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COATINGS FOR PROTECTION OF HIGH TEMPERATURE NEW GENERATION STEAM PLANT COMPONENTS: A REVIEW

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Abstract

Since 1998 during the European Action COST 522 coatings were developed for the first time in Europe to be used in future supercritical high temperature steam turbines to prevent component oxidation. Slurry applied, pure and Si modified aluminide coatings, electroless Ni and a series of thermal sprayed alloys (FeAl, FeCrAl, NiCr and AlFeCoCr) were deposited on P92. Most of these coatings showed excellent behaviour up to at least 10,000 h for the thermal spray coatings and to 20,000 h for the plain aluminides when exposed to steam at 650°C in the laboratory. Since then, other researchers in Europe, North America and Japan have also begun to look at coatings for steam oxidation protection including a number of alternative deposition techniques such as pack cementation, electro-plating, CVD (fluidized bed and organometallic as well as thermal), etc. A summary of all available results, including steam oxidation and other testing data will be presented together with a critical analysis of the different alternatives both from the materials behaviour and deposition techniques suitability perspectives.

Keywords: Steam power plant, high temperature, ferritic/austenitic steels, oxidation resistance, coatings.

1. Introduction and Background

Future high efficiency coal-fired steam power plants will operate at higher temperatures. Under steam atmosphere, existing ferritic and austenitic alloys, commonly employed in steam plants, form Cr containing oxides which become less protective at temperatures higher than 550° C. New alloy development activities have been very successful in improving the creep strength at higher temperatures, generally by lowering the chromium content [1, 2]. However, when the Cr content is lower that 10 w%, such as P92, very thick oxide scales form, consisting of a top layer of and an inner zone mainly (Fe, Cr)$_3$O$_4$ spinels (figure 1a). These scales spall causing metal cross-section loss (figure 1b), blockage and erosion of components located down-stream and also produce a thermal insulating effect resulting in overheating [3, 4].

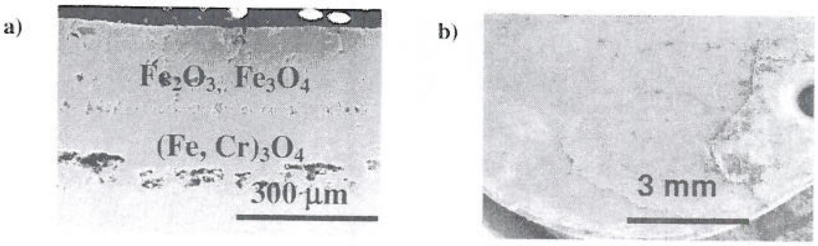

Figure 1: SEM images of uncoated P92 exposed to steam at 650° C for 10,000 h: a) cross-section and b) top view

A similar situation occurred for gas turbine many years ago and was resolved by employing protective coatings. For steam power plants, some work was performed in the US around 30 years ago, particularly addressing the protection of boiler tubes of 2.25 wt.% Cr steels and austenitic stainless steels. The range of coatings and surface treatments investigated included chromizing [5], chromate conversion, application of a Cr_2O_3 ceramic coating, and application of layers of aluminium, electroless nickel or silicon [6, 7]. It was concluded that the only satisfactory behaviour was achieved using chromizing and chromate conversion. However, there is increasing resistance to use chromate conversion processes due to the health and environmental hazards related to Cr^{+6}, and on the other hand pack cementation is carried out at temperatures too high (>800° C) for the steels currently employed in the manufacture of steam turbine components.

After a gap of some 20 years, no other published work appeared in the literature, until 1998, when as part of the activities carried out in COST 522, a feasibility study regarding the use of coatings to prevent component oxidation in future supercritical high temperature steam plants (650° C) was initiated for the first time in Europe [8]. Since then, several groups have begun exploring a number of coating process and materials including formers of all three known protective oxides, Al_2O_3, Cr_2O_3 and SiO_2. This paper includes a summary of available results, including steam oxidation and other testing data along with a critical analysis of the different alternatives both from the materials behaviour and deposition techniques suitability perspectives.

2. Coating Materials and Processes

2.1 Diffusion Coatings

2.1.1 Slurry Aluminide Coatings

Slurries are suspensions of particles (metallic or ceramic) on a binder solvent system that can be applied on a substrate by means of a brush or by spraying. After application, the coated specimen is subjected to a curing heat treatment to eliminated liquids and set the coating.

