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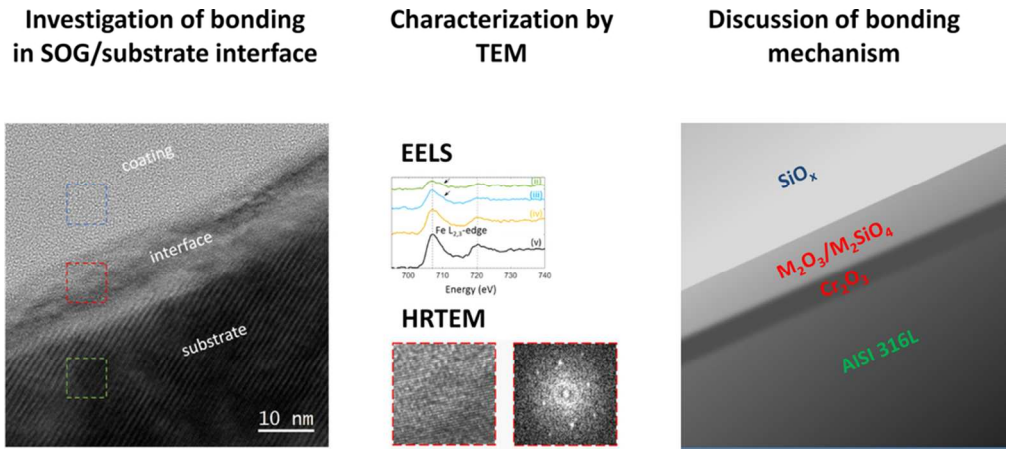

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Probing the chemistry of adhesion between a 316L substrate and spin-on-glass coating

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Abstract

Hydrogen silsesquioxane ($[HSiO_{3/2}]_n$) based "spin-on-glass" has been deposited on 316L substrate and cured in Ar/H_2 gas atmosphere at 600 ºC to form a continuous surface coating with sub-micrometer thickness. The coating functionality depends primarily on the adhesion to the substrate, which is largely affected by the chemical interaction at the interface between the coating and the substrate. We have investigated this interface by transmission electron microscopy and electron energy loss spectroscopy. The analysis identified a 5-10 nm thick interaction zone containing signals from O, Si, Cr and Fe. Analysis of the energy loss near edge structure of the present elements identified predominantly signal from $[SiO_4]^{4-}$ units together with Fe^{2+}, Cr^{2+} and traces of Cr^{3+}. High-resolution transmission electron microscopy images of the interface region confirm a crystalline Fe_2SiO_4 interfacial region. In agreement with computational thermodynamics, it is proposed that the spin-on-glass forms a chemically bonded silicate-rich interaction zone with the substrate. It was further suggested that this zone is composed of a corundum-type oxide at the substrate surface, followed by an olivine-

structure intermediate phase and a spinel-type oxide in the outer regions of the interfacial zone.

1 Introduction

Due to their inherent resistance towards galvanic corrosion combined with good formability, austenitic stainless steels belong to the most widely used engineering materials. Apart from the chemical composition and the mechanical/thermal history, the functionality of the materials is greatly determined by the surface finish, and hence their surface modification plays a major role in the development of improved stainless steel engineering components. Over the recent years, intense research effort has been directed into the surface modification by SiO_x-based micrometer/sub-micrometer thick coatings to improve the wear resistance[1,2], biocompatibility[3,4], bio fouling characteristics and cleanability[5,6], surface morphology[7–10] and corrosion resistance in saline[11–13], acid[11,14,15] or high temperature[16] environments of stainless steel components at a minimal impact on the component geometry. Apart from the traditional deposition processes, such as chemical vapor deposition[17], physical vapor deposition[18], sol-gel processing[19] or liquid phase deposition[20], the deposition from hydrogen silsesquioxane (HSQ), $[HSiO_{3/2}]_n$, spin-on-glass (SOG) has shown excellent results for the processing of high quality SiO_x-like thin films[21,22]. In addition to the deposition of near stoichiometric silica films, SOG-technology offers the possibility to deposit fully inorganic films with various degrees hydrogenation as intermediate reaction products, resulting in a broad range of film properties[21–23]. While the material was mainly developed for microelectronics applications[23,24] or as electron beam resist[25], it has recently emerged into the surface finishing industry and shown an outstanding performance as coating material for metallic substrates such as aluminum or tool steel[7–10].

