Accepted Manuscript

Formation and stability of oxide layer in FeCrAl fuel cladding material under high-temperature steam

Dong Pan, Ruiqian Zhang, Hui Wang, Chao Lu, Yunming Liu

PII: S0925-8388(16)31478-5

DOI: 10.1016/j.jallcom.2016.05.145

Reference: JALCOM 37665

To appear in: Journal of Alloys and Compounds

Received Date: 12 April 2016

Revised Date: 12 May 2016

Accepted Date: 14 May 2016

Please cite this article as: D. Pan, R. Zhang, H. Wang, C. Lu, Y. Liu, Formation and stability of oxide layer in FeCrAl fuel cladding material under high-temperature steam, *Journal of Alloys and Compounds* (2016), doi: 10.1016/j.jallcom.2016.05.145.

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.



Formation and stability of oxide layer in FeCrAl fuel cladding material under high-temperature steam

Dong Pan^a, Ruiqian Zhang^a, Hui Wang^{a,b}*, Chao Lu^c*, Yunming Liu^a

^a National Key Laboratory for Nuclear Fuel and Materials, Nuclear Power Institute of China, Chengdu, 610041, China

^b Science and Technology on Surface Physics and Chemistry Laboratory,
P.O.Box No. 9-35, Huafengxincun, Jiangyou city, Sichuan Province,
621908, P.R.China

^c Chengdu Polytechnic, Chengdu, Sichuan, 610041, China

* Corresponding author. Tel.: +86 02885903294, Fax: +86 02885903294 E-mail: yinchanggeng5525@163.com (H. Wang). **Abstract:** The high-temperature steam oxidation(HTSO) experiment of FeCrAl alloy was carried out at 1000°C and 1200°C by simultaneous thermal analyzer. The oxidation kinetics curves and characteristics of generated oxide layer were analyzed. The results show FeCrAl alloy exhibits remarkable HTSO resistance with an oxidation constant (k_p) over three orders of magnitude lower than that of zirconium alloy. By XRD and XPS, the oxide layer consists of FeO and Al₂O₃ and a little Fe₂O₃ and Cr₂O₃ at 1000°C. When steam oxidized at 1200°C, there is only Al₂O₃ on the surface with the volatilization of CrO₃. The micromorphology shows the generated oxide layer at 1200°C is thicker than that at 1000°C due to the accelerated growth of Al₂O₃ at high temperature. The oxide layer at 1200°C presents distinct folds and peeling because of cyclic thermal stress, oxidation of chromium matrix, reduction of oxide adhesion and the gap crack between oxide layers.

Keyword: FeCrAl Alloy; Al₂O₃; high-temperature steam oxidation; oxide layer; nuclear fuel element

1. Introduction

Nuclear fuel elements, the core components of a nuclear reactor, are mainly comprised of cladding materials and nuclear fuel cores. The lifespan and safe reliability of nuclear fuel elements are significantly determined by the performance of cladding materials [1-2]. It is well

known that the disastrous Japan nuclear leakage in 2011 was caused by the brittle fracture of fuel claddings resulting from the loop water loss[3]. From then on, cladding materials for good accident tolerant fuel have been regarded as important research topics, which include the exploitation of advanced coating technology and novel cladding materials.

FeCrAl-based alloy have been widely used in many industrial fields due to their excellent high-temperature oxidation resistance [4]. Extensive high-temperature oxidation and mechanical experiments for commercial alloy conducted by Oak Ridge National Laboratory suggest that FeCrAl alloy are potential anti-accident cladding materials [5-8]. The FeCrAl alloy exhibits anti-oxidative capacity under high temperatures by virtue of the rapidly generated Al₂O₃ passivation layer with the aid of the "third element effect" of Cr [9, 10] and the "selective oxidation" of Al [11] at the early stage of steam oxidation. However, in order to guarantee the high-temperature oxidation resistance, the chromium and aluminum contents in traditional FeCrAl alloy are required to reach up to 20% and 10% [12], respectively, which, to some extent, aggravates the irradiation hardening of alloy and greatly reduces the processability [13], restraining the widespread application of high-Cr and high-Al FeCrAl alloy in nuclear reactors.

