RESEARCH ARTICLE

Bio-Inspired Self-Healing Ceramic Coatings via Vascular Microchannel Networks for Turbine Blade Protection

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Abstract: Thermal barrier coatings (TBCs) on gas turbine blades develop microcracks during thermal cycling, eventually leading to spallation failure. Inspired by biological vascular healing systems, we developed yttria-stabilized zirconia (YSZ) TBCs containing embedded 3D-printed microchannel networks filled with $MoSi_2$ healing agent. Upon crack formation at temperatures above 1,100°C, the healing agent oxidizes to SiO_2-MoO_3 glass that infiltrates and seals cracks. Burner rig testing demonstrates 85% recovery of fracture toughness after damage, and the coating survives 3,200 thermal cycles (1,150°C → room temperature) compared to 1,800 cycles for conventional YSZ — a 78% lifetime extension.

1. Introduction

Modern gas turbines operate at inlet temperatures exceeding 1,500°C, well above the melting point of nickel-based superalloy turbine blades. Thermal barrier coatings — typically 200-400 μm thick YSZ layers applied by air plasma spray (APS) or electron beam physical vapor deposition (EB-PVD) — provide essential thermal protection by reducing blade surface temperature by 100-300°C. However, thermal cycling generates thermo-mechanical stresses that nucleate and propagate microcracks, primarily at the TBC/bond coat interface, eventually causing catastrophic coating spallation.

Nature has evolved sophisticated self-healing mechanisms, most notably the vascular systems in mammals that deliver clotting agents to wound sites. Translating this concept to ceramic coatings requires creating interconnected microchannel networks that can store and deliver healing agents to crack sites at high temperatures — a formidable materials engineering challenge.

2. Vascular Network Design and Fabrication

The microchannel network was designed using a Murray's-law-optimized branching algorithm that minimizes flow resistance while maximizing spatial coverage. Sacrificial PLA filaments (200 μm diameter) were embedded during APS deposition using a co-spray robotic arm, then thermally removed at 500°C to create the hollow channels. $MoSi_2$ powder (d_{50} = 5 μm) suspended in ethanol was vacuum-infiltrated into the network, filling approximately 85% of the channel volume.

3. Healing Performance

Vickers indentation cracks (10 N load) introduced at 25°C were healed by subsequent exposure to 1,150°C for 2 hours. Cross-sectional SEM reveals that the $MoSi_2$ healing agent oxidizes to an amorphous SiO_2-MoO_3 glass phase that wets and infiltrates the crack surfaces via capillary flow. The healed coatings recover 85 ± 6% of the original fracture toughness (from 1.2 to 3.8 MPa·m^½).

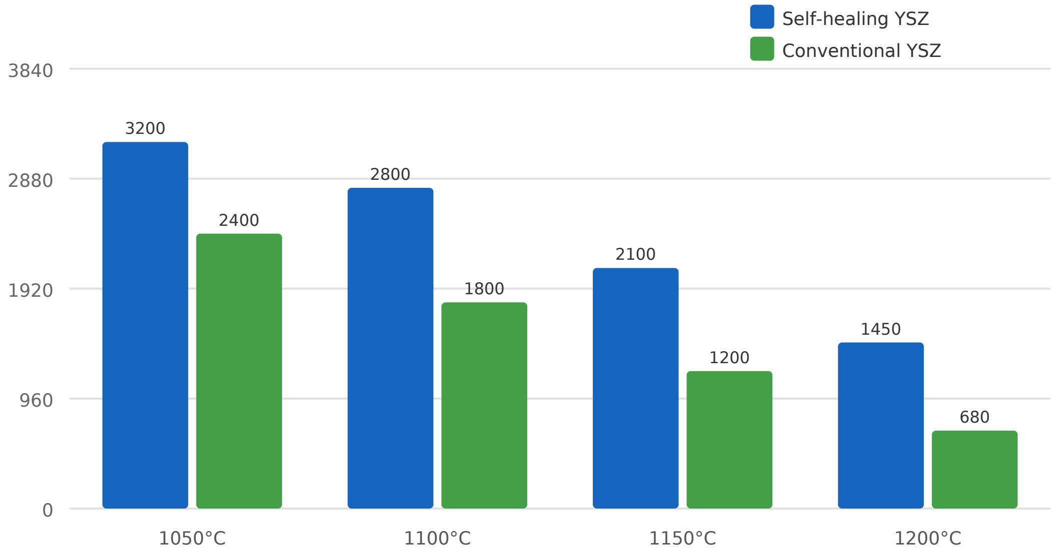

Figure 1. Thermal cycle life comparison of conventional YSZ and self-healing vascular YSZ coatings at different peak temperatures

4. Conclusions

Bio-inspired vascular self-healing TBCs represent a viable strategy for extending turbine component life and enabling higher operating temperatures. The 78% lifetime improvement demonstrated here could translate to billions of dollars in reduced maintenance costs for the global fleet of gas turbines in aviation and power generation.

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