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Adhesion behavior of thermal barrier coating on nickel alloy in the bullet shock testing

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Abstract

This paper applies bullet to induce shock wave and detects the adhesion behavior of multiple interfaces in typical thermal barrier coating system. Post-shock metallography examination is carried out to show the real characteristic of interface delamination. A finite element-based acoustic wave mechanics simulation is conducted to calculate the stress history. It is found that delamination can occur in every interface, depending on bullet velocity and stress feature. An interesting phenomenon of the failure at multiple interfaces during a single shot needs to be paid more attention in the future.

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Keywords: thermal barrier coatings, adhesion, metallography, shock testing.

1. Introduction

Thermal barrier coatings (TBCs) find their applications in various harsh environments [Bhattacharya et al., 2011]. However, it is still a significant challenge to evaluate and understand coating adhesion [Barradas et al., 2004, Chen et al., 2011]. The most common method to determine the adhesion, i.e. bond-pull test, has obvious drawbacks. Firstly, it applies for interface with low adhesion level, like 75MPa, depending on the glue. Secondly, TBC is a multilayer system comprising multiple interfaces, i.e. top coat/bond coat (TC/BC) and bond coat/substrate (BC/substrate). Normally, TC/BC is the weakest part and subjected to failure prior to delamination at BC/substrate. Therefore, it is hard to measure and control the adhesion at BC/substrate. More embarrassly, bond-pull test is not as simple as it seems. In fact, interfacial delamination may be initiated in the area where the coating is less adhering or

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at sample periphery where stresses are concentrated. As a consequence, the bond-pull test determines a non-representative adhesion value for the sample, representing merely a local failure at a singularity [Arrigoni et al., 2006].

Shock adhesion test techniques, based on shock wave propagation, open up more possibilities. They have unique advantage of applying well-controlled stress state and level at the interface. By systematically changing the sample geometry, interface loading of well-controlled mode-mixity from pure tensile to pure shear, up to GPa range, can be realized [Hu et al., 2006]. Indeed, the ability of laser shock to test coating within the range <50 μm has already been widely demonstrated in the nanosecond pulse duration during the last 30 years.

Comparing with laser shock, a newly developed method of bullet shock has a longer pulse duration, up to a few hundreds of nanoseconds [Wu et al, 2009]. It thus seems to be the most convenient for thicker coating like TBC. Furthermore, the analysis and modeling considering the interaction between the bullet and the sample is relatively simple. As we know, laser shock involves complicated phenomena such as rapid melting and ablation of the materials. The purpose of present study is to apply bullet shock method for conventional TBC, i.e. the ceramic TC of partially stabilized zirconia combined with the metallic BC of MCrAlY, and explore the underlying mechanism based on experimental and numerical simulation.

2. Experimental Study

In this experiment (Fig.1), a 12.7 mm diameter bullet is driven by a gas gun system to vertically impinge on the back surface of a 100 mm diameter nickel disc. The bullet diameter is much larger than disc thickness of 2.5mm to ensure a planar shock wave propagation, which allows a one-dimensional interpretation of shock phenomena. The bullet velocity of V_0 from 50 to 400m/s is adopted to adjust the impact intensity and detect the response of multiple interfaces. A compressive stress pulse from impact propagates toward a 0.45 mm thickness test coating, which is deposited on the substrate's front surface by conventional plasma spray process. This compressive stress wave reflects into a tensile pulse from the coating's free surface and loads the interface.

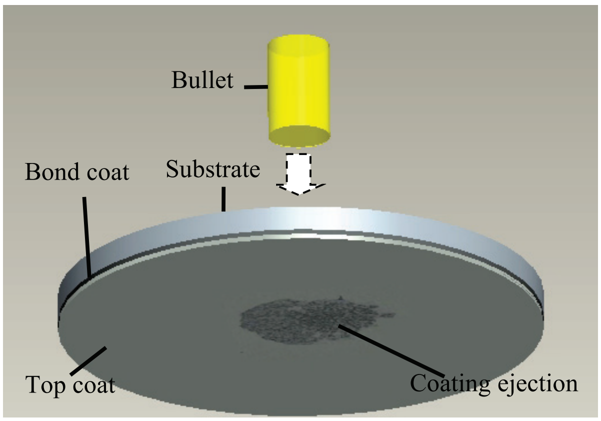
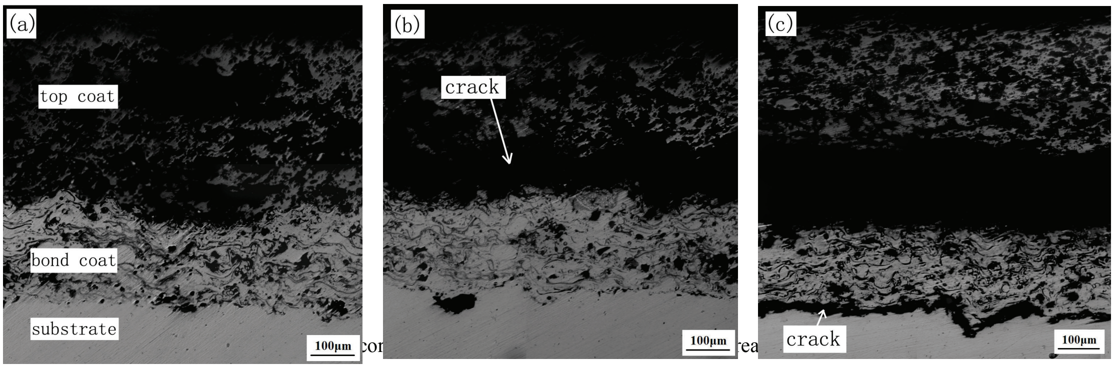


