

# **Isothermal Oxidation Behavior of Electrosark Deposited NiCrAlY Coatings on Gun Steel at 950°C**

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**Abstract.** A NiCrAlY coating has been prepared by electrosark deposition (ESD) technology on gun steel and its isothermal oxidation behavior at 950°C investigated. The results indicated that the NiCrAlY coating consists only of a homogeneous single  $\beta$ -NiAl phase; NiCrAlY coatings substantially increase the high-temperature oxidation resistance of gun steel and the oxidation process is retarded mainly by the presence of  $\theta$ -Al<sub>2</sub>O<sub>3</sub> and  $\alpha$ -Al<sub>2</sub>O<sub>3</sub> oxide scales formed on the coating.

## **Introduction**

Thermal damage observed in fired cannons has increased noticeably in recent years, owing to the use of higher and more sustained combustion gas temperatures for improved cannon performance [1]. The bore surfaces of many medium and large caliber guns have been coated to enhance the service performance of the gun barrels, which are subject to erosive and corrosive wear [2]. Earlier work by Cote and Rickard [3] on specimens from 120 and 155 mm guns showed that damage initiation at chromium crack tips occurs by rapid oxidation of the exposed steel beneath the chromium plating, causing chromium spallation. Oxidation thus plays a key role in initiating the erosion process [4]. MCrAlX (where M is nickel and/or cobalt and/or iron and X is one or more reactive elements such as yttrium, hafnium, etc.) coatings have been given the greatest attention due to their good plasticity, high strength, and excellent high-temperature oxidation and hot-corrosion resistance [5,6,7]. Electrosark deposition is a relatively simple, highly efficient and cheap method for surface treatment. It has recently been used to prepare high temperature oxidation-resistant coatings such as TiAl<sub>3</sub> coatings [8], MCrAlX coatings [9] and oxide dispersion strengthened (ODS) alloy coating [10].

Up to now, there are few reports about MCrAlX coatings to be coated by electrosark deposition technology on gun steel substrate to improve the performance of the gun barrel by other authors, therefore, in the present work, A NiCrAlY coatings was deposited on a gun steel substrate used for gun barrel by means of electrosark deposition technology and its microstructure and oxidation resistance in air at 950°C have been investigated.

## **Experimental Procedures**

A gun tube steel named as CrNi3MoVA was chosen as the substrate for the coating deposition and its chemical composition has been given previously [11], . The steel was cut into specimens with

the dimension of 20×10×5mm, grounded with silicon-carbide paper down to 600-grit, then followed by ultrasonic cleaning in acetone. A coating of Ni-30Cr-6Al-0.5Y (wt.%) approximately 200μm in thickness was then deposited onto the substrate by ESD. The ESD parameters were as follows: power=1200W, voltage=60V.

Isothermal oxidation tests were carried out in ambient air in a muffle furnace at 950°C. The specimens were put in alumina crucibles, oxidized at elevated temperature and then cooled to room temperature at regular intervals for mass measurement. The sensitivity of the electronic balance used was 0.1mg.

The phase compositions of the deposited coatings before and after oxidation were identified by means of X-ray diffractometry (XRD). The morphologies and chemical compositions of the coatings and the oxide scale were observed and determined by scanning electron microscopy (SEM) equipped with an energy dispersive spectrometer (EDS).

## Results and Discussion

### Microstructure of the Coating

Fig.1 shows the surface morphology (a) and the cross-sectional morphology (b) of the NiCrAlY coating. It can be seen that the surface of the coating was rough with splattered appearance on it and there were numerous small particles stuck in the surface. There were no observable interfaces within the coating, and the adherence between the coating and the substrate was excellent. XRD analysis results show that the NiCrAlY electrode consisted of  $\gamma$ -Ni and  $\beta$ -NiAl while the coating consisted of only the single  $\beta$ -NiAl phase (Fig. 2), which indicates that the ESD process can be beneficial to the formation of a homogenous coating when the less homogenous NiCrAlY electrode with a dual phase  $\gamma/\beta$  structure is used.

