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Shear strength and sliding at a metal–ceramic (aluminum–spinel) interface at ambient and elevated temperatures

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Abstract

We show that the shear strength of aluminum–spinel (Al–$MgAl_2O_4$) interfaces at room temperature, as measured by the periodic cracking method, increases by a factor of 2 when the interface is annealed at 625 °C for 1 h. The same method was used to measure the interfacial sliding resistance at elevated temperatures, following the work of Jobin et al. on copper–silica interfaces. A simplified analysis for studying diffusional sliding by the periodic cracking technique is presented. The crack spacing distributions at ambient temperature and at elevated temperature are quite different. While the ambient temperature spacing is bounded by a factor of 2 (as predicted), the distribution is much broader at elevated temperature. This discrepancy is tied to the time-dependent evolution of the interfacial tractions when the experiment is carried out at a high temperature.

Keywords: Metal–ceramic interfaces; Interfacial shear strength; Diffusional sliding; Periodic crack spacing

1. Introduction

While our understanding of the mechanical behavior of metal–ceramic interfaces at ambient temperatures has grown over the last decade [1], the study of high temperature mechanical properties of these interfaces remains in its infancy. The composite shown in Fig. 1 outlines the various mechanisms for the mechanical behavior of metal–ceramic interfaces. The ambient temperature response is most likely dominated by interactions between dislocations in the metal, interfacial dislocations and the resistance to cleavage fracture. The transition from cleavage fracture to sliding-without-fracture should have a characteristic ductile-to-brittle transition temperature. At higher temperatures, self-diffusion of metal atoms can accommodate sliding over the asperities in the interface, as illustrated on the left in Fig. 1.

The periodic cracking method is a simple technique for studying the shear properties of metal–ceramic interfaces [2]. In this technique the metal carrying a thin ceramic film is pulled in tension. Plastic deformation in the metal is accommodated by elastic deformation in the ceramic until the fracture stress of the ceramic is reached. When fracture occurs, the tensile, in-plane traction in the film is transferred as shear traction to the interface adjacent to the free edge of the crack in the ceramic film. The shear traction has a characteristic relaxation distance over which the in-plane traction in the film gradually builds up to its remote value. Thus, the shortest spacing between the cracks is equal to this relaxation distance, while the largest spacing is equal to twice the relaxation distance. Following the analysis in Refs. [2,3], the maximum shear traction supported at the interface, $\tau_{\max}$, can be related to the fracture stress of the ceramic film, σ_{fract}, by the following equation:

$$\tau_{\max} = \frac{3\pi\sigma_{\mathrm{fract}}h}{4\lambda_{\mathrm{ave}}} \qquad (1)$$

where λ_{ave} is the average spacing of the cracks and h is the thickness of the ceramic film.

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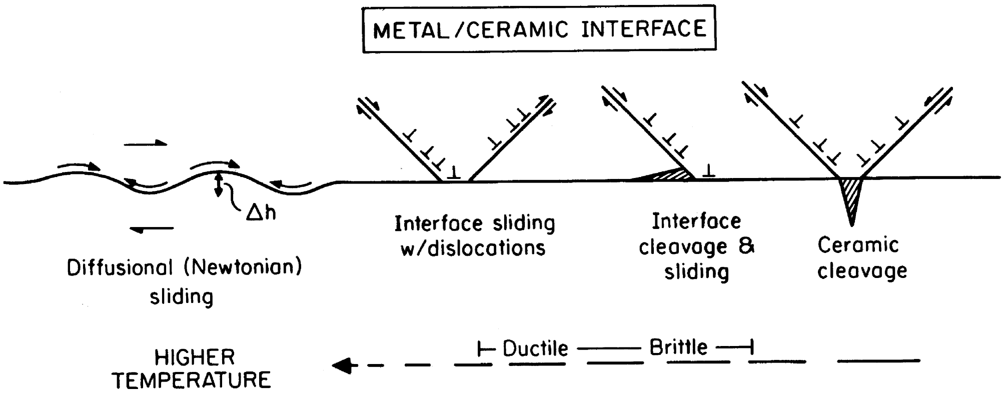

Fig. 1. A depiction of various mechanisms for mechanical behavior of metal–ceramic interfaces, as a function of temperature.

