Oxidation in air at 1400 K and optical properties of Inconel 625, FeCrAlloy and Kanthal Super ER

Johann Colas, Ludovic Charpentier*, Marianne Balat-Pichelin

PROMES-CNRS, 7 rue du four solaire, 66120 Font-Romeu Odeillo, France

* Corresponding author. +33 468 307 741; e-mail address: ludovic.charpentier@promes.cnrs.fr

Abstract

The materials used for the design of the solar receiver are one of the critical parts of the concentrated solar power (CSP) plants. An increase of the working temperature of the solar receiver could induce an increase of the efficiency of the CSP plants. Historically stainless steels were used for the solar receiver. However one limit of these materials is their poor creep resistance at high temperature. Nowadays Ni-based alloys are used, but they are limited at 1400 K by their oxidation resistance. Thus, to reach higher temperatures other materials have to be used. The alumina formers as FeCrAlloy possess a very good oxidation resistance at high temperature. The Kanthal Super ER also shows an excellent oxidation resistance. Consequently, FeCrAlloy and Kanthal Super ER were oxidized at 1373 K in air up to 48 h and compared to the currently used nickel based alloy Inconel 625. Inconel 625 shows an important mass gain followed by the spallation of its oxide scale. On the contrary, FeCrAlloy and Kanthal Super ER have a low mass gain (less than 0.40 mg cm^{-2}) with an adherent oxide layer up to 48 h. Besides the oxidation resistance, the materials have to possess a high solar absorptivity and a total emissivity as low as possible. Oxidized Inconel 625 shows both high solar absorptivity and total emissivity. The other mentioned materials are more suitable due to their high solar absorptivity (> 0.70 for oxidized FeCrAlloy, > 0.80 for oxidized Kanthal Super ER) and their relatively low total emissivity (< 0.35 for oxidized FeCrAlloy, < 0.45 for oxidized Kanthal Super ER). Due to its high oxidation resistance and high solar absorptivity, the Kanthal Super ER seems to be the best candidate for the solar receiver application.

Keywords: functional alloys, oxidation, optical properties, high temperature

Acknowledgements

This work was supported by the French “Investments for the future” program funded by the French National Research Agency (ANR) under contracts ANR-10-LABX-22-01-SOLSTICE and ANR-10-EQPX-49-SOCRATE, and by the 2MAC-CSP project also funded by the ANR under contract ANR-16-CE08-0019. We also thank Christophe Escape and Stanislaw Einchendorff from PROMES-CNRS and Yonko Gorand from the University Perpignan Via Domitia (UPVD) for their help for the reflectivity measurements, XRD analyses and SEM imaging, respectively.

1 Introduction

Nowadays, most commercial solar tower power plants are using a Rankine cycle to convert heat in mechanical energy [1,2]. In order to improve the efficiency of this type of solar plants, the Brayton cycle (or combined cycle) is proposed as an alternative to Rankine cycle. This implies to use a pressurized gas at a temperature higher than 1070 K [3–5]. Consequently, the materials that compose the solar receiver – element which permits to convert solar energy into heat – have to withstand a temperature greater than 1200 K in air.

Ni-based alloys are more suitable than stainless steels due to their better corrosion resistance to molten salts (the most used heat transfer fluids) [6]. Moreover their creep resistance is also higher than that of stainless steels [7]. However one of the limits of Ni-based alloys is their poor oxidation resistance in air at temperature higher than 1300-1400 K. Greene and Finfrock have shown for Inconel 718 that the oxidation kinetics is parabolic in the temperature range 973-1620 K in air up to 24 h, with different oxidation mechanisms depending on the temperature [8]. Buscail *et al.* also showed that the oxidation kinetics of alloy 625 is parabolic between 1173 and 1373 K under air up to 50 h [9]. Seo *et al.* have oxidized Inconel 625 at 1173 and 1273 K in air, and they also observed that the oxidation kinetics is parabolic up to 200 h and that the oxide scale, mainly composed of Cr_2O_3 , was porous [10], and Kim *et al.* showed that Inconel 617 lost weight after 36 h at 1373 K in air which is explained by the spallation of the oxide scale and/or the volatilization of the chromia scale [11]. Fe-Cr-Al alloys with reactive element (RE) additions, like yttrium or zirconium, possess a better oxidation resistance than most of Ni-based alloys [12–15]. This resistance is due to the formation of an adherent and dense alumina scale during oxidation [15,16]. Liu *et al.* showed that the growth of the alumina scale on FeCrAlloy (Fe – 22 % Cr – 5 % Al – 0.3 wt.% Y) is governed by the oxygen diffusion through the oxide grain boundaries which implies an oxidation kinetics fitted by a power law with an exponent of 1/3 [12,15]. Despite its good oxidation resistance FeCrAl alloys exhibit a poor creep resistance compared to Ni-based alloys [14]. Another alternative to the Ni-based alloys could be the intermetallics, especially the ones based on MoSi_2 , because of their very low oxidation kinetics [17].

