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Effect of NiTi Addition on the Wear Resistance of YSZ Coatings

N. Mansourinejad[a], M. Farvizi[a]*, K. Shirvani[b], M. R. Rahimipour[a], M.r Razavi[a]

[a] *Department of Ceramic, Materials and Energy Research Center, Karaj, Iran.*
[b] *Department of Materials Engineering, Iranian Research Organization for Science and Technology, Tehran, Iran.*

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ABSTRACT

In this study,a small fraction of NiTi particles (5 wt.%) was added to Yttria stabilized zirconia (YSZ) top coat to improve its sliding wear resistance. The measurement of width of wear tracks after wear tests under a 15 N load for 100 m sliding distances showed that the width of wear track in NiTi-YSZ coating is shorter than that of the YSZ coating which depicts the higher wear resistance of NiTi-YSZ coating samples. It is believed that the higher hardness/elastic modulus (H/E)value and pseudoelasticity effect of NiTi are two important factors which improved the wear performance of applied coatings. Also, to evaluate the role of addition of a NiTi (5 wt%)–YSZ buffer layer on the durability of YSZ coatings during wear operation, wear tests with a 20 N normal load and with a constant frequency were conducted on coated samples. It was observed that the conventional YSZ coating cracked and delaminated after about 60 m sliding distance. However, in samples which contain a NiTi (5 wt%) –YSZ buffer layer, delamination was not observed until 100 m sliding distance which is attributed to the ability of NiTi for accommodation of interface stresses and hindering of premature delamination during wear test under higher loads.

1. INTRODUCTION

Superalloys that work at elevated temperatures and hostile environments have many advantages in comparison with conventional alloys. However, for increasing engine efficiency, enduring higher temperatures and longer periods of service time, thermal barrier coatings (TBCs) should be applied on superalloys. Thermal barrier coatings are used to protect hot section components such as gas turbine and aero engine parts at high temperatures. These coatings, as the name suggests, are coatings which prepare a barrier to the heat flow and increase the lifetime of components, energy efficiency and operating temperature [1,2]. TBCs consist of four layers, the first layer is a superalloy substrate, the second layer is a metallic bond coat, the next layer is a thermally grown oxide (TGO) and the last one is a ceramic top coat [3].

Over the years, a number of materials have been suggested and studied as TBCs. The selection of TBCs materials is a critical problem, because there are certain characteristics that a good thermal barrier coating should satisfy. TBCs should have high melting point, low thermal conductivity, resistance to oxidation, and high thermal coefficient of expansion (in order to reduce the thermal mismatch between the top coat and substrate) and resistance to mechanical erosion [4].Up to now, just a few materials including Zirconates, Alumina, Garnets, Yttria Stabilized Zirconia (YSZ) have been found to basically fulfill these requirements [5]. YSZ seems to be the desired choice as determined originally by NASA [6]. This material displays a good resistance to thermal shock and fatigue up to 1150°C [4].

Of diverse processing techniques for applying TBCs on considered substrate, atmospheric plasma spraying (APS) method is very attractive and common because of its low economic cost, high deposition efficiency and, more importantly, lamellar structure of APS coatings with some porosity that reduces the thermal conductivity and improves the insulation of the components [7, 8].

Long lifetime and/or high operating reliability are two important factors in hot sections, that depend on the frictional behavior of protective coatings and it is mostly determined by the properties of their surfaces. Erosion is one of the degradation mechanisms of thermal barrier coatings that decreases the lifetime and reliability of TBCs. The coatings should exhibit good mechanical erosion and wear resistance against the different particles existing in the exhaust gas coming from the combustion chamber [3]. Zirconia-based TBCs, and especially 7-8YSZ coatings, are sensitive to erosion due to presence of particles and debris in the high velocity gas flow of a gas turbine engine. In

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*Corresponding Author's Email: mmfarvizi@merc.ac.ir (M. Farvizi)

addition, adjoining hardware within a gas turbine engine may erode the thermal barrier coating and lead to the oxidation of underlying metal substrate [9, 10]. As a result, there is a high need for impact and wear-resistance in thermal barrier coating systems. Hence, a thermal barrier coating system is required which is distinguished by the ability to resist wear and spallation when exposed to impact and erosion in a harsh thermal environment. Extensive researches have recently been conducted to improve the wear behavior of thermal barrier coatings. For example, N. Xiang et al. [8] improved the wear resistance of TBCs by applying nanostructured 8YSZ coating instead of micron-structured coating. Y. Ye [11] has suggested the addition of a secondary phase with higher thermal conductivity and a higher level of hardness into the zirconia phase for improving wear resistance.

