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ARTICLE

Study on the Tensile and the Fatigue Behavior of Air Plasma Sprayed YSZ TBC Systems

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ABSTRACT

Thermal barrier coating (TBC) system composing of bond coat, having two different metallic bond coating materials such as NiCoCrAlY and CoNiCrAlY, and top coat, 8YSZ (8 wt%Y_2O_3-ZrO_2) ceramic coating was deposited on aluminum-based alloy by atmoshpheric plasma spray (APS). Fatigue test and tensile test both was performed for TBC sample. The tensile test and fatigue, both results showed that that fracture occurred in 8YSZ coating near the interface of ceramic-bond coating. These lead to the formation of weak inter-bonding strength and the failure of APS 8YSZ TBC. Moreover, in order to better understand the failure process, a deposition mechanism of coating was proposed. Experimental observations of the failed specimens subjected to tensile as well as fatigue loading exhibited different mode of failures in the form of coating cracking and spallation. However, the tensile results highlighted the different fracture mode in the mud of vertical cracks and crack propagation up to macroscopic failure.

1. Introduction

Conventionally, thermal barrier coating systems (TBCs) are double layer coating (DBC) composing of both, bond coat (BC) deposited on metallic substrate and a top coat (TC) deposited on as-sprayed bond coat. It is very familiar that the metallic powder alloys namely MCrAlX (M= metal like Co, Ni, NiCo or CoNi and X= Reactive element earth metals) is used as bond coat whereas top coat is any ceramic powder composition but conventionally yttria stabilized zirconia (YSZ) is taken in the weight percent of either 7%, mostly, or 8%. Top coat is conventionally deposited by two techniques, namely air plasma spray (APS) and Electron beam physical vapour deposition (EB-PVD), however some non-conventional techniques such as sol-gel was successfully developed for top coat deposition, whereas bond coat can be deposited by any available thermal spray techniques such as APS, EB-PVD, High velocity oxyfuel (HVOF) and others [1-9].

As far as the concerning of TBC application, it is normally used on the high temperature zone surface of components such as piston in internal combustion (IC) engines, and on the blades in gas turbine. It is the application of TBCs due to which it is large number of

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researchers is still attracting attention. Therefore, TBC damage, whether it is in the mode of spallation, delamination or cracks, is one of the major concerning fields that should be prevented. Therefore, the induced coating stress set-up, thermal stress, in the TBC systems during services needs to measure precisely. As we know that the APS deposition technique works on uninterrupted impact with the deposition of melted micro powder particles onto the target surface and resulting it is cooled down after spreading along a flat surface. This rapidly cooled down phenomenon of powder particles is the reason for high quenching thermal stress turn in formation of microcracks. Due to spreading of melted powder particle over flat surfaces of substrate, in APS techniques, contributing to the formation of lamellar-type of microstructure inbuilt with many inter-splat cracks and pores. Due to this characteristic, the TBC application is strongly associated with the plasma spray condition and the stress-strain behaviour of YSZ top coat as thermo- mechanical properties induced in the TBC system [5-9].

Cruse et al.[10] studied the stress-strain behaviour on the compression part of YSZ cube-shaped sample, which extracted from a TBC sample and they observed the quite different nonlinear stress-strain relationship from heat-treated ceramic materials. It was again examined and performed, by Rejda et al., the stress-strain behavior of the YSZ coat[11]. YSZ/CoNiCrAlY and $CaTiO_3$/CoNiCrAlY both TBC systems fabricated on the thin carbon steel shaft, and this shaft was etched and made hollow thin coating specimen from the shaft using a 50% solution of nitric acid and water. It was then tested to figure the compressive stress-strain, stress relaxation, and change in elastic modulus diagram subjected to fatigue loading. They found common characteristics in irreversible, time dependent and temperature dependent deformation in thermal sprayed coating and almost similar observations were reported by Wakui et al.[12] using miniaturized mechanical testing equipment with an optical microscope and scanning electron microscope (SEM). They also observed that how the deformation and damage occurring in the top coat under tensile and compressive loads both. The trends of the stress-strain response, which was measured directly from the SEM image was agreed with the above results, and the overall 0.3% critical strain was identified at cracking site in the YSZ coat. In addition to this observation, the larger elastic modulus in the compressive side was found against the tension side. Furthermore, Thompson et al.[13] reported major microcrack opening in the inelastic deformation of the YSZ coating, and they also investigated the microcrack closure phenomenon due to large elastic modulus in the compression side. Waki et al. [14] studied on compressive stress-strain curve for YSZ top coat with the help of a laser speckle strain measurement system.

Due to low equipment investment and production costs, since it can be performed under atmospheric pressure, in comparison to among other thermal spraying techniques, APS gives a comparably better performance[15-18]. Therefore, APS techniques, in this study, is selected for spraying both the bond coat and top coat.

The objective of the current study is to study the fatigue life and tensile fracture for a two different TBC system fabricated on aluminum alloy substrate, in which two different bond coated materials having NiCoCrAlY and CoNiCrAlY , and a Y_2O_3–ZrO_2 was treated as top coat, were fabricated by APS techniques.