The present work had two objectives. The first was to determine whether the shear strength between aluminum and magnesium aluminate spinel is influenced by annealing at elevated temperature. Earlier work [4] on aluminum–matrix composite dispersed with 1 μm sized spinel particles had shown an interfacial reaction upon annealing just below the melting temperature of aluminum. The reaction involved diffusion of cations [5], and was suspected to underlie the high mechanical strength of the metal–ceramic interfaces in these composites. Experiments carried out on thin aluminum films grown on spinel single crystals of $MgAl_2O_4$ have corroborated the presence of an interfacial reaction [6]. The present experiments were carried out to evaluate if such a reaction can affect the interfacial strength.

The second objective of the experiments was to study the sliding behavior at the Al–spinel interface along the same lines as Jobin et al.'s work [3] on copper–silica interfaces at elevated temperatures. The most striking result from that work, which supported the conclusions of Riedel [7], was that sliding at metal–ceramic interfaces is linear-viscous. Peterson et al. [8] also showed a linear sliding friction behavior in their experiments with Al–Si interfaces; they measured sliding rate directly as a function of the shear stress and did not see a transition to power law behavior with increasing load.

These experiments have consistently shown that power law sliding behavior (equivalent to power law creep in metals) is absent in the study of frictional sliding at metal–ceramic interfaces. The athermal mechanical behavior of these interfaces transitions immediately into linear-viscous sliding as the temperature is raised. The absence of nonlinear sliding is ascribed to the difficulty of developing a dislocation substructure near the interface (a cellular network of dislocations is a characteristic feature of power law creep in metals).

Another result from Jobin's experiments is the difference in the distribution of the crack spacings in low- and high-temperature experiments. At ambient temperature the minimum and the maximum spacings are, as predicted [2], bounded by a factor of 2. However, the distribution of the crack spacings in the high temperature sliding experiments was much broader [3]. We wished to see if similar results would be obtained with the Al–spinel interfaces.

Before describing the experimental results, the analysis for periodic cracking at elevated temperatures is presented.

2. Analysis for elevated temperature periodic cracking experiments

The shape of the interfacial tractions, and the corresponding in-plane stress in the ceramic film, at low and at high temperatures are contrasted in Fig. 2. The low tem-

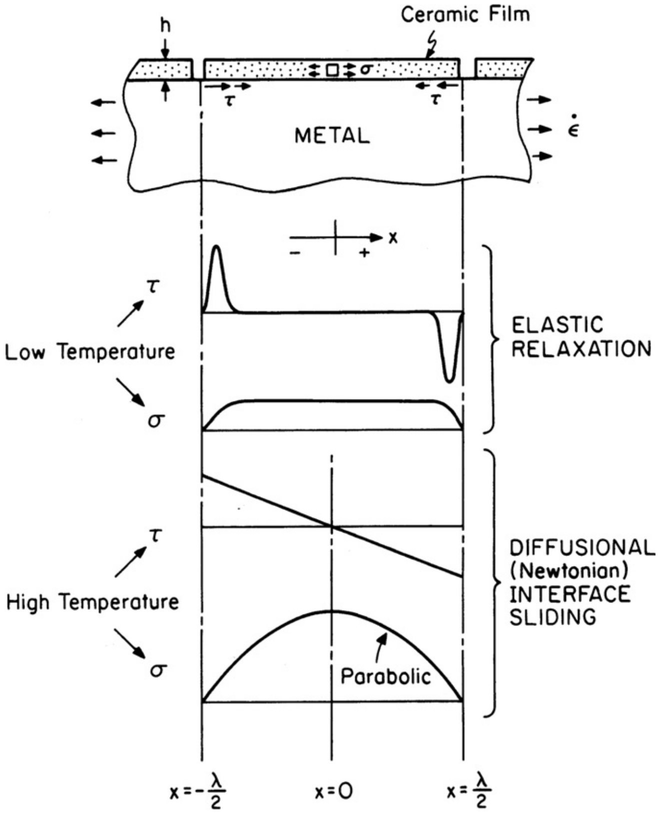

Fig. 2. Schematics of interfacial tractions and the in-plane stress in the ceramic film at ambient temperature and at elevated temperature.