

Research Papers

High-temperature corrosion behaviour of stainless steel welds in molten $\text{NaNO}_3\text{-KNO}_3\text{-KCl}$ environment for concentrated solar power

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ABSTRACT

The use of fossil fuels has caused adverse effects, notably carbon emissions and climatic change. Thermal energy storage (TES) systems can be used to store energy and, when integrated with CSP, can help mitigate the intermittency of renewable sources. Higher TES working temperatures correspond to higher efficiencies which may lower costs. Various substances have been proposed as TES media; molten salts (MS) emerge as one of the most attractive options due to their stability at high temperatures. However, they can accelerate corrosion on materials, and therefore, compatibility between materials and media is crucial. Additionally, the impact of MS on welds (or welded components) has received less attention than for parent material. To address this research gap, this study compares the corrosion behaviour of plain and welded SS316L and SS304L in a mixture of $10\text{NaNO}_3\text{-}78\text{KNO}_3\text{-}12\text{KCl}$ mol% at $600\text{ }^\circ\text{C}$ for up to 500 h. The samples were analysed by dimensional metrology (DM), scanning electron microscopy (SEM), and energy-dispersive X-ray spectroscopy (EDS). Dimensional metrology shows a higher metal loss and sound metal loss for SS304L than SS316L. SEM micrographs showed the formation of non-adherent corrosion products on alloys surfaces. The EDS shows a selective dissolution of Fe and Cr, along with Na, K and Cl penetration into the alloy. Comparing the results, the welded areas experienced higher metal loss as compared to plain alloy samples. Another key observation was that the SS304L samples displayed lower overall corrosion resistance than SS316L.

1. Introduction

Amidst a growing global population and increasing energy consumption, countries worldwide strive to adopt clean and affordable energy solutions to mitigate harmful greenhouse gas (GHG) emissions which are the cause of various contemporary problems [1]. These include, rising atmospheric CO_2 levels [2], associated climate changes and shifts in energy demand [3], health issues like cardiopulmonary ailments [4] and, according to the World Meteorological Organization's "State of the Global Climate 2022" report [5], the rise of global mean temperatures by approximately $1.15\text{ }^\circ\text{C}$ in 2022 compared to pre-industrial levels. To help limit global mean temperature rise, the United Nations (UN) have established several goals for a sustainable development (sustainable development goals, SDG) which set new targets for clean and affordable energy [6]. The increasing global energy demand, coupled with the urgency to reduce GHG emissions, fuels the exploration and large-scale installation of various renewable energy sources to ensure demand is met. The leading renewable technologies are solar, wind, biomass, tidal and geothermal energy [7]. Two major

solar technologies are (1) solar photovoltaic (PV), which converts light directly into electricity using the photovoltaic effect, and (2) concentrated solar power (CSP), which uses a system of lenses or mirrors to focus sunlight onto a receiver [8]. However, the intermittent nature of solar based energy generation is a hard challenge to tackle when it comes to deploying these alternatives on a global scale. One possible solution is the use of energy storage as this aids in (i) reducing power fluctuations, (ii) managing peak load demands, (iii) improving system flexibility, (iv) enabling smart grids, (v) reducing energy imports and (vi) facilitating the storage and distribution of electricity produced from variable renewable energy (VRE) sources like solar and wind [9,10].

Even though CSP systems have been in commercial use for many years now, the cost of CSP generation remains relatively high (USD $0.118/\text{kWh}$ in 2022 [11]) when compared to the cost of solar PV generation (USD $0.049/\text{kWh}$ in 2022 [11]). However, the latest advancements have achieved lower costs for TES as compared to chemical batteries, encouraging the deployment of integrated CSP + TES systems [12]. Molten salts (MS) have gained attention as next-generation TES media due to: (i) high specific heat, which makes them excellent heat

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storage and transfer agents, (ii) high thermal conductivity which guarantees effective heat transfer and (iii) high energy density of around 1350–3900 kJ/m³K, as compared to other solid and liquid storage options such as ceramics, concrete and synthetic oils [13]. Molten salts can be classified as nitrate, chloride, carbonate, or fluoride salts. The choice of MS depends on factors such as: operating temperatures, storage tank material, corrosion resistance, availability, environmental impacts, regulatory and safety considerations, and inherent costs [14].

Corrosion of industrial components is an issue of paramount importance when they are exposed to a high-temperature MS environment. Studies [15–20] have aimed to understand the high temperature corrosion mechanism of nickel superalloys in MS mixtures. It has been deduced that Cr exhibits the highest level of reactivity, followed by the other elements found in alloys such as Al, Ni, Fe, Si and Mo [15]. Similarly, Patel et al. [16] observed corrosion damage even though elements such as Cr, Al and Si can form protective oxide layers. This is caused by the dissolution of the oxide layers and selective dealloying of the base material. Hence, the analysis of corrosion products or oxide scales holds substantial significance in understanding the selective attack on elements as well in formulation of corrosion mechanisms. Kruienza [15] compared the corrosiveness of chloride and carbonate salts and stated that it is unlikely for stable, protective oxide scales to form on structural alloys in chloride salt environments in the first place.

For deployment, industrial components require welding together to construct the final solar plant. Since such joints are inevitable during the construction of large structures, the extent of a weld's corrosion resistance is equally significant when considering the overall stability and life of a TES system. Research on MS compatibility with welded regions include that by Ruiz-Cabañas et al. [18], where the performance of welded joints of A516 Gr70 carbon steel was analysed in environments of 1.2 % and 3 % of chloride content, respectively, in solar salts. It was observed that greater corrosion penetration depth was present in the heat affected zone (HAZ) of welded coupon as compared to the base metal. This phenomenon is attributed to the microstructural changes, the phases precipitated and the residual stresses present in the HAZ [18]. Zhu et al. [19] tested the corrosion performance of a welded joint for a Ni-Mo-Cr alloy (i.e., GH3535) in a eutectic mixture of LiF–NaF–KF: 46.5–11.5–42 mol% at temperatures of 550 °C, 700 °C and 850 °C for a period of 400 h. The results suggested that, in the weld joint, the corrosion mechanism is governed by the diffusion of Cr from the metal matrix into the salt. As the temperature increased the Cr-depleted layer becomes thicker due to preferential formation of Cr-oxide due to its more negative Gibbs potential [20]. Although initially protective in nature, the selective formation of Cr-oxide results in more severe corrosion attack, due to its dissolution in molten salts. In a study on the corrosion performance of AISI 316 L welded joint in molten solar salt at 565 °C for 1008 h, Vilchez et al. [21] reported that the corrosion rates were twice as high for the weld bead as compared to base metal in comparable experimental conditions. This is mainly because of the ferrite phase found in the weld microstructure, which prohibited the homogeneous formation of protective FeCrO₄ spinel. The primary corrosion products on the weld area's surface consisted of iron and chromium oxides, with an increased concentration of nickel observed in the substrate beneath the oxide layer [21].

Past [17–20] and ongoing research primarily explores corrosion behaviour of various alloys exposed to CSP-TES operating conditions. In the present study, interest is directed towards addressing the impact of MS corrosion at welded regions. This work aims to improve the understanding of corrosion mechanisms in welded joints and inform component design, which is crucial for the uptake of the technology.

2. Materials and methodology

2.1. Material selection

The alloys chosen for testing were stainless steels SS316L and SS304L

which were machined from seamed tubes of outer diameter 76.2 mm, and their approximate dimensions were 15x15x3mm³. Their elemental composition was determined using EDS techniques on unexposed reference samples, as provided in Table 1. Since the topic of interest is the effect on welds, both plain (P) and seam-welded (W) counterparts were considered. The samples were cleaned in an ultrasonic bath of isopropyl alcohol (IPA) and acetone for a duration of 15 min each, to remove any trace of impurities, and then dried in a laboratory oven to remove any trace of moisture.

Table 2 displays a test matrix which details all the samples considered in the current experiment, along with testing conditions.