In this study, the chromium and aluminum contents for traditional

FeCrAl alloy are adjusted to a lower level based on ensuring that the alloy can not only reserve prominent high-temperature oxidation resistance but also improved reactor stability and processability. The performances of high-temperature steam oxidation resistance for the modified FeCrAl alloy at 1000°C and 1200°C were investigated. The formation mechanism and stability of oxide layers were analyzed in details. The results are expected to supply conducive technological guidance and theoretical basis for the study of advanced anti-accident cladding materials used as nuclear fuel elements.

2. Experiment

The composition of FeCrAl alloy is shown in Table 1. Specimens of FeCrAl alloy for oxidation, which were hot-rolled, were cut into slices with dimension of $10\times10\times1$ mm and a pore with a diameter of 2 mm in the corner of slice by hot-rolling (Fig.1). The HTSO experiment was conducted in a simultaneous thermal analyzer (Setsys Evo, Setaram, France) equipped with a steam generator (Wstsys). After the specimens were fixed, the system was pre-heated at 70°C and was simultaneously filled with hybrid steam of H₂O and Ar (Rh=70%). The reaction furnace was then heated at a rate of 10 K·min-1 and the temperature of specimens was real time measured by B-type thermocouples. The specimens in two groups were respectively heated up to 1000°C and 1200°C for 4h. The

weights of specimens were real time recorded by a photoelectric balance with a precision of 0.1 μ g. The grazing-incidence X-ray diffraction analysis for oxide layer was performed on a PANalytical diffractometer at an incidence angle of 1.5° within a scanning range from 15° to 90°. X-ray photoelectron spectroscope (XPS, XSAM800) was used to determine the chemical valence state of oxide layer. The morphologies of oxide layer were observed by scanning electron microscope (SEM, Hitachi S4800), which was equipped with energy dispersive spectrometer (EDS) for the semi-quantitative elements analysis. The oxide alloy layer was observed by laser scanning confocal microscope (LSCM, Olympus-LEXT).



Fig.1 Microstructures of specimens :(a) microstructure of FeCrAl alloy-typical running water hot rolling state; (b) scanning electron photograph of FeCrAl alloy, in which the elliptical second phase particle is Laves phase Fe2Nb based on EDS

analysis.

Fe	Cr	Al	Mo	Nb	С	Ν
Bal	13.09	4.33	2.27	1.04	0.004	0.0036

Table 1 Composition analysis of FeCrAl alloy (wt. %)

3. Results and discussion

3.1 Weight increase after steam oxidation

Fig. 2 shows the oxidation kinetics of FeCrAl alloy under HTSO at 1000° C and 1200° C, respectively. The oxidation kinetics of Zr-4(Zr-1.5Sn-0.3Fe) under HTSO at 1000 $^{\circ}$ C is shown in Fig.2 as a reference. FeCrAl alloy has better HTSO resistance than Zr-4 alloy. According to Wagner's theory of oxidation [14], the oxidation process of FeCrAl alloy and Zr-4 alloy fit with parabolic law when diffusion of ions and electrons through oxide layer are the rate determining step of oxidation process. The weight gain of oxidation (W) and oxidation time (t) can be expressed as follows:

$$W^2 = k_p * t \tag{1}$$

where $k_p (g^2 \cdot cm^{-4} \cdot s^{-1})$ is the parabolic rate constraint of oxidation process, demonstrating the oxidation rate of alloy.