Recently, we have shown the applicability of SOG as material for sub-micrometer thick coatings on stainless steel substrates[26–28]. Our studies have proven the concept of precursor deposition by an industrially applicable dip-coating process and the subsequent coating curing in both oxidizing[27,28] and non-oxidizing[26] atmosphere, showing that both processes may yield well adherent coatings with 200-400 nm thickness on substrates with 2B finish[29]; however, we have also demonstrated that the coating efficiently levels the substrate surface, and thus fills substrate defects (e.g. surface voids), which may consequently lead to a local increase in coating thickness exceeding 1400 nm[26]. Further, we have shown that oxidative curing induces thermal oxidation of the substrate[27], leading to adhesive failure of the coating and ultimately to functional component failure[28]. We have reported that the formation of a thick, detrimental interface was driven by an abundance of oxygen in the curing atmosphere[27], and that the formation of a thick interfacial zone can be suppressed by a removal of oxygen from the curing atmosphere, i.e. by curing in a non-oxidizing atmosphere such as Formiergas[26]. However, the methods applied in the previous work were inadequate to clearly resolve the interface between the coating and the substrate and, hence, the interfacial chemistry, morphology and the bonding mechanism between coating and substrate are unclear.

In agreement with other studies[11,13,30–35], our previous findings[27,28] emphasize the significance of the coating/substrate interface for both the adhesion and the performance of glass coatings on stainless steel. However, to the author's knowledge, previous studies have generally focused on the formation of thick interface oxides[31–33], traditional enameling technology of complex industrial porcelains[30] or on vapor deposition techniques[34,35], which may lead to significantly different bonding mechanisms. Consequently, the interface formation of well adherent, non-oxidatively cured HSQ-based coatings cannot be adequately deduced based on previous literature. Hence, the present study aims at a detailed characterization of the interfacial chemistry of non-oxidatively cured SOG on type 316L substrate by Transmission

Electron Microscopy (TEM). The interface was characterized by electron energy loss spectroscopy in scanning-TEM together with and high resolution TEM and the analytical results are discussed based on the thermodynamical oxide/metal phase equilibrium at the interface. This analysis provides novel insights into the metal-glass bonding mechanism of silica-like coatings on stainless steel substrate and, in conclusion, the adhesive performance of the coatings.

2 Experimental section

To analyze the bonding mechanism between a stainless steel substrate and a SOG coating, AISI 316L substrates (composition in Table I) with no. 2B surface finish were coated with HSQ-based SOG by the method previously described in Lampert *et al.*[26]: The test coupons were dip coated in commercial HSQ-solution (Dow Corning FOx 25) and subjected to a two stage heat treatment, the first step being a soft bake at 160 ºC in air and the second a polymerization at 600 ºC under flow of 0.5 l/min Ar/H_2 gas mixture (10 vol.% H_2) for 2h. The temperature of the polymerization stage was elevated with respect to our previous work[26] in order to decrease the susceptibility of the coating material to ionizing irradiation [36] during ion beam milling and the TEM investigation.

Lamellae for TEM investigations were prepared by focused ion beam (FIB) milling in a FEI Helios NanoLab 600 dual beam scanning electron microscope (SEM). The specimens were first sputter coated with 20-30 nm of Au to avoid surface charging during the FIB preparation, followed by in-situ deposition of a Pt layer prior to milling to protect the sample from irradiation damage. FIB-milling was carried out at 30 kV ion beam accelerating voltage, followed by final polishing at 2 kV ion beam accelerating voltage and 0.44 nA ion beam current. The lamellae were additionally polished in a Fischione NanoMill precision Ar-ion mill (500 V accelerating voltage and 100 pA beam current) to remove the residual FIB