The molten salt considered was proposed in a recent study by Sang et al. [22], where a novel ternary chloride mixture with improved working temperatures was developed and evaluated using FactSage software, three-layer back propagation (BP) algorithm and experimental methods. The reason for choosing this salt was not just the novelty of its composition, but also because upcoming CSP plants will benefit from using chloride salts to improve working temperatures and, thus, plant efficiency. The suggested mixture is NaNO₃–KNO₃–KCl in the molar ratio 10:78:12. The mixture was obtained by mixing the following salts NaNO₃ (purity ≥99.5 %), KNO₃ (purity ≥99.0 %) KCl (purity ≥99.0 %). Before mixing in the correct proportions, the individual salts were heated in a laboratory oven for <24 h to remove any traces of moisture and then mixed in the solid state until a homogeneous mixture was obtained. The molten salt's chemical properties are listed in Table 3.

2.2. Experimental setup

The exposure was conducted in a horizontal furnace (Fig. 1) under an inert N₂ atmosphere with a flow rate of 100cm³/min. The tested samples were placed in individual alumina crucibles and fully covered with 5 g of the prepared salt mixture, the MS addition was performed in laboratory atmospheric environment, this could have entrapped trace quantities of oxygen and water vapour in the mixture. The exposure temperature was 600 °C ± 5 °C and the samples are exposed for periods of 315 and 500 h (salt was added for the samples exposed for 500 h after the first 315 h of exposure). The furnace was cooled down after the first 315 h exposure, and once at room temperature, samples were removed from crucibles. The samples were then mounted in low shrinkage epoxy resin filled with ballotini glass bead, without removing the scale/deposit. The samples were then cross-sectioned, ground and polished up to a 1 µm diamond suspension. All cutting, grinding and polishing was performed using oil-based lubricants, to avoid the dissolution of the chemical compounds from the scale. The same process has been followed for the 500 h samples. The analysis techniques used for both quantitative and qualitative analysis in this study includes dimensional metrology (DM), scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDS). The SEM used was a Tescan VEGA 3 equipped with an Oxford Instruments X-Max 20 EDS detector, with Aztec software and a typical sensitivity of 0.2 wt%.

2.2.1. Dimensional metrology

The corrosion damage was recorded as 'metal change' and 'sound metal change' (metal change plus any visible internal damage) versus a cumulative probability of observing that damage. Negative numbers represent the amount of material lost during the experiment. The same standards used for assessing high temperature corrosion and hot corrosion [26–28] have been used to assess the corrosion behaviour of the samples. Use of these statistical methods for analysing corrosion data is becoming more widespread and it has been used to assess and quantify the extent of corrosion [23–25] as well as base to create a model to predict corrosion damage [29,30]. A schematic of the process is illustrated in Fig. 2. Locations for analysis were taken with equal distances between each point around the samples, to avoid the user's biases, in accordance with the standard for hot corrosion evaluation of materials change [26–28].

Table 1

Elemental compositions of the considered alloys, collected on unexposed samples via EDS.

Alloy	Elemental composition (wt%)									
	Cr	Ni	Mo	Mn	Si	Cu	P	S	C	Fe
SS316L	17.2	9.7	2.8	1.1	0.7	0.3	0.1	–	Trace	Bal
SS304L	18.5	8.2	–	0.1	0.6	–	0.1	0.1	Trace	Bal

Table 2

Test matrix for exposed samples.

Alloy	Sample name	Exposure time (h)	Inert gas atmosphere	Temperature (°C)	Salt
SS316L	SS316L no weld 315 h	315	N ₂	600	NaNO ₃ -KNO ₃ -KCl
	SS316L weld 315 h				
	SS316L no weld 500 h	500			
	SS316L weld 500 h				
SS304L	SS304L no weld 315 h	315			
	SS304L weld 315 h				
	SS304L no weld 500 h	500			
	SS304L weld 500 h				

Table 3

Chemical properties of the molten salt mixture [22].

Chemical property	Value
Melting point	206.12 °C
Decomposition temperature	641.73 °C
Latent heat	110.48 J/g
Specific heat capacity	1.5298 J/(g.K) (from 250 to 450 °C)

3. Results

3.1. Dimensional metal change data

Fig. 3 compares the metal change distributions, which are the extent of metal deterioration, and the sound metal change distribution, which are amount of metal regression along with internal damage, for SS316L and SS304L. Since the data is spread across the cumulative probability range of 0 to 100, the median value has been considered when comparing the corrosion resistance of the alloys. For this purpose, the median values (50 % probability) of metal loss and sound metal loss are plotted in Fig. 4. The data confirms that the median metal loss of the welded samples was around twice as severe as that of the plain samples. SS304L no weld 315 h suffered metal loss of 30 μm as compared to 59 μm for SS304 weld 315 h. Similarly, after 500 h, metal losses of 37 and 70 μm were recorded for the plain and welded samples respectively. Further results from the sound metal change data confirms that penetrative damage occurred for all samples, with a more prominent effect on the welded specimens. The sound metal change for SS304L no weld and SS304L weld were 34 and 79 μm respectively. The sound metal loss significantly increased to 60 and 92 μm for the same samples after 500 h, respectively.

Moreover, SS316L no weld 315 h and SS316L weld 315 h recorded metal loss median values of 32 μm and 46 μm respectively, where the metal change in the welded sample is higher than that of the plain sample. However, after 500 h, the median values noted were 33 μm and 48 μm respectively. A look at the sound metal change data shows that plain samples had median penetrative damages in depth of 54 μm and 49 μm after 315 and 500 h respectively. However, for the welded samples, the median penetrative damages were found to reach depths of 61 and 65 μm respectively. Here, the overall picture is that the corrosion resistance of the SS316L weld was much less than SS316L no weld. Additionally, the overall damage suffered is of a lower degree for SS316L than SS304L.

Looking at Fig. 4, it can be seen that the cumulative probability of metal and sound metal change for the welded samples in both alloys,

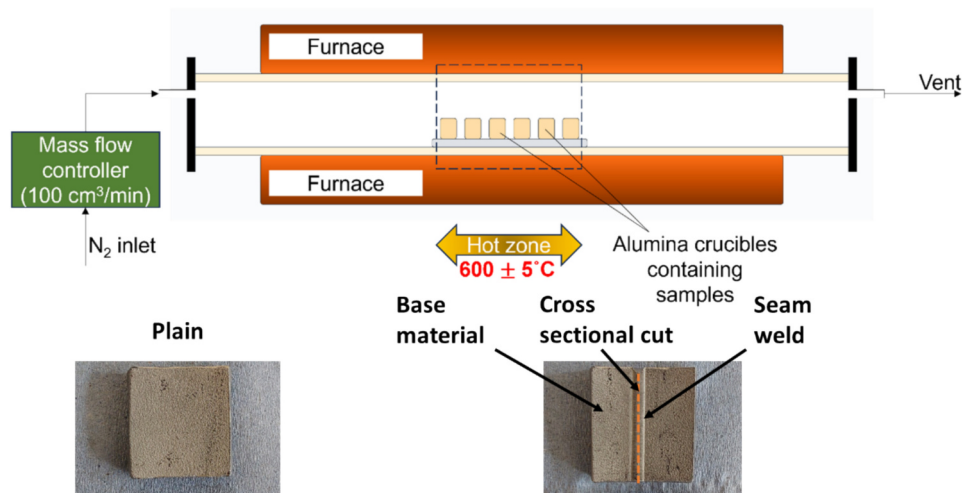


Fig. 1. Schematic diagram of the horizontal furnace setup for the high-temperature corrosion test and an example of a plain sample and a sample containing a seam welds, highlighting the location of the cross-sectional cut (orange dotted line).