Besides oxidation, the material used for solar receiver has to possess good radiative properties, in particular, a high solar absorptivity and a low total emissivity at high temperature. These properties are very important because they impact the efficiency of the solar power plants [3]. Decreasing the solar absorptivity or increasing the total emissivity decreases the efficiency. The total emissivity of oxidized Inconel 718 was studied by Greene *et al.* in the temperature range 573 to 1273 K [18]. They showed that the total emissivity highly increases with oxidation, exceeding 0.80 at 1000 K. Balat-Pichelin *et al.* have also measured the total hemispherical emissivity of in situ oxidized Inconel 718 up to 1450 K and found a value around 0.90 [19]. Moreover the normal spectral absorptivity of an oxidized Inconel alloy was found to be higher than 0.80 in the wavelength range 0.5 to 2.5 μm [20]. Oxidized Kanthal A, a Fe-Cr-Al alloy, shows a lower normal spectral emissivity than mentioned Inconel 718 [20]. Gopalakrishnan *et al.* [21] measured the total emissivity of a FeCrAlY alloy oxidized at 1473 K for 100 and 500 h. However, to understand how the oxide layer impacts the radiative properties, it is important to analyze the spectral emissivity, and this property is not available for FeCrAlloy. Due to its very good oxidation resistance, Kanthal Super ER could be a good alternative to nickel based alloys, but its radiative properties are unknown and were determined in this paper.

In this study, three different materials were oxidized at 1373 K up to 48 h in air. Inconel 625 was used as a reference. FeCrAlloy and Kanthal Super ER were also studied due to their excellent oxidation resistance. The spectral emissivity at room temperature was also measured on as-received and oxidized samples, and their solar absorptivity and their total emissivity were calculated from the spectral emissivity.

2 Materials and methods

Inconel 625 and FeCrAlloy were supplied by Goodfellow. Squares of 20 mm length and 1 mm thickness were used. The composition of both alloys is given by the supplier and is summarized in Table 1. The samples of Kanthal Super ER were supplied by Kanthal (Sandvik). Kanthal Super ER is composed by three phases: 80 vol.% hexagonal $\text{Mo}(\text{Si},\text{Al})_2$, 6 vol.% $\text{Mo}_5(\text{Si},\text{Al})_3$ and 13 vol.% Al_2O_3 [22]. Ingemarsson *et al.* measured by EDX the nominal composition of both silicide phases: 34 at.% Mo, 27 at.% Al and 35 at.% Si in $\text{Mo}(\text{Si},\text{Al})_2$ and 59 at.% Mo, 5 at.% Al and 30 at.% Si in $\text{Mo}_5(\text{Si},\text{Al})_3$ [22]. The samples are disks of 18 mm diameter and a thickness between 2 and 3 mm. The Kanthal Super ER samples were polished using a Struers polishing machine with SiC grinding papers, starting with the 220 paper (68 μm grain size) and ending with the 4000 paper (5 μm grain size). Polishing procedure was set to reach a mean square surface roughness (measured using a Leica 3DCM optical profilometer) is in between 0.5 and 0.8 μm . All the samples were cleaned with acetone and with ethanol in an ultrasonic bath before oxidation.

	Al	C	Cr	Fe	Mo	Mn	Nb+Ta	Ni	Si	Other
Inconel 625	0.25	0.1 max.	21.5	5.0 max.	9.0	0.25	3.65	bal. (+Co)	0.5 max.	0.015 max. S
FeCrAlloy	5.0	0.02	22.0	bal.		0.2			0.3	0.1 Y, 0.1 Zr

Table 1 Composition (in at.%) of Inconel 625 and FeCrAlloy provided by suppliers

Oxidation cycles were performed using an electrical muffle furnace at 1373 K in ambient air (total pressure around 87 kPa). Between each cycle, samples were cooling down the room temperature (around 300 K). The mass was measured by a microbalance Ohaus which has an accuracy of 0.1 mg. XRD analyses were performed on a PANanalytical X'Pert Pro diffractometer (MPD) operating at 40 kV and 20 mA ($K\alpha$ radiation of Cu, $\lambda = 0.15418$ nm) and in the 2θ range of $20 - 100^\circ$ and 20 min acquisition time. Micro Raman spectra were measured by Horiba-Yvon Jobin spectrometer with a 532 nm-laser and the x100 objective in the range of wavenumber 50 to 1000 cm^{-1} . The collection time was 10 s and 2 accumulations were done to avoid artifacts. Hitachi S-4500 apparatus permits to take the SEM pictures coupled with energy-dispersive X-ray spectroscopy (EDS). The roughness measurements were performed with an optical profilometer with a magnification of 50 (Leica DCM 3D). The hemispherical reflectivity at 300 K was measured with a Perkin Elmer HDR 950 for the range 0.25 and 2.5 μm and with a SOC 100 HDR for the range 1.5 to 25 μm . The use of these two devices implies a discontinuity at 2 μm on the 0.25 to 25 μm spectra. All the samples are considered as opaque, consequently the spectral hemispherical emissivity (ϵ) is assumed as being related to the spectral hemispherical reflectivity (ρ) by the following relation (λ is the wavelength):

$$\epsilon(\lambda) = 1 - \rho(\lambda) \quad (1)$$

Equation 2 shows that the solar absorptivity, α_{sol} , is the ration of the integration of the product of the measured spectral hemispherical emissivity, $\epsilon(\lambda)$, by the spectral solar irradiance, $I_{\text{sol}}(\lambda)$, that ranges in an interval from 0.25 to 2.5 μm (the reference solar spectrum AM1.5 [23] is used), on the total solar irradiance. The total

emissivity, ϵ_{tot} , is obtained by equation 3 and using the measured spectral hemispherical emissivity and the calculated spectral blackbody emittance at 300 K, $E_{bb}(\lambda, 300K)$, according to the Planck's law. The total emissivity is integrated between 0.25 and 25 μm . The discrete versions of the following equations are used.

$$\alpha_{sol} = \frac{\int_{0.25}^{2.5} \epsilon(\lambda) \cdot I_{sol}(\lambda) \cdot d\lambda}{\int_{0.25}^{2.5} I_{sol}(\lambda) \cdot d\lambda} \quad (2)$$

$$\epsilon_{tot} = \frac{\int_{0.25}^{25} \epsilon(\lambda) \cdot E_{bb}(\lambda, 300K) \cdot d\lambda}{\int_{0.25}^{25} E_{bb}(\lambda, 300K) \cdot d\lambda} \quad (3)$$

3 Results and discussions

3.1 Oxidation

Figure 1 shows the evolution of the mass change per unit of area versus the oxidation time up to 48 h at 1373 K for the three materials. All the samples present a mass gain but their behavior is different. Among them, Inconel 625 presents the highest mass gain per unit area, but it lost mass after 36 h due to the spallation of the oxide layer (Fig. 1). Buscail *et al.* studied the oxidation at 1173 and 1373 K of the alloy 625 up to 50 h exposure time and they did not observe the spallation of the oxide [9]. Chyrkin *et al.* observed the spallation of the oxide on 1 mm thick alloy 625 oxidized at 1273 K under air [24]. Spallation occurred during the sample cooling, and continued on the cooled sample. A high residual stress (greater than the ultimate tensile strength of the oxide) is the reason of this spallation. According to Huntz [25], the residual stress depends on the elastic modulus, the Poisson's coefficient and the thicknesses of the substrate and of the oxide layer. The differences in the coefficients of thermal expansion (CTE) and of the temperature also play a huge role in the residual stress. The latter two parameters are probably the main factors leading to the spallation of the oxide as the CTEs of Inconel 625 and of the chromia are respectively around 12 and 9 $\mu m m^{-1} K^{-1}$. The XRD pattern (Fig. 2) shows that powders from the spalled oxide are mainly composed of chromia (ICDD 01-082-1484). NiO (ICDD 01-073-1523) and NbCrO₄ spinel (ICDD 01-074-1941) are present, and an unidentified MeCr₂O₄ spinel (where Me is a metal and could be Ni or Mn in this work) is also identified in lower amounts.

Fig. 1 Mass gain versus time for Inconel 625, FeCrAlloy and Kanthal Super ER at 1373 K in air (at 87 kPa)

Fig. 2 XRD pattern of powders from Inconel 625 spalled oxide (oxidation at 1373 K for 12 h)

FeCrAlloy shows a lower mass gain than Inconel 625, and the oxide layer seems adherent up to 48 h (Fig. 1). XRD patterns show that the substrate was identified as Fe_2CrAl form (ICDD 00-054-0387). Based on the same analysis, the oxide scale on FeCrAlloy is mainly composed of Al_2O_3 (ICDD 01-089-3072) with a small amount of MgAl_2O_4 spinel (ICDD 01-070-6023) (Fig. 3). This spinel was found by Josefsson *et al.* in flowing dry O_2 at lower temperature (< 1173 K) [26] and by Mayer *et al.* at 1473 K [27]. These two studies explain that its presence was due to the diffusion of magnesium impurities from the metallic substrate to the surface of the material. Moreover Josefsson *et al.* supposed that magnesium is diffusing through the grain boundaries of both the substrate and the oxide, and then formed nodules of MgAl_2O_4 [26]. SEM images of the surface do not permit to corroborate this observation (Fig. 4). However the oxide scale seems to cover all the surface with a constant thickness and seems adherent (Fig. 4 and 5). EDS analysis (not shown here) of the surface of the 48 h-oxidized sample confirmed the composition of the oxide (Al_2O_3 and a low amount of MgAl_2O_4). The cross section pictures show that the oxide scale thickness is between 1 and 2 μm (Fig. 5). These values are in agreement with the thickness calculated using the mass gain data.

Fig. 3 XRD patterns of as-received and oxidized FeCrAlloy samples

a) As received

b) Oxidized for 24 h

c) Oxidized for 36 h

d) Oxidized for 48 h

Fig. 4 SEM images (x2000) of the surface of a) as-received, and b) 48 h-oxidized at 1373 K in air FeCrAlloy samples

a) Oxidized for 24 h

b) Oxidized for 36 h

Fig. 5 SEM images (x6000) of the cross section of oxidized FeCrAlloy after 24 h and 36 h at 1373 K in air

The SEM picture of the as-received Kanthal Super ER sample highlights the three phases of the material: $\text{Mo}(\text{Si},\text{Al})_2$, $\text{Mo}_5(\text{Si},\text{Al})_3$ and Al_2O_3 (Fig. 6). The XRD pattern confirms this observation (Fig. 7). The three phases in the raw material is identified as MoSiAl (ICDD 01-074-6555), tetragonal Mo_5Si_3 (ICDD 01-076-1578) and alumina (ICDD 01-089-3072). Alumina is an additive which permits to reinforce the material and to start and/or help the grain-growth [22]. During the 1373 K air exposure, Kanthal Super ER shows the lowest mass gain of the three studied materials (Fig. 1), its oxide layer seems to entirely cover the surface and to be adherent as the surface SEM pictures show. Ingemarsson *et al.* previously showed that the oxide scale is adherent and covers the entire surface on the same material for oxidation temperatures between 1173 and 1873 K and 72 h exposure time. [22]. The XRD pattern does not allow to establish the composition of the oxide due to the presence of alumina in the substrate material (Fig. 7). However the increase with oxidation time of the $\text{Mo}_5(\text{Si},\text{Al})_3$ phase peaks suggests a consumption of silicon and/or aluminum present in the $\text{Mo}(\text{Si},\text{Al})_2$ phase (Fig. 7). The Raman spectra show that the oxide scale is composed of silica and alumina (Fig. 8). The Raman peaks were identified using previous publications on the Raman analyses of silica [28,29] and of alumina [30,31]. The EDS analysis was performed on the 36 h-oxidized sample and showed that the oxide is mainly composed of alumina with a small amount of silicon. The silica was not detected by Ingemarsson *et al.* [22] who determined that the oxide is mainly alumina for 72 h-oxidation at 1173 K based on XRD analyses and EDX maps. Crystallites are formed on the surface and are probably composed of alumina based on the EDS analysis. The size of these crystallite also seems to increase with the oxidation time [Fig. 6]. Furthermore the oxide layer is not well visible on the SEM cross section pictures of the oxidized samples probably due to their small thickness (Fig. 9). The oxide scale seems to be less than 1 μm thick, whereas Ingemarsson *et al.* [22] measured a 2 μm thick oxide scale for a sample oxidized for 72 h at 1173 K. They also showed that the oxide is continuous and adherent and that Mo_5Si_3 phase is present between the core of the material and the oxide. This explains the increase of the Mo_5Si_3 peaks in the XRD pattern.

