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Thermal stress analysis of the FGLCS in hypersonic vehicles: Their application to fuel injection struts in scramjets

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ABSTRACT

This paper proposes a novel functionally graded layer composite structure (FGLCS) for use in hypersonic vehicles. It consists of a passive thermal protection layer made from ultra-high temperature ceramic composites, an interface layer of high temperature insulating material and an active thermal protection layer of alloy. The transient thermal stress alleviation characteristics of an FGLCS plate and an FGLCS strut under aerodynamic heating conditions were studied using a finite element method. Compared to a traditional ultra-high temperature ceramic (UHTC) plate and strut, FGLCS can greatly reduce the thermal stress level of structures, the stress relief can be up to 84% in a case study considered in this paper. In addition, the long-term and reusable performance of a prepared FGLCS strut, with much lower thermal stress, was completely validated for the first time by an oxy-propane testing system in a combustion environment.

1. Introduction

The most serious problem facing a fuel injection strut is failure of the thermal protection structures of hypersonic vehicles at high Mach number [1]. To obtain good aerodynamic characteristics, these structures should withstand high temperatures and oxidising environments while maintaining their shape [2,3]. Under severe aerodynamic heating, these requirements lead to huge challenges for thermal protection materials and structures, such as ultra-high temperature resistance, chemical stability, thermal shock resistance, erosion resistance and oxidation resistance [4].

Although structures based on C/C and C/SiC composites can withstand higher temperatures than super alloy, unfortunately severe oxidation ablation will still occur when temperatures exceed 1500 °C [5–7]. Compared to C/C and C/SiC composites, UHTC composites are the best candidate materials due to their high melting points and good oxidation resistance as well as their excellent mechanical and chemical stabilities at high temperatures. These are essential for struts in scramjets [8–10]. However, their low fracture toughness and brittleness mean that the ceramic injector is easily broken at extremely high temperatures in an oxidising environment [11–15]. Thus, improving the performance of UHTC structures by material modification and structure improvement may be an effective approach for resolving the engineering application of UHTC structures [16,17].

In fact, not all materials in a thermal protection structure with active cooling need the above performance requirements, such as the material in the structure not being exposed to aerodynamic heating. For example, material near the active cooling medium, which has a relatively low surface temperature, can be replaced with other materials, such as alloy. This material has good fracture toughness, machinability and imperfection sensitivity. Thus, based on the concept of functionally graded materials that have the desired range of performance due to composition gradient [18,19], we can use different components in thermal protection structures to meet different actual needs [20].

This paper will present a novel structure, that is called a functionally graded layer composite structure (FGLCS). It consists of a UHTC layer, a high temperature insulating material layer and a high-temperature alloy layer. Furthermore, using a verified finite element analysis (FEA) model of an FGLCS plate, which can consider complex boundaries and temperature-dependent material properties, we will discuss the thermal stress problem of an FGLCS plate under extremely high temperatures and high thermal gradient environments.

Based on the concept and mechanical performance advantages of an FGLCS plate, we will study an FGLCS strut used for fuel injection in scramjets through an FEA model. To verify the superiorities of the proposed structure, we will compare it with a simple UHTC strut. Finally, we will prepare complex FGLCS struts made of a

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UHTC thermal protection layer, a thermal insulation material layer and an active cooling layer for fuel injection. We will verify their excellent performance - they can be used for a long time and are reusable - in an oxy-acetylene testing system.

2. Functionally graded layer composite structure (FGLCS)

FGLCS is made of three components: the UHTC composites layer facing the ultra-high temperature and oxidising environment, the high temperature flexible insulation material layer preventing the heat from transferring to the inner structure and the inner alloy layer with active cooling. The interface of two adjacent layers are not bonded. The three layers are combined into the whole FGLCS through the shrinkage fit, the screw extrusion connection and the bolt mechanical connection. To be more specific, we assemble the FGLCS by the following steps. Firstly, let the flexible insulation layer cover the inner metal layer. Then place both the flexible insulation layer and the alloy layer into the groove of the UHTC layer to assemble the whole FGLCS by shrinkage fit. Finally, fix the FGLCS to the fixture through screw extrusion connection, as shown in Fig. 7. In practical engineering applications, the structure will be more complex and need bolt mechanical connection to fix the FGLCS.

In extremely high temperature environments, such as in aerodynamic heating, high temperature alloy structures using active cooling may not satisfy thermal protection requirements. UHTC composites are a broad family of materials, including several borides, carbides and nitrides of fourth and fifth sub-group transition metals. They have melting points above 3000 °C and can potentially be used at temperatures in excess of 2000 °C in extreme aerodynamic heating environments [21]. They are the ideal candidate materials for the outer layer of an FGLCS exposed to high temperature oxidising environments. Although a UHTC structure has excellent high temperature and oxidation resistance performance, it may easily fracture due to its inherent brittleness under high thermal gradient conditions, such as in an active cooling fuel injection strut structure.

