Microstructural characterization and evolution under high temperature oxidation of CoCrAlYTa-10%Al₂O₃ coating deposited by high-velocity oxygen fuel thermal spraying

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Keywords: HVOF thermal spraying, CoCrAlYTa-10%Al₂O₃ coating, microstructure, oxidation, microhardness

Abstract

The CoCrAlYTa-10%Al₂O₃ coating was fabricated on H13 steel substrate using high-velocity oxygen fuel (HVOF) thermal spraying. A detail characterization on the microstructures, element distribution and phase composition of the HVOF sprayed CoCrAlYTa-10%Al₂O₃ coating was conducted using scanning electron microscopy (SEM) equipped with energy-dispersive spectroscopy (EDS), x-ray diffraction (XRD) and transmission electron microscopy (TEM). The microstructural evolution and microhardness of the coating at different temperatures were investigated. The results showed that the coating had a dense and uniform microstructure with a low porosity of 0.44%. The primary phases for the CoCrAlYTa-10%Al₂O₃ coating were identified as Co-based solid solution, Cr-based solid solution, Al₂O₃ phase and TaC particles. Compounds such as Cr₇C₃, Al₁₃Co₄ and aluminum-yttrium oxides Al₅Y₃O₁₂ were also confirmed by TEM observation results. Owing to the rapidly cooling rates of the molten droplets, nano-crystalline phase was existed in the coating. The average microhardness of the coating was 640 HV₀.₁. Its high microhardness derived from the presence of certain volume fraction of hard Al₂O₃, Cr₇C₃ and TaC grains within the coating. After 1h of oxidation, oxides like CrO₂ and Ta₂O₅ were formed when the coating exposed at the temperature up to 800 °C. At the temperature above 600 °C, the hardness of the coating remained at a high level (600 HV₀.₁). It possessed better high temperature softening resistance than H13 steel, indicated that the coating exhibited good mechanical properties at high temperature.

1. Introduction

MCrAlX coatings (where M is Ni and/or Co and/or Fe and X is one or more reactive elements added in minor proportion, which may be Y, Hf, Ta, etc) are known for their superior resistance to high temperature oxidation [1, 2]. Generally, these MCrAlX coatings contain high chromium (15–30 wt%) for higher hot corrosion resistance, while the aluminum concentrations are less than 12 wt% to ensure the ductility of the coatings [3]. When exposed at high temperature, the surface of the MCrAlX coating could form a uniform and dense alumina (α-Al₂O₃) scale, which is desirable to protect the underlying metal from further oxidation [1, 2]. Therefore, MCrAlX coatings are widely used in thermal barrier coatings (TBCs), especially applied on the hottest sections of gas turbine engines, allowing the thermal insulation for the turbine engines with additional protection from corrosion and high temperature oxidation. Common processes for the MCrAlX coatings deposition are low pressure plasma spraying (LPPS), vacuum plasma spraying (VPS) and high velocity oxy-fuel (HVOF) thermal spraying [1, 4–6]. Because of the high particle velocities and relatively low flame temperatures induced in the deposition process, HVOF thermal spraying has become more widely used with relatively high density for the prepared coating (porosity ≤ 1%) and superior coating-substrate adhesion, which improved the mechanical properties of the coating [7–9].
H13 steel is one of the most representative hot work die steels, which is generally used to make metal forging dies. As the surface of the mold cavity become ever more demanding, the continuing requirements for composite coatings to protect the dies means that there is a need to enhance strength, hardness and ductility of the dies in elevated temperature. The metal matrix composites (MMC) are carbides or oxides particles distributing in the ductile matrix. They are developed with the specific aim of improving microhardness, tensile strength and hardness by the presence of the second-phase particles [10]. Recently, many investigations have been conducted on microstructures and performance of MCrAlX/oxide metal-matrix coatings [10–13]. Among the potential hard and thermally stable oxide phases, alumina (Al$_2$O$_3$) has attracted much attention due to its high wear resistance, acceptable corrosion resistance, and good thermal insulating behaviors [11]. Wu et al found that using the plasma-laser sprayed NiCrAlY-Al$_2$O$_3$ coating, a homogeneous dispersion structure with fine Al$_2$O$_3$ particles could hinder the diffusion of Ni, Cr and obtain refiner grain of the coatings during crystallizing the NiCrAlY, which led to further increase in oxidation resistance [12]. Moreover, Hou et al recently reported that the HVOF sprayed CoCrAlYTaCSI-Al$_2$O$_3$ coating exhibited much better wear resistance than the CoCrAlYTaCSI coating due to the significantly increased hardness and greatly improved mechanical properties of the MMC coating associated with Al$_2$O$_3$ dispersion strengthening [13]. Although extensive works have addressed the microstructures of MCrAlX/oxide metal-matrix coatings, the detailed phase formation and high temperature behaviors of HVOF sprayed CoCrAlYTa-10%Al$_2$O$_3$ coating is still less investigated.