Fig. 2 The oxidation kinetics of FeCrAl alloy and Zr-4 alloy

Here, the values of k_p are obtained by linear fitting the curves in Fig. 1 according to Equation (1), as shown in Table 2. By comparison, we can see that the parabolic rate constraint of FeCrAl alloy at 1000 °C is three orders of magnitude lower than that of Zr-4 alloy. Good oxidation resistance of FeCrAl alloy can be attributed to the formation of α -Al₂O₃ layer, which is thermostable and reduces the diffusion rate of ions and electrons through oxide layer and keeps the oxidation rate at a low value. When the oxidation temperature rises up to 1200°C, the parabolic rate constraint (k_p) accordingly increases due to the diffusion flux of Al ions increasing. C. Badini thinks the growth mechanism of the oxide film of FeCrAl is different at different temperatures. At 900 °C the main diffusion mode for oxidation is the diffusion of Al ions, while at 1200 °C the main diffusion mode for oxidation is that of O ions. It is obvious that the

	-	Ĩ.	•
Specimens	Temperature(°C)	Time (h)	$k_{p} (g^{2} \cdot cm^{-4} \cdot s^{-1})$
FeCrAl alloy	1000	4	9.77E-13
FeCrAl alloy	1200	4	2.01E-11
Zr-4 alloy	1000	4	1.33E-10

diffusion rate of O ion is higher below 1200 $^\circ\! C$, so k_p is higher. [15]

Table 2 The parabolic rate constraint of specimens alloy

3.2 The composition of oxide layer

Fig. 3 shows the grazing-incidence XRD patterns of specimens steam-oxidized at 1000 °C and 1200 °C. It is seen that the phases of oxide 1000°C formed were FeO(ICSD#49-1447) and layer at α-Al₂O₃(ICSD#73-2294), while those at 1200°C were mainly α - Al₂O₃ and FeAl₃(ICSD#45-1203) solid solutions. At the early stage of oxidation [16, 17], the initial products such as iron oxides (FeO, Fe_2O_3 , Fe_3O_4) and Cr_2O_3 grew up at the interface of gas/matrix with at a high rate. With the increase of temperature, Cr₂O₃ layer was formed between matrix and initial layer, which reduced the diffusion flux of oxygen ions and the concentration of aluminum ions. Benefiting from the "third element effect" of Cr [18], the critical concentration to α -Al₂O₃ layer formed at the interface of Cr_2O_3 -layer/matrix. Because α -Al₂O₃ layer was passive and thermostable, oxidation rate decreased seriously and occurred as α -Al₂O₃ instead of iron or chromium oxides.

At high temperature, the oxides of iron and chromium react with the high-temperature steam to generate volatile hydroxides and thus peel off from alloy surface [19]. Additionally, the AlFe₃ solid solutions are formed due to the external diffusion of Al atoms by exchanging with Fe atoms as well as the defects in the ferrite [20].



Fig.3 Grazing-incidence XRD patterns of FeCrAl alloy after steam oxidation at 1000 \square and 1200 \square

It is well known that XRD technology is not suitable for the characterization of surface layer. In order to investigate the initial product, XPS technology is used to determine the element valence state of oxide layer. The results are shown in Fig. 4 and 5. On the surface layer of FeCrAl alloy there are Fe₂O₃, Cr₂O₃ and FeCr₂O₄, which are not found in the XRD patterns. Fe₂O₃ and Cr₂O₃ are oxidation products generated at low temperatures at the early stage of the oxidation of alloy. FeCr₂O₄ is

one of the oxidation products of FeCr-base alloy at high temperatures. The oxidation products are formed on gas/scale interface as early as the start of the oxidation. But because of their poor adhesion with matrix or easy formation of volatile hydroxide, oxidation consumption continues in the process of oxidation, which does not affect the oxidation resistance of the alloy.