damage. The TEM examination of the samples was performed in a FEI Titan 80-300kV instrument fitted with a FEG electron source, a monochromator and a GIF Tridiem electron energy loss spectroscopy (EELS) spectrometer. Scanning-TEM (STEM) -EELS measurements were carried out at 120 kV accelerating voltage. In STEM, spatial resolutions of 5 Å and 1.5 Å, respectively with and without the monochromator excited, were obtained. The EELS measurements were acquired with the monochromator excited and had an energy resolution of 0.15 eV. High-resolution TEM (HRTEM) imaging was carried out at 300 kV and with the point to point resolution of 1.4 Å. Thermodynamic phase equilibrium calculations were performed in Thermo-Calc version 2017a[37] using version 7.0 of the Thermo-Calc Software steel database TCFE. The elements Fe, Cr, Mn, Ni, Si and O were considered in the calculations.

3 Results and Discussion

A high-angle annular dark-field (HAADF) STEM image of the coating – substrate cross-section is shown in Figure 1(a). Image intensity in HAADF STEM is primarily related to the atomic number (Z-contrast) of the material, indicating an interfacial region distinct from the coating and the substrate (labelled "interface"). This is similar to our previous investigation of an oxidatively cured coating[27], where an interfacial reaction zone was detected. Here, a much thinner interfacial zone of 5 – 10 nm is detected, compared to in the oxidatively cured coating. EELS line scans spanning energy ranges 400 – 1000 eV (covering the O K-edge and Cr, Mn, Fe and Ni $L_{2,3}$-edges) and 90 – 150 eV (containing the Si $L_{2,3}$-edge) were acquired from the coating/substrate interface, in order to probe the chemistry of this interfacial zone. The Si $L_{2,3}$-edge had to be recorded separately, as our experimental setup limits the spectral energy range to 600 eV at most, and thus we were unable to record all edges of interest together in the same spectrum. The relative composition profile of O, Cr and Fe calculated from the EEL spectra along with the HAADF intensity profile and the intensity of the Si signal along a line across

the interface are plotted in Figure 1(b). Approximate boundaries for the substrate and the coating, determined from the changes in the HAADF image intensity profile along the recorded line scans, are marked in the graphs. We were unable to analyze the composition profile of Ni, due to the pronounced overlap between the Ni $L_{2,3}$-edge and the Fe L_1-edge. The detection of the Mn $L_{2,3}$-edge was also hindered due to its low concentration and low signal level in the measurements. The measurements were repeated across different regions of the sample and were found to be reproducible. As evident in the graphs in Figure 1(b) the constituent elements have relatively unchanged concentrations in the substrate and the coating. An interfacial zone of approximately 6 nm, containing all four elements Fe, Cr, O and Si is detected. The concentrations of Fe and Cr in the interface decrease from the substrate towards the coating and those of O and Si increase.

The energy-loss near-edge fine-structure (ELNES) in EELS is a powerful tool in probing the local chemistry of a sample, containing information such as chemical bonding, oxidation state, crystal structure and coordination[38]. EEL spectra recorded at different points along the interface are plotted in Figure 2(a) (O, Cr, Fe) and Figure 2(b) (Si). Here we analyze the ELNES of the spectra in different regions:

Coating. The signal acquired in the coating contains the Si L- and the O K-edges. The ELNES in both the Si $L_{2,3}$- and O K-edges in this region (spectra at position (i)) resemble closely those for amorphous SiO_2 with SiO_4 tetrahedral networks[39–41]: the Si $L_{2,3}$-edge contains three main peaks at ~ 106 eV, ~ 108 eV and ~ 115 eV. The first peak corresponds to 2p to unoccupied s-type states in Si and its onset has been shown to vary from ~ 100 eV for Si^0 to ~ 103 eV for Si^{2+} to ~ 105 eV for Si^{4+} [42]. The peaks at 108 eV and 115 eV arise from 2p to dominantly d-type states, and are influenced by the Si – O tetrahedral coordination in silica[39,40]. The O K-edge in the coating features a main peak at ~ 537 eV and a broad peak at ~ 560 eV.

Interface. The spectra acquired in the interface contains signals from Si, O, Cr and Fe. Little change is observed in the fine structure of Si $L_{2,3}$-edge at position (ii) in the interface relative to the coating. This indicates the continued dominant presence of $[SiO_4]^{4-}$ units in the interface. The splitting in the initial peak at 106 eV, due to spin-orbit coupling of 2p electrons in Si, can be clearly resolved here[41,43]. A pre-peak at ~ 103 eV appears in the spectra at positions (iii) and (iv). The reduced onset energy of the Si $L_{2,3}$ edge signifies a lower oxidation number of Si at these positions, which may be related to the presence of Fe and Cr in the interface, *e.g.* due to the formation of olivine (Me_2SiO_4)-structure phases such as Fe_2SiO_4[39] or Cr-bearing Si sub-oxides[40]. The O K-edges from positions (ii) and (iii) have overall similar profiles to that acquired in the coating. The first peak at ~ 537 eV arises mainly from scattering of excited electrons (from 1s state in O) by second nearest O neighbors and beyond[44] and has been shown to have little dependence on *e.g.* the Si – O – Si bond angle[45,46]. The peak at ~ 560 eV has been shown to shift to lower energies with increasing Si – O bond length (*i.e.* reduced ionic character)[44]. Such a shift is observed in the O K-edge at position (ii) and (iii). Additionally, the peak at ~ 537 eV in the spectra acquired at positions (ii), (iii) and (iv) contains a shoulder on the right hand side, indicating a larger crystal field effect[47] compared to position (i). This could be the result of distortion or change in the structure of the interface relative to the coating. A decrease in the onset energy of the O K-edge and a hint of a pre-peak can be seen in the spectra at positions (iii) and (iv). A pre-peak is typically present in the ELNES of the O K-edge of transition metal oxides[48,49] and a similar decrease in onset energy of the O K-edge can be observed for silicates such as Fe_2SiO_4 (fayalite)[50]. The $L_{2,3}$ edges of transition metals reveal valuable information regarding their oxidation state, crystal structure and chemical environment. For example, the position of the L_2 and L_3 peaks are shown to be sensitive to their oxidation and shift typically to higher energies with increasing oxidation state[49,51–54]. The intensity ratio of L_3/L_2 edges in transition metals is another important parameter related to the d-orbital occupancy (and subsequently

the oxidation state). Each of the L_2 and L_3 peaks can also contain fine details, stemming from crystal field effects, which provide further clues to the chemical state of the transition metal[49,51,54]. The peak maxima of the Fe L_3 and L_2 here are positioned respectively at ~ 707 eV and ~ 720 eV, without showing any noticeable change across the interface (see spectra (ii) – (iv)). The average integrated intensity of L_3/L_2 edges of Fe in the interface region determined according to the method described by van Aken *et al.*[47] is 3.5 (L_3/L_2 ratio in the substrate is ~ 2.8). Both the peak maxima energies and the L_3/L_2 ratio in the interface region correspond well to those for Fe^{2+} [47,49,51,55]. The fine structure present on the Fe $L_{2,3}$ edge across the interface is also consistent with this observation: A splitting in the L_3 edge (marked with arrows in spectra (ii) and (iii) of Fe $L_{2,3}$ edges in Figure 2(a)) can be resolved, characterized by a small bump at ~ 710 eV after the main peak[47,49,51]. We thus conclude that the Fe present in the interface region is predominantly in Fe^{2+} state. In the case of Cr, small shifts in the L_3 peak maxima at different points across the interface are detected. The measured L_3 and L_2 peak maxima at position (iii) of ~ 576 eV and ~ 585 eV correspond closely to Cr^{2+} [52,54]. Although the fine structure on the Cr L_3 edge cannot be clearly resolved in our measurements, its overall profile at position (iii) also suggests the presence of Cr^{2+} [52,54]. In comparison, the Cr L_3 peaks at positions (ii) and (iv) have their maxima at slightly higher energies (approximately 1.0 eV and 0.6 eV shifts at positions (ii) and (iv), respectively). Their overall shapes also varies compared to the Cr $L_{2,3}$ edge at position (iii): this is in particular clear at position (ii), where Cr L_3 has a longer tail to the left of its main peak, suggesting that Cr^{3+} may also be present[52,54].

Substrate. The spectra collected from the substrate contain signals from Fe and Cr in metallic form.