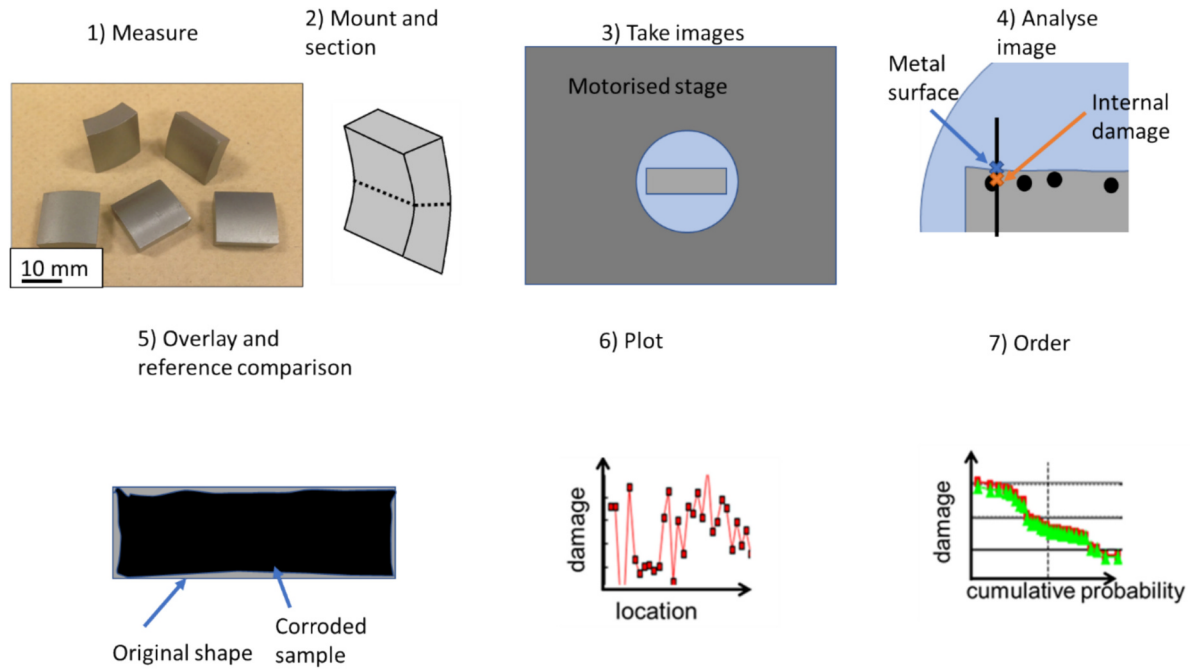


Fig. 2. Schematic representation of the dimensional metrology process. The steps are 1) measurement of samples prior to exposure, 2) mounting the samples in resin, 3) imaging of samples' perimeters, 4) selecting of points at the metal surface and for internal damage, 5) comparison with pre-exposure measurements and reference samples, 6) subtraction of the environmental effect by comparison to a sample without deposit, 7) plot of the resulting change in metal against location and 8) re-order of the data based on cumulative probability [23–25].

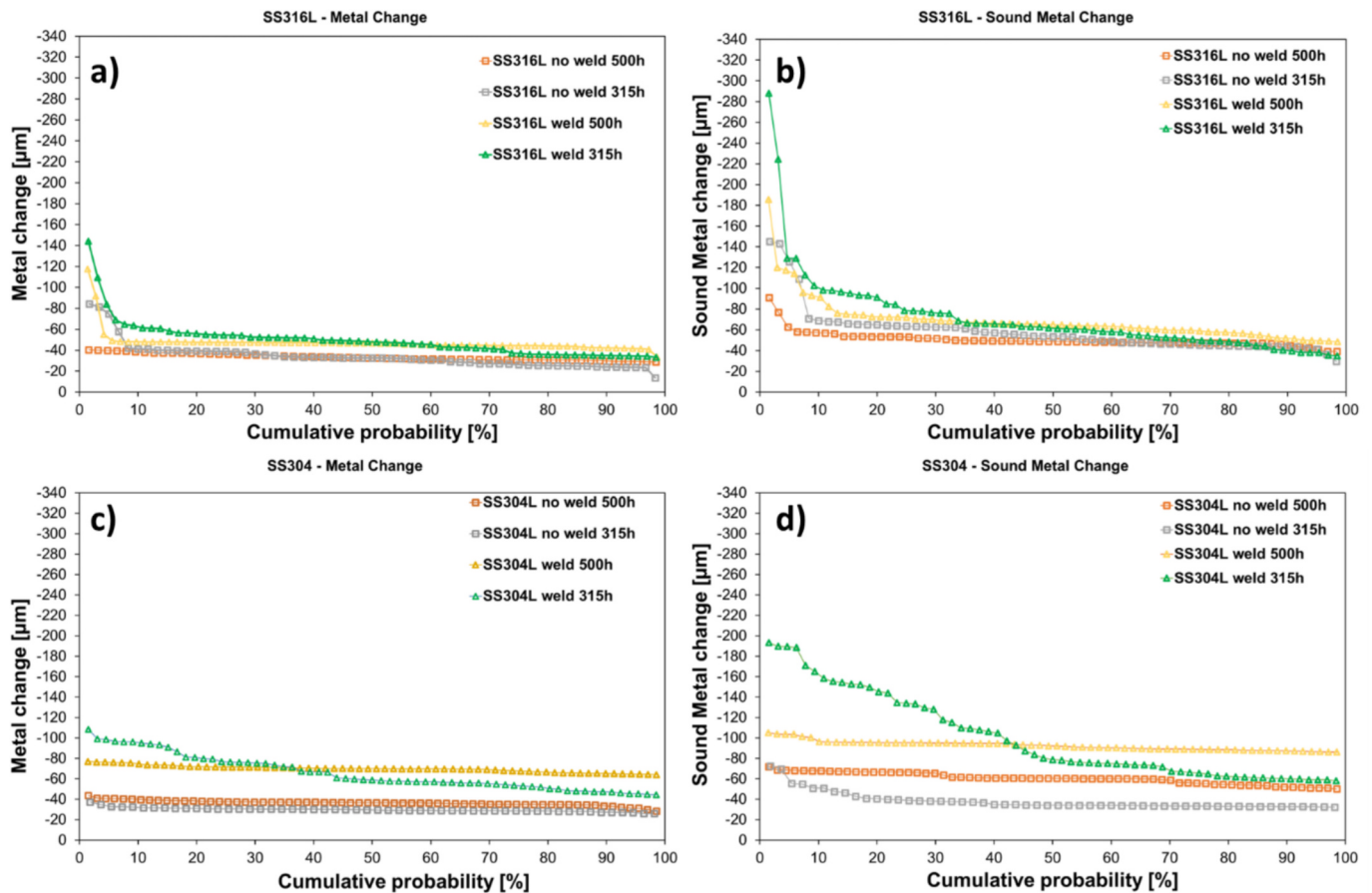


Fig. 3. Graphical representation at the different exposure times of (a) Metal change vs cumulative probability distribution for SS316L welded and base metal, (b) Sound metal change vs cumulative probability distribution for SS316L welded and base metal, (c) Metal change vs cumulative probability distribution for SS304L welded and base metal, and (d) Sound metal change vs cumulative probability distribution for SS304L welded and base metal.

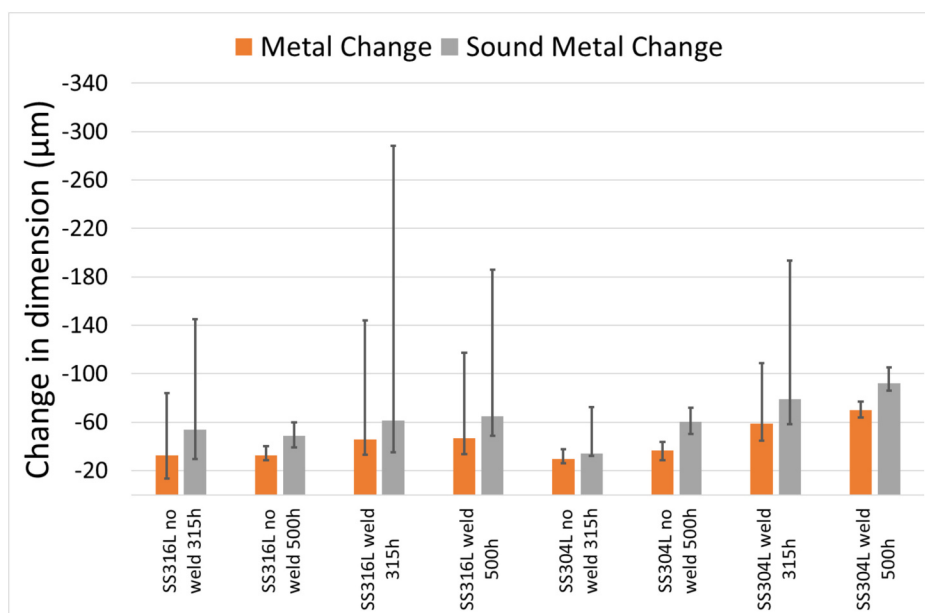


Fig. 4. Median metal change and sound metal change for SS316L and SS304L, welded and unwelded, at different exposure times. The error bar represents the two extremes the cumulative probability curves (namely <3 % and > 97 %).

seems to be more spread. This could be linked with part of the samples experiencing corrosion at an incubation stage still, while other parts undergoing a rapid corrosion degradation (propagation stage). This seems to be particularly evident for samples after 300 h exposure, where the extent of the sound metal change is more than twice the median value. This behaviour is usually linked to pitting corrosion. The reason why the 500 h samples do not seem to show a similar behaviour might be linked to differences between the individual samples.

3.2. SEM/EDS data

Figs. 5 to 8 give the SEM images at the peripheries of the samples considered, along with their corresponding EDS elemental mapping data. The SEM images were taken at position showing interesting features, and the micrographs were not used to quantify the corrosion damage. Elemental analysis of the corrosion products on the stainless-steel coupons using EDS revealed that they consisted of a complex mixture of iron-based oxides that contained several other elements derived from both the alloying elements (Cr, Mn) and constituents of the molten salt (Na, K).

3.2.1. SS3304L

Figs. 5 and 6 show the SEM micrographs and EDS maps after 500 h exposure for the SS304L plain and welded, respectively. In both Figs. 5 and 6 a detachment of the oxide can be seen. This could be an indication that the formed oxides are not providing corrosion protection to the bulk alloys in both cases, with and without weld. In SS304L no weld 500 h (Fig. 5) and SS304L weld 500 h (Fig. 6), the Fe/Cr oxide layer was completely non-adherent from the metal. Also, significant Ni and Mn dissolution from the base material was noticed from the EDS maps. This could mean that, after 500 h exposure, non-protective oxides of base elements such as Ni and Mn are formed due to the dissolution and spallation of protective Fe/Cr oxides. The samples also seem to have presence of Na and K oxides along the inner and outer layer of the Fe-Cr oxides. In Fig. 6, the presence of Cl can be seen between the oxide scale and the base alloy. The presence of Cl could have led to the weakening and spalling of oxide layers [31]. From the picture the presence of a Na/K chloride mixture at the surface of the metal can also be seen for both samples (see Figs. 5 and 6).

3.2.2. SS3316L

Fig. 7 and Fig. 8 show the SEM micrographs and EDS maps for the SS316L plain and welded, respectively. From the figures it can be noted that the general corrosion mechanism remains the same for both, plain and welded samples. After 500 exposure hours, thick oxide layers were observed on P and W samples (Figs. 7 and 8), primarily Fe-oxides, with a thin band of Cr-oxide adjacent to the sample surface. The presence of chloride was observed diffusing into the sample, with some spots of Cl deposits on the metal-oxide interface. The most interesting feature found in SS316L no weld 500 h and SS316L weld 500 h was seemingly internalised pitting corrosion which was not present for SS304L alloy samples. By looking at their EDS maps, the presence of Na, K and O were identified in these corroded pits, which leads to the possibility that it might not be elemental penetration into the alloy, but oxides of Na and K, potentially from the molten salt melt [32]. Also, a distance of around 100 μm was noted between the metal interface and the presence of pits, which leads to the hypothesis that there could be other diffusing pathways for the Na-K penetrative contamination. Apart from the current hypotheses, it is plausible that these are simply artifacts which were present in the sample all along. However, comparison with the reference sample shows that no such artifacts were present pre-exposure. Also, the mentioned pit-like structures were present throughout the periphery of the SS316L no weld 500 h and SS316L weld 500 h samples, and not only on one portion. Hence, more research is needed to understand the complex diffusing pathways of Na and K oxides as reported by Fernández et al. [20]. Some evidence of the presence of Na/K chlorides were found at the surface of the metal, even if they are not as evident as for the SS304 samples.

3.2.3. Analysis of corrosion mechanisms

Fernández et al. [20] reported that the oxide and peroxide ions in a nitrate-containing salt can sustain the formation of Na_2O and KO_2 , depending on the affinity of the Na^+ and K^+ ions. This may decrease the corrosive ability of the salt by hindering the movement of electrons. The governing equations are listed below:



This could explain why the metal loss and sound metal loss results

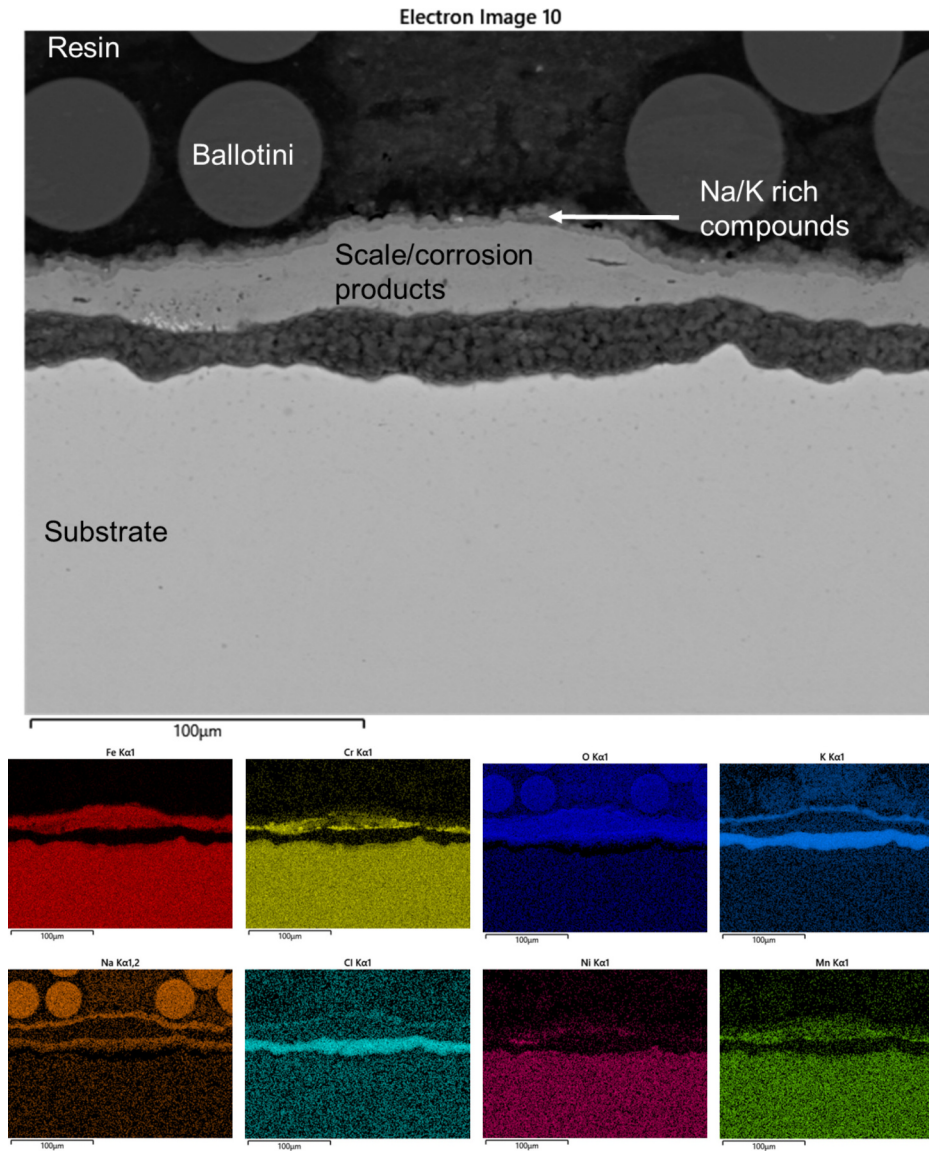


Fig. 5. Backscattered SEM micrograph of plain SS304L after 500 h exposure to the molten salt condition at 600 °C, with EDS elemental maps.

reported a decrease in rate of corrosion during the time from 315 h to 500 h for SS304. However, it remains clear that, despite the possible formation of Na^+ and K^+ oxides along with the inherent Fe-Cr rich oxides, the preliminary mode of corrosion is driven by the presence of chlorine and its attack on the protective oxides causing them to dissolve, exposing more metal for further attack. The corrosion products, primarily comprised of an outermost Fe-oxide layer followed by a thin Cr-oxide layer closer to the surface, could also contain complex oxides such as sodium ferrite (NaFeO_2) which can weaken the adherent effects of the outer iron and chromium oxide layers, as reported by Li et al. [33].

Also, if oxygen was present even in trace amounts at any stage of the experiment, this could lead severe chloride penetrative damage. This is possible in the current experiment as oxygen could be trapped in between the salt mixture pre-exposure. Thus, the chloride melt can react with traces of oxygen and moisture present in the research grade N_2 environment to produce corrosive Cl_2 and HCl which further attacks the metal (Eqns. 3 and 4) [31].



In stainless steels, the main alloying elements Fe, Cr and Ni are oxidised according to the following equations (Eqns. 5–7) [34]:



Additionally, chloride ions from the MS melt react with traces of oxygen present to form chlorine gas. The higher partial pressure of chlorine gas as compared to O_2 causes Cl_2 diffusion into the base material to form metallic chlorides [35]. The formed metallic chlorides diffuse to the scale interface and continue to react with O_2 to form further metal oxides. The higher volatile pressure of CrCl_2 combined with the more negative standard Gibbs free energy for Cr_2O_3 formation leads to preferential generation of Cr_2O_3 and Cl_2 which further attacks the metal. In a process called ‘active oxidation’ [36], the generated chloride would migrate back to the metal/oxide interface due to the presence of cracks and pores and facilitate further corrosion. The governing chemical reactions are given below [34] [37]:



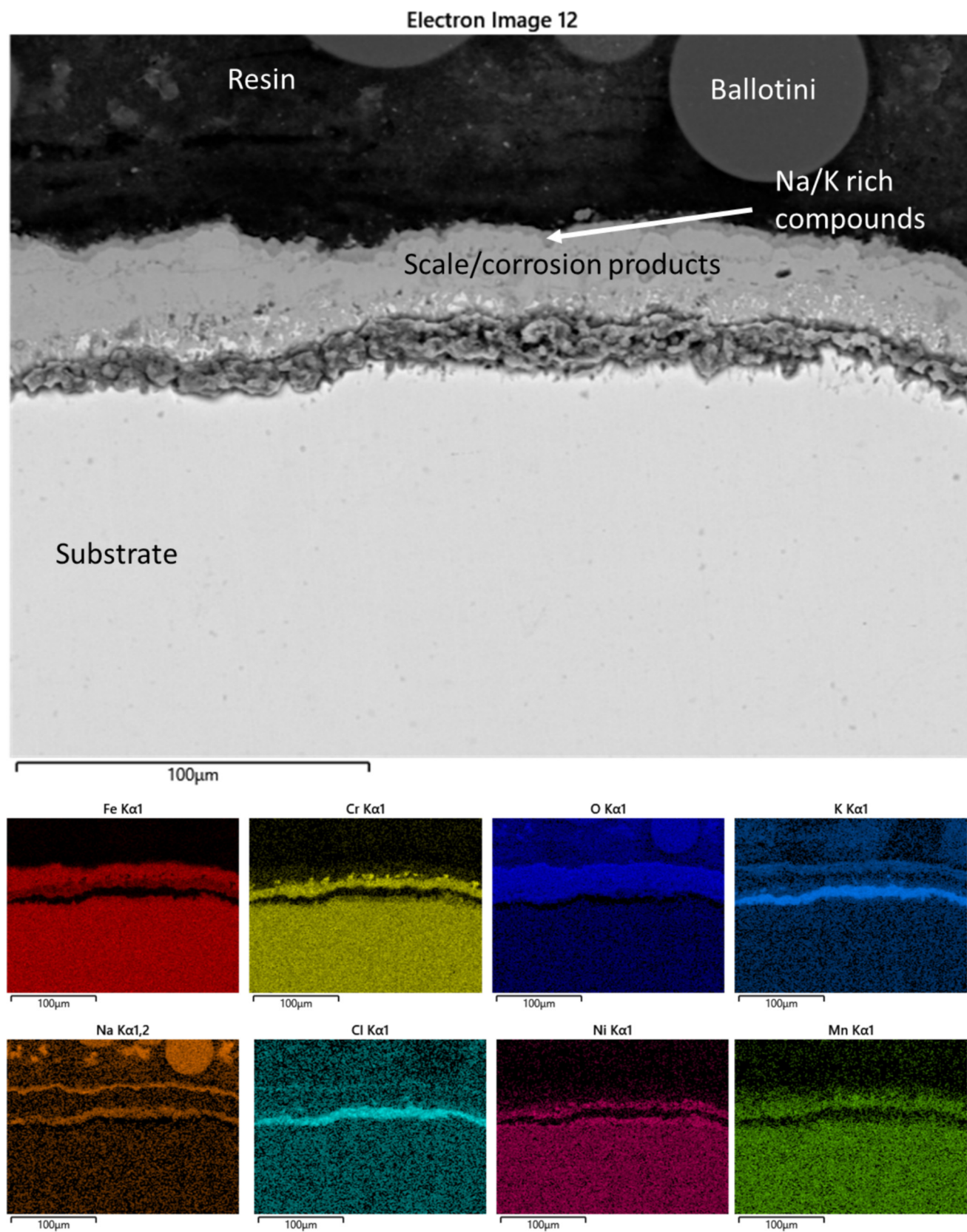


Fig. 6. Backscattered SEM micrograph along the seam weld of SS304L after 500 h exposure to the molten salt condition at 600 °C, with EDS elemental maps.