In the framework of COST Actions 522 and 536 and of the on-going European project "Coatings for Supercritical Steam Cycles" (SUPERCOAT), commercially available aluminium slurries have been applied on several substrates such as P91 [9], P92 [8, 10-13], P22 and P23 [14], following the manufacturer's recommendations to be subsequently heat treated at 700° C under flowing Ar. The resulting coating cross section microstructure is shown in figure 2. Thicknesses of 40-100 µm can be deposited and electron microprobe analysis as well diffraction carried out in a Transmission Electron Microscope, confirmed the presence of an outer Fe_2Al_5 zone with Cr rich precipitates, and an inner and thinner FeAl layer on top of a zone containing acicular precipitates of AlN [8]. The lower Cr substrates P22 and P23 exhibited a similar microstructure with less Cr containing precipitates and no precipitation of AlN within the substrate (both substrates have lower N content than P91 and P92) [14].

Such formed aluminides exhibit stress relieving cracks, present already after the initial diffusion heat treatment, probably due to brittleness of the Fe_2Al_5 phase and to thermal expansion coefficients mismatch. On exposure to steam, the coating develops a protective Al_2O_3 layer and the cracks do not propagate into the base material, nor become sites of

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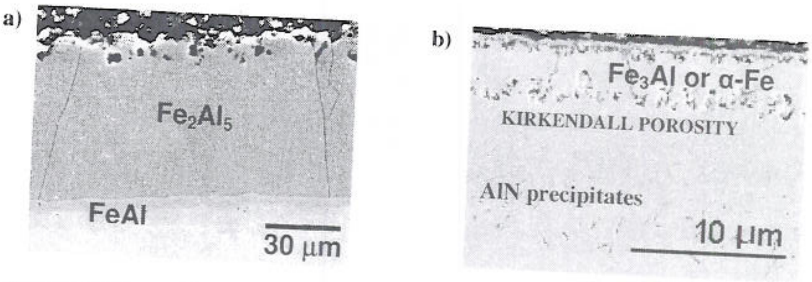

Figure 2: Slurry aluminide coating on P92: a) before exposure and b) after 30,000h of steam oxidation at 650° C

preferential attack by steam. However, slow degradation is observed by a reduction of the Al surface concentration by Al inwards diffusion rather than by spallation and regeneration of the protective scale. In steels with a N content > 0.040 wt.%, the diffused Al causes precipitation of AlN within the substrate as shown in the cross section of a specimen exposed to pure flowing steam for 30,000 h at 650° C (figure 2b). The coating has recently surpassed 40,000 h of exposure without evidence of substrate attack and cracks did not propagate into the substrate after 2,000 cycles (1 cycle: 1 h at 650° C cooling to 100° C for 5 min in 5 min, heating in 5 min) [13]. Moreover, on exposure to high steam pressures both in the laboratory at TU Darmstadt (300 bar) [9] and in a test tube connected to a steam turbine operating at 640° C (180 bar) in Westfalen, Germany [11], the behaviour was similar to that observed in the 1 bar laboratory tests. In addition, creep and Thermo-Mechanical Fatigue (TMF) testing of coated specimens have indicated that these coatings do not affect the properties of P91 at 650° C [15].

A similar process was also developed and patented by Schmitz but thinner and very irregular, non uniform coatings were obtained [16].

Some elements, such as Si and Ni were added to the aluminide coating in an attempt to stabilize the intermetallic phases to retard aluminium interdiffusion from the coating into the substrate, and therefore degradation of the aluminide coatings. The coatings microstructure was modified with new phases rich in Si and Ni. However, after exposure to steam at 650° C, the degree of Kirkendall porosity at the coating-substrate was much higher than that of a pure aluminide after the same exposure. This indicate that both Si and Ni contributed to retard Al inwards diffusion but without significant reduction of Fe outwards diffusion with the consequent generation of pores which with time increase in number and size until coating detachment is caused as shown in figures 3a and b respectively [9, 13].

2.1.2 Chemical Vapour Deposition (CVD) Coatings

In CVD, one or two vapour phase precursor species are brought in contact with a heated substrate and on its surface said vapours decompose or react among themselves respectively, resulting in the deposition of a coating and the release of volatile by-products. In the cases of metals being deposited, if the deposition temperature is sufficiently high, said metal(s) will interdiffuse with the substrate as it is being deposited resulting in an intermetallic diffusion coating.