After the comparison of Fig. 4 and Fig. 5, Cr elements on the surface of the oxidation layer are consumed badly after oxidation at 1200 \Box for 4h (No Cr2p peak can be clearly observed in XPS score), suggesting that Cr₂O₃ becomes unstable at 1200 \Box . Earlier studies on Fe-Cr alloy have found that stable Cr₂O₃ generated CrO₃(g) when the temperature is above 1000 \Box , which leads to increasing oxidation by Equation (2) [19].

$$2Cr_2O_3(s) + 3O_2(g) = 4CrO_3(g)$$
 (2)





Fig. 4 X-ray photoelectron spectroscopy spectrum of FeCrAl alloy after HTSO at 1000 □. (a) spectrum of Fe2p,(b) spectrum of Al2p, (c) spectrum of O1s and (d) spectrum of Cr2p3/2.



Fig. 5 X-ray photoelectron spectroscopy spectrums of FeCrAl alloy after HTSO at 1200□. (a) Spectra of Fe2p and Cr2p peaks disappear. FeCr₂O₄ is formed with a spinel structure after a small number of Cr atoms replace Fe atoms in Fe3O4; (b) spectrum of Al2p; (c) spectrum of O1s

3.3 Thermal stability of oxide layer

Fig. 6 shows the morphology of specimens steam-oxidized at $1000 \square$ and $1200 \square$. It can be seen that FeCrAl alloy oxidized at $1000 \square$ (Fig. 6a) still displays some polishing marks that develop before oxidation, suggesting that the oxide layer is thin enough and the inner oxidation occurs merely.

The dark points show a size of about 1µm, similar to the particle size of Fe₂Nb. However, on the surface of FeCrAl alloy oxidized at 1200 \Box (Fig. 6b), the initial polishing marks are vanished with only some dark points and white points left. According to the XRD results, the phase of oxide layer at 1200 \Box is α -Al₂O₃.



Fig. 6 OM images of specimens after HTSO at (a) $1000 \square$; and (b) $1200 \square$ SEM images of specimens after HTSO at 1200° C; (c) Round white dots in OM are circular corrosion pits formed after oxide film flakes; (d) After the magnification of corrosion pits, it is found that the oxide films around the circular corrosion pits peel off layer by layer, which might be a warp gap between two layers of oxide film. The spalling of the whole round Al₂O₃ piece caused the outer Al₂O₃ spalling on the boundary; (e)The morphology of the most outer layer of α -Al₂O₃; (f) The matrix

morphology is clear in the position where oxide film peel off, totally different from the outer Al₂O₃; (e) and (f) are processed with energy-spectrum scanning and the results are listed in Table 4.

FeCrAl alloy oxidized at 1000 °C and 1200 °C show obvious differences in parabola constant and oxide on surface layer. At a higher temperature (1200 $^{\circ}$ C), the diffusion rate of FeCrAl oxide film is higher and more reactions occur on the surface of oxidation film, causing the morphology of oxidation film is different from that at a lower temperature (1000 °C). After oxidation of FeCrAl alloy at 1000 °C for 4 h, the oxide film is uniform without falling off or folding observed, which is closer to the morphology of the alloy polished surface before oxidation(Fig. 6a). (Fig. 6 b) Corrosion pits with a similar size can be observed on the surface of oxide film at 1200 °C, suggesting that oxide film flakes in the process of heating, heat preservation and cooling. Oxide film peeling does great harm to the alloy oxidation resistance, especially when peeling occurs at the stage of heating or thermal insulation. The exposed matrix after oxide film peeling makes the oxidation corrosion deeper into the alloy.

