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Study of mechanical properties and high temperature oxidation behavior of a novel cold-spray Ni-20Cr coating on boiler steels

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ABSTRACT

In the current investigation, high temperature oxidation behavior of a novel cold-spray Ni-20Cr nano-structured coating was studied. The nanocrystalline Ni-20Cr powder was synthesized by the investigators using ball milling, which was deposited on T22 and SA 516 steels by cold spraying. The crystallite size based upon Scherrer's formula for the developed coatings was found to be in nano-range for both the substrates. The accelerated oxidation testing was performed in a laboratory tube furnace at a temperature 900 °C under thermal cyclic conditions. Each cycle comprised heating for one hour at 900 °C followed by cooling for 20 min in ambient air. The kinetics of oxidation was established using weight change measurements for the bare and the coated steels. The oxidation products were characterized by X-ray Diffraction (XRD), Scanning Electron Microscopy/Energy Dispersive Spectroscopy (SEM/EDS) and X-ray mapping techniques. It was found from the results that the coating was successful in reducing the weight gain of SA213-T22 and SA 516-Grade 70 steel by 71% and 94%, respectively. This may be attributed to relatively denser structure, lower porosity and lower oxide content of the coating. Moreover, the developed nano-structured Ni-20Cr powder coating was found to perform better than its counterpart micron-sized Ni-20Cr powder coating, in terms of offering higher oxidation resistance and hardness.

1. Introduction

Materials degradation is imposing a cost penalty on almost all the engineering systems. Erosion and corrosion alone are responsible for multi-million dollar loss to the machinery used in the high-temperature applications. The surface protection of high performance machinery, such as in boilers, steam turbines and gas turbines, subject to high temperature environments, is required to avoid their premature failure. Therefore, the thermal degradation of materials due to oxidation and corrosion is a serious issue in high-temperature applications [1]. One possible way to counter this problem is the application of surface coatings by thermal spray process. The thermal spraying processes have gained wider popularity because they can help to develop high temperature oxidation and corrosion resistant coatings. These processes offer capability to coat almost any material on almost any substrate, high service life and safety and economical solutions [2–5]. Further, the thermal spray coatings can induce desired surface properties without affecting the metallurgical properties of the substrate material, without any significant impact on the environment [6–9]. In the thermal spray process, coating material is heated rapidly in a hot gaseous medium, and simultaneously projected at a high velocity onto a prepared substrate surface, where it deposits to produce the desired thickness of coating. A coating material is fed to a heating zone to become molten, and is propelled from there to surface of substrate material [3]. However, during these processes, chances of oxidation of feedstock powder during coating process due to high temperature involved are very high. Therefore, a relatively young thermal spray process namely, cold-spray (CS) process was developed at the Institute of Theoretical and Applied Mechanics of the Siberian Branch of the Russian Academy of Sciences [10]. This process gained considerable popularity since this process uses high kinetic energy of the carrier gas, to formulate the coatings with the temperature of carrier gas well below the melting point of the feed stock powder. Therefore, the particles are not melted in the gas flow and thereby avoid/minimize various critical reactions during the deposition of

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Table 1
Nominal composition of SAE 213-T22 (T22) and SA 516-Grade 70 (SA 516) steels [28].

Substrate material	ASTM code	C	Mn	Si	S	P	Cr	Mo	Fe
T22	SA213-T22	0.15	0.3–0.6	0.5	0.03	0.03	1.9–2.6	0.87–1.13	Bal.
SA 516	SA 516-Grade 70	0.27	0.93	0.1	0.06	0.05	–	–	Bal.

coatings [11]. High pressure gas is accelerated through a de Laval nozzle, which results into high gas velocities exceeding 1000 m/s, depending on the type of gas (He, N_2 or Air), pressure, and temperature [12]. Thus, momentum transfer from the supersonic gas jet to the particles, results in high velocity particle jet. These particles plastically deform upon impact onto the substrate surface and form interlocking splats, leading to the formation of coating [13]. Cold spraying is an effective method of depositing dense coatings with very low porosity and pure coatings with low oxygen content [14]. Owing to these attributes, CS is a promising thermal spray process to deposit nanostructured coatings, and coatings having microstructures similar to original feedstock powder for several applications such as corrosion and wear protection [11].

In the recent past, nanostructured coatings have received a considerable attention worldwide, due to their superior mechanical properties in comparison to their conventional counterpart coatings [15–17]. Nanocrystalline powders, synthesized by ball milling route are reported to possess superior material properties [18,19]. It is further learnt that the cold-spray process can effectively be used to deposit nanostructured coatings, since low operating temperature helps to retain the nanocrystalline structure of the feedstock powder.