2. Experimentation

2.1 TBC Sample Preparation

The cast Al--based aluminium alloy was selected as a base metallic alloy, i.e. substrate. The chemical composition (in wt.%) of used base metallic alloy is refer in Table 1[3,5,6]. The feedstock material was agglomerated 8YSZ designated as M6700 (Oerlikon Metco). Testing sample, used for tensile testing and fatigue testing, made of aluminium alloy, with a diameter of 15 mm, were used as substrates and the top side edge of the specimens was rounded. Shape of both test tensile and fatigue were in cylindrical shape. Before the application of TBC, the substrates were coated with a 150 μm thick of bond coating materials, NiCoCrAlY & CoNiCrAlY (Amdry 386, Oerlikon Metco) by using the APS. The applied APS parameters for both the bond coat and top coat used are, as shown in Table 2 [3,5,6] and Table 3 [5,6]. Bare substrate used for both fatigue and tensile testing, before the application of bond coat and top coat, are shown in Fig.1(a&b) whereas Fig.1(c&d) presents the application of TBC on two different bond coats.

Table 1. Chemical Composition of AA2024-T351

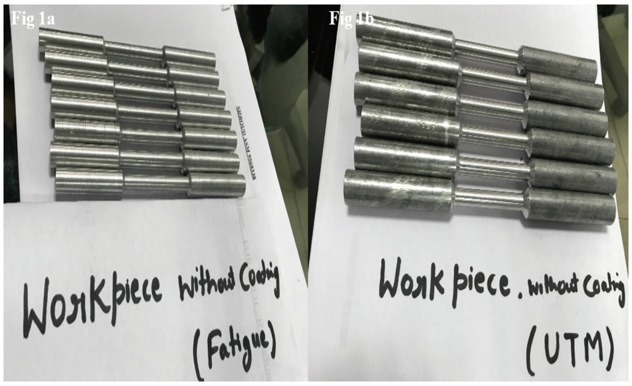
Elements	Cu	Mg	Si	Zn	Mn	Al
Compositions (%)	4.7	1.4	0.5	0.25	0.5	Balance

Table 2. Spraying Process Parameters for Bond Coat

Current (A)	Voltage (V)	Pr.gas, Ar (l/min)	Sec.gas, H2 (l/min)	Powder feed rate (g/min)	Spray distance (mm)	Power (kW)
550	67	43	9.5	20	102	37

Table 3. Spraying Process Parameters for 7YSZ coating

Current (A)	Voltage (V)	Pr.gas, Ar (l/min)	Sec.gas, H2 (l/min)	Powder feed rate (g/min)	Spray distance(mm)	Power (kW)
600	71	44	13	20	102	42.6



(a) (b)

Figure 1 c. NiCoCrAlY bond coated TBC sample.

Figure 1 d. CoNiCrAlY bond coated TBC sample.

Figure 1. Fatigue testing and Tensile testing samples without coatings respectively(a&b)

2.2 TBC Testing

Here, two type of testing, fatigue tests, and tensile tests of specimens, were performed on fatigue testing machine, see in Fig.2a., and universal tensile testing (UTM) machine, see in Fig.2b., respectively. Cross sectional optical micrograph of TBC is shown in Fig. 3.

Figure 2a. Fatigue testing machine

Figure 2b. Universal testing machine for tensile testing

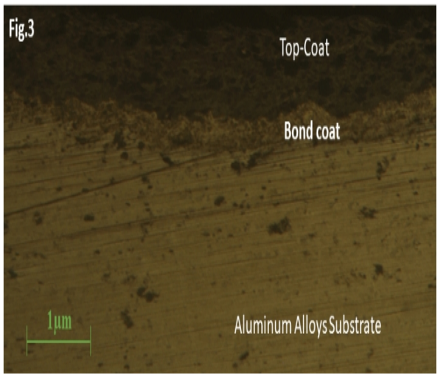


Figure 3. Optical cross sectional micrograph of TBC

3. Results and Discussion

3.1 Experimental Observation of Fatigue Testing

In fatigue test, the testing samples in cylindrical shape, were subjected to mechanical loading imposed by a putting a 150N load on load span using a lever mechanism. For finding the mean values and variations of the results, here, minimum three samples were taken.

Observed photos of failed specimens taken by a camera are shown in Fig. 4a, & 4b. It can be seen that the similar fatigue failure behaviors in two different bond coated TBC systems are observed. The specimens failed in the gauge lengths in the fatigue tests for various three bond coated TBC sample, there are no cracking found in the top coat, and the observed interfaces region coatings are almost intact with the bond coat and substrate within the gauge region of TBC sample, which indicates the in-phase condition, reported by Chen et al.,2011[19]. From the Fig. 4b, it can be seen that some spallation on top coat was located. However, no other mode of failure in terms of cracking was observed.

