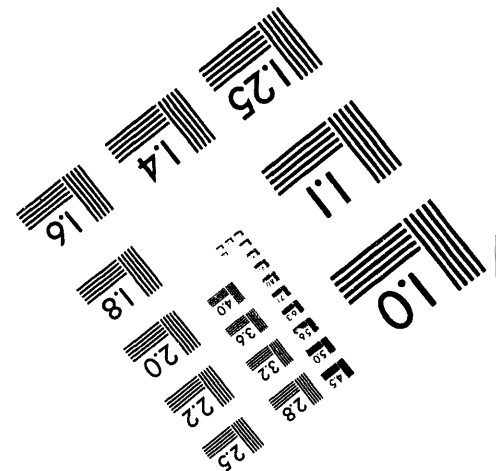
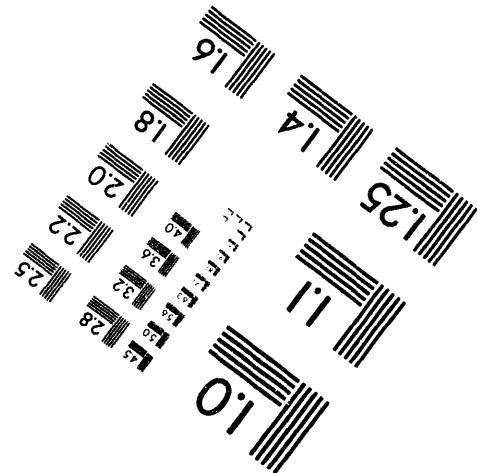
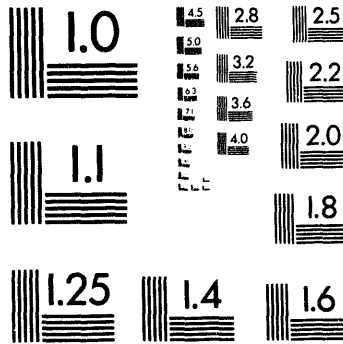
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RECENT PROGRESS AND FUTURE PROSPECTS IN THE
SURFACE ENGINEERING AND TRIBOLOGY
OF CERAMICS*

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RECENT PROGRESS AND FUTURE PROSPECTS IN THE SURFACE ENGINEERING AND TRIBOLOGY OF CERAMICS

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Advanced tribosystems for future uses present new challenges to tribologists and lubrication engineers. These systems can provide superior performance, lifetimes, and efficiency, but their operation involves high thermal and mechanical loadings and aggressive environments that render traditional materials and lubricants essentially useless. Ceramics, because of their excellent mechanical, chemical and thermal properties are considered good prospects for such demanding applications. Among their current and potential applications are cutting tool inserts, precision bearings, mechanical seals, and various engine components such as ring/liner assemblies, valve train components, cam followers, rocker arms, and tappet inserts [1]. Despite these prospects, the widespread utilization of ceramics has not yet been realized. High fabrication cost, insufficient reliability and knowledge base, and, most important, generally poor friction and wear performance of ceramics are thought to be some of the reasons. The current consensus is that without the development of advanced lubricants and lubrication concepts, the large-scale use of ceramics in future tribosystems is highly unlikely.

Recent experimental studies have revealed that most ceramics wear under the collective and/or concurrent actions of microfracture, tribochemical interactions, deformation, and thermal and/or thermomechanical instabilities. Because of their inherently low fracture toughness, poor thermal conductivity and thermal-shock resistance, most ceramics were found to experience microfracture associated with high mechanical and thermal loadings in sliding contact [2-5]. Except for SiC and AlN, most ceramics are good thermal insulators, consequently, they cannot dissipate frictional heat generated at sliding interfaces as effectively as most metallic alloys do. Large temperature gradients often develop between areas of real contact and surrounding regions, thus creating high thermal stresses. When these thermal stresses are combined with normal and tangential stresses (due to applied load and frictional traction), plastic yielding and microfracture may occur and result in wear [4]. Alternatively, ceramics with poor thermal-shock resistance and conductivity may undergo severe thermal cracking and local melting that give rise to severe wear losses [6]. Also, despite their relatively high chemical inertness under static conditions, some nonoxide ceramics (e.g., Si₃N₄ and SiC) react with oxygen and moisture during sliding and thus undergo tribochemical wear [4,7].

These deficiencies overshadow the favorable properties of ceramics and thus new means must be developed to reduce their high friction and wear losses. Specifically, the sliding contact interfaces of ceramics must be furnished with a film that can shear easily and prevent opposing asperities from coming into frequent contact. Easy shear at contact interfaces is analogous to low friction, and fewer asperity/asperity interactions mean reduced wear. When friction is low, the magnitude of tensile stresses developing behind the moving asperities is also reduced. As a result, the location of the maximum orthogonal shear stresses is displaced away from the plane of contact, and this reduces the probability of radial crack formation and microcrack initiation on or in the vicinity of contact surfaces [8,9].

Thin films with low shear strength are produced on sliding ceramic surfaces by vapor, liquid, and solid-phase lubrication. However, most of these lubrication methods present some problems. Most liquids and additives are not compatible with ceramic surfaces; they cannot form effective boundary films on ceramic surfaces or function properly at high temperatures [10]. Lubrication from vapor phases [11] and by catalytic cracking [12] have appeared promising but were mostly effective at elevated temperatures. A recent approach involving tribopolymerization [13] has also been shown to be effective in lubricating ceramic surfaces.

