Protection of 310L Stainless Steel from Wear at Elevated Temperatures using Conicraly Thermal Spray Coatings with and without Sic Addition

Yan Zhang¹,², Tao Zhang¹,², Kaiyang Li² and Dongyang Li³

¹Jiangsu Key Laboratory of Advanced Structural Materials and Application Technology, Nanjing, 211167, China
²School of Materials Science and Engineering, Nanjing Institute of Technology, Nanjing, 211167, China
³Dept. of Chemical & Materials Engineering, University of Alberta, Edmonton, AB, Canada T6G 1H9
E-mail: Zhangyan3@njit.edu.cn

Abstracts: Due to its high oxidation resistance, 310L stainless steel is often used for thermal facilities working at high-temperatures. However, the steel may fail prematurely at elevated temperatures when encounter surface mechanical attacks such as wear. Thermal spray coatings have been demonstrated to be effective in protecting the steel from wear at elevated temperatures. In this study, we investigated the effectiveness of high velocity oxy-fuel(HVOF) spraying CoNiCrAlY/SiC coatings in resisting wear of 310L stainless steel at elevated temperature using a pin-on-disc wear tester. In order to further improve the performance of the coating, 5%SiC was added to the coating. It was demonstrated that the CoNiCrAlY/SiC coating after heat treatment markedly suppressed wear. However, the added SiC particles did not show benefits to the wear resistance of the coating. Microstructures of CoNiCrAlY coatings with and without the SiC addition were characterized in order to understand the mechanism responsible for the observed phenomena.

1. Introduction

310L stainless steel containing high contents of Cr and Ni, possesses many attractive properties, such as excellent oxidation resistance, corrosion resistance, and creep strength. It can be used as heat-resistant steel and can continuously operate at high temperature because of favorable high-temperature resistance. However, they may fail prematurely at elevated temperatures when encounter surface mechanical attacks such as hot crack, corrosion and wear [1, 2]. Considerable efforts have been made to improve the high-temperature performance of the steel. Various surface modification techniques have been conducted, such as aluminized coating, laser coating, nano-crystalline coating, and so on[3-5]. MCrAlY (M=Co, Ni or Co+Ni) coating was widely used for high-temperature oxidation resistance coating due to its favorable high-temperature oxidation resistance, hot-corrosion resistance and better associability with base metal[6]. The high content of Cr can provide hot corrosion resistance, the contents between 5~15wt.% of Al can provide oxidation resistance, and Y addition around 1wt.% maintain stability during cyclic oxidation[7]. As one of the best coatings for high temperature oxidation resistance, CoNiCrAlY alloy was selected. But its hardness is relatively lower, so is wear resistance at ambient and elevated temperatures [8-11]. As we
all know, SiC powder has high hardness and excellent chemical stability, and it is often selected as reinforcement phase. In this study, a small content of nano SiCp has been added to coatings for wear and corrosion application. The coating is provided with the high toughness and ductility of metallic binder phase and the high hardness and wear resistance of ceramic-carbide.

Comparing with other coating techniques such as APS and LPPS, HVOF can deposite CoNiCrAlY bond coat with lower extent of oxide contaminants[12]. This work converted the conventional two step spray (to deposite bond layer and functional layer) to once, and the coating consists of CoNiCrAlY and SiC. We studied the microstructure and wear and friction properties of the CoNiCrAlY/SiC coat formed using HVOF.

2. Materials and Methods

2.1. Coating and Substrate Metal

Commercial 310L stainless steel (C 0.08%, Si 1.3%, Mn 1.6%, P 0.03%, S 0.025%, Ni 20%, Cr 25%) was used as the base metal in 3mm thickness. CoNiCrAlY and CoNiCrAlY–SiC powder were employed as the feedstock to produce the coatings respectively, supplied by Sulzer Metco Ltd and Van composites research Institute. The size distribution of CoNiCrAlY is -38+5.5μm, the chemical composition of CoNiCrAlY is Ni 32%, Cr 21%, Al 8%, Y 0.5%, Bal Co. The average diameter of SiC is 50nm, purity ≥99.9%, apparent density ≤0.09 g/cm3, density 3.2 g/cm3, specific surface area 60 g/cm2, cubic crystalline. The feedstock powder was the mixture of CoNiCrAlY and SiC.