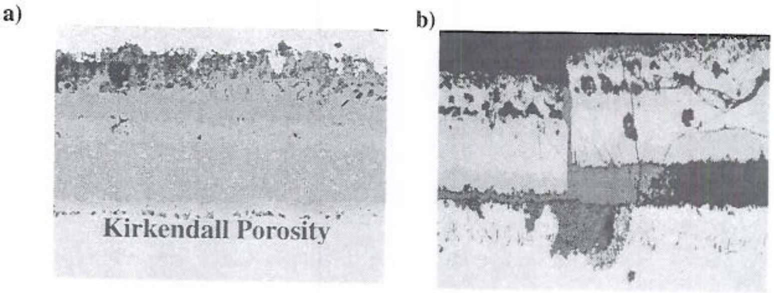

Figure 3: SEM image of the cross section of a (20 wt.%) Si modified aluminide coating on P92: a) after 72 h and b) after 4500 h of exposure to steam at 650° C

Pint, Zhang and co-workers have deposited aluminide coatings on ferritic and austenitic steel substrates by CVD from $AlCl_3$ and H_2 at 900-1100° C [17]. The resulting structure consist of two crack free layers, the top thinner (3-25 μm depending on the temperature) and richer in Al (25 at.%) while the most inner layer is thicker (60-275 μm), with a gradually decreasing Al content and exhibiting acicular AlN precipitates (figure 4). Cyclic oxidation testing of these coatings in air containing up to 10 vol.% of H_2O was carried out at 700-800° C. After 2000 short term cycles (1 cycle: 1 h at 700° C, 10 min at room temperature) thickness through cracks that propagated into the substrate could be observed as well as substrate oxidation through said cracks. However, at a longer cycle length (1 cycle: 100 h and 10 min at R.T.) the coatings were still protective after 14,000 h [18-20].

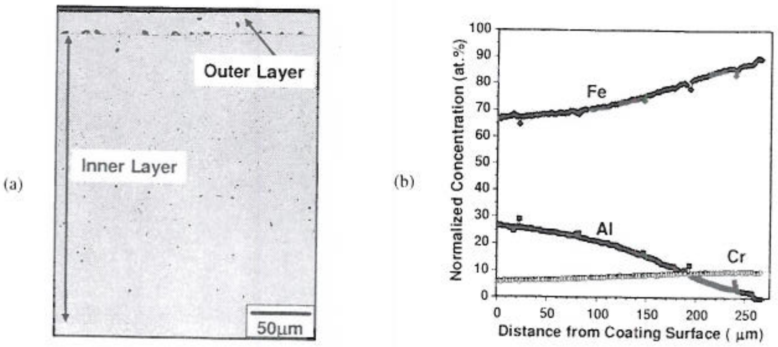

Figure 4: CVD aluminide coating on Fe9Cr1Mo deposited at 1050°C: a) back scattered electron image and b) compositional profiles of the principal elements [21]

Aluminide, silicide and Si modified aluminide diffusion coatings have also been deposited by Pérez and collaborators employing lower temperatures by means of Fluidised Bed CVD (FBCVD) under atmospheric pressure [22-24]. In FBCVD the specimens to be coated are placed in contact with a fluidised mixture of powders comprising the precursors (Al and/or Si) and inert filler through which HCl is flowed. In this manner transport of the vapours (Al and/or Si chlorides) to the substrates is enhanced. For instance aluminide coatings could be obtained at 550° C as opposed to the much higher temperature required by the above mentioned CVD process. As shown in figure 5a, the aluminide coating deposited by FBCVD is similar in microstructure to those obtained by slurry deposition, but without stress relieving cracks and significantly thinner (10 μm). After 10,000 h of isothermal steam oxidation laboratory testing at 650° C, the coating began to fail, showing "islands" of Fe_3O_4/(Fe, Cr)$_3O_4$ spinel as seen in figure 5b. The subscale Al content in zones where attack has not begun, was 4.5 wt.%. This observation is in agreement with recent works that indicate that if Cr is present, the critical Al concentration required to form a protective may be lower 5 wt.% [25, 26].

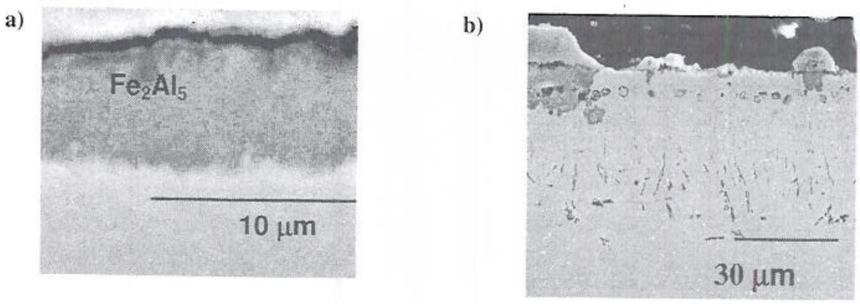

Figure 5: Aluminide coating deposited on P91 by FBCVD at 550° C: a) as deposited and b) after 10,000 h of steam oxidation testing at 650° C [27].

Pure Al coatings have been deposited by Metal-Organic CVD (MOCVD) at 300° C. In this modality of CVD, organometallic precursors are employed and as this type of compounds is less stable than halides typically used in conventional CVD, the deposition can take place at lower temperature. After a diffusion heat treatment at 650° C, a coating similar to that obtained by slurry deposition was obtained [28]. Thicknesses higher than 50 μm (after diffusion) are easily achieved at coatings time of 1 h or less and long exposure testing (over 10,000 h at 650° C) have also indicated excellent behaviour.

High temperature CVD has also been employed to deposit Si inside tubes by K. Berreth and K. Maile and collaborators [29]. At 1050° C, Si was deposited on the inner surfaces of T91 tubes (Ø 42 mm) from $SiCl_4$ and H_2. No prior surface machining was necessary as "in situ" H_2 cleaning is possible. The resulting coating consists of a crack free 20-30 μm diffusion layer containing 4-6 at.% of Si as well as excess Si which was converted to Si_3N_4 employing NH_3. Moreover, the process allows to increase the Si content of inner surfaces of tubes without needing to machine to remove the original scale resulting form the tube's production process (figure 6). Tensile testing up to 700° C indicated that there was only a minor influence on the strength of the base material and exposure to a 10 % water vapour atmosphere at 600° C shows a protective behaviour up to at least 1100 h of exposure.

2.1.3 Pack Cementation Coatings

In Al pack cementation, components to be coated are "buried" in a mixture of powders including Al, an activator which is usually NH_4Cl and inert filler (Al_2O_3). Upon heating, Al reacts with NH_4 producing aluminium chlorides vapours that reach the hot surface of the component reacting with H_2 to deposit Al (by CVD) which diffuses as it is being deposited.

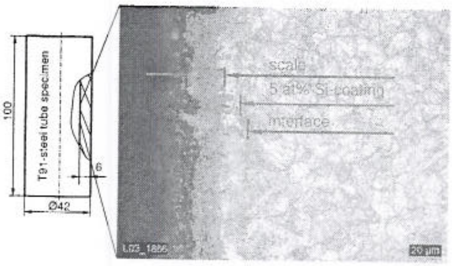

Figure 6: Inner tube surface enriched with Si deposited by CVD [30]

Rohr and Shütze have explored pack cementation as a method to coat the inner surfaces of heat exchanger tubes and they have shown that diffusion coatings essentially consisting of Fe_2Al_5, can be produced at 650° C. Their results also showed that glass bead blasting prior to coating resulted in a thicker and denser coating [31, 32]. Chromizing was also carried out at 1000° C resulting in a Cr enriched 30-50 µm layer [33]. Moreover, chromizing at 1000° C followed by aluminizing at 650° C resulted in 10 µm of Al_4Cr over a Cr rich layer as seen in figure 7. Cr enrichment reached 45 at.% below the surface of the P91 substrate [24]. Pack siliconizing was also carried out and the resulting coating consisted of a porous 10 µm Si rich (24 at.%) layer [24].

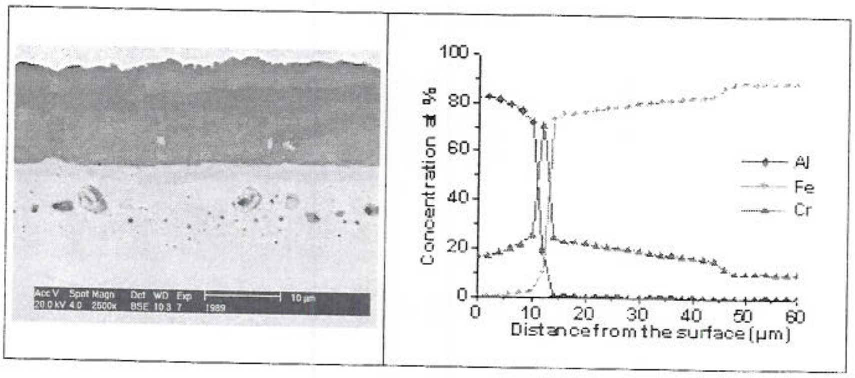

Figure 7: Two step Cr+Al pack cementation coating on P91. 1st step Cr deposition at 1000 °C for 2 hours in Ar followed by a rapid cooling . 2nd step Al deposition at 650° C for 1h in Ar-10 %H2 [34]

