Effects of the dissolution of thermal barrier coating materials on the viscosity of remelted volcanic ash

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Abstract

The chemical interaction between remelted volcanic ash and ceramic coatings of yttria-stabilized zirconia (YSZ) and/or gadolinium zirconate (GZO) is of special importance for the design of volcanic ash melt-resistant thermal barrier coatings (TBCs) for aviation turbine technologies. The spreading and infiltration potential of the melts is strongly influenced by the melt viscosity. Thus the interpretation of infiltration experiments and modeling of infiltration processes both rely on accurate viscosity data. Melt viscosity may be significantly altered by the dissolution of the YSZ or GZO thermal barrier coatings during the infiltration process. Here, we have determined the influence of YSZ and GZO additions to the viscosity of a series of volcanic ash melts using high-temperature concentric cylinder viscometry. All samples have been characterized fully after viscometry. At 6.5 wt% of YSZ or GZO, both dopants lead to a reduction of viscosity in a temperature range between 1297–1640 °C in air. The magnitude of the decrease in viscosity depends weakly on volcanic ash melt composition. The viscosity effect has been parameterized in the following form:

\[ \Delta \eta = x \cdot m_{\text{dopant}} \]

whereby \( x \) is a melt-composition specific coefficient of viscosity decrease, and \( m_{\text{dopant}} \) represents the added amount of YSZ/GZO (wt%). This viscosity reduction should contribute to an acceleration of the physical infiltration of TBCs via remelted volcanic ash.

Keywords: Gas-turbine, aviation, rare earth oxides, yttria-stabilized zirconia (YSZ), gadolinium zirconate (GZO)

Introduction

Yttria-stabilized zirconia (YSZ) is a typical material used for thermal barrier coatings on turbine blades in aviation engines. Gadolinium zirconate (GZO) has been proposed as a potential replacement for YSZ in thermal barrier coatings to improve resistance to environmental dust. The lifetime of thermal barrier coatings (TBCs) is mainly limited by mechanical stresses, induced by thermal cycling, which lead to mechanical degradation and eventual exposure of the underlying alloy. Exposure of such TBCs to environmental debris in the atmosphere such as dust, sand, or volcanic ash initiates a further degradation of TBCs that is also chemical in nature as the ingested environmental debris may “re-melt” (via melting of minerals or softening of a pre-existing glass phase), leading to a chemical reaction with and partial dissolution of the TBC ceramics. Even in the absence of catastrophic failure of turbine engines due to TBC degradation, chronic exposure will lead to a substantial decrease in the lifetime of the TBCs and thereby increase operating costs substantially. YSZ (containing 6–8 wt% \( \text{Y}_2\text{O}_3 \)) is state-of-the-art TBC material commonly used in the aviation industry (Clarke et al. 2012). It has, however, been demonstrated to possess a poor chemical resistance to attack by silicate melts at high temperatures (Zhao et al. 2014). Alternative TBC materials with higher chemical resistance to silicate melts are thus being investigated (Clarke and Phillpot 2005; Vaßen et al. 2010). Recently, gadolinium zirconate (GZO) has been shown to exhibit particularly improved performance in the presence of silicate melts (Krämer et al. 2008; Drexler et al. 2012).

The area as well as the infiltration depth and speed of silicate melts into TBCs is inferred to depend strongly on the viscosity of the melt (Jackson et al. 2015; Song et al. 2017) together with the TBC structure (Kabir et al. 2019) and chemical reactivity (Krämer et al. 2008; Drexler et al. 2012). Low viscosity melts are inferred to cover larger areas and infiltrate more easily into the open pore space of modern TBCs, leading to an enhanced chemical reaction between the melt and the TBC and heightened risk of mechanical degradation during operative thermal cycling. The viscosity of silicate melts is strongly influenced by their chemical composition (Giordano et al. 2008). An enhanced concentration of network-formers (e.g., \( \text{SiO}_2 \)) generally leads to more viscous melts, whereas network-modifiers (e.g., excess alkalis) generally act to decrease the viscosity.

It has been reported that the addition of \( \text{Gd}_2\text{O}_3 \) and/or \( \text{Y}_2\text{O}_3 \) to silicate melts will decrease the viscosity (Wang et al. 2012), while smaller amounts of up to 5 mol% \( \text{ZrO}_2 \) will increase viscosity (Barbieri et al. 2003; Karell et al. 2008). Recent viscosity models for multicomponent melts (Fluegel 2007; Giordano et al. 2008) do not incorporate Zr, Y, or Gd, and thus their influences on viscosity cannot yet be predicted for multicomponent melts. As a result, any model-based predictions represent a simplified