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The effect of microstructure at interface between coating and substrate on damping capacity of coating systems

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ABSTRACT

Samples with various interface microstructures between the coating and the substrate were designed and fabricated in this paper. Dynamic mechanical thermal analyzer (DMTA) was utilized to investigate the dynamic mechanical properties of the samples and scanning electron microscopy (SEM) was used to observe the interface microstructure between the substrate and coating. The effect of the interface microstructure on damping was studied, and results indicated that the larger the coating/substrate interface thickness was and the more interface defects were, the higher interface system damping was. When the micro-hardness ratio of substrate to coating was increased, the damping of coating system was enhanced. The effect of the APS and EB-PVD coating on damping capacity was investigated. There was a dramatic increase in the damping value of the APS coating when the strain was higher than 20 ppm, while the damping amplitude effect of the EB-PVD coating was not so obvious, which could mainly be caused by the different energy dissipation mechanisms of the two coatings.

1. Introduction

Aircraft gas turbine engine blades are prone to fatigue or damage by vibration, which usually in turn leads to shorten their service life. Currently, the development of turbine blades and airfoils for aero-engines largely depends on the improvement of the thermal barrier coatings (TBCs) [1,2]. Thermal barrier coatings (TBCs) with NiCrAlY bond coat and 8 wt.% Y_2O_3-stabilized ZrO_2 ceramic top coat have been widely used in aircraft engines and gas turbines to increase the lifetime of components [3]. Vibration damping is very important to the service life of the turbine blade in aeroengine, and a basic understanding of the damping mechanism under the vibration load was studied. Numerous research [4,5] results have shown that the interface structure between coating and substrate was complex. The interface of coating structure includes the interface between coating and substrate, the interface between layer within coating and the boundary of particle and pores in coating.

Chia and Khor [6–8] used dynamic mechanical analyzer techniques to measure the temperature dependence of the damping properties of NiAl, NiCrAlY, and NiCoCrAlY in high temperature. Patsias and Tassini [9,10] utilized amplitude dependent damping (ADD) to test the differences in the mechanical damping and elastic stiffness of an yttria-stabilised zirconia (YSZ with 8 wt.% yttria) coating deposited by APS and by EB-PVD. The coating produced by APS with higher damping and lower stiffness was correlated with the microstructure. In these works, the damping may be attributed to the coating microstructure and phase transformation, and it was not discussed the damping caused by interface between coating and substrate.

One of the earliest works on slip damping was studied by Goodman [11] and a review of progress in analysis of interfacial slip damping was given. In Torvik's research [12], layered medium was discussed and some numerical results were presented. In these works, the cementation state of interface including layered medium and composite was supposed to be idealization, which was very different to an actual interface state of the coated system consisting of many defects. A reversible micro-slip under the vibration load would result in a frictional energy loss under external stress [13].

The thickness of the protective coatings (for heat insulation, corrosion and wear resistances) on the turbine blade is as small as 1% of that of the blade. Since the damping effect usually becomes significant only when the coating thickness is about 2–5% of that of the blade, the coating itself, which provides a very low damping vibration capability, cannot meet the requirements for the damping vibration [14].

Karimi [14,15] and Yen [16,17] investigated the damping capacity of Fe–Cr–X ferromagnetic coatings using a cantilever method and the damping mechanism was the hysteresis effect. Vaidya [18] and Bamberg [19] demonstrated that the damping mechanism of

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Al_2O_3-coated sample was attributed to the higher porosity and defects in the coating as a result of the spraying process.

The damping performance can significantly be improved by rational design of the interface structure between metal coating and the substrate [13,20]. Cross investigated the damping capacity of metal and ceramic gradient coating Mo–$MgO{\cdot}Al_2O_3$, the coating of Ni-based alloys (Hastelloy-X), Hastelloy-X-ZrO_2 gradient coating, Hastelloy-X-$MgO{\cdot}Al_2O_3$ gradient coating and also demonstrated that the coating interface structure had a significant impact on the damping capacity [21]. Therefore, the introduction of metal coating interface may increase the damping capacity. In point of this view, the interface of the metal coating structure is one of the key constraining elements influencing the damping properties [22].

Samples with various microstructures at the interface between the coating and the substrate were designed in this paper and the effect of interface microstructure on damping were analyzed, which established a theoretical basis for the design of thermal barrier coating with high damping capacity based on NiCrAlY bond layer.

2. Experimental procedure

2.1. Preparing coating samples

The Ni-based high-temperature alloy was used as substrate in coating systems, and the composition is Ni–7.8Al–14Mo–(0.02–0.06)B. The substrate was cut into 48 mm × 6 mm × 1 mm sections and polished using fine grade sandpaper. The NiCrAlY coatings were prepared onto the substrate by the air plasma sprayed (APS) process and electron beam-physical vapour deposition (EB-PVD) technology, respectively. The coating was applied on one side only and the thickness of the APS and EB-PVD coating was 50 μm.