After oxidation of FeCrAl alloy at 1200 °C the corrosion pits in oxidation film are circular or elliptic pits with the size of 50 μ m (Fig. 6c). Fig. 6d shows the partial morphology of corrosion pit border. From the figure, it is easy to find the following points: 1) The folds of FeCrAl

(1200)4h) oxide film show the same direction. 2) Al_2O_3 oxide film is layered. Between the white and bright Al₂O₃ on the surface layer and matrix there is a dark layer of Al_2O_3 , suggesting that the growth direction of Al_2O_3 may change in the process of heating and heat preservation. 3) Wavelike ravines inside the exposed matrix are seen along the direction of the fold. There have been no signs of Al_2O_3 growth from the matrix surface. To prove that no α - Al₂O₃ is formed in the exposed matrix from the morphology, the matrix in corrosion pit (Fig. 6f) and outer α - Al₂O₃ (Fig. 6e) are magnified, respectively. Outer α - Al₂O₃ film presents an image of stack-based particles growing with different sizes. Larger α -Al₂O₃ are closely arranged, and smaller α - Al₂O₃ grow between the grain boundary. The morphology of matrix in the corrosion pits is totally different from that in Fig. 6e. One shows a flat convex surface, while another shows tightly arranged grains and similar concave surface along the intergranular fracture. In Fig. 6d, it can be seen that the direction of ravines in the corrosion pit is in line with the fold direction of surface Al₂O₃, showing there is also fold where peeling occurs. Convex plate in corrosion pit is the location where oxide film fold warps. Since the oxide film has fallen off from matrix, the surface is very smooth. And the "ravines" are the intergranular fracture formed when the oxide film falls off matrix (Fig. 7). SEM and EDS are used to analyze oxide film and partial matrix, and the results (Tab. 3) show that there is no oxidation of the matrix in oxidation corrosion pits. Therefore, the oxide film peeling occurs at the cooling stage (If it occurs at the stage of heating or thermal insulation, the oxidation of the exposed matrix will continue.)

						Y	
	Fe	Cr	Al	0	Mo	Nb	
Fig.1	56.59	8.47	2.27	(5	32.67	
Fig.6e	-	-	46.29	53.71) -	-	
Fig.6f	75.86	12.85	4.30	5	3.75	3.23	

Table 3Element ratios in different micro-areas for FeCrAl alloy after steam
oxidation at 1200 (wt.%)



Oxide film folds can be observed during the oxidation of FeCrAl alloy at 1200 \Box (Fig. 6d). Oxide film peeling is closely associated with fold. The driving force of both is oxidative stress in the process of heating- thermal insulation-cooling. Oxidative stress includes the growth

stress from the growth of oxide film and thermal stress from the difference of thermal expansion between alloy matrix and oxide.

The judgment formula for protective oxide film peeling in the state of compressive stress is shown as follows [21].

$$(1-v) \sigma^2 h/E \ge G_c \tag{3}$$

E and v are elasticity modulus and poisson's ratio of oxide film, h is the thickness of the oxide film, and σ is medium biaxial residual stress of the film .When elastic strain energy in the complete oxide film is over the fracture resistance of metal-oxide film interface (Gc), flaking occurs.

During oxidation of FeCrAl alloy at a constant temperature of $1200 \square$, the growth of α - Al₂O₃ film, the increasing thickness of oxide film h, and internal oxidation contribute to the increase of σ , leading to the increasing tendency of α -Al₂O₃ film peeling. Most oxide films in the state of compressive stress flake by means of fold or wedge-shaped cracking [22]. Based on elastic mechanics, Formula (4) shows the critical stress, which is necessary for the formation of stack-based warp with radius of a in the film under the action of biaxial stress.

$$\sigma_c = 1.22 \frac{E}{(1-v^2)} \left(\frac{h}{a}\right)^2 \tag{4}$$

In the process of oxidation, oxide film fold forms when $\sigma > \sigma_c$. But when the strain release rate does not meet Formula (3), fold will not continue to peel off. Apparently FeCrAl alloy oxide film at 1200 °C

accords with this kind of situation, so in the process of heating and heat preservation only fold occurs but not peeling. Based on the results and discussion, we can judge the oxide film peeling mostly occurs at the cooling stage of oxidation.