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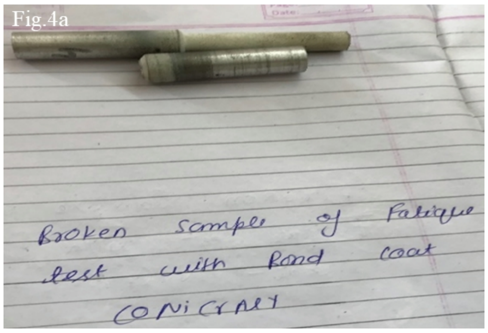

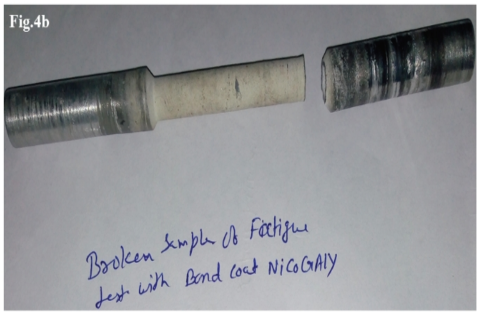

Figure4a. Typically failed TBC sample under fatigue loading(a) CoNiCrAlY, and (b)NiCoCrAlY bond coat.

3.2 Experimental Observation of Tensile Testing

The tensile stress–strain curves of the TBC specimens and the corresponding material of the substrate at room temperatures (RT) are performed. It is also observed that the strength of the bare substrate is higher than that of the TBCs at RT, clear from result data of tensile testing as shown is given in Table 4.

Table 4. Result data of tensile testing

S.N.	Bare substrate/TBC with Bond Coat	Tensile Strength (MPa)	Elongation(m)
1	Bare Substrate	392.27	12
3	NiCoCrAlY/YSZ	264.39	12
4	CoNiCrAlY/YSZ	275.37	14

However, the strength of TBC systems with CoNiCrAlY bond coating materials was found to higher than to NiCoCrAlY bond coat, which approves the earlier reported that CoNiCrAlY as bond coat material is more preferable to NiCoCrAlY [1,4-6]. Possible reason of larger magnitude of tensile strength in bare substrate comparison to applied coating material to substrate can be understood as the effect of stiffness in term of "thickness", which is strongly influenced by smaller thickness of applied coating by plasma.

Experimentally observed failure region appears at the border between the bond coat and the top coat, clear from the Fig.5(a&b), approving the weak interlocking bonding strength [20]. However, similar nature of failure location was found in various bond coated, CoNiCrAlY & NiCoCrAlY, TBC systems. Fig. 5b clearly shows small part of the top coat intact to the bond coat and most part of the top coat was observed spall. It occurs due to the crack propagates along the BC/TC interface confirming to the low bonding strength again, contributing to spallation of the top coat from the bond coat only. However, no spallation of bond coat from substrate was observed, confirming to strong interlocking between bond coat and metallic substrate.

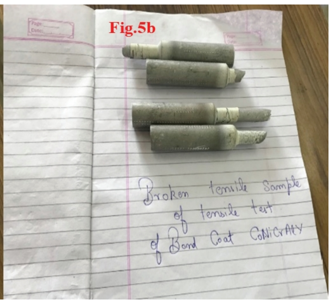

Figure 5. Failed TBC sample under tensile loading for: (a) NiCoCrAlY, (b) CoNiCrAlY Bond coat.

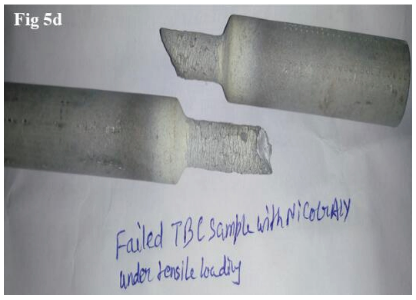

Figure 5. Failed TBC sample under tensile loading for: (c) NiCoCrAlY, (d) CoNiCrAlY Bond Coat.

All the fractured TBC specimens under tensile loadings as representative photos are shown in Fig. 5(a-d); however, the bond coating materials was different. Several vertical cracks to the direction of loading can be seen at the surface of the top coat and a small part of the top coat spalled in the fractured specimen of TBC as shown in Fig. 5(b-d). However, cracks can't be visible at the surface of the bond coat, see in Fig. 5(b). Similar observations were reported by various researchers; however, the metallic substrates were super-alloys[14,19-22].

Overall, it is concluded that the fracture surface of the

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TBC specimen under the tensile loading depicts different failure mode with the change in bond coat material. Almost similar failure mode was, reported by Chen et al., 2011[19]; however, the nature of loading is the out-of-phase thermomechanical fatigue (TMF). The fracture surfaces of both loading, tensile and fatigue loading, are almost similar appearance as in TMF failed specimens [19].

4. Conclusions

In the present work, the tensile and fatigue fracture behavior of the TBCs on aluminium alloy has been investigated at RT. The main conclusions are summarized below:

(1) The bond coating has no observable effect on the tensile property and fatigue behavior of the substrate and the strength of the TBC system almost equals to that of the substrate.

(2) The different mode of TBC failure under fatigue loadings and tensile loading was observed. The TBC specimens failed at the gauge length region without delamination, subjected to fatigue loading whereas the mud of vertical crack and spallation was observed in the tensile cases.

(3) Tensile strength of TBC sample with CoNiCrAlY bond coat material was significantly more; hence suggested preferable comparison to NiCoCrAlY bond coat material.

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