2.2. Coating Procedures

The mixture of SiC and CoNiCrAlY were homogenized by Pulverisett-6 tank type high-energy ball mill. High performance stainless steel vials and balls were used as the milling components. The 310s substrates were roughed by a grit blasting machine, cleaned and dried. The CoNiCrAlY/ SiC powder was taken in a JP5000 high-velocity oxygen fuel spraying facility operated with a spray distance of 350- 380 mm, fuel pressure 120MPa, flow velocity of powder 50- 60 g/min, N2 pressure of powder feeder 10kPa, flow velocity of O2 1800psi, and flow velocity of N2 21scfh.

Sprayed coatings were heat-treated in a vacuum hot pressing furnace (ZRVS1500), and the parameters were: heating time 110min, at 1050°C for 2h, and vacuum degree 1×10-3Pa.

2.3. Coating Microstructure

X-ray diffraction analysis was made to determine phases on the coating using a Siemens diffractometer (D5005) with Cu Ka radiation. The depth of XRD analysis is decided by the diffraction angle and material. According to the 3~15μm of Cr3C2–CoNiCrAlY coatings[13], the consequently received results is about the phase structure of the superficial layers of the coatings. The coatings’ microstructure was characterized using SEM and EDS with a Vega-3 TESCAN Scanning Electron Microscope at 20kV voltage and an EDXS oxford instrument was employed to analyze local compositions.

2.4. Coating Hardness

Micro-hardness measurements were conducted on a polished cross-section of the coating under a load/force of 300gf for 15s using a FM-700 Micorhardness tester with a Vickers diamond indenter. Every location was performed five indents. 5 data points were measured and averaged for each hardness value. Hardness was tested from base metal to coating. The surface of the coated samples’ cross-section was mechanically polished, finished with a 1-μm diamond paste, cleaned and dried.

2.5. Coating Wear Resistance

Dry Sliding wear tests were performed on a pin-on-disc tribometer (CSEM Instruments CH-2007, Neuchatel, Switzerland) at ambient with a relative humidity of approximately 50% and 500° C temperature. The pin was a silicon nitride (Si3N4) ball, with a diameter of 6mm and the disc was the sample under study. All tests were carried out at a sliding speed of 1cm/s along a circle path in diameter under a normal load 10N for 72m. The friction coefficient curves were recorded continuously.
during the test process. The wear track and volume loss of the samples was calculated by measuring
crosssectional area of the wear scars with a surface profilometer (Form Talysurf PGI 1240, Taylor
Hobson) Each reported value is an average of results received from at least three tests.

3. Results and Discussion

3.1. Morphology and Microstructure of the Powders
The morphology of the CoNiCrAlY and CoNiCrAlY+5wt.%SiC powders is shown in Fig. 1a and b,
respectively. The powder is both predominantly spherical. The particle surface is smooth in
CoNiCrAlY powders, and irregular and fuzzy in the SiC-CoNiCrAlY powders.

![SEM micrograph of feedstock: (a) CoNiCrAlY and (b) CoNiCrAlY+5wt.%SiC](image)

Fig. 2 shows the phase structures of the two powders, which exhibit the comparison of XRD
patterns for the CoNiCrAlY and mixed CoNiCrAlY/SiC spraying powder. In the both powder,
Co-Ni-Cr matrix and CoAl phase were the major phases. These results are in agreement with the
previous results published by A.S. Khanna and W.S. Rathod in the study of CoNiCrAlY oxidation
resistant hard coatings[14]. SiC was also detected in CoNiCrAlY/SiC powder.

![XRD pattern of the two powders](image)

3.2. Microstructural Characterization of the Coatings
The BSE images of the cross-section of the as-sprayed HVOF CoNiCrAlY and CoNiCrAlY+5%SiC
coating are shown in Fig. 3. Under the same spraying parameters, the coating of CoNiCrAlY+5%SiC
coating is thinner than CoNiCrAlY coating. The most significant difference is a transition zone, about
50µm width, rich of Co, Ni, Cr and Al in the coating of CoNiCrAlY. Element Fe in the steel matrix diffused to the coating in both coatings.