The middle layer, made of a flexible heat-insulating material, prevents heat from passing inside the structure. It also avoids contact between the higher and lower temperature components of the FGLCS which would lead to a local high thermal gradient. Meanwhile it can mitigate thermal stress due to its flexibility. The inner layer using active cooling is made of alloy which has good machinability, imperfection insensitivity and high damage tolerance.

3. Thermal stress constitutive of FGLCS

The FGLCS is made of three components. The UHTC composites layer is placed in contact with combustion gas to protect the high temperature inner alloy structure. The middle layer is made of a high temperature thermal insulation material. The inner layer is made of alloy that utilises active cooling, as shown in Fig. 1. However, compared with the flexible insulating material component and the lower temperature alloy component, the UHTC component easily breaks due to brittle fracture in the extreme aerodynamic heating environment, as some studies in the literature have reported [12,22]. Therefore, the ultra-high-temperature ceramic composites layer is the most important component and its thermal stress level determines the safety of FGLCS. In this paper, we focused on the ultra-high-temperature ceramic composites layer and its superiorities in thermal stress mitigation. Therefore, we only consider the FGLCS as thermally linear elastic materials and the thermal diffusion in the layers as a linear heat diffusion problem.

The FGLCS is initially at a uniform temperature T_0. The upper surface of the outer layer is imposed with surface heat flux q_s

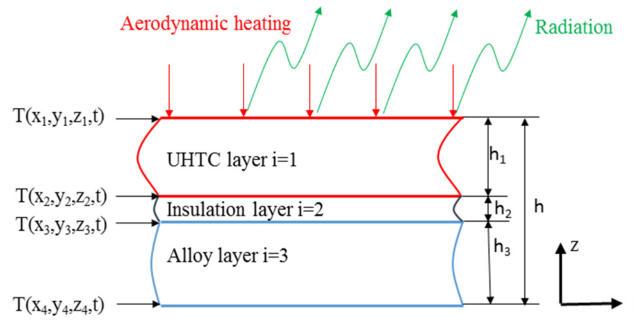

Fig. 1. Schematic of the FGLCS plate with upper surface under aerodynamic heating and lower surface with active cooling. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

induced by aerodynamic heating, and radiates heat to the surrounding environment. Convection cooling of the inner layer is accomplished by circulating coolant through passages in the structure to remove the absorbed heat from aerodynamic heating. The temperature of the coolant is T_c and the convective heat transfer coefficient is h_c. The transient thermal conduction basic equation of the ith layer of FGLCS is given by:

$$\frac{\partial}{\partial x}\left(k_i(T)\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_i(T)\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_i(T)\frac{\partial T}{\partial z}\right) = \rho_i C_{pi}(T)\frac{\partial T}{\partial t} \quad i=1,2,3 \tag{1}$$

where $k_i(T)$ is the thermal conductivity per layer of FGLCS, ρ_i is the density per layer, and C_{pi} is the specific heat at constant pressure per layer. The initial temperature field and heat transfer boundary conditions of FGLCS are expressed in the following form:

$$T(x,y,z,0)=T_0 \tag{2}$$

$$k_1(T)\frac{\partial T}{\partial x}+k_1(T)\frac{\partial T}{\partial y}+k_1(T)\frac{\partial T}{\partial z}\bigg|_{surface=outer}=q_s-\varepsilon\sigma(T(x_1,y_1,z_1,t)-T_{env}) \tag{3}$$

$$k_3(T)\frac{\partial T}{\partial x}+k_3(T)\frac{\partial T}{\partial y}+k_3(T)\frac{\partial T}{\partial z}\bigg|_{surface=inner}=h_c[T(x_4,y_4,z_4,t)-T_c] \tag{4}$$

where ε is the emissivity of UHTC, σ is the Stefan Boltzmann constant, T_{env} is environment temperature, $T(x_1,y_1,z_1,t)$ is the upper surface temperature of the UHTC layer, and $T(x_4,y_4,z_4,t)$ is the lower surface temperature of alloy layer. Because the interface is discontinuous, the heat transfer between adjacent interfaces has the following form:

$$k_i(T)\frac{\partial T}{\partial x}+k_i(T)\frac{\partial T}{\partial y}+k_i(T)\frac{\partial T}{\partial z}\bigg|_{i\sim i+1} = k_{i+1}(T)\frac{\partial T}{\partial x}+k_{i+1}(T)\frac{\partial T}{\partial y}+k_{i+1}(T)\frac{\partial T}{\partial z}\bigg|_{i\sim i+1}=q|_{i\sim i+1} \tag{5}$$

$$q|_{i\sim i+1}=h_{\text{interface}}|_{i\sim i+1}(T_i|_{i\sim i+1}-T_{i+1}|_{i\sim i+1}) \tag{6}$$

where $i\sim i+1$ indicates the interface between ith layer and $(i+1)$th layer and $h_{\text{interface}}$ is the thermal conductance of the interface $i\sim i+1$.

Since the material properties are all temperature dependent and the boundaries are complex, a closed form solution of the above heat transfer equation cannot be obtained.

The constitutive relation for the three-dimensional problems of the thermo-elasticity can be expressed as follows: