

High-temperature performance studies of plasma-sprayed NiCrAlY based composite coatings

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Abstract. This study explores the oxidation behavior of plasma-sprayed NiCrAlY-based composite coatings developed to T91 boiler steel, aiming to enhance its high-temperature performance for sustainable applications. Coatings of NiCrAlY, based composites were developed using plasma spraying techniques and exposed to thermal oxidation tests at 800°C and 1000°C for 50 cycles. The outcomes show that ceramic reinforcements addition significantly enhance oxidation resistance. Composite NiCrAlY + YSZ coating had the lowest weight gain and best oxidation resistance due to its sound barrier properties and thermal stability. Microstructural, elemental analyses verified protective oxide layer formation on the coatings, thus improved durability in cyclic thermal conditions. This work demonstrates the potential for sustainable high temperature material performance of NiCrAlY based composite coatings, especially with YSZ reinforcement, in power plants and industrial applications.

Introduction

For the modern era of energy production and industrial operations, there are very challenging environments for materials that operate at high temperatures because of oxidation and degradation. T91 is a kind of boiler steels which are widely utilized in power plants and industrial applications, which have very good mechanical strength and creep resistance [1,2]. However, performance at elevated temperatures is greatly hindered by rapid oxidation, causing degradation of material, loss in efficiency, and increased maintenance cost. Since the service life of boiler steels is crucial for improving the lifespan of the steels, it is thus important to enhance the oxidation resistance of the boiler steels [3,4]. NiCrAlY-based plasma sprayed coatings offer high temperature oxidation resistance for structural materials. Ceramic additions like aluminum oxide and yttria stabilized zirconia improve coating performance, reducing oxidation rates and thermal stability [5]. These composite coatings minimize material loss and maintain substrate integrity. With increasing global



pressure for energy efficiency and sustainability, NiCrAlY-based coatings can extend boiler steels' service life and be low-cost, environmentally friendly [6]. Recent studies including plasma spray and other plasma spray related techniques, which investigate the cyclic oxidation resistance of composite coatings (NiCrAlY) are summarized in the table 1. Results from these studies show that the elevated temperature oxidation protection of coatings is substantially improved by incorporating ceramic reinforcements, such as Cr_3C_2 , Ti_2SnC , and YSZ, and by optimizing coating parameters, such as powder size and composition. A proper combination of defending oxides and self-healing ability was found to improve the durability and performance of these coatings in particular industrial applications. The studies highlight the importance of NiCrAlY composite coatings in sustainable high temperature environments such as aerospace, power generation and industrial systems.

Table.1. Recent Advances in Cyclic Oxidation behaviour of NiCrAlY-Based Composite Coatings.

Materials and Methods	Key Findings	Reference
NiCrAlY Based + TiO_2 and NiCrAlY based (Cr_2O_3 + YSZ)	Uncoated alloys exhibited much lower oxidation resistance than coated alloys.	Reddy et al [7]
Substrate: Titanium-15 alloy Method: Plasma spray coating; oxidation studies at 700°C for 50 cycles	NiCrAlY based (Cr_2O_3 + YSZ) coating offered greater protection due to the development of Al_2O_3 phases, Cr_2O_3 , NiCr_2O_4 .	
Coating: NiCrAl alloy	NiCrAl-coated steels showed lower oxidation rates than uncoated steels.	Ramesh et al [8]
Substrates: SA210 and T-11 boiler steels Method: HVOF spraying; hot corrosion and oxidation tests were conducted on 900°C for 50 cycles	Development of shielding oxides like Cr_2O_3 and $\alpha\text{-Al}_2\text{O}_3$ contributed to improved high-temperature stability.	
Coatings: NiCrAlY based (TiO_2) and (Cr_2O_3 + YSZ)	Composite coating exhibited the highest oxidation resistance.	Reddy et al [9]
Substrate: MDN-420	Protective behavior attributed to the development of NiCr_2O_4 , Cr_2O_3 , Al_2O_3 and NiO phases.	
Coating: NiCrAlY based (WC-Co/Cenosphere)	Coated substrate revealed lower oxidation rates compared to uncoated steel.	Mathapati et al [10]
Substrate: MDN 321 steel Method: Plasma spray coating; cyclic oxidation at 600°C for 20 cycles	Formation of oxides such as CoWO_4 , Cr_2O_3 , Al_2O_3 , NiO , and contributed to enhanced oxidation resistance.	

This work provides cyclic oxidation observations of plasma spray NiCrAlY based composite coatings on T91 boiler steel. This study analyzes weight gain after 50 cycles of test to determine the most effective coating system for sustainable high temperature applications. This work helps develop novel materials to overcome these challenges in the energy and materials industries, and to work towards better protection of the environment and resources.

Materials and Methods:

Plasma spraying of T91 low alloy ferritic stainless steel was performed in the study using METCO USA 3 MB equipment. Deposition of the coatings was carried out in controlled pressures and flow rate with argon and hydrogen gases. Surfaces were grit blasted and polished for best adhesion properties and the base material was NiCrAlY powder. The 15% concentration of ceramic particles (Al_2O_3 and (ZrO_2 + Y_2O_3)) was incorporated into the NiCrAlY matrix. The as coated final compositions were pure NiCrAlY, NiCrAlY + 15% Al_2O_3 and NiCrAlY + 15% (ZrO_2 + Y_2O_3).

Table 2. Summary of Plasma Spraying Parameters and Coating Compositions.

Parameter	Details
Substrate Material	T91 low-alloy ferritic stainless steel
Coating Technique	Plasma spraying using METCO USA 3 MB equipment
Main Gases Used	Argon and Hydrogen
Gas Parameters	- Argon: 0.7 MPa, 40 L/min
	- Hydrogen: 0.35 MPa, 7 L/min
Spraying Parameters	- Current: 490 A
	- Voltage: 60 V
	- Powder feed rate: 60 g/min
	- Spray distance: 100–125 mm

Oxidation Testing Procedure: Thermal cyclic oxidation tests were carried out on the coated substrates in a muffle furnace (Fig. 1(a)) for 50 cycles at 800°C and 1000°C to evaluate the oxidation resistance of coated substrates. The specimens were heated in the furnace for one hour, then cooled to temperature for 20 minutes. Each specimen was first surface cleaned in acetone, and its surface area prior to the experiment was measured with a vernier caliper. The crucible and specimen were weighed together and the initial weight recorded. Under a humidity chamber equipped with a shielded channel, the specimens were loaded into an alumina boat and then transported into a preheated furnace at 800°C for the furnace test. The specimen crucible was heated for one hour and then removed and cooled at room temperature for 20 minutes. One oxidation cycle was completed using a Contech Analytical Balance (Model CAI-234) to measure the combined weight of the crucible and specimens.

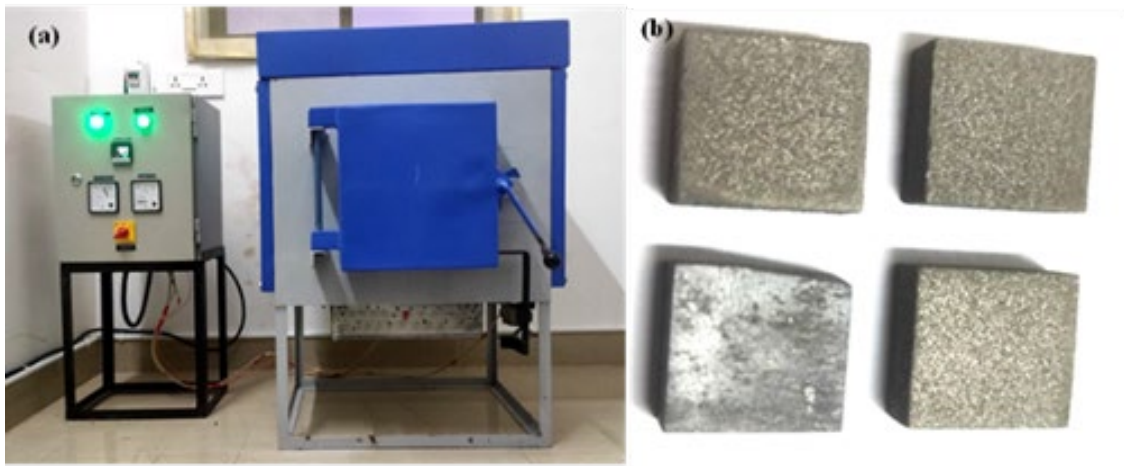


Figure 1 Shows the (a) Experimental setup, (b) Oxidised samples.

The specimens were reintroduced into the furnace after each weight measurement and this process was repeated 50 cycles. Mass gain after each cycle was recorded as a measure of the oxidation kinetics, enabling the oxidation resistance of the coatings to be followed. Data were analyzed after 50 cycles completion to evaluate the behavior of the coatings under the cyclic oxidation conditions. Fig 1.b shows the oxidised samples.

Results and Discussions

Microstructure Analysis: The pure NiCrAlY coating revealed in Fig.2 (a) has a characteristic of plasma-sprayed coatings, including a lamellar structure and splats originating from the impact of molten particles. Inherent porosity (black areas) and probable oxide inclusions (darker areas) can be identified through the micrograph obtained. These features influence the coating characteristics by offering a foundation for oxidation protection by developing a stable alumina (Al_2O_3) layer at elevated temperatures, thus improving the coating's performance. The microstructure of the NiCrAlY + Al_2O_3 coating (Fig.2 (b)) is more complex and is characterized by the dispersion of Al_2O_3 particles. This coating appears to have a denser microstructure with less and much smaller porosities than that observed in the NiCrAlY coating.

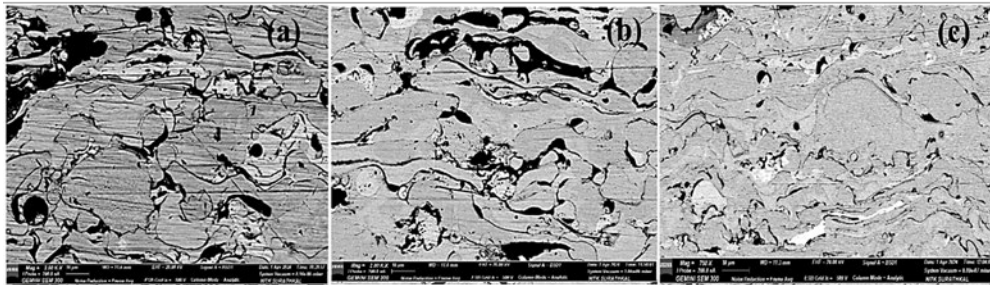


Figure 2 SEM images displaying a sectional view of NiCrAlY based composite coatings, (a) Pure NiCrAlY (b) + Al_2O_3 coating, (c) + YSZ coating.

The smaller size and uniform distribution of Al_2O_3 (light shades) tends to provide more hardness and better wear properties in the NiCrAlY base coatings. Reducing in the splat boundaries is advantageous to the cohesiveness hence enhanced thermal stability and thermal shock resistance. In the NiCrAlY + YSZ coating shown in Fig.2 (c), the microstructure has the appearance of both metallic and ceramic phases. This is seen from the darker region that represents the matrix of NiCrAlY which has embedded in it YSZ particles of finer size and uniformly distributed as seen by the lighter shades in the figure which offer thermal stability. This hybrid design provides for good thermal insulation properties that allows for minimal heat flow to the substrate. For example, the property that enables a material to form protective oxide scales and to stabilize phases is the factor that is very vital in determining the performance of such coatings especially for applications in the aerospace and power generation industries where the coatings in use are expected to last longer.

Elemental Analysis

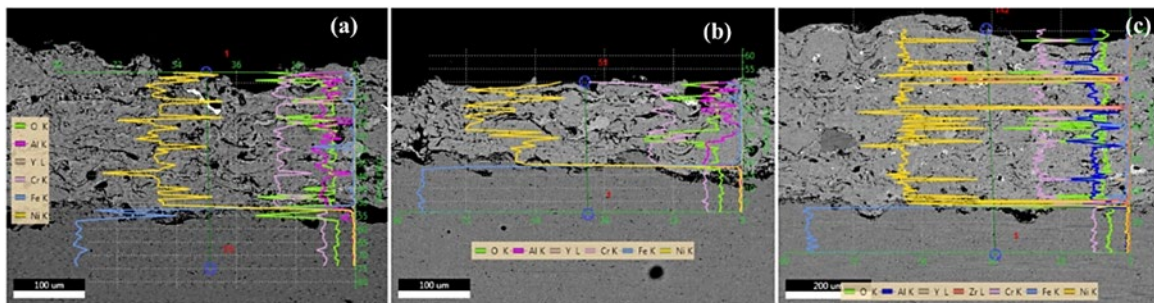


Figure 3 Presents EDS line scanning analysis of the developed composite coatings.

The EDS analysis of pure NiCrAlY coating revealed in Fig.3 (a) reveals that the principal components that make up the coating include Ni, Cr, Al, Y, Fe, and O, with Ni being the most predominant in the coating matrix and uniformly distributed throughout the coating deposit to

provide mechanical strength and oxidation resistance. Chromium (Cr) and aluminium (Al) are also uniformly distributed, providing oxidation layers like Cr_2O_3 and Al_2O_3 . The oxygen (O) peaks near the surface represent these oxide layers necessary for high-temperature oxidation protection. Yttrium (Y) content is lower but plays a role in stabilizing the oxide layers, while the Fe signals are found to increase towards the substrate in the coating. This elemental distribution also validates a uniform spread of alloy, which is crucial for uniformity in mechanical characteristics and resistance to thermal stress. EDS analysis of the elemental distribution for Ni, Cr, Al, Fe and O in the NiCrAlY + Al_2O_3 coating of Fig. 3(b) is performed, but with much higher Al peak because of the presence of Al_2O_3 particles. The enhanced and equally intense Al confirms this coating to be denser and less porous and hence harder and more resistant to wear. As seen from the energy-dispersive spectroscopy (EDS) result of NiCrAlY + YSZ (Fig 3 (c)), we have metallic and ceramic phase with identified elements, Ni, Cr, Al, Y, Zr, Fe and O. The peaks corresponding to Yttrium (Y) and Zirconium (Zr) are due to the presence of YSZ particles which improved the thermal barrier performance of the coating. The higher maximum density of oxygen peaks is attributed to YSZ and oxide phase, which increases temperature insulation and thermal stability.

Cyclic oxidation behaviour

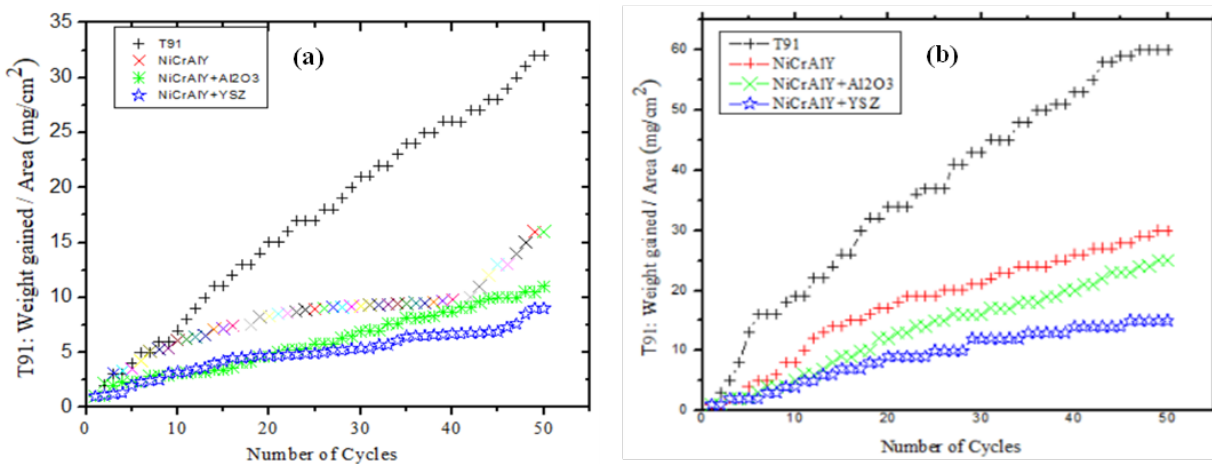


Figure 4 Weight gained after 50 oxidation cycles test at (a) 800°C , (b) 1000°C .

Figure. 4 shows the weight gain of the developed plasma-sprayed composite coatings and substrate T91 steel during 50 cycles of test at 800°C (a) and 1000°C (b). T91 steel shows highest weight gain (Fig. 4a) indicating oxidation, and a less protective oxide scale at 800°C. Although the NiCrAlY coating has improved oxidation resistance as compared to T91, further improvements can be obtained by adding commercial reinforcements such as Al_2O_3 and YSZ. The lowest weight gain among these is exhibited by the NiCrAlY + YSZ composite coating, indicating superior oxidation resistance as well as reduced oxide scale formation by enhancing the thermal stability and the barrier effect presented by YSZ. At 800°C (Fig 4b), oxidation behavior becomes more intense at higher weight gain across all materials compared to 1000°C. The maximum weight gain again appears in T91 steel, indicating poor performance at elevated temperatures. But noticeably lower oxidation rate is achieved by coating with NiCrAlY composites containing Al_2O_3 , which is 17 times more active and even more successful are composites with YSZ. It is indicated that YSZ in the composite coating contributed as a stabilizer and diffusion barrier, which enabled the composite coating NiCrAlY + YSZ to continue to show the lowest weight gain, reflecting its excellent high temperature oxidation resistance due to the synergistic effects. The superior performance of NiCrAlY based composite coatings, especially those containing YSZ, in limiting oxidation and maintaining long term thermal stability of T91 steel subjected to cyclic thermal

conditions is demonstrated. Therefore, they are promising candidates for applications at high temperature and with sustainable material performance.

Oxidation performance of T91 steel and NiCrAlY based composite coatings are summarized into table 3, These results show the possibility of using NiCrAlY based coatings with YSZ reinforcement for sustainable high temperature applications.

Table.3. Oxidation behavior of T91 Steel and NiCrAlY-Based Composite Coatings After 50 Cycles.

Parameter	T91	NiCrAlY	NiCrAlY+Al ₂ O ₃	NiCrAlY + YSZ
Temperature (°C)	800 / 1000	800 / 1000	800 / 1000	800 / 1000
Maximum Weight Gain (mg/cm ²)	35 / 60	15 / 40	10 / 30	7 / 20
Oxidation Resistance	Poor	Moderate	High	Very High
Key Observations	Rapid oxidation and poor protective scale	Oxidation resistance improves with NiCrAlY	Al ₂ O ₃ reduces oxidation, forms dense oxide layer	YSZ enhances stability and provides best performance

Conclusions

The following conclusions are observed from the current research work.

1. Nickel chromium aluminium alloys (NiCrAlY) based composite coatings plasma sprayed onto T91 boiler steel improve significantly the cyclic oxidation resistance of the substrate at 800°C and 1000°C.
2. Addition of ceramic reinforcements like Al₂O₃ and YSZ to the coatings increases the oxidation resistance, and the NiCrAlY + YSZ composite coating shows the best performances based on its superior thermal stability and barrier properties.
3. Outcomes of microstructural analysis showed that the coatings have dense structure, lower porosity and effective oxide scale formation important to high temperature performance.
4. Elemental analysis confirmed the coatings to have a uniform distribution of coating materials with the formation of stable oxides which lead to the coatings' increased durability.
5. The oxidation rate of NiCrAlY + YSZ coatings shown in weight gain data was the lowest, which suggested that NiCrAlY + YSZ coatings were highly appropriate for applications requiring long term resistance to high temperature.
6. This work proves that NiCrAlY based composite coatings are sustainable solutions to extend the service life and enhance the efficiency of critical components in power plants and other industrial systems.

These results underscore the need for advanced coating technologies to improve degradation issues in materials, and further advancement of more sustainable industrial practices.

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