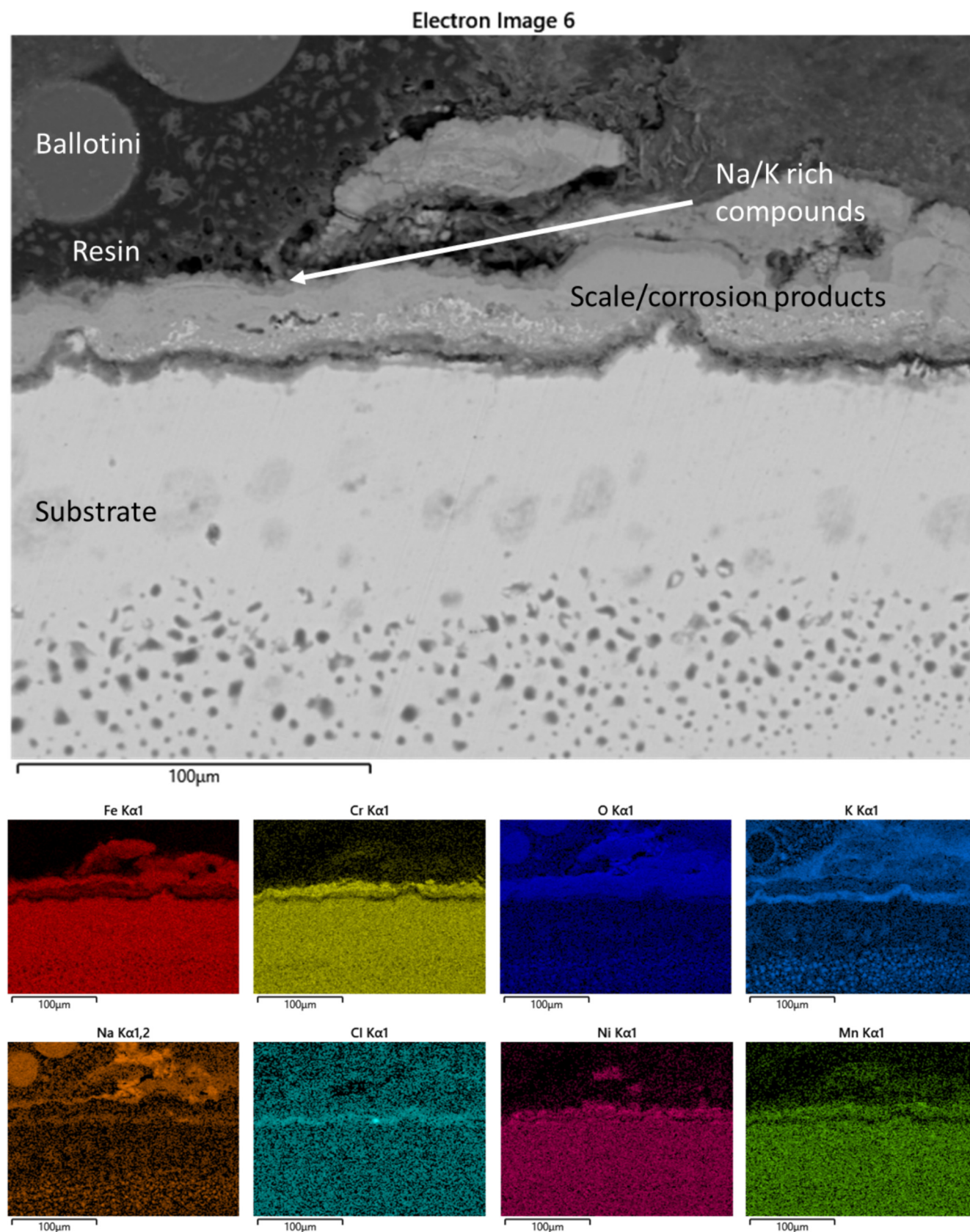


Fig. 7. Backscattered SEM micrograph of plain SS316L after 500 h exposure to the molten salt condition at 600 °C, with EDS elemental maps.

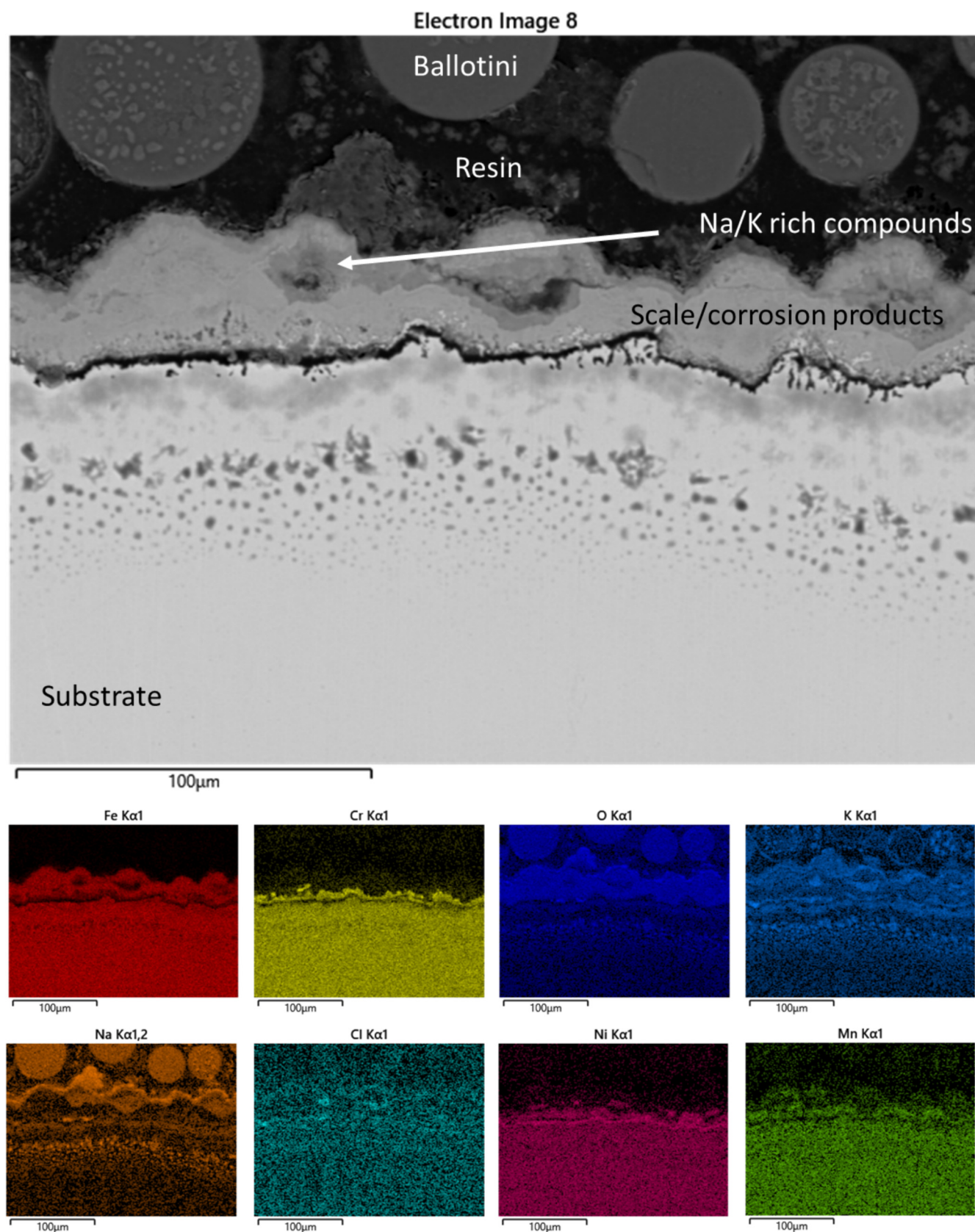


Fig. 8. Backscattered SEM micrograph along the seam weld of SS316L after 500 h exposure to the molten salt condition at 600 °C, with EDS elemental maps.



Hence, the selective formation of CrCl_2 , in turn, fuels the selective dissolution of Cr_2O_3 , and this reaction chain keeps propagating to cause further damage. This would hint to the fact that high Cr steel alloys might be more susceptible to corrosion damage in the environment studied. This study cannot be directly compared with previous ones, as the salt used for this paper differs from what has been found in the literature. It has been shown though, that Cl impurities could increase the corrosion rate of different materials [21,38,39]. A schematic representation is showed in Fig. 9.

The work highlighted the difference in terms of damage between welded and unwelded samples. At this stage no clear evidence of a difference in mechanism has been highlighted through SEM/EDS. The study of more realistic welded materials rather than this model example of weld, might shed more light on the difference. Some of the differences could be due to the fact that FeCr_2O_4 protective oxide might not have formed, as proposed by Vilchez et al. [21].

The data seem to suggest also that the presence of O_2 in the environment could promote a higher corrosion rate, for this reason it would be crucial to avoid O_2 pockets in the CSP systems, in order to decrease the availability of ions to sustain reaction (1), (2) and (3). Furthermore,

more research is needed to understand the role of the Cr in different alloys mixture and the corrosion behaviour of alloys (Fe and Ni based) with different Cr concentration. Understanding the mechanism involved in the formation of CrCl_2 would enable a faster uptake of the CSP technologies and help towards the achievement of the UN SDG 7.

4. Conclusion

In conclusion, the experimental investigation into the hot corrosion behaviour of SS304L and SS316L in a ternary salt mixture of NaNO_3 - KNO_3 -KCl highlights critical insights pivotal for advancements in CSP-TES systems. The findings underscore the importance of material selection of TES components as well as effect of molten salts on the welded areas of these components. The main conclusions formed are as follows:

- Dimensional metal loss and sound metal loss data for median (50 %) cumulative probability reveals that the welded samples suffered higher levels of corrosion as well as penetrative damage as compared to the plain samples. Furthermore, the damage on SS316L samples were lower than the SS304L samples.
- The SEM images provided valuable insight on the nature of the oxide scales formed on the alloys. It is observed that the corrosion products were generally non-protective in nature, as they were non-adherent to the base alloy and showed signs of dissolution, away from the metal/oxide interface. Some signs of pitting corrosion were observed for the SS316L no weld 315 h and SS316L no weld 500 h samples, which could either be evidence of penetrative corrosion.