Fig. 8 is SEM of the cross section of FeCrAl oxide film (1200 \Box for 4 h). Fig. 8 shows the cross-section morphology of oxide film folds. Gaps form between oxide film and the matrix because of fold warp. These gaps are widespread between scale/matrix, causing the decrease of adhesion area of oxide film and matrix. Therefore, the oxide film peels off more easily. From Fig. 8 it can be observed that inside the oxide film there are cracks in the normal direction of oxide film. They are considered to be the starting point of circular peeling. At the cooling stage, there is mainly tensile stress in the oxide film. With the release of the thermal stress, oxide film is easy to crack in the place of stress concentration (Fig. 9). Obviously, when cracks in the normal direction run through the whole oxide film, through-wall cracks extend and eventually peel off under the action of tensile stress.



Fig. 9 Schematic diagram of oxide film cracking

4. Conclusions

In summary, high-temperature steam oxidation of FeCrAl alloy has been investigated in this study and the conclusions can be listed in the following aspects. Firstly, the modified FeCrAl alloy with low concentration of Cr and Al still keeps an excellent high-temperature steam oxidation resistance, with an parabolic rate constraint of three orders of magnitude lower than that of Zr-4 alloy at 1000 \square . The FeCrAl alloy has low oxidation rate at 1200 \square , although the weight during oxidation increases. Secondly, the composition of oxide layer on alloy surface mainly consists of FeO and α -Al₂O₃ at 1000 \square , while the product at 1200 \square is only α -Al₂O₃. The behavior of oxidation at 1200 \square refers to the growth of α -Al₂O₃ layer. At the high temperature reaction occurs in the initial oxide Cr₂O₃ with the formation of CrO₃ gas which volatilizes. Therefore, Cr₂O₃ consumes severely at 1200 \square .

Furthermore, the oxide layer after HTSO peels off from surface without resulting in oxidation of the exposed matrix, indicating that the layer-peeling occurs for cooling. During the oxidation at constant temperature oxide folds form in oxide film without peeling. Gaps form at the interface of matrix/scale because of fold, causing the decrease of adhesion area of oxide film and matrix. Therefore, oxide film peeling tends to increase. In the process of cooling, cracks in the normal direction run through the whole oxide film, through-wall cracks extend and eventually peel off under the action of tensile stress. To sum up, in simulating LOCA accident under the condition of temperature below $1200 \ \Box$, the improved FeCrAl alloy still shows very good high temperature steam oxidation resistance, but oxide film peeling appears at the cooling stage after oxidation at $1200 \ \Box$. Therefore, the heat cycle oxidation properties of the alloy still needs more research.

Acknowledgements

Great thanks for the financial support to our work from the Project Funded by China Postdoctoral Science Foundation (58 group, Grant No: 2015M580799). Great thanks to China Academy of Engineering Physics and Nuclear Power Institute of China for help in terms of experimental conditions.

References

[1] L.J. Ott, K.R. Robb, D. Wang, Preliminary assessment of accident-tolerant fuels on LWR performance during normal operation and under DB and BDB accident conditions, Journal of Nuclear Materials 448 (2014) 520-533.

[2] B. Cox, C. Wu. Transient effects of lithium hydroxide and boric acid on Zircaloy corrosion. Journal of nuclear materials, 1995, 224:169-178.

[3] Wang D. Study of Fukushima Daiichi Nuclear Power Station Unit 4 Spent-Fuel Pool, Nuclear Technology, 2012, 180(2): 205-215.

[4] K.G. Field, M.N. Gussev, Y. Yamamoto, L.L. Snead, Deformation behavior of laser welds in high temperature oxidation resistant Fe-Cr-Al alloys for fuel cladding applications, Journal of Nuclear Materials, 454 (2014) 352-358.

[5] I.G. Wright, B.A. Pint, P.F. Tortorelli. High-Temperature Oxidation Behavior Of Ods-Fe₃Al, Oxidation of Metals, 2001, 55(3-4):333-357.