Xiang, Datta and co-workers have also deposited suitable thickness aluminide coatings by low temperature pack cementation (700° C) in a reasonably short period of time (a few hours) within the frame of the already mentioned SUPERCOAT project [35, 36]. These pack cementation coatings exhibit a smooth surface in contrast with slurry deposited aluminides as shown in figure 8 but although it is not shown on the figure, these coatings also develop

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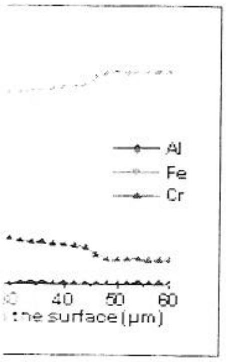

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thickness through cracks. XRD indicated that the "as deposited" coating consist of $Fe_{18}Al_{84}$, differing from Rohr and Shütze Fe_2Al_5 coatings, also deposited by pack cementation as mentioned earlier. Laboratory testing under pure flowing steam at 650° C has shown a similar behaviour to that of slurry deposited aluminides for at least 5000 h and degradation also occurs by coating-substrate interdiffusion.

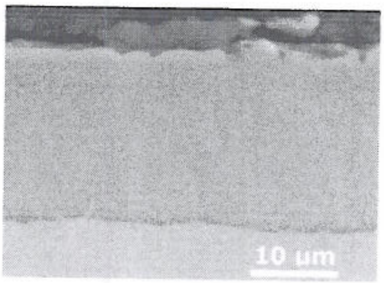

Figure 8: Aluminide coating deposited on P91 by pack cementation at 700° C [37]

Low alloyed steels have been boro-aluminized by Tsipas and co-workers at 715° C [34, 38]. In these 20-30 μm crack-free coatings, B is localized at the coating-substrate interface but does not seem to retard Al interdiffusion as illustrated in figure 9, where a sample exposed to steam at 650° C for 300 h is shown. Results of steam cyclic oxidation testing at 650° C for up to 1,000 h are very satisfactory.

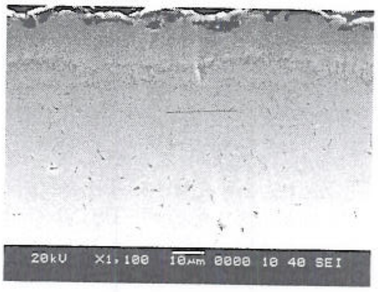

Figure 9: Boron-aluminide coating deposited by pack cementation at 715° C after 300h of steam oxidation at 650° C [39]

Nava and collaborators have also explored Cr, Cr-Si and Cr-Al diffusion coating deposited by pack cementation but at higher temperatures [40]. For instance, pack chromizing of T92 at 1140-1200° C results in a 360 μm Cr rich layer, free of Cr-carbide precipitates as seen in figure 10, with a surface Cr concentration of 30 wt. % which gradually decreases down to 9 wt.% (Cr content of P92). After short periods of exposure to steam at 750° C, there were no apparent signs of attack as well as no indication of breakaway corrosion.

2.2 Overlay Coatings

2.2.1 Thermal Spray Coatings

During thermal spray, finely divided molten or semi-molten droplets of the coating material are accelerated towards the surface to be coated. The particles hit the surface deforming and coalescing on cooling forming a coating.

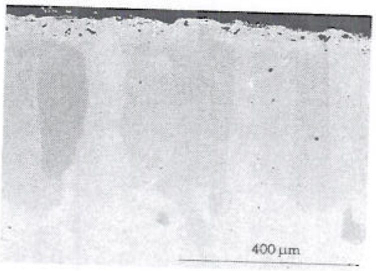

Figure 10: As deposited Cr diffusion coating on T92 by pack cementation at 1200° C [41]

Several intermetallic coating materials have been deposited both by Atmospheric Plasma and High Velocity Oxyfuel Thermal Spray (APS and HVOF respectively) in the framework of COST Actions 522 and 536 and of the European project SUPERCOAT [8-11, 13]. In APS, material particles are passed through an electric plasma supported by an inert gas and/or H_2 and produced by low voltage, high current electric discharges. Fe30Cr5Al, Ni20Al and Al25Fe coatings with a significant degree of porosity were deposited and exposed to steam at 650° C with satisfactory results at least for 500 h [8].