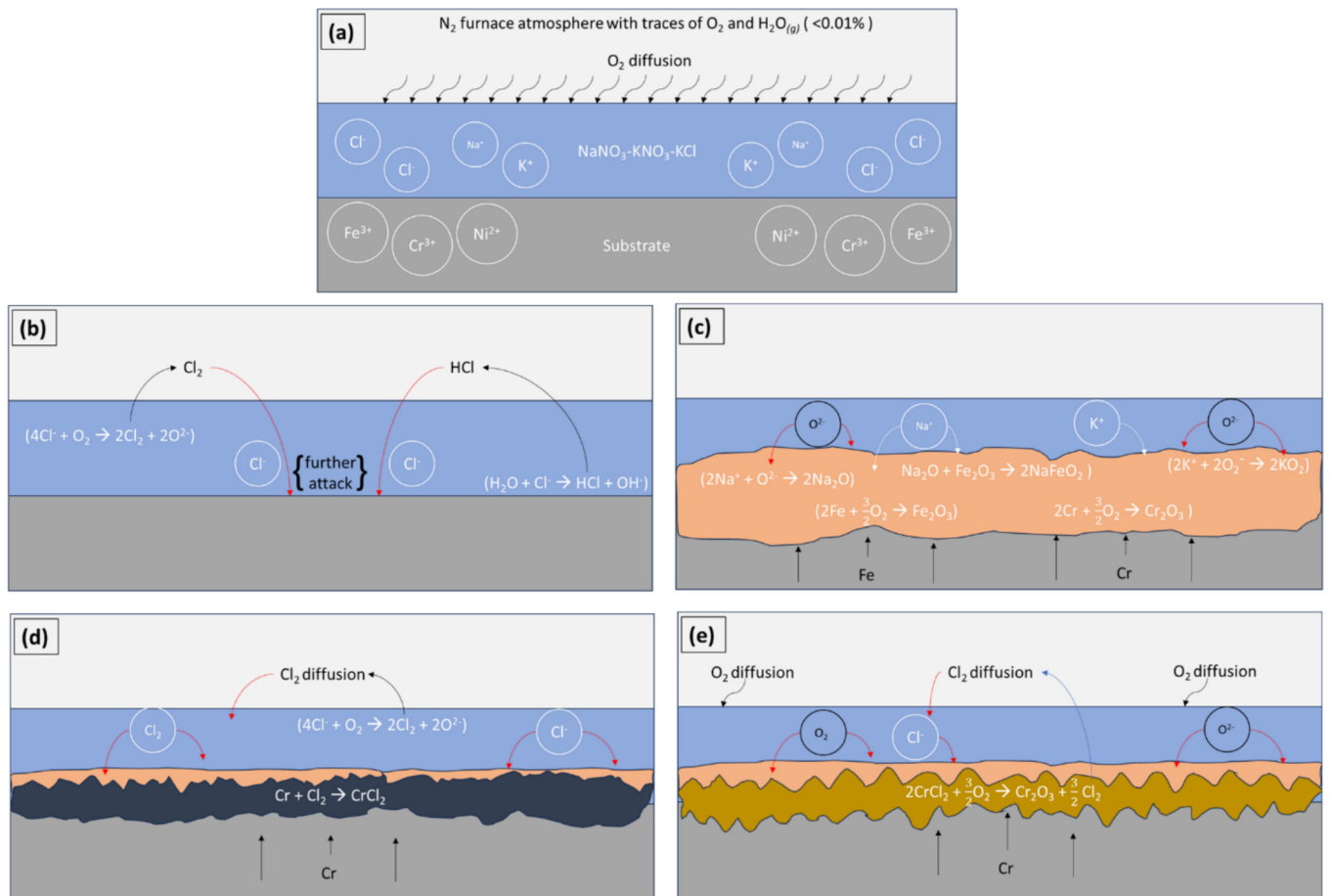


Fig. 9. Schematic representation of the various stages of the proposed corrosion mechanism: (a) start of experiment (b) formation of Cl_2 and HCl which also attacks the alloy, (c) formation of complex mixture of non-protective oxide scales, (d) preferential formation of CrCl_2 , and (e) selective attack of Cr (active oxidation) which leads to further metal loss and Cl_2 formation.

- The EDS elemental maps provided clearer insight on the corrosion products formed. For all samples considered, the oxide scales were primarily characterized by an outer layer rich in Fe-oxide followed by a thinner layer of Cr-oxide near the metal interface. Signs of Ni enrichment were also found at the boundary which confirms the selective dissolution of major elements such as Fe and Cr. Signs of K and Na penetration were also observed for the samples, especially after 500 h of testing.

The welded samples suffered higher metal losses and penetrative metal losses, which encourages more research in the field of comparing the corrosion resistance of welded areas. Upcoming TES systems will attempt to incorporate salt mixtures with higher levels of impurity (for example, chlorides) to cut costs, achieve higher working temperatures, and increase overall efficiency. Hence, critical attention needs to be directed towards evaluating the integrity of TES components with modern salt mixtures to ensure safe, reliable, and efficient working of CSP plants.

CRedit authorship contribution statement

Tony Joy: Writing – original draft, Visualization, Investigation, Formal analysis. **Stefano Mori:** Writing – review & editing, Supervision, Methodology, Formal analysis, Conceptualization. **Joy Sumner:** Writing – review & editing, Supervision, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