Due to the nature of TBCs applied by APS method, a variety of defects such as microcracks, microvoids, and pores exist in these coatings [12]. Also, the difference between coefficients of thermal expansion (CTE) of ceramic top coat, TGOs and metallic bond coat is another important factor which leads to formation of initial thermal stresses. The evolution of these stresses during operational conditions of TBCs gradually leads to spalling and failure in coatings [12]. One of the well-known methods for reduction of thermal stresses is introduction of a buffer layer between the ceramic top coat and the metallic bond coat.

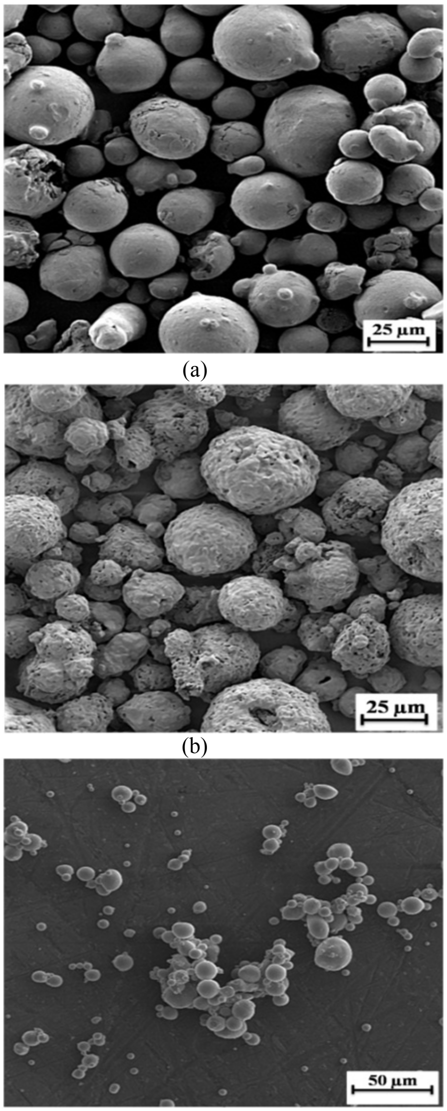
NiTi alloy has unique properties such as pseudoelasticity effect, good oxidation resistance, considerable toughness and high wear resistance which makes it a great candidate for various industrial applications [13-16]. Also, the CTE value of NiTi in the austenitic condition is about 11×10^{-6} 1/K [16] which is very close to the CTE of YSZ ($\alpha_{YSZ}=10.7\text{-}11.5\times10^{-6}$ 1/K). According to above-mentioned properties of NiTi, in this study, (i) the wear resistance of YSZ and NiTi (5 wt.%) -YSZ top coats were compared, and (ii) the effect of introduction of NiTi (5wt.%)-YSZ buffer layers between MCrAlY metallic bond coat and YSZ top coat on the durability of TBC coatings during wear tests was studied.

2. MATERIALS AND METHOD

2.1. Substrate and spray feedstocks

In this study, Inconel 738(15.5 wt.%Cr–8.5 wt.%Co–3.5 wt.%Al–3.5 wt.%Ti–2.6 wt.%W–1.8 wt.%Mo–1.6 wt.%Ta, balanced Ni) was used as the substrate. Disk-shape superalloy samples with diameter of 25.4 mm and thickness of 5 mm were prepared with electro discharge machining (EDM) method.