2.2. The microstructure characteristic and hardness analysis

A scanning electron microscopy (SEM, CS3400) was used to observe the interface microstructure. The interface microstructure was analyzed by using image analysing techniques based on quantitative metallography to get outline of defects handled by binary image processing. Defect rate was defined as the ratio of the area of defect at interface to the area of interface between substrate and coating. Various interface microstructures between coating and substrate were designed and prepared to study the effect of interface microstructure on damping. Samples with different interface microstructure was respectivly denoted by S1, S2 and S3. Samples with different interface microstructure are denoted as S1, S2 and S3, respectively. The substrates of samples are the Ni-based high-temperature alloys, and the coatings of the samples are the NiCrAlY coatings prepared by air plasma sprayed.

Sample S1: the interface thickness is 5.0 μm and the interface defect rate is 22% (Fig. 1a).
Sample S2: the interface thickness is 13.4 μm and the interface defect rate is 23.7% (Fig. 1b).
Sample S3: the interface thickness is 12.6 μm and the interface defect rate is 16.5% (Fig. 1c).

The micro-hardness of the various samples was determined by micro-hardness tester (HXZ-1000). A 0.098 N (10 g) load was applied during 15 s in air at room temperature. Vickers diamond pyramid hardness is determined in practice by measuring the diagonal length of the indentation produced by the penetration of a square-based pyramid having an angle of 136° between opposite pyramid faces. The hardness number HV is given by the relation [23]:

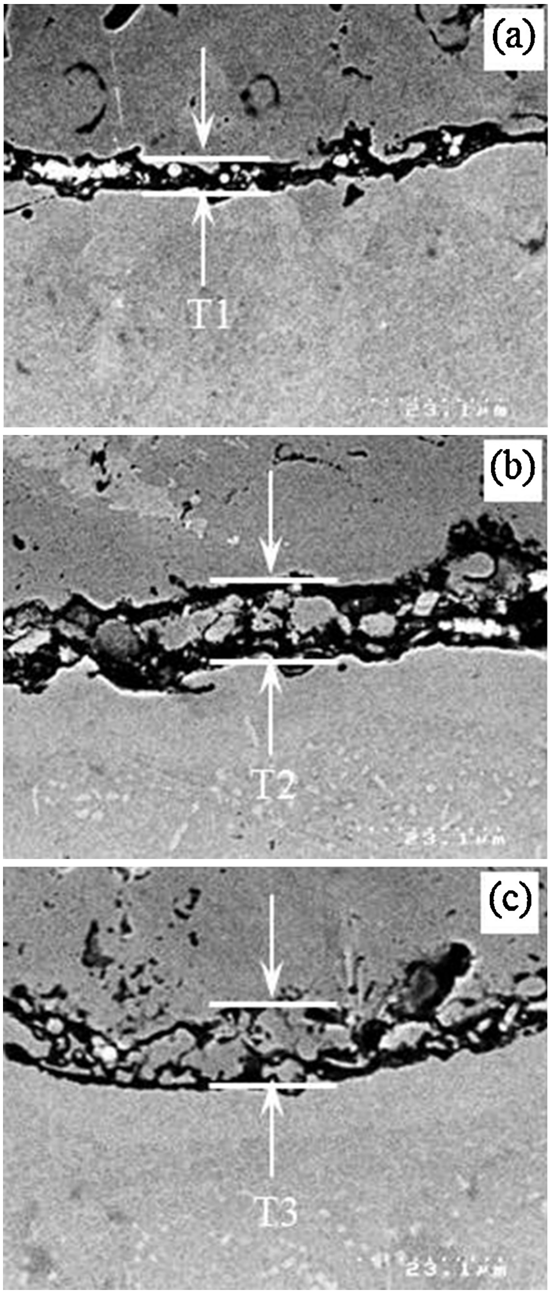

Fig. 1. Interface microstructure between coating and substrate in various samples: (a) sample S1, (b) sample S2 and (c) sample S3.

$$H_V = \frac{2P_1 \sin_2^{\alpha}}{d^2} = 1.8544\frac{P_1}{d^2} = 0.1891\frac{P_2}{d^2} \tag{1}$$

where $P_1(P_2)$ is the applied load, d is the average value of the diagonals and α is 136°. P_1 is in n kgf, P_2 is in newtons, and d is in millimeters.

2.3. The dynamic mechanical properties

The dynamic mechanical properties were tested by a DMTA IV made by Rheometric Scientific Company. The testing mode was three-point bending method. The dynamic storage modulus (E') and loss modulus (E'') could be simultaneously measured by DMTA, and the damping capacity ($\tan\delta$) can be expressed as: $\tan\delta = E''/E'$.