During HVOF, a fuel gas as well as oxygen are mixed in the combustion chamber of a specially designed spray gun. Powders are injected, heated and accelerated to hypersonic gas velocities. As a result of the significantly higher kinetic energy, very dense coatings can be obtained. Fe30Cr5Al, Ni20Cr and Al20Co11Fe11Cr have been deposited and tested at 650ºC under pure steam for periods of at least 10,000 [9, 10]. The first two coatings did not show signs of degradation and formed protective Al_2O_3 and Cr_2O_3 oxide scales respectively. Remarkably, in Ni20Cr there is no evidence of Cr depletion near the protective scale interface as the Cr content remains unchanged except in the zone near the substrate interface where some coating-substrate interdiffusion has taken place (figure 11).

On the other hand, Al20Co11Fe11Cr lost Al by interdiffusion causing phase transformations and Kirkendall porosity [12]. Cermet coatings such as WCCoCr as well as CrCNiCr have also been tested with satisfactory results [9, 11] and more recently, inexpensive Fe12Cr, Fe50Cr, Fe16Al and Fe32Al have also been deposited by HVOF. Both Fe12Cr and Fe50Cr are very stable under steam at 650° C and while Fe50Cr develops a thin Cr_2O_3 protective layer, Fe12Cr the scale also contains Fe (figures 12a and b respectively). Both Fe16Al and Fe32Al form protective Al_2O_3 but Fe32Al develop thickness through cracks that cause substrate attack and eventually spallation probably due to the very brittle nature of FeAl intermetallics with high Al content, exhibiting high resistance to steam oxidation at 650° C [13].

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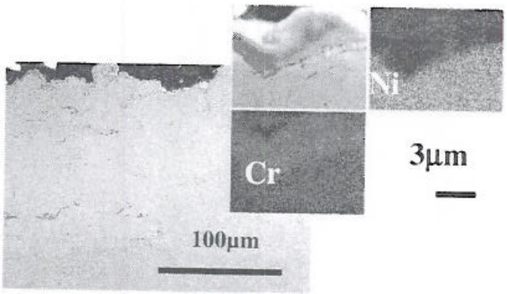

Figure 11: Cross-section of Ni20Cr deposited by HVOF after exposure to steam for 10,000 h at 650° C

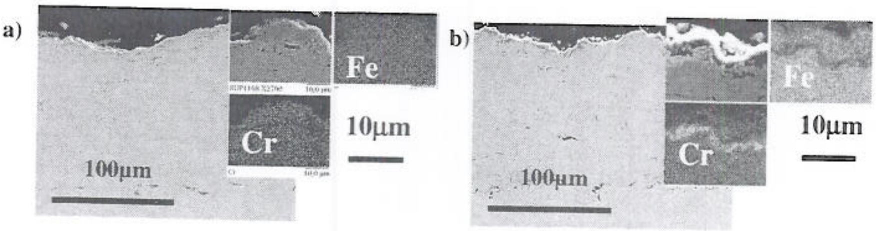

Figure 12: Cross-section of: a) Fe50Cr and b) Fe12Cr deposited by HVOF after exposure to steam for 1,000 h at 650° C

Sundararajan and co-workers have also explored APS and HVOF thermal spray to deposit Al and NiCr coatings for steam oxidation protection. The APS Al coatings deposited on T91 [40] interdiffuse on exposure to steam at 600 and 750° C forming FeAl intermetallic phases similar to those obtained in the already mentioned diffusion aluminide coatings. However, since the APS deposited Al coating exhibits some degree of porosity, steam reaches the substrate surface before the interdiffusion process has been completed resulting in a partially oxidised aluminide layer. The same behaviour was observed when an Al slurry coating was exposed to steam without a prior diffusion heat treatment [9]. Ni20Cr as well as Ni50Cr were also deposited by both APS and HVOF [43-45] exhibiting good steam oxidation resistance up to 750° C for at least 1,000 h. However at 700 and 750° C Fe diffuses from the substrate and through the coating in Ni20Cr, and Ni also diffused into the substrate (see figure 13). A similar behaviour was observed for Ni50Cr but to a significantly lower extent.

The effect of Mn and Si present in NiCr coatings in small concentrations was also studied by Sundararajan and collaborators and the results indicated that $MnCr_2O_4$ and Mn_2SiO_4 spinels formed at the coatings surface on top of the Cr_2O_3 scale at 750°C in Ni20Cr but were not observed in Ni50Cr [47]. The APS "as deposited" NiCr coatings were very porous and partially oxidised, and after steam exposure at 750° C developed a scale at the coating-substrate interface. In the HVOF deposited coatings, Cr carbide was found at the coating-substrate interface.