Commercial CoNiCrAlYSi powder with the composition of Co-29 wt.% Ni-26 wt.%Cr-8 wt.%Al-0.6 wt.%Si-0.8 wt.%Y (Sicoat 2231), Zirconia-8 wt.%Yttria (PAC 2008P) and Nitinol (Ti-56 wt.% Ni) were used as feedstocks to produce coatings with Atmospheric Plasma Spraying process (APS) onto a superalloy substrate. The CoNiCrAlYSi,8YSZ, and NiTi powders, all have been characterized as a spherical morphology (Fig. 1).



(a)

(b)

(c)

Figure 1. SEM micrographs of starting materials (a) MCrAlYSi, (b) 8YSZ, and (c) NiTi powders.

Before applying coatings, substrate samples were polished using silicon carbide abrasive papers. For increasing the roughness of the substrate and reaching a suitable mechanical interlocking between coatings and substrate, the superalloy substrate was sand-blasted with alumina particles, and then ultrasonically cleaned in ethanol. The plasma sprayed coatings were deposited with an APS 3MB system from Sulzer-Metco. Three groups of coatings deposited on Inconel substrate were encoded as: Group (i): CoNiCrAlYSi-YSZ, group (ii) CoNiCrAlYSi-(5 wt.% NiTi+YSZ), and group (iii) CoNiCrAlYSi-(5 wt.% NiTi+YSZ)-YSZ. The thickness and composition of layers are summarized in Table 1 and Fig. 2. Details of APS parameters are presented in Table 2.

TABLE 1. Thicknesses and chemical composition of TBC coatings.

	CoNiCrAlYSi	YSZ+5%NiTi	YSZ
Group (1)	150 µm	-------------	350 µm
Group (2)	150 µm	350 µm	-------------
Group (3)	150 µm	150 µm	200 µm

TABLE 2. APS parameters used for preparation of coatings.

Layer	Current (A)	Gas Flow (Ar/H_2)	Feeding rate (g/min)	Distance spray (mm)
MCrAlY	450	80/15	10	120
YSZ	500	80/15	20	100
YSZ+NiTi	500	80/15	10	100

2.2. Wear test

After spraying TBC coatings on Inconel substrate, the wear resistanceof samples was examined using a pin-on-disk configurationin dry conditions at room temperature in air. Tungsten carbide pin with a hardness of 75 HRC was used as the counter friction pair. A load of 15 N and a sliding frequency of 15 rpm for a sliding distance of 100 m were employed.

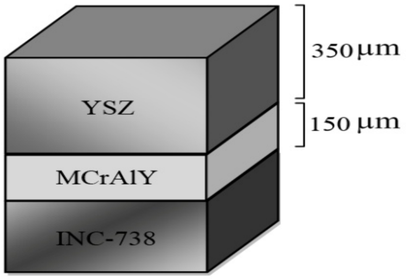
2.3 Characterization

The morphologies of the powders, the cross section of coatings and worn surfaces were studied by Scanning Electron Microscopy (SEM/EDS), (SEM: VEGA-TESCAN-XMU, Czech Rep.). For phase identification of the coatings, X-ray diffraction analysis (Siemens D500 model) was carried out with voltage, current, and radiation of 30 kV, 25 mA, and Cu-K_α (λ=0.154 nm), respectively.

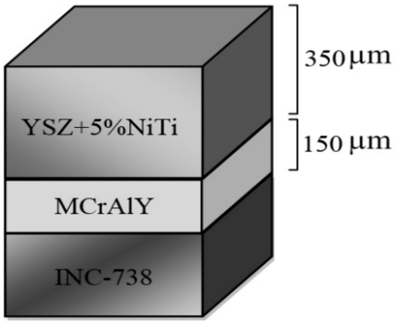
3. RESULT AND DISCUSSION

3.1 Microstructure of coatings

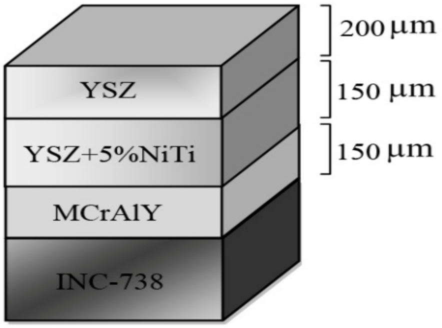
SEM micrographs (cross section) of three groups of coatings which were deposited on Inconel 738 substrate are represented in Figs. 3(a-c). It is seen that a dense CoNiCrAlYSi bond coat and a porous bimodal microstructure which mainly consists of molten particles and small fraction of unmolten particles exist in YSZ top coat.



(a) Group (1)



(b) Group (2)



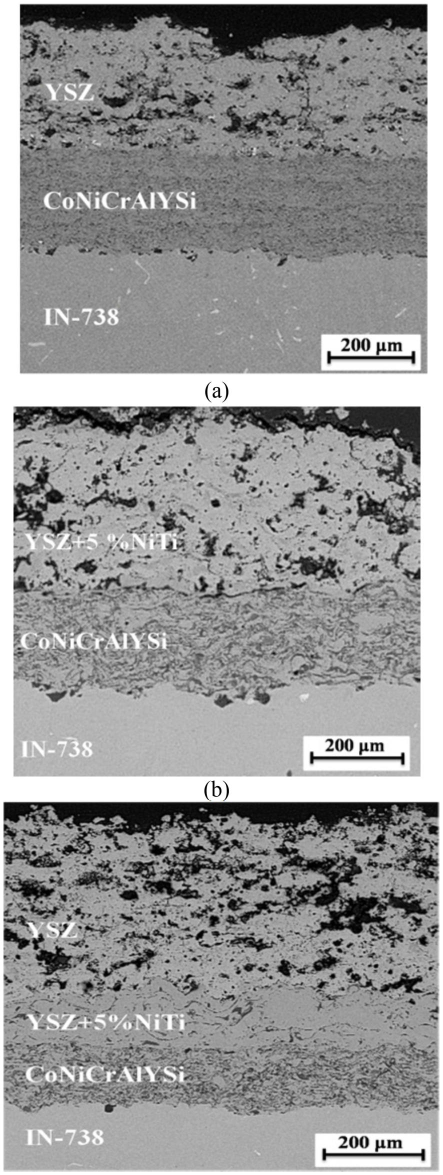
(c) Group (3)

Figure 2. Schematic of three groups of coatings applied with APS method on Inconel 738 substrate.

The x-ray diffraction (XRD) patterns of the as-sprayed coating layers are illustrated in Fig. 4. It is seen that these peaks are well-matched with tetragonal zirconia (JCPDS 01-083-0113) and B2-NiTi (ICDD 18-899) structures.

3.2 Wear test

n order to understand the influence of NiTi addition on the wear resistance of YSZ coating, the tribological behavior of samples related to group 1 and group 2 are studied using a pin-on-disc configuration under a 15 N normal load for a sliding distance of 100 m. The SEM micrographs related to worn surfaces of samples groups 1 and 2 are represented in Fig. 5(a,b). The markers on the SEM pictures show the width of wear track which is a criterion to evaluate the wear resistance of samples. It is clear that the width of wear track in NiTi-YSZ coating (group 2) is shorter than that of the YSZ coating (group 1) which depicts the higher wear resistance of group 2 samples in abovementioned conditions.



(c)

Figure 3. SEM micrographs of coatings deposited on IN-738 substrate, (a) CoNiCrAlYSi-YSZ, (b) CoNiCrAlYSi-(YSZ+5 wt%NiTi)-YSZ, and (c) CoNiCrAlYSi-(YSZ+5 wt %NiTi)-YSZ.

The EDS analysis results obtained from worn surfaces show that while the wear track of YSZ coating only consists of oxygen, yttrium and zirconium elements (Fig. 5(c)), in NiTi-YSZ in addition to these elements, small peaks related to nickel, titanium, and tungsten elements were also detected. It is believed that the tungsten element was introduced from WC ball during wear test which again approves the higher wear resistance of NiTi-YSZ coating compared with YSZ coating. According to Archard equation [17], hardness has been considered as a primary material property which controls wear resistance. However, there is strong evidence tosuggest that the elastic modulus can also have an important influence on wear behavior.