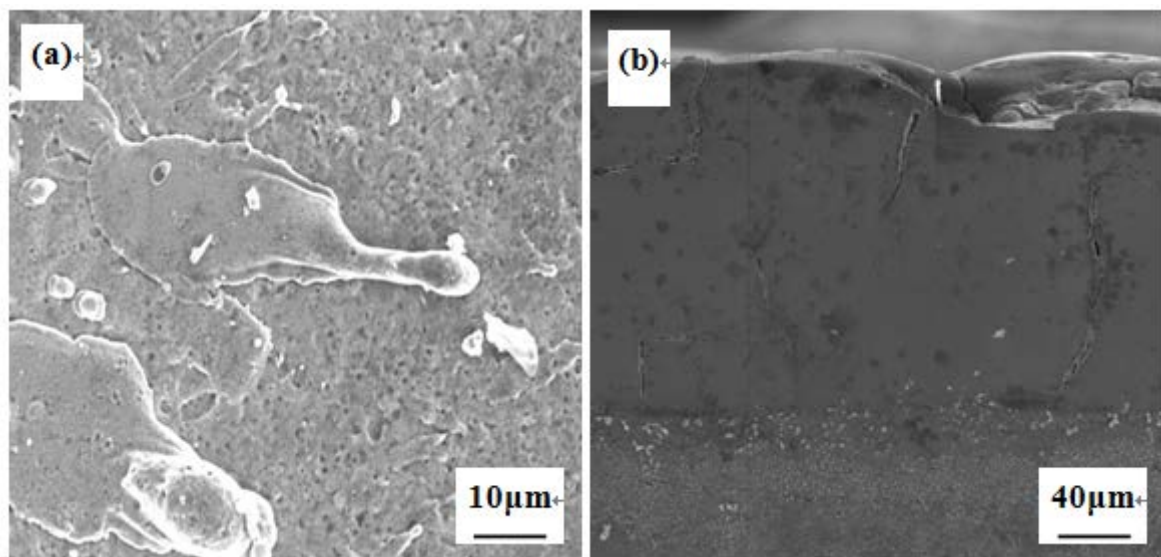


Fig.1 Surface morphology (a) and cross section (b) of the NiCrAlY coating

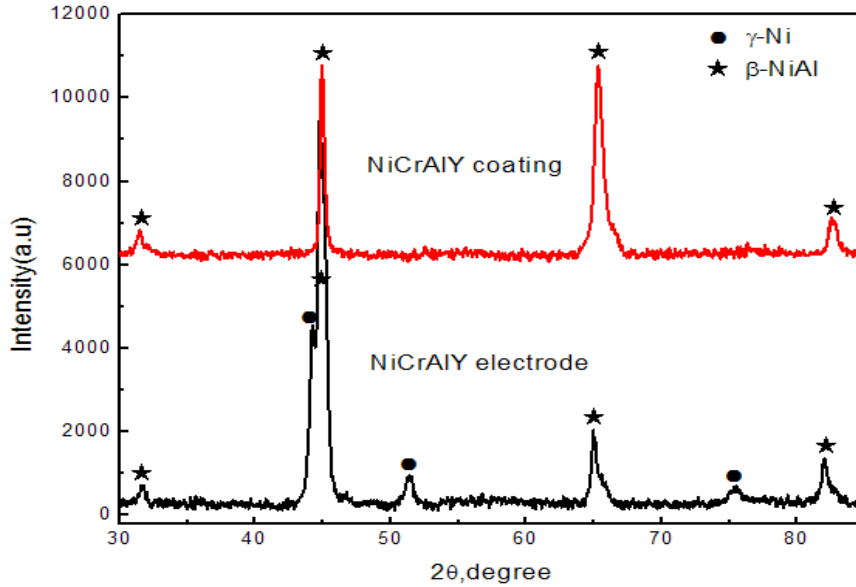


Fig. 2 XRD patterns of the NiCrAlY electrode and the as-electrospark deposition coating