In our past studies, it was found that the coating had excellent wear resistance at high temperature, which was related to the special structure and excellent high temperature resistance [14]. Thus, a detail characterization on the phase composition and element distribution and microstructure of HVOF sprayed CoCrAlYTa-10%Al$_2$O$_3$ coating was conducted in the present work. As the heterogeneous microstructures in the as-sprayed coating, TEM was used to assess phase and finer microstructural features. In addition, microhardness of the coating in different temperatures and phase transformation at 800 °C were also investigated. The results of this research will act as an indicator for the study of coating performance in elevated temperature.

### 2. Experimental procedure

#### 2.1. Coating preparation

A commercial CoCrAlYTa-10%Al$_2$O$_3$ powder was used for the HVOF thermal spraying, its chemical compositions are reported in Table 1. Figure 1 shows the morphology of the selected CoCrAlYTa-10%Al$_2$O$_3$ composite powders. It can be seen that the powder is of spherical or near-spherical shape and exhibits a size in the rage of 20 ~ 50 μm, which is suitable for HVOF thermal spraying. The CoCrAlYTa-10%Al$_2$O$_3$ powders were thermally sprayed onto the H13 steel substrate (50 mm diameter, 3 mm thick) via the JP8000 HVOF thermal spraying system.

| Elements | Cr | Fe | Y | C | Ta | Al | Al$_2$O$_3$ | Co |
|----------|----|----|---|---|----|----|------------|----|
| Content  | 24.7 | 0.12 | 0.7 | 1.8 | 8.9 | 7.3 | 10 | Bal. |

| Figure 1. SEM micrographs of CoCrAlYTa-10%Al$_2$O$_3$ powders with (a) low magnification and (b) high magnification. | Figure 1. SEM micrographs of CoCrAlYTa-10%Al$_2$O$_3$ powders with (a) low magnification and (b) high magnification. |
Before the thermal spraying, the substrate was sand-blasted to yield a surface roughness of \( R_a = 6.3 \sim 12.5 \mu m \) and then degreased by acetone, dried in hot air in order to roughen and clean the surface. The kinematic and nonkinematic spray parameters used in the present study were reported in tables 2 and 3, respectively. After spraying process, the deposited coating was ground using abrasive papers with grit sizes from \#200 to \#800, and polished using diamond suspension fluid to yield a surface roughness of \( R_a = 0.12 \mu m \). The polished surface was cleaned with distilled water in an ultrasonic bath.

### 2.2. Coating characterization

Phase identification of the powders and the as-sprayed coating were carried out by a Bruker D8-ADVANCE x-ray diffraction (XRD) with Cu-K\( \alpha \) radiation, at 40 kV and 40 mA. The scan range (2\( \theta \)) was set from 20\(^\circ\) to 90\(^\circ\).

The surface topographies, microstructures, and chemical compositions of the as-sprayed coating were observed by using a SIGMA field emission scanning electron microscope (SEM) equipped with a BRUKER-QUANTAX XFlash 5030 energy-dispersive spectroscopy (EDS) apparatus. The DT-2000 image analysis software was employed for the measurement of porosity. For in-depth microstructural analysis, selected area electron diffraction (SAED) pattern and finer scale microstructural characterization of the coating were performed using a transmission electron microscopy (TEM, FEI Tecnai G2 T20). Cross sectional samples for TEM investigations were firstly prepared by mechanically grinded to 50 \( \mu m \) and then perforated by using dimpling and ion thinning.

### 2.3. High temperature oxidation and microhardness

The CoCrAlYTa-10%Al\(_2\)O\(_3\) coating and the H13 steel were heated to 200 \( ^\circ\)C, 400 \( ^\circ\)C, 600 \( ^\circ\)C, 800 \( ^\circ\)C in a KSL-110X-S high temperature resistance furnace for 1h, and then cooled inside the furnace to room temperature. The phase identification of the CoCrAlYTa-10%Al\(_2\)O\(_3\) coatings in different temperatures was conducted by XRD analysis. Microstructural characterization and the interface behavior of elements like O in the as-sprayed coating oxidized at 800 \( ^\circ\)C was analyzed by the line scans of SEM. Microhardness of the CoCrAlYTa-10%Al\(_2\)O\(_3\) coating and the H13 steel in room temperature (RT), 200 \( ^\circ\)C, 400 \( ^\circ\)C, 600 \( ^\circ\)C, 800 \( ^\circ\)C were performed on the polished cross-section of the as-sprayed coating by Vickers micro-indentation (HXD-1000TC) at a load of 100 g and a dwell time of 15 s. The average hardness of 15 indentation points was calculated.