For applications involving high temperatures, corrosive media, vacuum environments, and high loads and speeds, solid lubricants may be the only option available for friction and wear control. However, they are effective only as long as they remain intact on the sliding surfaces [14,15]. Because of the high shear forces that concentrate at or near the contact interfaces during sliding, films with poor adhesion delaminate quite rapidly and leave the underlying substrates unprotected. Except in a few cases, production of adherent solid lubricant films on ceramic surfaces has been rather difficult, especially with conventional deposition techniques (e.g., vacuum evaporation, sputtering, ion plating, and chemical vapor deposition). Solid lubricant coatings (e.g., Ag [16,17], Au [18], MoS₂ [14,19], diamond [20], and diamondlike carbon [21]) produced on ceramics by such advanced surface engineering methods as ion-beam assisted deposition, ion-beam mixing, microwave-plasma CVD, and RF sputtering have exhibited excellent bonding and tribological performance on sliding ceramic surfaces. A novel approach involving hybrid solid and liquid lubrication was also explored in recent years and demonstrated to be very effective in controlling friction and wear of ceramics at high temperatures [22]. For chemically compatible film/substrate

combinations (e.g., B_2O_3 on Al_2O_3), strong bonding was obtained even with vacuum evaporation. Erdemir et al. found that boric acid (H_3BO_3), which forms spontaneously on the surfaces of B_2O_3 coated-ceramics, is remarkably lubricious [23]. Alternatively, in magnetron sputtering, a reactive metal layer such as Cr, Si or Ti was used to promote greater chemical interaction, and hence, stronger bonding between solid lubricant Au films and Al_2O_3 substrates [18]. These films afforded fairly low friction coefficients and wear rates to sliding Al_2O_3/Al_2O_3 interfaces during tests from room temperature up to $800^\circ C$. Placing ceramic substrates in an electrically conducting screen-cage during ion-plating also seems to enhance adhesion between solid lubricant films and ceramic substrates [24]. Ag films deposited by this method on Al_2O_3 surfaces exhibited excellent adhesion and performance during sliding against diamond hemispheres. Preliminary work with burnished monochalcogenide (i.e., GaS, GaSe) films revealed a unique lubrication possibility for ceramic materials [25].

In recent years, a number of new surface-engineering methods, e.g., ion implantation (II), ion-beam mixing (IBM) and ion-beam-assisted deposition (IBAD), have been used to deposit solid-lubricant films on ceramic substrates [26]. High-energy ions used in these processes resulted in substantial alloying and/or intermixing of film and substrate atoms and promoted adhesion. The major limitations of these methods are that they are expensive and are effective only in the line-of-sight, i.e., only the areas in the direct path of ions are covered with the adherent coatings.

The II method has rarely been used for modifying ceramic surfaces in tribological applications. A few attempts were made with this technique to improve surface strength and toughness of Si_3N_4 , Al_2O_3 , and ZrO_2 . In one case, Bhattacharya et al. [27] tried to synthesize MoS_2 by co-implanting Mo and S atoms into Al_2O_3 and ZrO_2 substrates, but this effort failed to produce crystalline/lubricious form of MoS_2 .

IBM involves the mixing of previously deposited single- or multilayer films with ceramic surfaces by using a flux of high-energy ions (ranging from few hundred keV to several MeV) [26]. Because of the broadening of an otherwise sharp interface, adhesion of the surface films improves dramatically. Wei et al. [28] used ion-beam mixing to improve the tribological properties of Si_3N_4/ZrO_2 . Recently, Bhattacharya et al. [29] accomplished ion-beam mixing of sputtered MoS_2 films with sapphire, Si_3N_4 , and ZrO_2 surfaces and reported improvements of two to three orders of magnitude in the functional lifetimes of these films in humid and dry air and in argon environments.

IBAD, which can also afford excellent adhesion to solid lubricant films, could be a viable alternative to II and IBM. In this process, substrate surfaces and growing films are subjected to concurrent bombardment with energetic ions (e.g., 50 eV to 10 keV) both before and during film formation. The striking ions are energetic enough to effectively sputter-clean the surfaces before film deposition and to enhance adhesion by intermixing film and substrate atoms at the onset of film formation. Recent tribological studies have demonstrated that IBAD-produced Ag films of 1 to 2 μm thickness could virtually eliminate the wear of Al_2O_3 and ZrO_2 disks in dry and humid air [14,15]. Uncoated counterface balls sliding against these disks experienced two to three orders-of-magnitude lower wear than those slid against the uncoated disks, depending on sliding velocity. The lifetime of these coatings could range from 100,000 to more than 1,000,000 sliding passes, depending on test conditions.

In conclusion, ceramics have much to offer for demanding tribological applications. However, their widespread use in advanced tribosystems will have to await the development of effective lubricants and lubrication concepts. Depending on the tribological and environmental constraints, both microfracture and tribochemical/thermomechanical interactions may occur and dominate the wear behavior of these materials. While inherent brittleness and poor thermal conductivity appear to be particularly detrimental, ceramics may live up to their promise with proper lubrication. The solid, liquid, and vapor phase lubrication approaches have been explored in recent years and shown to be effective under certain conditions. Strong adhesion appears to be by far the most important requirement for a thin solid film intended for lubrication of ceramic surfaces. Ion-beam processes are quite capable of imparting strong adhesion between solid lubricant films and ceramic substrates. For ceramics with poor thermal conductivity, solid lubricant films that combine high thermal conductivity with low shear strength and good chemical inertness should be considered. Initial results from diamond and diamond-like carbon-coated ceramics, and monochalcogenides are also encouraging.

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