### Isothermal Oxidation Result

Fig. 3 shows oxidation kinetics of the NiCrAlY-coated at 950°C and the bare CrNi3MoVA steel specimens at 850°C for 100 hr. The oxidation kinetics of uncoated CrNi3MoVA specimens followed an apparently parabolic rate law while the behavior of the coated specimens was different. The oxidation performance of the specimens with NiCrAlY coating was far superior to that of the uncoated specimens. The results indicated that the oxidation resistance of CrNi3MoVA steel was obviously improved by covering NiCrAlY coating. X-ray analysis of the oxide scale of the NiCrAlY coating formed 100 hr is presented in Fig. 4. The results indicated that the oxide scale was composed primarily of  $\theta$ -Al<sub>2</sub>O<sub>3</sub> and  $\alpha$ -Al<sub>2</sub>O<sub>3</sub>, Al consumption during the oxidation is believed to have led to the transformation of  $\beta$  to  $\gamma'$  to  $\gamma$ .

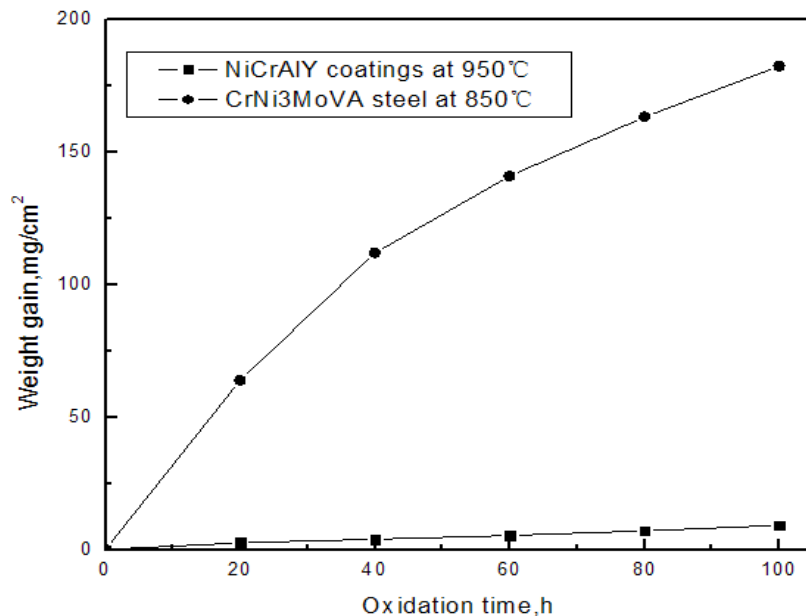


Fig. 3. Oxidation kinetics curves of the CrNi3MoVA specimens at 850°C, the NiCrAlY-coated specimens at 950°C for 100 hr