![Figure 3. BSE image of the polished cross-section of the as-sprayed HVOF CoNiCrAlY(a) and 5%SiC+CoNiCrAlY (b), (c) and (d) are linear EDS of (a) and (b)](image)

![Figure 4. BSE image of the polished cross-section of the as-sprayed HVOF CoNiCrAlY(a) and 5%SiC+CoNiCrAlY (b) heated treatment](image)

Fig. 4 shows the BSE images of cross-sections of as-sprayed HVOF CoNiCrAlY and CoNiCrAlY+5%SiC coating after heat treatment at 1050°C. There are many microcracks and white or grey plots in the both coatings.
Fig. 5 shows the comparison of XRD patterns for the spraying powder and for CoNiCrAlY /SiC coatings (as-sprayed and heat treated at 1050 °C). In the both coatings, Ni₃Al and Ni₃Al₄ diffraction peaks were the major phases. With the addition of SiC, the Ni₃Al₄ content decreased.

Figure 5. XRD patterns for the spraying powder and for CoNiCrAlY /SiC coatings (as-sprayed and heat treated at 1050°C).

3.3. Microhardness of the Coatings

The microhardness values were measured in the polished cross-section of the CoNiCrAlY and CoNiCrAlY/SiC coatings, shown in Table 2. Although there is some dispersion of the results, a trend in the evolution of microhardness values could be observed. The hardness of the coating is the maximum value of all the samples, perhaps double the matrix. This response was attributed to the precipitation of Ni₃Al to strengthen the structure. The trend to softening of the near surface was resulted in the structure coarsening and non-homogeneous. The hardness of both contents coatings are higher than heat treated. At the transition area, the hardness of CoNiCrAlY+5wt.%SiC coating are higher than CoNiCrAlY coating.

Table 1 Microhardness evolution of coatings

|                | CoNiCrAlY | CoNiCrAlY (heat treated) | CoNiCrAlY+5wt.%SiC | CoNiCrAlY+5wt.%SiC (heat treated) |
|----------------|-----------|--------------------------|---------------------|-----------------------------------|
| 1              | 204.45    | 154.57                   | 266.16              | 192.64                            |
| 2              | 336.19    | 230.12                   | 459.27              | 263.96                            |
| 3              | 479.72    | 372.82                   | 474.55              | 378.78                            |
| 4              | 409.6     | 276.21                   | 420.02              | 328.56                            |

The number show the locations. 1 is the matrix, 2 is the transition zone, 3 is the coating, 4 is the near surface.

3.4. Tribological Performance and Thermal Shock Resistance of the Coatings

In order to study the effect of SiC on the tribological performance of the coating, the wear performance of CoNiCrAlY coating on the steel substrate was compared with the wear behaviour of the CoNiCrAlY+5wt.%SiC coating. Based on the tribological testes results, the abrasion mark of CoNiCrAlY coating is narrow and deep, and that of CoNiCrAlY+5wt.%SiC coating is wide and shallow, as in Figure 6. And the specific volume wear loss of CoNiCrAlY coating is only 54.89% of CoNiCrAlY /SiC coating. The higher hardness of CoNiCrAlY /SiC coating can preserve the wear from deeper area.
But there are some microcracks in the CoNiCrAlY+5wt.%SiC coating surface that involves an increase in the wear rate. The cracks is caused probably because of the significant differences between CoNiCrAlY and SiC thermal expansion coefficients, which increased the residual stresses and reduced the coating’s integrity.

4. Conclusions
Effects of SiC and heat treatment on mechanical and tribological performances of HVOF sprayed CoNiCrAlY coating on 310L steel substrate has been investigated and the following conclusions are drawn:

(1) Co-Ni-Cr matrix and CoAl phase were the major phases, and SiC was only detected in CoNiCrAl/SiC powder. The most significant difference between the coatings is a transition zone, about 50µm width, rich of Co, Ni, Cr and Al in the coating of CoNiCrAlY. Element Fe in the steel matrix diffused to the coating in both coatings.

(2) The hardness of the coating is nearly double the matrix. At the transition area, the hardness of CoNiCrAlY+5wt.%SiC coating are higher. And at the near coating surface, they are almost the same of CoNiCrAlY and CoNiCrAlY/SiC coating as sprayed.

(3) The addition of SiC increases the residual stresses and reduced the integrity of the coating. The volume wear loss of CoNiCrAlY coating is less than CoNiCrAlY/SiC coating. And the abrasion mark of CoNiCrAlY coating is narrow and deep.

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6. References
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