References

- [1] T. Wei, J. Wu, S. Chen, Keeping track of greenhouse gas emission reduction progress and targets in 167 cities worldwide, *Frontiers in Sustainable Cities* 3 (Jul. 2021), <https://doi.org/10.3389/frsc.2021.696381>.
- [2] P. Friedlingstein, et al., Global carbon budget 2022, *Earth Syst. Sci. Data* 14 (2022) 61, <https://doi.org/10.5194/essd-14-4811-2022>.
- [3] R.J. Andres, et al., A synthesis of carbon dioxide emissions from fossil-fuel combustion, *Biogeosciences* 9 (5) (2012) 1845–1871, <https://doi.org/10.5194/bg-9-1845-2012>.
- [4] M.B. Rice, G.D. Thurston, J.R. Balmes, K.E. Pinkerton, Climate change a global threat to cardiopulmonary health, *Am. J. Respir. Crit. Care Med.* 189 (5) (Mar. 01, 2014) 512–519, <https://doi.org/10.1164/rccm.201310-1924PP>. American Thoracic Society.
- [5] World Meteorological Organization (WMO), State of the Global Climate 2022, Accessed: Jul. 04, 2023. [Online]. Available: https://library.wmo.int/index.php?lvl=notice_display&id=22265#.ZEef-xBzjC, 2023.
- [6] THE 17 GOALS | Sustainable Development, Accessed: Apr. 08, 2024. [Online]. Available: <https://sdgs.un.org/goals>.
- [7] N.Kh.M.A. Alrikabi, Renewable energy types, *Journal of Clean Energy Technologies* (2014) 61–64, <https://doi.org/10.7763/jocet.2014.v2.92>.
- [8] S. Nabi Mughal, R.K. Jariyal, S. Mughal, Y.R. Sood, A review on solar photovoltaic technology and future trends dissolved gas analysis view project power system view project a review on solar photovoltaic technology and future trends, (NCRACT) International Journal of Scientific Research in Computer Science, Engineering and Information Technology © 2018 IJSCSEIT 1 (4) (2018) 227–235 [Online]. Available: <https://www.researchgate.net/publication/324922616>.
- [9] S. Ould Amrouche, D. Rekioua, T. Rekioua, S. Bacha, Overview of energy storage in renewable energy systems, *Int. J. Hydrog. Energy* 41 (45) (Dec. 2016) 20914–20927, <https://doi.org/10.1016/j.ijhydene.2016.06.243>.
- [10] X. Luo, J. Wang, M. Dooner, J. Clarke, Overview of current development in electrical energy storage technologies and the application potential in power system operation, *Appl. Energy* 137 (2015) 511–536, <https://doi.org/10.1016/j.apenergy.2014.09.081>.
- [11] International Renewable Energy Agency, Renewable Power Generation Costs in 2022 [Online]. Available: www.irena.org, 2023.
- [12] K.M. Kennedy, et al., The role of concentrated solar power with thermal energy storage in least-cost highly reliable electricity systems fully powered by variable renewable energy, *Advances in Applied Energy* 6 (Jun. 2022), <https://doi.org/10.1016/j.adapen.2022.100091>.
- [13] O. Achkari, A. El Fadar, Latest developments on TES and CSP technologies – energy and environmental issues, applications and research trends, *Appl. Therm. Eng.* 167 (Feb. 25, 2020), <https://doi.org/10.1016/j.applthermaleng.2019.114806>. Elsevier Ltd.
- [14] T.C. Ong, et al., Review of the solubility, monitoring, and purification of impurities in molten salts for energy storage in concentrated solar power plants, *Renew. Sust. Energ. Rev.* 131 (Oct. 2020) 110006, <https://doi.org/10.1016/j.rser.2020.110006>.
- [15] L. Ma, C. Zhang, Y. Wu, Y. Lu, Comparative review of different influence factors on molten salt corrosion characteristics for thermal energy storage, *Sol. Energy Mater. Sol. Cells* 235 (Jan. 01, 2022), <https://doi.org/10.1016/j.solmat.2021.111485>. Elsevier B.V.
- [16] N.S. Patel, V. Pavlik, M. Boča, High-temperature corrosion behavior of superalloys in molten salts—a review, *Critical Reviews in Solid State and Materials Sciences* 42 (1) (Jan. 02, 2017) 83–97, <https://doi.org/10.1080/10408436.2016.1243090>. Taylor and Francis Inc.
- [17] A.M. Kruizenga, Corrosion Mechanisms in Chloride and Carbonate Salts, Accessed: Aug. 08, 2023. [Online]. Available: <https://energy.sandia.gov/wp-content/gallery/uploads/SAND2012-7594-Corrosion-Mechanisms-in-Chloride-and-Carbonate-Salts-Kruizenga.pdf>, Sep. 2012.
- [18] F.J. Ruiz-Cabañas, C. Prieto, V. Madina, A.I. Fernández, L.F. Cabeza, Materials selection for thermal energy storage systems in parabolic trough collector solar facilities using high chloride content nitrate salts, *Sol. Energy Mater. Sol. Cells* 163 (Apr. 2017) 134–147, <https://doi.org/10.1016/j.solmat.2017.01.028>.
- [19] Y. Zhu, J. Hou, G. Yu, J. Qiu, S. Chen, X. Zhou, Effects of exposing temperature on corrosion performance of weld joint of a Ni–Mo–Cr alloy, *J. Fluor. Chem.* 182 (Feb. 2016) 69–75, <https://doi.org/10.1016/j.jfluchem.2015.12.005>.
- [20] A.G. Fernández, M.I. Lasanta, F.J. Pérez, Molten salt corrosion of stainless steels and low-Cr steel in CSP plants, *Oxid. Met.* 78 (5–6) (Dec. 2012) 329–348, <https://doi.org/10.1007/s11085-012-9310-X/METRICS>.
- [21] F. Vilchez, F. Pineda, M. Walczak, J. Ramos-Grez, The effect of laser surface melting of stainless steel grade AISI 316L welded joint on its corrosion performance in molten solar salt, *Sol. Energy Mater. Sol. Cells* 213 (Aug. 2020), <https://doi.org/10.1016/j.solmat.2020.110576>.
- [22] L. Sang, X. Lv, Y. Wu, NaNO₃-KNO₃-KCl/K₂CO₃ with the elevated working temperature for CSP application: phase diagram calculation and machine learning, *Sol. Energy* 252 (Mar. 2023) 322–329, <https://doi.org/10.1016/j.solener.2023.02.009>.
- [23] S. Mori, A. Pidcock, J. Sumner, N. J. Simms, and J. E. Oakey, Fireside corrosion of heat exchanger materials for advanced solid fuel fired power plants, *Oxid. Met.*
- [24] S. Mori, J. Sumner, J. Bouvet, N.J. Simms, Fireside and steamside performance in biomass power plant, *Mater. High Temp.* 39 (2) (Mar. 2022) 106–121, <https://doi.org/10.1080/09603409.2021.2019657>.
- [25] S. Mori, T. Sanusi, N. Simms, J. Sumner, Fireside corrosion and deposition on heat exchangers in biomass combustion systems, *Mater. High Temp.* 40 (1) (Jan. 2023) 36–47, <https://doi.org/10.1080/09603409.2022.2138007>.
- [26] D.B. Meadowcroft, et al., A code of practice for discontinuous corrosion testing in high temperature gaseous atmospheres, *Mater. Sci. Forum* 251–254 (1997) 973–978, <https://doi.org/10.4028/www.scientific.net/MSF.251-254.973>.
- [27] ISO - ISO 26146:2012 - Corrosion of metals and alloys — Method for Metallographic Examination of Samples After Exposure to High-temperature Corrosive Environments, Accessed: Oct. 11, 2021. [Online]. Available: <https://www.iso.org/standard/54021.html>.
- [28] H.J. Grabke, *Guidelines for Methods of Testing and Research in High Temperature Corrosion* EFC 14, London, 1995.
- [29] J. Sumner, A. Encinas-Oropesa, N.J. Simms, et al., Type II hot corrosion: kinetics studies of CMSX-4, *Oxid. Met.* 80 (2013) 553–563, <https://doi.org/10.1007/s11085-013-9395-x>.
- [30] J. Sumner, A. Potter, N.J. Simms, J.E. Oakey, Modeling gas turbine materials' hot corrosion degradation in combustion environments from H₂-rich syngas, *Mater. Corros.* 68 (2) (2017) 205–214, <https://doi.org/10.1002/maco.201508779>.
- [31] E. Hamdy, A. Pochi, C. Geers, Direct and Indirect Contact of an Austenitic High-temperature Alloy to Eutectic Chloride Melts with Possible Consequences for Inhibitor Strategies, 2023, <https://doi.org/10.1016/j.engfailanal.2023.107332>.
- [32] S. Yasir, J.L. Endrino, E. Guillén, et al., Suppression of molten salt corrosion by plasma sprayed Ni₃Al coatings, *Emergent Mater.* 4 (2021) 1583–1593, <https://doi.org/10.1007/s42247-021-00334-yA.G>.
- [33] H. Li, X. Yang, X. Yin, X. Wang, J. Tang, J. Gong, Effect of chloride impurity on corrosion kinetics of stainless steels in molten solar salt for CSP application: experiments and modeling, *Oxid. Met.* 95 (3–4) (Apr. 2021) 311–332, <https://doi.org/10.1007/s11085-021-10025-y>.
- [34] M. Wang, S. Zeng, H. Zhang, M. Zhu, C. Lei, B. Li, Corrosion behaviors of 316 stainless steel and Inconel 625 alloy in chloride molten salts for solar energy storage, *High Temp. Mater. Processes* 39 (1) (Jan. 2020) 340–350, <https://doi.org/10.1515/htmp-2020-0077>.

- [35] A. Ibrahim, H. Peng, A. Riaz, M. Abdul Basit, U. Rashid, A. Basit, Molten salts in the light of corrosion mitigation strategies and embedded with nanoparticles to enhance the thermophysical properties for CSP plants, *Sol. Energy Mater. Sol. Cells* 219 (Jan. 2021) 110768, <https://doi.org/10.1016/J.SOLMAT.2020.110768>.
- [36] H. Li, X. Wang, X. Yin, X. Yang, J. Tang, J. Gong, Corrosion and electrochemical investigations for stainless steels in molten solar salt: the influence of chloride impurity, *J Energy Storage* 39 (Jul. 2021), <https://doi.org/10.1016/j.est.2021.102675>.
- [37] S. Bell, T. Steinberg, G. Will, Corrosion mechanisms in molten salt thermal energy storage for concentrating solar power, *Renew. Sust. Energ. Rev.* 114 (Oct. 01, 2019), <https://doi.org/10.1016/j.rser.2019.109328>. Elsevier Ltd.
- [38] K. Federsel, J. Wortmann, M. Ladenberger, High-temperature and corrosion behavior of nitrate nitrite molten salt mixtures regarding their application in concentrating solar power plants, *Energy Procedia* 69 (2015) 618–625. ISSN 1876-6102,, <https://doi.org/10.1016/j.egypro.2015.03.071>.
- [39] M. Walczak, F. Pineda, Á.G. Fernández, C. Mata-Torres, R.A. Escobar, Materials corrosion for thermal energy storage systems in concentrated solar power plants, *Renew. Sust. Energ. Rev.* 86 (2018) 22–44. ISSN 1364-0321,, <https://doi.org/10.1016/j.rser.2018.01.010>.



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