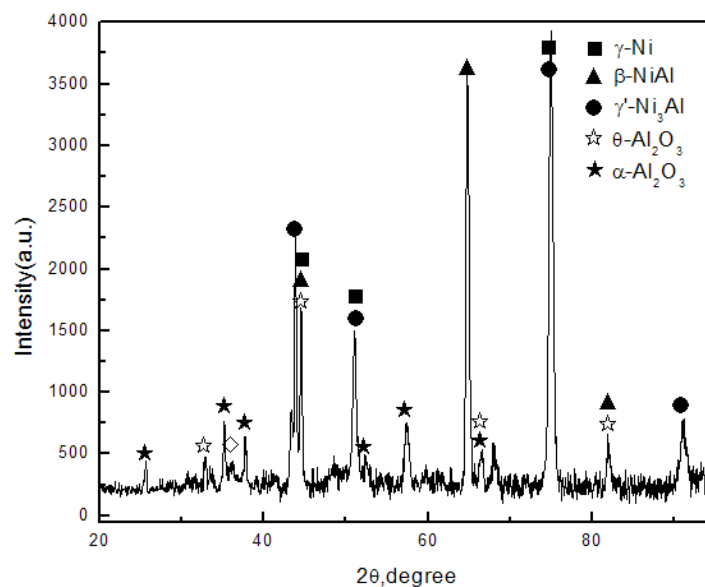


Fig. 4 XRD patterns of the NiCrAlY coating at 950°C after 100hr oxidation

Fig. 5 shows the surface morphologies of the coating that had been oxidized at 950°C for 100 hr. At low magnification, four typical areas with different color contrast can be found in Fig. 9a, a dark area (area 1), a grey area (area 2), a white area with scattered white spots (area 3), and a white area (area 4). At higher magnification, the oxides were porous and coarsely needle-like in the dark area (Fig. 5b, area 1). EDS analysis detected the presence of Cr, Al and O, with Al and O the most prominent. The needle-like morphology suggests that the oxide was  $\theta$ - $\text{Al}_2\text{O}_3$ . In the grey area (Fig. 5c, area 2), besides a few scattered coarse needles, most of the oxide was fine-grained and very compact. EDS analysis showed that the oxides were rich in Al and O. From the XRD analysis results, this is believed to be  $\alpha$ - $\text{Al}_2\text{O}_3$ . It was observed that the white spots were agglomerations of oxide grains on the surface of the scale (Fig. 5d, area 3). EDS analysis of these white spots gave strong Cr, Ni, and O peaks and small Al peaks, which suggests that the white oxide could be the  $\text{NiCr}_2\text{O}_4$  spinel phase. In the white area (Fig. 5e, area 4), the surface morphology of the oxide layer was featured with a few micro-holes. EDS analysis that the oxides were rich in Cr and O, which suggests that the white oxide could be mainly  $\text{Cr}_2\text{O}_3$ .