Fig. 1. Schematic representation of bullet shock test

Prior to modelling the stress history, a series of qualitative experiments are carried out to asses the impact velocity on damage and spallation of the test coating. At velocity higher than 300m/s, coating is partially expelled, shown in Fig.1, and a closer optical examination shows that only TC has been expelled. Very few remains of TC can be found on the BC surface from which brittle TC has been spalled off. Note that coating detachment is in the shape of irregular rather than theoretically penny. This characteristic was also found in laser shock test and explained by some heterogeneousness of coating microstructure and impact intensity in the focal spot.

At lower impact velocity of 50m/s, there is no visual sign on the bare face of coating. It is known that interface delamination may not necessarily correspond to coating spallation, as found in laser shock test [Guipont et al, 2010, Berthe et al., 2011]. This is because the ends of the interfacial crack formed upon interface decohesion may not have enough energy to break through coating to form a free spall. As such, a series of samples are tested at bullet impact velocity ranging from 50-300m/s in increments of 50m/s. This experimental protocal let a linear increase in compressive stress pulse amplitudes, according to the previous modelling [Wu et al, 2009]. Correspondingly, the tensile stress is gradually amplified until the weakest interface fails. After impact, a fine checking of coating cross section is carried out on the samples by embedding in an epoxy resin, cutting and polishing them through a plane parallel to shock axis.

Typical damage patterns on TBC are shown in Fig.2. At lower impact velocity of 50m/s, no interface damage is observed (Fig.2(a)). Here, sparse black regions in the coating and interface denote as-deposited pores which are not supposed to alter by shock. Increasing velocity (50-100m/s), delamination of TC/BC occurs (Fig.2(b)). Further increasing velocity(-300m/s), duplex interfaces are incurred delamination, shown in Fig.2(c). The extreme case is that TC ejects and leaves BC alone, as shown in Fig.1. These results obey the general concept that interfaces are the weaker sites in the coated sample. In addition, the adhesion of BC/substrate is better than that of TC/BC. The failure of multiple interfaces is an interesting phenomenon which is unlikely to occur under bond-pull test.



3. Analysis of one-dimensional shock wave

A finite element-based acoustic wave mechanics simulation is conducted to calculate the stress histories. The materials are assumed to be ideally elastic and their mechanical properties collected from literature are listed in Table 1. Here, E, ρ, ν are elastic modulus, density, and Poisson's ratio, respectively. The bullet velocity V_0 is set to be 50 m/s. The initial gap between bullet and sample is estimated to be 5 μm and the resulted impact time is 0.1μs.

Table 1. Mechanical properties for three layered sample shot by bullet.

Materials	ρ(kg/m$^{3)}$	E/GPa	ν
Substrate	8780	213	0.25
Bond coat	7320	200	0.3
Top coat	5600	48	0.1
Bullet	1050	1.2	0.4

Fig.3 shows the axissymmetric stress field over the bullet radius around the impact centre at the time of 0.344 μs. The arrow and dash-dot line indicate impact direction and axis, respectively. At this time, the input compressive stress has propagated away from the substrate and reflected from the coating surface. The tensile stress converted reaches the maximum. As can be seen, the tensile stress shows the configuration of thin strip. It is mainly confined to circular region of bullet radius and roughly uniform along the interface direction.