a) As received

b) Oxidized for 24 h

c) Oxidized for 36 h

d) Oxidized for 48 h

Fig. 6 SEM images (x2000) of the surface of as-received and oxidized at 1373 K in air Kanthal Super ER samples

Fig. 7 XRD patterns of as-received and oxidized Kanthal Super ER samples

Fig. 8 Raman spectra of oxidized Kanthal Super ER samples

a) As received

b) Oxidized for 24 h

c) Oxidized for 36 h

Fig. 9 SEM images (x6000) of the cross section of as-received and oxidized at 1373 K in air Kanthal Super ER samples

3.2 Optical properties

The hemispherical emissivities of as-received and oxidized Inconel 625 were measured and are shown in figure 10.a. The emissivity reaches around 0.85 between 0.25 and 10 μm with oxidation. Consequently the solar absorptivity as well as the total emissivity is strongly increased compared to non-oxidized material. The oxidation of FeCrAlloy and Kanthal Super ER increases the emissivity on almost all the measured wavelength range [Fig. 10.b & .c]. On both materials, oscillations of the spectral emissivity appear with oxidation, due to the semi-transparency of the thin oxide scale that implies interferences of the electromagnetic waves. Berghaus *et al.*

[32] showed a similar behavior for W-Al₂O₃ cermet on copper as well as Li *et al.* [33] for TiO₂ on TA6V. The oxidized Inconel 625 does not show this behavior because of the nature of its oxide (Cr₂O₃) which is opaque. The emissivity of the oxidized samples of FeCrAlloy and Kanthal Super ER seems stable after 24 h oxidation in the range 0.25 and 0.8 μm except the interferences.

The integrated optical properties of the as-received and oxidized materials are depicted as a function of the oxidation time in figure 11.a. An increase of the solar absorptivity and the total emissivity with oxidation duration are observed up to 12 h as it was expected from the emissivity spectra. The solar absorptivity of oxidized Inconel 625 is higher than 0.85, and its total emissivity is also very high (more than 0.60) which could imply high radiative losses. For both FeCrAlloy and Kanthal Super ER, the solar absorptivity and the total emissivity also increase with the oxidation duration, however they tend to be stable after 24 h. Kanthal Super ER shows a good solar absorptivity at around 0.80 which is higher than that of the FeCrAlloy for which the solar absorptivity is around 0.70. On the contrary the total emissivity of FeCrAlloy which is around 0.30 is lower than the one of Kanthal Super ER which is around 0.45. Moreover the solar absorptivity/total emissivity ratio, α/ϵ , is another criteria for solar receiver application. The higher the α/ϵ ratio of the material the better is the efficiency of the solar receiver. Oxidized FeCrAlloy possess a α/ϵ ratio around 2.2 which is less than the α/ϵ ratio of the as-received material (3.5). The α/ϵ ratio of the oxidized Kanthal Super ER (around 1.9) is also lower than that of the raw material. The ratio of both oxidized FeCrAlloy and Kanthal Super ER are much higher than the one of oxidized Inconel 625 (< 1.4). The lower values of absorptivity and emissivity of the FeCrAlloy compared to those of Kanthal Super ER could be due to the difference of the respective mean square surface roughness of the oxidized surfaces (Fig. 12). Indeed a rough surface emits more than a smooth surface, as Del Campo *et al.* [34] and He *et al.* [35] have shown.

a) Inconel 625

b) FeCrAlloy

c) Kanthal Super ER

Fig. 10 Hemispherical emissivity as function of wavelength at 300 K of as-received and oxidized
a) Inconel 625, b) FeCrAlloy, and c) Kanthal Super ER samples

Fig. 11 Evolution with the oxidation time of a) the solar absorptivity, α_{sol} , and total emissivity, ϵ_{tot} , and b) the $\alpha_{sol}/\epsilon_{tot}$ ratio at 300 K

Fig. 12 Evolution of the mean square surface roughness of FeCrAlloy and Kanthal Super ER with the oxidation time

Conclusions

Inconel 625 is not suitable for solar receiver application, because of its poor oxidation resistance at 1373 K in air, which is due to the oxidation kinetics and the oxide spallation. This spallation is due to a combination of factors that implies a residual stress higher than the rupture strength of the oxide. The oxidation at 1373 K of the

FeCrAlloy does not present oxide spallation up to 48 h. The oxide scale seems physically stable, and this material has a low mass gain up to 48 h in the same condition (less than 0.35 mg cm^{-2}). This is due to the formation of alumina which is more protective than chromia. The oxidation kinetics of FeCrAlloy is governed by the diffusion of the oxygen and/or the aluminum through the oxide scale. The diffusion of magnesium towards the surface results in the formation of outer the MgAl_2O_4 spinel. Kanthal Super ER has a lower mass gain than FeCrAlloy ($< 0.30 \text{ mg cm}^{-2}$). The oxidation kinetics of Kanthal Super ER seems to be also governed by the diffusion of the elements through the oxide scale, and the oxide seems physically stable on the material.

A high solar absorptivity and a low total emissivity are desired for the solar receiver. The increase of the spectral emissivity of Inconel 625 as a result of oxidation is due to the formation of chromia. That implies a high solar absorptivity (around 0.86) but also a high total emissivity (around 0.65) which would mean significant thermal radiative losses. The integrated optical properties of oxidized FeCrAlloy increase with the oxidation time which could be due to an increase of the oxide scale thickness and seem to be stable after 24 h. Its solar absorptivity is around 0.72 and its total emissivity is almost 0.32. These values are more suitable for solar receiver application, as the thermal radiative losses are expected to be lower than the ones of Inconel. Kanthal Super ER seems to be the best choice because for the oxidized samples the solar absorptivity is quite high (~ 0.81) and the total emissivity remains low (~ 0.42).

FeCrAlloy has a good oxidation resistance, however the poor creep resistance is its limit for the solar receiver application. Kanthal Super ER also appears to be a promising material for solar receiver applications thanks to its oxidation resistance and its optical properties. The most important problems today are, first, the mechanical and thermal properties that are still not well known, and, second, the welding to the other parts of the solar receiver that is not yet studied. It will be essential in a future work to study the evolution of the thermo-radiative properties at higher temperature of these materials in order to evaluate their thermal efficiency at the working temperatures of the solar receiver (*i.e.* at $T > 1300 \text{ K}$).

References

- [1] Concentrating Solar Power Projects, NREL. (n.d.). <https://www.nrel.gov/csp/solarpaces/index.cfm> (accessed June 22, 2018).
- [2] O. Behar, A. Khellaf, K. Mohammadi, A review of studies on central receiver solar thermal power plants, *Renew. Sustain. Energy Rev.* 23 (2013) 12–39. <https://doi.org/10.1016/j.rser.2013.02.017>.
- [3] L.A. Weinstein, J. Loomis, B. Bhatia, D.M. Bierman, E.N. Wang, G. Chen, Concentrating Solar Power, *Chem. Rev.* 115 (2015) 12797–12838. <https://doi.org/10.1021/acs.chemrev.5b00397>.
- [4] P. Poživil, V. Aga, A. Zagorskiy, A. Steinfeld, A Pressurized Air Receiver for Solar-driven Gas Turbines, *Energy Procedia.* 49 (2014) 498–503. <https://doi.org/10.1016/j.egypro.2014.03.053>.
- [5] R. Buck, S. Giuliano, R. Uhlig, Central tower systems using the Brayton cycle, in: *Adv. Conc. Sol. Therm. Res. Technol.*, Elsevier, 2017: pp. 353–382. <https://doi.org/10.1016/B978-0-08-100516-3.00016-2>.
- [6] C.K. Ho, Advances in central receivers for concentrating solar applications, *Sol. Energy.* 152 (2017) 38–56. <https://doi.org/10.1016/j.solener.2017.03.048>.
- [7] B.A. Pint, R.G. Brese, High-temperature materials, in: *Fundam. Appl. Supercrit. Carbon Dioxide SCO2 Based Power Cycles*, Elsevier, 2017: pp. 67–104. <https://doi.org/10.1016/B978-0-08-100804-1.00004-9>.
- [8] G.A. Greene, C.C. Finfrock, Oxidation of Inconel 718 in Air at High Temperatures, *Oxid. Met.* 55 (2001) 505–521. <https://doi.org/10.1023/A:1010359815550>.
- [9] H. Buscail, R. Rolland, C. Issartel, F. Rabaste, F. Riffard, L. Aranda, M. Vilasi, Effects of water vapour on the oxidation of a nickel-base 625 alloy between 900 and 1,100 °C, *J. Mater. Sci.* 46 (2011) 5903–5915. <https://doi.org/10.1007/s10853-011-5544-2>.
- [10] D. Seo, M. Sayar, K. Ogawa, SiO₂ and MoSi₂ formation on Inconel 625 surface via SiC coating deposited by cold spray, *Surf. Coat. Technol.* 206 (2012) 2851–2858. <https://doi.org/10.1016/j.surfcoat.2011.12.010>.
- [11] D. Kim, C. Jang, W.S. Ryu, Oxidation Characteristics and Oxide Layer Evolution of Alloy 617 and Haynes 230 at 900 °C and 1100 °C, *Oxid. Met.* 71 (2009) 271–293. <https://doi.org/10.1007/s11085-009-9142-5>.
- [12] D. Naumenko, B.A. Pint, W.J. Quadakkers, Current Thoughts on Reactive Element Effects in Alumina-Forming Systems: In Memory of John Stringer, *Oxid. Met.* 86 (2016) 1–43. <https://doi.org/10.1007/s11085-016-9625-0>.
- [13] B.A. Pint, Experimental observations in support of the dynamic-segregation theory to explain the reactive-element effect, *Oxid. Met.* 45 (1996) 1–37. <https://doi.org/10.1007/BF01046818>.
- [14] B. Jönsson, Q. Lu, D. Chandrasekaran, R. Berglund, F. Rave, Oxidation and Creep Limited Lifetime of Kanthal APMT®, a Dispersion Strengthened FeCrAlMo Alloy Designed for Strength and Oxidation Resistance at High Temperatures, *Oxid. Met.* 79 (2013) 29–39. <https://doi.org/10.1007/s11085-012-9324-4>.
- [15] Z. Liu, W. Gao, Y. He, Modeling of Oxidation Kinetics of Y-Doped Fe–Cr–Al Alloys, *Oxid. Met.* 53 (2000) 341–350. <https://doi.org/10.1023/A:1004545421739>.
- [16] C. Badini, F. Laurella, Oxidation of FeCrAl alloy: influence of temperature and atmosphere on scale growth rate and mechanism, *Surf. Coat. Technol.* 135 (2001) 291–298. [https://doi.org/10.1016/S0257-8972\(00\)00989-0](https://doi.org/10.1016/S0257-8972(00)00989-0).
- [17] M. Samadzadeh, C. Oprea, H. Karimi Sharif, T. Troczynski, Comparative studies of the oxidation of MoSi₂ based materials: High-temperature oxidation (1000–1600 °C), *Int. J. Refract. Met. Hard Mater.* 69 (2017) 31–39. <https://doi.org/10.1016/j.ijrmhm.2017.07.015>.
- [18] G.A. Greene, C.C. Finfrock, T.F. Irvine, Total hemispherical emissivity of oxidized Inconel 718 in the temperature range 300–1000°C, *Exp. Therm. Fluid Sci.* 22 (2000) 145–153. [https://doi.org/10.1016/S0894-1777\(00\)00021-2](https://doi.org/10.1016/S0894-1777(00)00021-2).
- [19] M. Balat-Pichelin, J.L. Sans, E. Bêche, V. Flaud, J. Annaloro, Oxidation and emissivity of Inconel 718 alloy as potential space debris during its atmospheric entry, *Mater. Charact.* 127 (2017) 379–390. <https://doi.org/10.1016/j.matchar.2017.02.016>.
- [20] Y.S. Touloukian, D.P. DeWitt, Thermal radiative properties - metallic elements and alloys, IFI/Plenum, 1970.
- [21] S.G. Gopalakrishnan, P. Huczowski, J. Pernpeintner, T. Fend, H. Hattendorf, R. Iskandar, J. Mayer, L. Singheiser, W.J. Quadakkers, Composition modifications and heat treatment procedures for increasing the emissivity of alumina surface scales on FeCrAl alloys, *Mater. High Temp.* 29 (2012) 249–256. <https://doi.org/10.3184/096034012X13343266865035>.
- [22] L. Ingemarsson, K. Hellström, S. Canovic, T. Jonsson, M. Halvarsson, L.-G. Johansson, J.-E. Svensson, Oxidation behavior of a Mo(Si,Al)₂ composite at 900–1600 °C in dry air, *J. Mater. Sci.* 48 (2013) 1511–1523. <https://doi.org/10.1007/s10853-012-6906-0>.
- [23] Reference Solar Spectral Irradiance: Air Mass 1.5, American Society for Testing and Materials (ASTM), (n.d.). <http://rredc.nrel.gov/solar/spectra/am1.5/> (accessed December 17, 2018).

- [24] A. Chyrkin, P. Huczowski, V. Shemet, L. Singheiser, W.J. Quadakkers, Sub-Scale Depletion and Enrichment Processes During High Temperature Oxidation of the Nickel Base Alloy 625 in the Temperature Range 900–1000 °C, *Oxid. Met.* 75 (2011) 143–166. <https://doi.org/10.1007/s11085-010-9225-3>.
- [25] A.M. Huntz, Stresses in NiO, Cr₂O₃ and Al₂O₃ oxide scales, *Mater. Sci. Eng. A.* 201 (1995) 211–228. [https://doi.org/10.1016/0921-5093\(94\)09747-X](https://doi.org/10.1016/0921-5093(94)09747-X).
- [26] H. Josefsson, F. Liu, J.-E. Svensson, M. Halvarsson, L.-G. Johansson, Oxidation of FeCrAl alloys at 500–900°C in dry O₂, *Mater. Corros.* 56 (2005) 801–805. <https://doi.org/10.1002/maco.200503882>.
- [27] J. Mayer, H.J. Penkalla, A. Dimyati, M. Dani, P. Untoro, D. Naumenko, W.J. Quadakkers, Time dependence of Mg-incorporation in alumina scales on FeCrAl alloys studied by FIB-prepared TEM cross sections, *Mater. High Temp.* 20 (2003) 413–419. <https://doi.org/10.1179/mht.2003.048>.
- [28] R.J. Hemley, Pressure dependence of Raman spectra of SiO₂ polymorphs: α-quartz, coesite, and stishovite, in: M.H. Manghnani, Y. Syono (Eds.), *Geophys. Monogr. Ser.*, American Geophysical Union, Washington, D. C., 1987: pp. 347–359. <https://doi.org/10.1029/GM039p0347>.
- [29] A.N. Trukhin, K. Smits, J. Jansons, A. Kuzmin, Luminescence of polymorphous SiO₂, *Radiat. Meas.* 90 (2016) 6–13. <https://doi.org/10.1016/j.radmeas.2015.12.002>.
- [30] A. Misra, H.D. Bist, M.S. Navati, R.K. Thareja, J. Narayan, Thin film of aluminum oxide through pulsed laser deposition: a micro-Raman study, *Mater. Sci. Eng. B.* 79 (2001) 49–54. [https://doi.org/10.1016/S0921-5107\(00\)00554-7](https://doi.org/10.1016/S0921-5107(00)00554-7).
- [31] M. Kadleiková, J. Breza, M. Veselý, Raman spectra of synthetic sapphire, *Microelectron. J.* 32 (2001) 955–958. [https://doi.org/10.1016/S0026-2692\(01\)00087-8](https://doi.org/10.1016/S0026-2692(01)00087-8).
- [32] A. Berghaus, A. Djahanbakhsh, L.K. Thomas, Characterisation of CVD-tungsten–alumina cermets for high-temperature selective absorbers, *Sol. Energy Mater. Sol. Cells.* 54 (1998) 19–26. [https://doi.org/10.1016/S0927-0248\(97\)00219-5](https://doi.org/10.1016/S0927-0248(97)00219-5).
- [33] L. Li, K. Yu, K. Zhang, Y. Liu, Study of Ti–6Al–4V alloy spectral emissivity characteristics during thermal oxidation process, *Int. J. Heat Mass Transf.* 101 (2016) 699–706. <https://doi.org/10.1016/j.ijheatmasstransfer.2016.05.069>.
- [34] L. del Campo, R.B. Pérez-Sáez, L. González-Fernández, X. Esquisabel, I. Fernández, P. González-Martín, M.J. Tello, Emissivity measurements on aeronautical alloys, *J. Alloys Compd.* 489 (2010) 482–487. <https://doi.org/10.1016/j.jallcom.2009.09.091>.
- [35] X. He, Y. Li, L. Wang, Y. Sun, S. Zhang, High emissivity coatings for high temperature application: Progress and prospect, *Thin Solid Films.* 517 (2009) 5120–5129. <https://doi.org/10.1016/j.tsf.2009.03.175>.