### 3. Results and discussion

#### 3.1. Phase and microstructures of the CoCrAlYTa-10%Al\(_2\)O\(_3\) coating

Figure 2 shows the XRD patterns of the CoCrAlYTa-10%Al\(_2\)O\(_3\) powders and as-sprayed coating. Diffraction peaks corresponding to Co, Cr, TaC and Al\(_2\)O\(_3\) are the major peaks clearly seen both in the powders and the as-sprayed coating patterns. It is noteworthy that the crystal structure of Co in this coating is FCC, and it is consistent with previous reported results [2, 13]. The crystalline structure of high-temperature FCC-Co phase is more likely to exist in the MCrAlX coatings than room-temperature HCP-Co phase after HVOF spraying process, which can be attributed to the rapid cooling rates of molten droplets [15]. A slight shift to smaller 2\( \theta \) values is observed in the Co peaks, which is attributed to a doping with alloying elements, causing a growing of the lattice parameters [2].
It can be observed that C phase is existed in the feedstock powders and a new Cr7C3 phase appears in the as-sprayed coating. This fact suggests that Cr7C3 resulted from metallurgical reaction between Cr and C during the spraying process [16]. The Al phase presents in the powders but is absent in the coating. Moreover, the intensity of Al2O3 peaks in the coating significantly increase compared with the powders, indicating an increasing content of Al2O3. This could be explained by the oxidation of Al in feedstock powders during the HVOF process. The formation of Al2O3 during HVOF process has been previously reported by other researchers [3, 17]. Furthermore, both patterns of powders and the as-sprayed coating exhibit strong intensity of TaC peaks, suggesting no decomposition of TaC in the spraying process. Among various spraying processes, the HVOF thermal spraying has been found to deposit coatings with significantly lower levels of phase transformation due to its relatively lower flame temperature (2500 °C ~ 3000 °C) [18]. Meanwhile, the formation of intermetallic phases Al5Co2 is also observed in the as-sprayed coating.

The CoCrAlYTa-10%Al2O3 coating was cross-sectioned and prepared for metallographic characterization. The typical microstructures of the HVOF sprayed CoCrAlYTa-10%Al2O3 coating are shown in figure 3. As seen in figure 3(a), the coating with a thickness in the range of 350–400 μm was deposited on H13 steel and appeared dense, well adhered and almost free of cracks. A certain amount of porosity exists in the as-sprayed HVOF coating [7]. The average porosity of CoCrAlYTa-10%Al2O3 coating was determined to be a relatively low value of 0.44% (the value range is 0.37%–0.58%) by image analysis. During thermal spraying process, molten or semi-molten droplets impacted on the substrate and rapidly cooled to form a laminar coating composed of many layers where the pores mostly existed [8]. The added Al2O3 particles were normally drawn into the pores of the coating, resulting in a lower porosity of the as-sprayed coating [19]. Figure 3(b) shows that white fine particles uniformly dispersed in the coating and many main gray phases with a shape of oval are observed from the microstructure. Under higher magnification, a more detailed microstructure of the coating was characterized (figure 3(c)). It shows that there are four kinds of phases present in the as-sprayed coating which are white phase (marked A), dark gray phase (marked B), light gray phase (marked C) and black phase (marked D). It’s worth noting that typical core-rim structures (as indicated by mark 1, 2 and 3) exist in the coating as shown in figure 3(d).