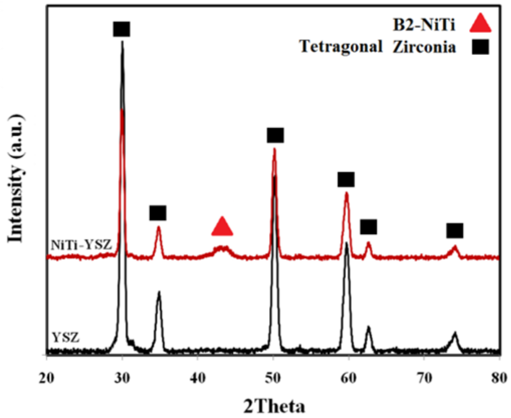


Figure 4. XRD pattern of coatings deposited on IN-738 substrate, (a) YSZ top coat related to group 1 and 3 samples and (b)(YSZ+5 wt%NiTi) top coat related to group 2 samples.

In particular, the elastic strain to failure, which is related to the ratio of hardness (H) and elastic modulus (E), has been shown by a number of authors to be a more suitable parameter for predicting wear resistance than hardness alone [18]. The measured and reported values for hardness and elastic modulus of YSZ coatings deposited with APS method with nanoindentation method are H=8.7 ± 2.1 GPa and E=144 ± 5 GPa [19], respectively, which yields H/E=0.0602 while these values for B2-NiTi are H=3.60±0.3 GPa and E=52.06 ± 8.5 GPa [14] which yields H/E=0.0691. So, it is observed that NiTi phase has a higher H/E value which shows its higher elastic strain to failure and better wear resistance. In spite of higher H/E value of NiTi, austenitic phase of nitinol shows a unique property which is called pseudoelasticity. Pseudoelasticity results from the reversible martensitic transformation and a large amount of deformation recovered due its complete or partial occurrence [20]. It is proved that this property is extremely beneficial inenhancing wear resistance under low load conditions [14]. As a consequence, due to higher H/E value and pseudoelasticity effect, addition of appropriate amountof NiTi to YSZ coating improved the wear performance of the applied coating. Also, while the signs of crack propagation and delamination can be easily found in the YSZ coatings, a smooth and delamination-free worn surface was evolved in the

NiTi-YSZ coatings. Due to similarity of YSZ top coat of group 1 and group 3 samples, the wear performance of these two groups under a 15 N normal load did not differ significantly.