Nickel-chromium based alloys are widely used as the coating materials due to their several attractive properties such as wear, erosion and corrosion resistance, and good thermal conductivity. Due to these properties, nickel-chromium coatings are frequently considered to control the problem of erosion–corrosion of power plant boilers [20]. Furthermore, the nanostructured Ni-Cr coatings are found to exhibit high corrosion resistance due to lesser porosity and enhanced grain boundary diffusion, promoting the formation of denser Cr_2O_3 scale.

In the present work, the high temperature oxidation behavior of cold-spray nanostructured Ni-20Cr coating on SA213-T22 (hereafter denoted as T22) and SA 516-Grade 70 (hereafter denoted as SA 516)—common boiler steels has been investigated. The authors have already reported some work [21], in which the same in-house developed Ni-20Cr nanocrystalline powder was used to develop high temperature resistant coatings on these steels by high-velocity oxy-fuel spraying. This study presents an incremental and novel attempt in which cold spraying process has been used to develop the coatings. The outcome of this study shall be useful to explore the possible use of the developed nanostructured coating for boiler tube protection in power plant boilers.

2. Experimental details

2.1. Substrate material and feedstock powder

The widely used boiler tube materials in the power plant boilers of Northern India, such as T22 and SA 516 steels, were selected as substrate materials in the present study. The chemical composition of the substrate steels is reported in Table 1. The test samples of 20 mm × 15 mm × 5 mm dimensions were cut from T22 and SA 516 boiler steels, procured in the form of rolled tubes. These samples were polished using standard metallurgical procedure down to 220 grit size. The nanocrystalline powder was synthesized by blending three types of powders in a planetary ball mill. One of the powders was a commercially available Ni-powder (Loba Chemie, India) having 99.9% purity and 74 μm average particle size, whereas the other powder constitutes of pre-synthesized Ni nano-particles (ball-milled) having an average particle of 67 nm. The third starting powder comprised pre-synthesized Cr nano-particles (ball-milled) with an average particle size of 60 nm. These three materials are designated as *X*, *Y* and *Z*, respectively for easy identification. These three powders were mixed so as to achieve a composition (wt%) of 72%X–8%Y–20%Z [21]. A planetary ball mill (Fritsch, P-7 premium line, Germany) was used for mechanical alloying (MA) of this composition under wet conditions. The parameters used in ball milling are reported in Table 2, which have been selected after a comprehensive literature review and extensive experimentation [22–26]. The average particle size of Ni-20Cr alloy powder obtained after 20 h of milling was confirmed by particle size analyser (Microtrac Inc, Bluewave, USA). The average crystallite size of powder was calculated by from peak the peak broadening of X-ray peaks using Scherrer's formula [21], which was further confirmed by transmission electron microscopy (TEM) (TECNAI G20).

Table 2
Parameters used for ball milling in planetary ball mill [27].

Parameter	Value
Ball-to-powder (B:P) weight ratio	10:1
RPM	300
Running time (min): pause time (min)	30:10
Process control agent	Toluene

Table 3
Process parameters for the cold-spray process [27].

Process gas	Air
Gun temperature	450 °C
Gun pressure	19 bar
Process gas flow rate	1.96 m^3/min
Powder feed rate	113 g/min
Carrier gas	Air
Flow rate of gas	1.96 m^3/min

2.2. Deposition of coating and its characterization

The polished samples were then grit blasted with 250-grit silicon carbide powder prior to the deposition of nanocrystalline Ni-20Cr coatings using cold-spray process. The coatings were deposited on the selected steels by cold spaying (CS) process at International Advanced Research Centre for Powder Metallurgy and New Materials (ARCI), Hyderabad, India. This cold-spray system uses a De Laval nozzle with a rectangular exit for deposition of the coating. The parameters used for the cold spraying are reported in Table 3 [27].

Surface characterization of as-sprayed samples was done using an X-ray diffraction machine (PANalytical X'Pert-Pro, Netherland) with Cu-Kα radiation. The surface morphology of as-sprayed samples was studied by SEM (JEOL, JSM-6610LV, Japan) equipped with EDS (Oxford). The surface images of the polished samples were obtained for measuring the porosity by an Optical Microscope (Leica, DM4000 M, Germany) fitted with Metallurgical software (Leica Microsystems, LMW V 3.6.6, Germany). The apparent porosity measurements were made with an image analyzer system having software of MicroCAM 4.1 software (Radical, Ambala, India). Each reported value of the porosity is the mean of ten readings