In order to identify the chemical compositions of different phases in the deposited coating, the EDS analysis is undertaken at point A (white phase), point B (dark gray phase), point C (light gray phase) and point D (black phase) under a magnified view as shown in figure 3(c). The quantitative analysis (at-%) of these points is given in figure 4. The EDS spectrum of point A reveals that the white particle is mainly rich in Ta and C (figure 4(a)), while other elements like O, Cr and Co are in small amounts, indicating the presence of TaC phase. Point B in dark gray region which distribute irregularly in the light gray phase contains primarily Cr, C and minor Co (figure 4(b)). The matrix in light gray color (point C) with oval morphology, on the contrary, contains primarily Co and minor Cr, C and Al (figure 4(c)). The atomic radius of Co, Cr, Al and C are 1.253 Å, 1.249 Å, 1.434 Å and 0.770 Å, respectively. Co and Al are FCC structure while Cr is BCC structure, which is necessary for the possibility of forming limited substitutional solid solution, according to the well-known Hume–Rothery rules [20]. C element is known to be an interstitial solid solution element, which open up the possibility of forming interstitial solid solution. Combining with the results of XRD analysis, it may indicate that Cr, C and Al were

![Figure 2](image-url)
Figure 3. SEM micrographs of cross-section of the CoCrAlYTa-10%Al₂O₃ coating with (a) low magnification, (b) higher magnification, (c) four kinds of phases and (d) typical core-rim structures.

Figure 4. EDS spectra of the (a) white phase (point A in figure 3(c)), (b) dark gray phase (point B in figure 3(c)), (c) light gray phase (point C in figure 3(c)) and (d) black phase (point D in figure 3(c)).
dissolved into the Co matrix phase while Co and C were dissolved into the Cr matrix phase, then induced the formation of Co-based solid solutions and Cr-based solid solutions, respectively. Meanwhile, the slight shift to smaller 2θ values of the Co peaks in the XRD patterns (figure 2) can be explained by the doping with Cr and Al elements, inducing a change of the lattice parameters. This observation agrees well with the experimental data of Hou et al. [13], who reported the metallic Co and Cr in the CoCrAlYTa–10%Al2O3 coating. Point D in the black region is rich in Al and O implying the presence of Al2O3 phase. In addition, Y was detected in the black region with a small content. Y is the rare earth element with a rather larger atomic radius and its excellent physicochemical characteristics such as special electronic structure and outstanding chemical activity show large capacities in improving the performance of the coatings under high temperature conditions [21]. However, no formation of yttria (oxide of yttrium) has been detected in the coating by the XRD analysis due to the very low yttrium content.

EDS elemental mapping (figure 5) was used to reveal the distribution of various phases in the as-sprayed coating. Figure 5(a) shows the investigated region of the coating and figure 5(b) exhibits the total distribution of elements. As seen in figures 5(c) and (d), Ta is only distributed in the white particle regions and also corresponds with the distribution of C further confirming white particle is TaC phase. Most Co and Cr are independently distributed (figures 5(d) and (e)) further suggesting the light gray phase and the dark gray phase are Co-based solid solution and Cr-based solid solution. Evidently, it can be seen in figures 5(e) and (f) that the distribution of C corresponds well with the distribution of Cr in the Dark light region, which indicates the presence of the chromium carbide Cr2C3 phase in the Cr matrix determined by XRD analysis. Compared with other alloy elements like Co and Al, Cr is an element having relatively strong tendency of carbide formation, when the C content exceeds its solubility in Cr, C and Cr will react and form Chromium carbide [22, 23]. Closely matching distributions of Al and O (figures 5(g) and (h)) suggest the existence of Al2O3 phase. Moreover, Al and O elements distribute as a rim along the interface of the oval-shaped Co-based phase forming a core-rim structure (figure 5(d)) and the rim is likely to be the Al2O3 formed on the surface of droplets during the HVOF process.

TEM was used to obtain more detail microstructural information at a finer scale of the CoCrAlYTa–10%Al2O3 coating. Figure 6 schematically shows TEM images in different regions and the corresponding SAED patterns, respectively. As seen in figure 6(a), Co matrix shows an FCC structure as indicated by the corresponding SAED pattern (figure 6(b)), which is in agreement with XRD results. A similar result has been observed by J. Cai who sprayed CoCrAlYTa coating using high current pulsed electron beam (HCPEB) [24]. It is generally known that HCP and FCC phases of cobalt exist in an equilibrium at temperature T_eq (427 °C), but heating and cooling transformations can affect this allotropic phase transformation with a considerable hysteresis [25]. Coatings deposited by HVOF and HCPEB techniques are heating and melting followed by rapid solidification, thus inducing HCP to FCC transformation as the enhanced symmetry in the FCC structure further lower its total internal energy [25]. Therefore, the crystal structure of Co in the coating depends on their manufacturing processes. Prieto-García E also reported the milling process induced HCP to FCC phase transformation by the reduction on the crystal size which stores a great amount of surface energy as well as the Gibbs free energy [2].