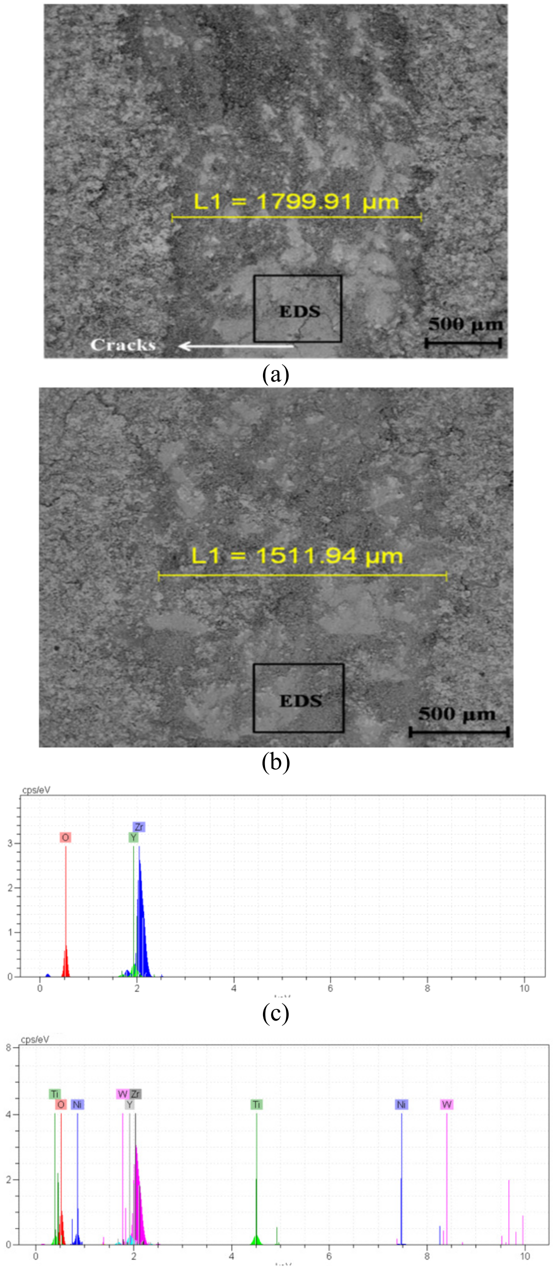


Figure 5. SEM micrographs of (a) YSZ top coat (group 1) and (b) NiTi (5 wt.%)–YSZ top coat (group 2); corresponding EDS of (c) YSZ top coat and (d) NiTi (5 wt.%) –YSZ top coat after wear test under 15 N load and 100 m sliding distance.

Generally, during sliding wear tests of TBC coatings, two kinds of failure mechanisms may occur: (i) surface damage due to the pin motion on coatings surfaces, and (ii) the flaking and delamination failure according to the lamellar structure of TBC coatings. In order to evaluate the role of addition of a NiTi (5 wt.%) –YSZ buffer layer on the durability of YSZ coatings during wear operation, wear tests with higher normal loads and with a constant frequency were conducted on coated samples of groups 1 and 3. It was observed that group 1 samples cracked and delaminated after about 60 m sliding distance under a 20 N normal load. However, in the group 3 samples delamination was not observed until 100 m sliding distance and only some cracks can be found in the worn area of this sample (Fig. 6). It is believed that addition of small fraction of NiTi to YSZ and formation of NiTi (5 wt.%) –YSZ buffer layer can help to provided better accommodation of interface stresses and hinders premature delamination during wear test under higher loads.

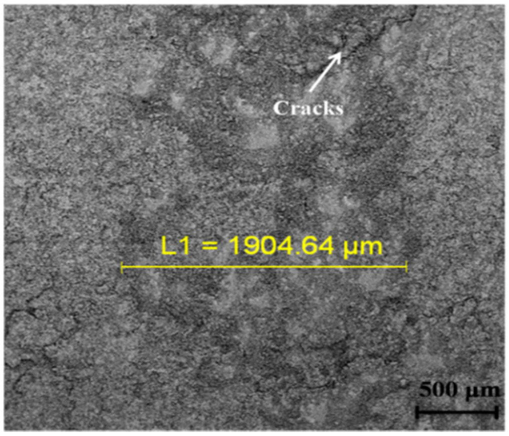


Figure 6. Worn surface related to group 2 samples after wear test under 20 N load and 100 m sliding distance.

4. CONCLUSION

During the wear tests of the thermal barrier coatings, two kinds of failure mechanisms may occur which include surface damage due to the pin motion, and the delamination failure according to the lamellar structure of TBC coatings. In this study, to improve the surface wear resistance of TBCs, 5 wt.% near equiatomic NiTi particles were added to APS-YSZ coatings. The results of wear track measurements showed that the width of wear track in NiTi-YSZ coating is shorter than that of the YSZ coating which confirms its better wear performance during wear tests under a 15 N load for 100 m sliding. Also, to enhance the resistance of coatings against delamination failure during wear test, a buffer layer with the composition of NiTi (5 wt.%)-YSZ was added between the YSZ top coat and MCrAlY bond coat. It was seen that while the conventional YSZ coating cracked and delaminated after about 60 m sliding distance under a 20 N normal load, coatings with

NiTi–YSZ buffer layer showed much better durability and delamination failure was not observed in these samples. The observed improvement in the tribological behavior of TBCs is attributed to the higher hardness/elastic modulus (H/E) value and pseudoelasticity effect of NiTi which enhances the toughness and ability of coatings for accommodation of internal stresses.

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