[6] Sebastien Dryepondt, Put R V, Pint B A. Effect of H₂O and CO₂ on the Oxidation Behavior and Durability at High Temperature of ODS-FeCrAl. Oxidation of Metals, 2013, 79(5-6):627-638.

[7] Yamamoto Y, B.A. Pint, Terrani K A, et al. Development and Property Evaluation of Nuclear Grade Wrought FeCrAl Fuel Cladding for Light Water Reactors, Journal of Nuclear Materials, 2015, 467:703-716.

[8] Field K G, Gussev M N, Yamamoto Y, et al. Deformation behavior of laser welds in high temperature oxidation resistant Fe-Cr-Al alloys for fuel cladding applications[J]. Journal of Nuclear Materials, 2014, 454(s 1-3):352-358.

[9] Brumm M W, Grabke H J. ChemInform Abstract: The Oxidation Behavior of NiAl. Part 1. Phase Transformations in the Alumina Scale During Oxidation of NiAl and NiAl-Cr Alloys.[J]. Cheminform, 1992, 23(51):18-18.

[10] Kear B H, Pettit F S, Fornwalt D E, et al. On the transient oxidation of a Ni-15Cr-6Al alloy, Oxidation of Metals, 1971, 3(6):557-569.

[11] Westbrook J H, Fleischer R L. Intermetallic compounds: principles and practice. Farfon.fulba.com, 1995.

[12] Yamamoto Y, B.A. Pint, Terrani K A, et al. Development and Property Evaluation of Nuclear Grade Wrought FeCrAl Fuel Cladding for Light Water Reactors, Journal of Nuclear Materials, 2015, 467:703-716.

[13] C heng X, Yuan Y C, Zhang L F. The 3rd International Symposium on Supercritical Water-Cooled Reactors-Design and Technology, Shanghai: Shanghai Jiao Tong University Press, 2007. 327.

[14] C. Wagner, Z. Phys. Chem. B 21 (1933) 25.

[15] Badini C, Laurella F. Oxidation of FeCrAl alloy: Influence of temperature and atmosphere on scale growth rate and mechanism[J]. Surface & Coatings Technology, 2001, 135(2):291-298.

[16] Wallwork G R. The oxidation of alloys[J]. Reports on Progress in Physics, 1976, 39(5): 401-485.

[17] Zhang Z G, Zhang X J, Pan T J, Niu Y. Initial stage oxidation of Fe-Al and Fe-Cr-Al alloys at high temperature, Research on Iron and Steel, 2007(03):38-42.

[18] Niu Y, Wang S, Gao F, et al. The nature of the third-element effect in the oxidation of Fe-xCr-3 at.% Al alloys in 1 atm O-2 at 1000 degrees C[J]. Corrosion Science, 2008, 50(2):345-356.

[19] Tedmon C S. The Effect of Oxide Volatilization on the Oxidation Kinetics of Cr and Fe-Cr Alloys, Journal of the Electrochemical Society, 1966, 113(8):766-768.

[20] An XPS/SEM/EDX study of the early oxidation stages of the Fe- 19Cr-5Al(+ Y)

alumina-forming alloy

[21] Lobb R C, Evans H E. A determination of the chromium concentration for 'healing' layer formation during the oxidation of chromium-depleted 20Cr-25Ni-Nb stainless steel, Corrosion Science, 1984, 24(5):385-388.

[22] Evans H E, Evans H E. Stress Effects In High Temperature Oxidation Of Metals, International Materials Reviews, 1995, 40(1): 1-40.

Highlights:

(1) The FeCrAl alloy has low oxidation rate at 1200° C, the weight during oxidation increases.

(2) The composition of oxide layer on alloy surface mainly consists of FeO and Al_2O_3 at 1000°C.

(3) While the product at 1200° C is only Al₂O₃.

(4) The oxidation behavior at 1200 $^\circ\! \mathbb C$ refers to the growth of Al_2O_3 layer.

(5) Low concentration of Cr and Al still keeps an excellent steam oxidation resistance