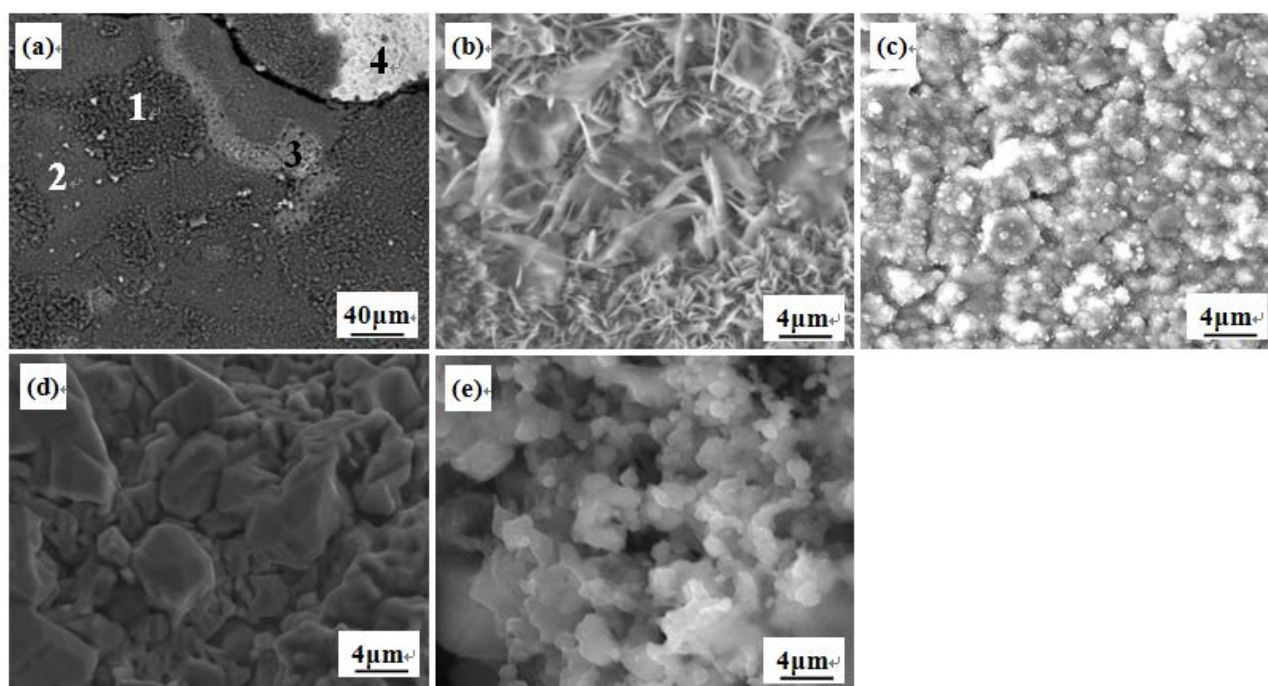


Fig. 5 Surface morphologies of the NiCrAlY coating at 950°C after 100-hr in air

Fig. 6 shows EDS line scan results of cross-section of the NiCrAlY coating at 950°C after 100hr in air. The results further confirmed the oxide products identified using x-ray diffraction. A continuous  $\text{Al}_2\text{O}_3$  layer may play an important role to prevent other elements from being oxidized or nitridized internally. Moreover, the main element Fe of the substrate didn't diffuse onto the surface through the NiCrAlY coating, which can prominently improve the oxidation resistance of the CrNi3MoVA steel.

Super alloys may be divided into two groups: "alumina former" and "chromia former" [12]. Felix [13] reported that an alloy with a chromium/aluminum ratio greater than 4 was a chromia former and an alloy with a ratio less than 4 was an alumina former. Recently, a study on a Ni-Cr-Al alloy indicated that nanocrystallization of alloys was able to enlarge the range for continuous  $\text{Al}_2\text{O}_3$  scale formation.

During the electrospark deposition, the short duration of the electric arc can produce a high temperature of 5000-10000K. This temperature causes the electrode materials to melt and resolidify extremely rapidly, resulting in micro- or nano-crystalline structure. Moreover, as the high cooling rates inherent in this process can approach  $10^5$  to  $10^6$  K/s, the microstructure coarsening and solute segregation will be suppressed, which will be likely to form the coating with a good homogenization. According to the XRD results, the composition of electrospark deposited NiCrAlY coating is characterized by a homogeneous single  $\beta$  phase structure.

In contrast to the chromia-former NiCrAlY electrode, the electrospark deposited NiCrAlY coating with a micro-crystallization structure plays key roles in high temperature oxidation, which were mainly attributed to (1) promotion of the selective oxidation of  $\text{Al}_2\text{O}_3$ ; and (2) improvement of the adherence between the oxide scale and base metal. Conversely, a major defect about electrospark deposited coating that has still not been effectively solved may be the rough and spattered surface. As was observed in Fig. 1a, the surface of the electrospark deposited coating was not fully dense, scattered with a great number of porous spattering particles and even micro-holes. When exposed at 950°C, the surface layer would first oxidize, but a continuous  $\text{Al}_2\text{O}_3$  layer was not formed because of the separation of those spattering particles and micro-holes, which need more Al concentration to

form  $\text{Al}_2\text{O}_3$  layer, and instead a complex outer oxide scale, including  $\theta\text{-Al}_2\text{O}_3$ ,  $\alpha\text{-Al}_2\text{O}_3$ ,  $\text{Cr}_2\text{O}_3$  and  $\text{NiCr}_2\text{O}_4$ , was formed.