There are black particles appeared in a relatively small size of 20 nm and well dispersed in figure 6(c). Convergent-beam electron diffraction (CBED) (shown in figure 6(d)) was used to focus on a smaller area of the black particle (point A), which was identified as the TaC phase. From the SEM results (figure 3), the size of TaC particles is range from 1 μm to 2 μm, indicating both micro-scale and nano-scale TaC carbides dispersed in the as-sprayed coating. Figure 6(e) shows a white particle with grain size of about 200 nm. The corresponding SAED pattern (figure 6(f)) confirmed crystallite grains possess a hexagonal Al2O3 phase. The shape of this white particle is the typical morphology of the added Al2O3 particles in the as-sprayed coating. Some particles have a regular rectangular shape with sides ranging from 50 to 200 nm in figure 6(g). As seen in figure 6(h), the related SAED pattern of Al2O3 phase was obtained. It indicates the formation of the nano-crystalline intermetallic phase during the HVOF thermal spraying process as a result of the rapid cooling rates of coating. Moreover, a view of the thin platelet is shown in figure 6(i). The corresponding SAED pattern (figure 6(j)) reveals the platelet is Cr7C3 phase, which grew in parallel to the [010] zone axis. This further confirmed that the in situ formation of Cr7C3 phase in the Cr matrix with the results of XRD analysis (figure 2) and EDS mapping analysis in (figure 5).

Al2O3, Al43Cr4Y6 and Al43Cr4Y6 phases containing element Y were confirmed by TEM investigations in figure 7. The typical TEM image of a grain near the Al2O3 particle (a size of 100 nm) was shown in figure 7(a) and the corresponding SAED pattern (figure 7(b)) reveals the presence of Al2O3 phase. Tawancy [26] observed that Y2O3 reacted with Al2O3 forming AlY2O3 and Al43Cr4Y6 phase, known as yttrium aluminum garnet (YAG), which could improve the protective nature of α-Al2O3 scale and the adhesion of the coating [17]. Toma [27] also reported that the high temperature experienced during spraying and the high affinity of both aluminum and yttrium for oxygen attributed to the formation of the aluminum–yttrium oxides (AlxYyOz). In addition, Al43Cr4Y6 phase was indicated with a size of 100 nm as shown in figures 7(c) and (d). These particles are very small and their identification by XRD is impossible because of the small amount of the phase in the coating.
Microstructures in TEM and related electron diffractions in figure 8 indicated that some regions of the coating appeared to be nano-crystalline, which is similar to the observation reported by G C Ji [14]. The individual splat deposited directly on the substrate surface can achieve a cooling rate to $10^6 \text{K} \cdot \text{s}^{-1}$ during HVOF thermal spraying.

Figure 5. SEM micrographs and corresponding EDS mappings of the CoCrAlYTa-10%Al$_2$O$_3$ coating with (a) the investigated region, (b) the total distribution of elements, (c) Ta, (d) Co, (e) Cr, (f) C, (g) Al and (h) O.
Figure 6. TEM micrographs and SAED patterns showing morphologies and lattice structure of (a), (b) the Co phase, (c), (d) the TaC phase, (e), (f) the Al$_2$O$_3$ phase, (g), (h) the Al$_{13}$Co$_4$ phase and (i), (j) the Cr$_7$C$_3$ phase.
Therefore, it is reasonable for the as-sprayed coating to solidify in the form of a nano-crystalline phase.

3.2. Oxidation behavior of the CoCrAlYTa-10%Al2O3 coating

CoCrAlYTa-10%Al2O3 coating and H13 steel were subjected to thermal oxidation for 1 h at 200 °C, 400 °C, 600 °C, 800 °C. Figure 9 shows the XRD patterns of CoCrAlYTa-10%Al2O3 coatings after oxidation tests at different temperatures. From the oxidation results at 200 °C, 400 °C, 600 °C, considerable phase changes were not detected compared with the as-sprayed coating, which is similar to the results studied by Hou [13]. However, at 800 °C, the diffraction peaks of CrO2 and Ta2O5 phases appeared in the XRD diffraction pattern of the coating, indicating that the coating began to oxidize. Ta2O5 phase was the oxidation product of TaC, this result was the same as phase identification measured by Charpentier at 1100 K (about 800 °C), which formed a barrier against the penetration of oxygen into the coatings [28, 29]. The studies show that CrO2, Ta2O5 and Al2O3 induced to the formation of a mixed oxide film with good oxidation resistance, preventing the further oxidation [2, 30].