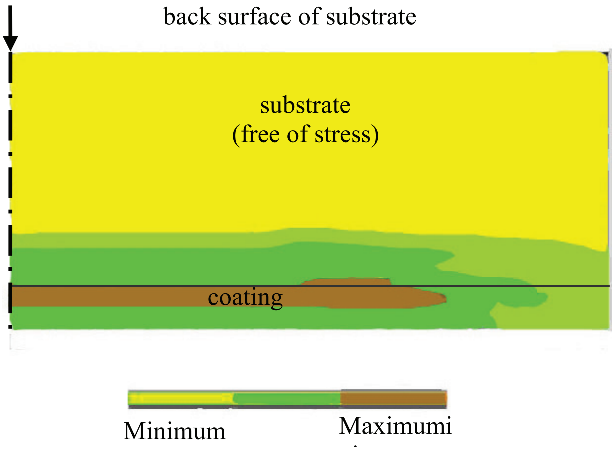


Fig.3. Simulation of creation of tensile stress during a bullet shock

To describe the stress profiles more accurately, we deduct the computation data at three different positions along the impact axis i.e. the back surface of substrate, BC/substrate and TC/BC interface. These data, plotted as a function of time in Fig.4, can be regarded as representative of the creation and propagation of the compressive and tensile stresses during a shock onto the sample. As can be seen, the compressive stress, originating from the back surface, reaches BC/substrate and TC/BC interface step by step. Its peak gradually decays due to energy dissipate, an inevitable hydrodynamic effect which has been found in laser shock test. However, the pulse duration is much longer, up to several hundreds of nanoseconds.

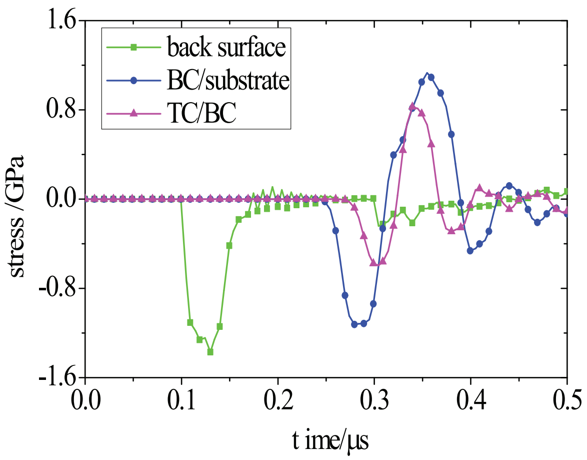


Fig. 4. The stresses acting on the back surface and duplex interfaces versus time

For BC/substrate and TC/BC interfaces, their stress history have the same characteristic, i.e. a first compressive pulse followed by a tensile one without relaxation. The difference lies in two aspects. First, substrate/BC is incurred by higher compressive stress and resulted higher tensile stress. Second, tensile stress at substrate/BC holds longer. It is known that high intensity and long duration promotes interfacial delamination. Therefore, delamination is expected to occur in every interface, shown in Fig.2 (c), even though substrate/BC has a better adhesion than TC/BC.

The above analysis does not concern the sequence and interaction of multi-cracking. Such a phenomenon has also been observed and analyzed in laser shock test, mainly for a single coating-substrate system. In 2002, M Boustile *et al.* reported an example of plasma sprayed alumina coating on Al [Boustie et al., 2002]. At a lower shock intensity, they observed a spall within the coating, but no delamination at the interface. Increasing the intensity, delamination appears besides the inner rupture of the coating. They believed that the interface was incurred sufficient tensile stress to achieve delamination, even if cohesive fracture occurred first. In 2005, they gave another example of cold sprayed Cu on Al [Barradas et al., 2005]. Through optimizing material thickness and shock loading features, they realized the similar tensile stresses at the interface and in the coating with lamellar structure. As expected, coating-substrate and interlamellar interfaces failed during a single shot without difference in the impact intensity level. They suggested that the first rupture occurred at the interface where maximum tensile stress initiated. For multi-layers and multi-materials combination, the failure of multiple interfaces may be complex [Kitey et al., 2010] and needs to study in the future work.

The calculated stress level, shown in Fig.4, should be higher than measured one by the static bond-pull method. The main reason should be the effect of dynamic loading as evidenced in laser shock [Arrigoni et al., 2006, Barradas et al., 2005, Tran et al., 2011]. In addition, the test coating is of large amount of porosities. The stress may possibly reflect at any interfaces in the coating besides test interfaces. It was evidenced that shock was attenuated on its path because of the presence of pores, involving oblique reflections with lateral releases. As pores are obstacles that disturb and impede the shock front in the case of the porous media, it provokes peaks that are stretched and lower in intensity than those obtained for solid media. To obtain a better estimation of the stress history during shock wave, one should implement compaction model. Anyway, the present study extends bullet shock test for TBC and obtains the main characteristic.

4. Conclusion

We have successfully used bullet shock to obtain decohesion of multiple interfaces in a thermal barrier coating on a nickel substrate. With numerical simulations, we further describe wave propagation in such a target to obtain information on the stress history at interfaces. A weaker bond of TC/BC than BC/Substrate is evidenced. If any rupture occurs under low velocity impact, the first sign of damaging appears at TC/BC interface although it incurs lower tensile stress. Under high velocity impact, a second damage area appears at BC/substrate interface which receives high stress intensity and long pulse duration.

Acknowledgements

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