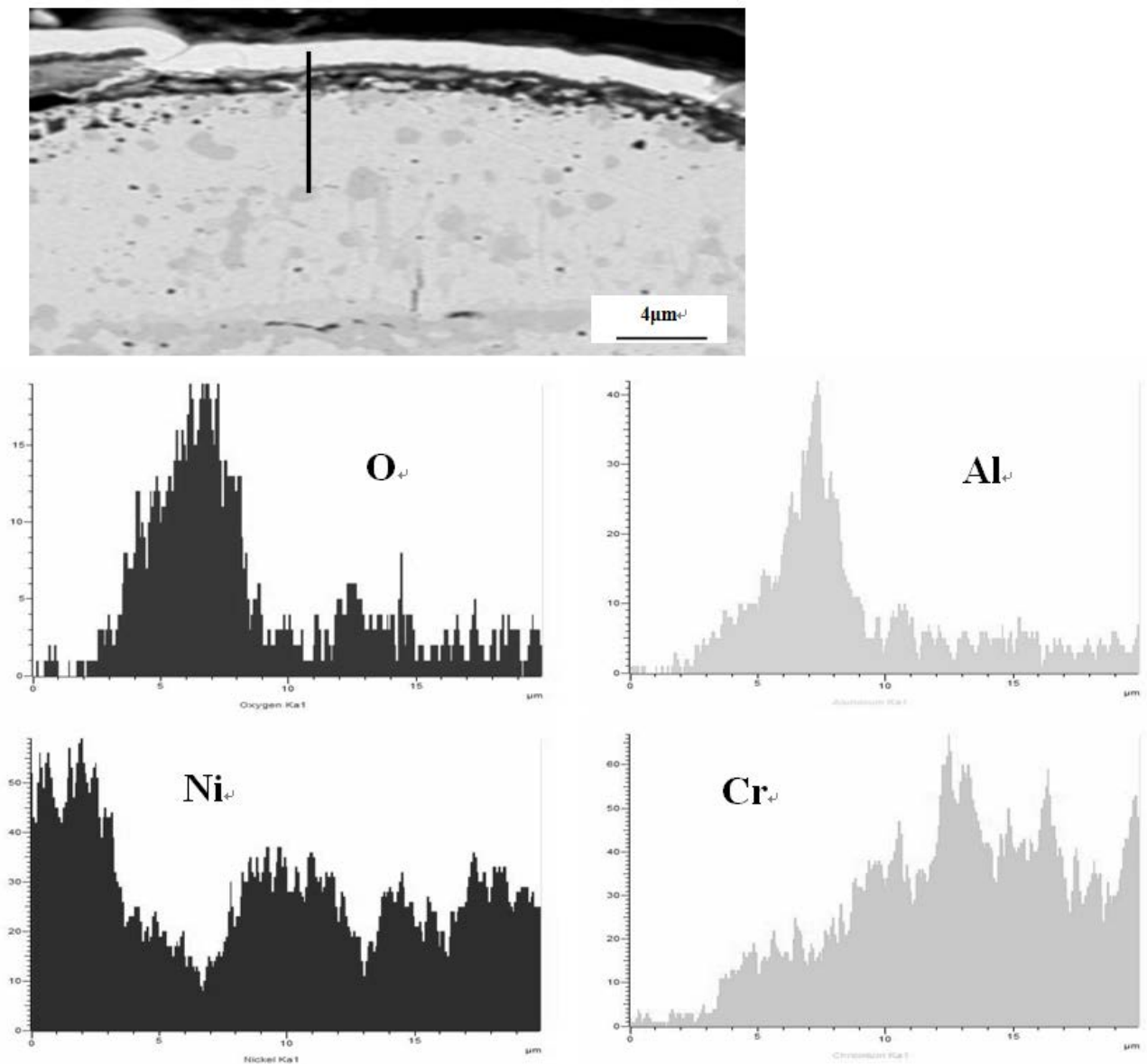


Fig. 6 EDS line scan results of cross-section of the NiCrAlY coating at 950°C after 100hr in air

## Conclusions

A NiCrAlY coating was successfully deposited on a CrNi3MoVA steel substrate used for gun barrel by electrospark deposition technology. The adherence between the coating and the substrate is excellent and the coating consists only of a homogeneous single  $\beta\text{-NiAl}$  phase. The NiCrAlY coating was oxidized at 950°C after 100 hr in air and it showed excellent oxidation resistance, which was mainly attributed to the formation of  $\theta\text{-Al}_2\text{O}_3$  and  $\alpha\text{-Al}_2\text{O}_3$  oxide scales on the coating, and at the same time, a complex outer oxide scale was locally formed due to the rough and spattered surface.

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