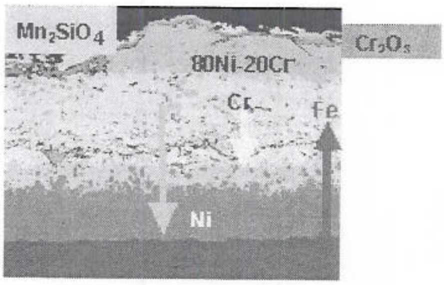

Figure 13: Cross section of Ni20Cr deposited by HVOF exposed to steam for 1,000 h at 750° C [46]

2.2.2 Electroless Nickel Coatings

Electroless nickel with a P-content of 12wt.% was applied onto E911 with a thickness of 40 – 60 µm by Scarlin and Knoedler [11]. After exposure times of up to 5000 h in the laboratory at 600 and 650° C, the oxidation stability of these coatings is high although the presence of cracks that reached the substrate was observed. Figure 14 shows that only thin oxide layers (predominantly Fe-oxides) grow on top of the coating. This is most pronounced in the vicinity of cracks in the nickel coating, and it is therefore important for future work to make efforts to avoid such cracks. At the interface between nickel and base alloy also thin oxides has been formed around the crack. These inner oxides are formed by Fe, Ni and Cr oxides.

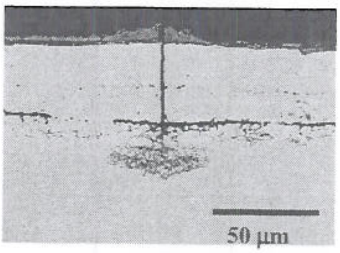

Figure 14: Electroless nickel on E911 after 4350 h at 600° C exposed to steam. Near the crack, thin oxide scales can be seen [48]

2.2.3 Sputtered Coatings

Itagaki and collaborators have coated ferritic steel with Pd and Pt by magnetron sputtering. These very thin coatings (1 µm) where heat treated at 750° C for 50 h in vacuum. Subsequently, the coated samples were strained by hammering on 320 grit SiC paper. An unidentified protective oxide layer formed after exposure to steam at 650° C for 100h. This oxide was more protective in the Pd sputtered sample than in the Pt specimen. These coatings require the straining process to be protective [49].

2.2.4 Dual layer Coatings

Two-layered coatings with a topcoat of Al on Ni20Cr were also deposited by APS and steam oxidation tested for 3,000 h at different temperatures comprised in the 600-750° C range by T.

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Sundararajan and co-workers [50, 51]. After 3,000 h, the Al topcoat transformed in a non-continuous NiAl layer over the originally deposited NiCr layer and a thick outer Al oxide layer containing small amounts of Ni and Cr and presenting a "grainy like" appearance. Even at a temperature of 750° C, chosen in order to accelerate the oxidation process, no evidence of substrate oxidation could be observed.

Scarlin and collaborators have patented another two-layer coating system for steam oxidation protection comprising a thin primer layer deposited on top on the component over which a thicker overlay is deposited [52]. The primer coating must be very ductile and oxidation resistant whereas the top layer can be a low cost, less ductile oxidation material. The preferred primer coating are MCrAlY (M = Ni, Co of Fe), stellite or WC-Co over which Ni electroless, Al, Al-Si or Cr alloys can be deposited. The primer coating can be deposited by thermal spray (HVOF or plasma) and prevents steam from reaching the substrate through cracks and/or any other defects present in the top lower-cost layer.

3. Discussion

The various coating materials and deposition techniques that have been explored for this application show advantages and disadvantages, and a number of factors must be taken into consideration when selecting the most appropriate coating and deposition method for a specific steam plants component. Some of these factors are: coating type and composition, application temperature, component size/weight and geometry capacity for coating "in situ" and cost among others.

For instance, diffusion coatings based on Al, Cr or Si are unexpensive and do not have adhesion problems, but on the other hand, require heat treatments, which in some cases are carried out at temperatures too high for the ferritic materials such as P91 and P92 which are subjected to annealing at 730-780° C to reduce stresses. For some components, such as heat exchanger tubes, the high temperature coating process such as $AlCl_3$ and Si CVD, as well as Cr and Si pack cementation can be combined with the base material austenitisation heat treament (see figure 15). However, other components, such as casings, valves, etc. can not be subjected to such high temperatures after having been machined to avoid distorsion.