For more details of the high temperature oxidation behavior, the SEM micrographs of cross-section of the CoCrAlYTa-10%Al2O3 coating are examined and shown in figure 10. From this figure it is observed a certain range of element transition regions at the bonding interface between the as-sprayed coating and the substrate, which means that the elements are interdiffused during high temperature oxidation. The O element in the CoCrAlYTa-10%Al2O3 coating is partially concentrated with low content on the coating surface after oxidation treatment at 800 °C for 1 h, and the O element peaks are corresponding to the Al element peaks. Apparently O
Figure 8. TEM micrographs of (a) the nano-crystalline phase and (b) SAED patterns of the nano-crystalline phase.

Figure 9. XRD patterns of CoCrAlYTa-10%Al₂O₃ coatings after oxidation tests at different temperatures.
element is from Al₂O₃ phase of the original coating, almost did not diffuse into the coating during the high temperature oxidation process at 800 °C, which shows that the coating has excellent high temperature oxidation resistance. It’s worth noting that the porosity of CoCrAlYTa-10%Al₂O₃ coating as determined was 0.44%. The lower porosity of the coating is also beneficial for high temperature oxidation performance.

3.3. Microhardness

Figure 11 shows the microhardness of the CoCrAlYTa-10%Al₂O₃ coating after oxidation tests at different temperatures. For comparison purposes, the results of the H13 steel substrate are also presented. The average microhardness of CoCrAlYTa-10%Al₂O₃ coating at room temperature (without oxidation, referring to as-sprayed coating) is 640 HV₀.₁, which is higher than that of other MCrAlX system coatings: NiCrAlY (430 HV₀.₃) and NiCrCoAlTaZr (450 HV₀.₁) [31, 32]. This is thought to be affected by the low porosity content (0.44%) and the presence of hard phases (i.e. Al₂O₃, Cr₂C₃ and TaC). Some researchers have developed oxide dispersion strengthened MCrAlX coatings, suggesting the hard phases strengthen the alloy matrix by impeding the motion of dislocations [33–36]. Additionally, after oxidation test at 200 °C and 400 °C, the microhardness of the CoCrAlYTa-10%Al₂O₃ coating and H13 steel was basically the same as that at room temperature. When exposed at temperature above 400 °C (600 °C and 800 °C), although the hardness of the coating remained basically unchanged, the hardness of H13 steel showed a significant decline. This is because Cobalt is a refractory metal (inherently harder than nickel or iron) and is often used as a base material for superalloys with high hardness and refractoriness [37]. On the contrary, when the tempering temperature up to 600 °C, H13 steel overaged as a result of the formation and growth of alloy carbide precipitated from the matrix and the
recrystallization of martensite matrix, leading to a sharp decline in strength and hardness of H13 steel \[38, 39\]. According to the hardness analysis, the CoCrAlYTa-10%Al2O3 coating exhibited good mechanical properties at high temperature.

4. Conclusions

In this study, the H13 steel was selected to be coated with CoCrAlYTa-10%Al2O3 coating using high-velocity oxygen fuel spraying process. Based on the experimental results of the microstructures, evolution under high temperature oxidation and microhardness, the most important results can be summarized as follows.

1. HVOF spraying of powders was successfully employed to deposit a CoCrAlYTa-10%Al2O3 coating on H13 steel substrate. The as-sprayed coating was well adhered to the substrate, relatively compact and essentially free of cracks. The coating had a porosity of 0.44% and the TaC particles homogeneously distributed in the coating.

2. There are four main phases exist in the as-sprayed coating, including Co-based solid solution, Cr-based solid solution, TaC, and Al2O3 phase. The content of Al2O3 is higher in the coating than that of the powders owing to the oxidation of Al element in the feedstock powders. The nano-crystalline phase, chromium carbide phase (Cr7C3), intermetallic phases (Al13Co4) and low content Aluminum-yttrium oxides (Al5Y3O12) were confirmed by TEM observation results.

3. The coating began to oxidize at 800 °C with the formation of oxide like CrO2 and Ta2O5 phases. The average microhardness obtained in the as-sprayed coating is 640 HV0.1. With the increase of temperature, the hardness of the coating did not decrease significantly compared with the H13 steel, indicated that the coating exhibited excellent mechanical behavior under high temperature.

Acknowledgments

The research was supported by the National Natural Science Foundation of China (Grant Nos. 51579087 and 51609067), the Fundamental Research Funds for the Central Universities (Grant No. 2018B48914), and the China Postdoctoral Science Foundation (Grant No.2018T110435).

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

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