Journal of the European Ceramic Society 42 (2022) 898–904

Contents lists available at ScienceDirect

Journal of the European Ceramic Society

journal homepage: www.elsevier.com/locate/jeurceramsoc

AlN with high strength and high thermal conductivity based on an MCAS-Y_2O_3-YSZ multi-additive system

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ARTICLE INFO

Keywords:
Aluminium nitride
Yttria-Stabilised zirconia
Thermal conductivity
Flexural strength
Ceramic substrate

ABSTRACT

The additive composition of an AlN ceramic substrate material was optimized to achieve high strength and thermal conductivity. MgO-CaO-Al_2O_3-SiO_2 (MCAS) glass and Y_2O_3 were used as basic additives for improved sintering properties and thermal conductivity, thereby allowing for AlN to be sintered at a relatively low temperature of 1600 °C without pressurization. Yttria-stabilized zirconia (YSZ) was added (0–3 wt%) to further improve the strength of the AlN ceramic. YSZ and Y_2O_3 reacted with AlN to produce ZrN, $Y_4Al_2O_9$, and $Y_3Al_5O_{12}$ secondary phases. The formation of these yttrium aluminate phases improved the thermal conductivity by removing oxygen impurities, while ZrN formed at the AlN grain boundaries provided resistance to grain boundary fractures for improved strength. Overall, the AlN ceramic with 1 wt% MCAS, 3 wt% Y_2O_3, and 1 wt% YSZ exhibited excellent thermal and mechanical properties, including a thermal conductivity of 109 W/mK and flexural strength of 608 MPa.

1. Introduction

The growing popularity of electric transportation vehicles (e.g., automobiles and aircraft) has led to rapid growth in the demand for electric devices (e.g., power modules) and related materials. Ceramic substrate materials are commonly used in power modules, as they offer excellent electrical insulation and thermal shock resistance against the heat generated by the electrical resistance of the circuit during power consumption. Further, high thermal conductivity and mechanical strength are required. Common ceramic substrate materials include aluminum oxide (Al_2O_3), zirconia-toughened alumina (ZTA), aluminum nitride (AlN), and silicon nitride (Si_3N_4). Al_2O_3 is associated with both low thermal conductivity and low strength, while ZTA offers high strength but low thermal conductivity. Further, Si_3N_4 offers excellent properties, but commercialization remains a challenge due to difficulties associated with the production of synthetic and sintered products. Alternatively, AlN is a promising heat dissipating and electrically insulating material that offers high thermal conductivity, and is relatively easy to produce [1–7]. However, AlN has a relatively low mechanical strength of 300–400 MPa.

Various studies have investigated the use of additives and heat treatment to improve the strength characteristics of AlN [8–12]. Lee et al. reported that the addition of $CaZrO_3$ to AlN led to intergranular pinning of the secondary phases, thereby facilitating a high flexural strength of 560 MPa [8]. Further, Kusunose et al. and Zhan et al. produced high strength AlN without compromising its high thermal conductivity by controlling the grain growth after low-temperature sintering using CeO_2 and SmO_2-CaO additives, respectively [9,10]. Liu et al. reported that the fracture mode at the grain boundaries of AlN was changed to intragranular fracture using Si_3N_4 as an additive, which led to increased hardness and strength [11].

Meanwhile, glass-based oxides have also been considered as additives to enhance the sinterability of AlN [13–15]. For example, Lee et al. reported that sintered bodies with a density close to theoretical density were obtained, and a thermal conductivity of 84 W/mK was attained via unpressured sintering for 1 h at 1600 °C with 1 wt% MgO-CaO-Al_2O_3-SiO_2 (MCAS) glass oxide additive-doped AlN [14]. Although the study of mechanical strength has not been conducted, this finding suggested that the mechanical properties of AlN can be improved by controlling the microstructure via lower temperature sintering.

Abbreviations: BEI, backscattered electron imaging; PET, polyethylene terephthalate; SEM, scanning electron microscopy; TEM, transmission electron microscopy; XRD, X-ray diffraction; YSZ, yttria-stabilized zirconia; ZTA, zirconia-toughened alumina.

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https://doi.org/10.1016/j.jeurceramsoc.2021.11.012
Received 3 August 2021; Received in revised form 12 October 2021; Accepted 8 November 2021
Available online 9 November 2021
0955-2219/