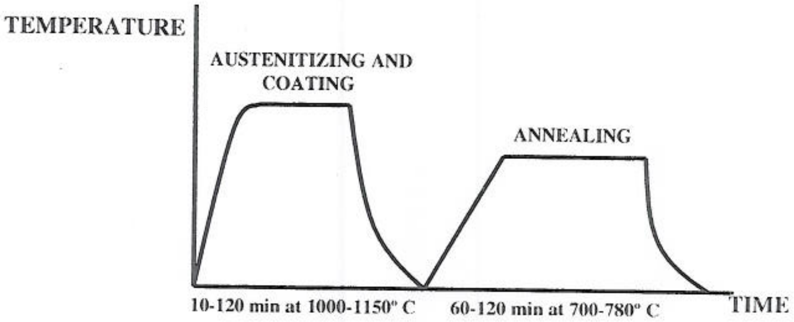

Figure 15: Combination of coating and the typical heat treatment of 9Cr ferritic steels

Moreover, diffusion aluminides degrade by coating substrate interdiffusion which not only reduces the subscale Al content but also may also affect the base materials mechanical properties. Cracks present in the high Al content coatings may propagate into the substrate although there is no evidence of such behaviour in the results available to present [14, 15]. Nitrogen is added to ferritic substrates such as P91 and P92 to improve their high temperature strength, and as mentioned in the previous parragraphs, when N containing substrates such as P91 and 92 are aluminized, AlN acicular precipates form, reaching 500 μm and more within the substrate. This loss of soluble N may therefore affect the materials strenght [11, 53]. Attempts to prevent or slow coating-substrate inerdiffusion have failed so far.

Less data is availabe regarding Si and Cr diffusion coatings, which should be more stable regarding degradation by interdiffusion. High temperature chromizing would only be possible for components that can be subjected to their corresponding heat treatment after they have reached their final shape. Siliconizing can take place at lower temperatures but there is evidence that SiO_2 based coatings are very soluble in high pressure steam [9].

Most studied Al and Cr oxide former overlay coatings deposited by thermal spray, are very resistant to steam, do not require heat treatment, and testing results published up to date do not indicate problems related to coating adhesion. Their higher cost may be justified by their higher stability and also because post coating heat treatments are generally not required. However, thermal spray is a "line-of-sight" deposition technique precluding it for certain complex geometries. Moreover, for some specific coating compositions, and for operating temperatures higher than 650° C, a significant degree of coating substrate interdifussion may result in coating degradation. Overlay Ni electroless coatings are easy to apply and low cost but the process is not reliable enough as thickness through cracks that cause substrate oxidation are often present [11]. On the other hand, Pd and Pt sputtered coatings are certainly not cost-effective for steam power plants.

Regarding the choice of a deposition technique, those that require placing the component in chambers (low or atmospheric pressure) such as CVD, pack cementation, and sputtering, or tanks as electroless plating, are suitable for small components, in particular blades where a smooth surface finishing is required. However, for large and heavy components such as rotors and casings these techniques may perhaps not be very practical as chambers with the required large sizes are not readily available and the fixturing could be quite complex. On the other hand, thermal spray or slurry deposition seem more appropriate as no containment is required and in addition, both techniques can be applied at the component manufacture site or at the plant, reducing transportation costs significantly. Finally, to coat the internal surfaces of heat exchanger tubes, CVD and pack cementation could be suitable as well as the application of slurries by inmersion. However, removing the scale present in the internal surfaces of "as manufactured" tubes may be quite challenging and it is required for most of the deposition techniques.

5. Conclusions and Outlook

Available results have demonstrated that coatings can significantly reduce steam oxidation at 600-750° C. Al, Cr and Si oxide former coatings have been deposited using a variety of deposition techniques and tested for steam oxidation resistance. However, a number of issues are still pending before oxidation resistant coatings can be used in steam turbines. For instance, most of the coatings described in this paper have not been tested under high steam

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pressure and moreover, their effects on the mechanical properties of the base materials have not been determined. In addition, although limited work has been carried out, there isn't enough data correlating laboratory and field testing results and there is no standard methodology for carrying out the steam laboratory testing. For instance, differences in steam chemistry (oxygen content and pH of feedwater for instance), flows, temperature cycles, etc. may also play a role. Another very important aspect that needs to be looked at is surface preparation and cleaning. As already mentioned, removing thick scales from inner surfaces of very long tubes is quite challenging.

Another important but little studied aspect is coating repairability. Limited work has been carried out in the EC project SUPERCOAT addressing the repair of slurry aluminide coatings with promising results but to present there are no other published or available results for other type of coatings and/or deposition techniques.

From a more fundamental perspective, such as understanding the degradation mechanisms, some work is already being carried out, for instance, in the frame of the EC project SUPERCOAT [9]. These aspects are of significant importance as the results can provide important tools for better coating design and for establishing life prediction, and therefore more work is required. Coating substrate interdiffusion, protective oxide stability in high pressure steam, protective scale as well as overlay coating spallation mechanisms, etc. are some of the very important aspects that need further in-depth studies.

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