A reasonable hypothesis based on the results of our ELNES analysis of the interface is that it is composed of Fe_2SiO_4, Cr_2SiO_4 and small amounts of Cr^{3+}-rich oxides such as Cr_2O_3 or

Cr^{3+}-bearing spinel, which have previously been reported as high temperature oxides of CrNi steels[56]. High-resolution TEM (HRTEM) images of the structure reveals that the interface is crystalline (see also Figure S1 in the supporting information (SI)). A HRTEM image of the substrate – coating structure with fast Fourier transform (FFT) patterns corresponding to regions within each of the substrate, interface and the coating are depicted in Figure 3. The crystalline nature of the substrate and the interface can be clearly seen in the image. However, the FFT patterns obtained from the substrate and the interface regions are distinctly different, indicating that the two regions have different crystal structures. Although not in a low-index zone-axis orientation, the FFT pattern of the interface is compatible with a Fe_2SiO_4 structure (see Figure S2 in the SI).

The interface formation is expected to resemble the thermal oxidation of the substrate at low oxygen partial pressure (O_2 pp.) and elevated Si-access, whereby the O_2 pp. is expected to show a decrease from the outer region of the interface (e.g. position (ii) in Figure 2) to its inner region (e.g. position (iv) in Figure 2). Thus, the interface formation has been simulated by computation of the phase equilibrium of the substrate composition vs. O_2 pp. at 600 ºC at elevated Si-level (for the computation a Si content of 2 wt.% has been assumed). The respective property diagram showing the phase equilibrium is shown in Figure 4. Clearly, the oxide-phase equilibrium is dominated by a Fe/Cr/Ni/Mn-rich spinel-structure oxide (M_3O_4), together with an Fe/Cr-rich corundum-structure oxide (M_2O_3) at high O_2 pp. and a stoichiometric Cr_2O_3 (corundum-structure) at low O_2 pp., which generally agrees with the medium temperature oxides that have been experimentally identified after the oxidation of CrNi steel[56]. Neither of the previously discussed phases is enriched in Si. Si is entirely bound in form of quartz (SiO_2) over a broad range of O_2 pp. or a Fe-rich olivine-structure phase at medium O_2 pp. (i.e. fayalite). Overall, the equilibrium calculation supports the hypothesis of fayalite formation in the interfacial zone together with the formation of Cr_2O_3 directly at the substrate surface, where the lowest O_2 pp. is expected. Further, the calculated phase

equilibrium is in agreement with the observation of Cr^{3+} in the outer region of the interfacial zone, which may be bound in a spinel-type oxide where the highest O_2 pp. is expected. Since no trace of Fe^{3+} was evident from the experiment, we propose that the formation of an outer corundum-structure layer was suppressed by the low oxygen availability during the thermal treatment. The formation of a thin, chemically bonded interfacial zone has been previously linked to good adhesion between glasses and metals[35,40]. Hence, the herein presented formation of a silicate-rich interaction zone may be directly linked to the adhesion of the coating, and thus prevent coating spallation and ensure an excellent performance and mechanical durability of SOG based coatings in industrial applications[57]. Further, the formation of a silicate-rich interface zone has been related to an increased corrosion resistance[11], and thus the herein observed interfacial zone may have a strong positive impact on the corrosion behavior of the coating system. A detailed study of the performance of SOG coatings on stainless steel substrates including a discussion of the impact of the herein reported interface layer will be the content of following investigations.

4 Summary and Conclusions

In summary, we investigated the chemistry of the interface between AISI 316L and SOG coating using STEM-EELS and HRTEM imaging. An interfacial region of ~ 10 nm thickness, containing Si, O, Cr and Fe was detected. Analysis of the ELNES indicated these elements to be in Fe^{2+}, Cr^{2+} (as well as, small amounts of Cr^{3+}) and $[SiO_4]^{4-}$ forms. HRTEM images of the structure reveals that the interface is crystalline, with the FFT patterns matching a Fe_2SiO_4 (fayalite) -structure. The experimental results have been validated by thermodynamics simulations and we suggest that thermal processing of the SOG leads to the formation of a chemical interaction zone with the substrate which may generate excellent adhesion of the coating.

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Tables

Table I: Chemical composition of the substrates (by Optical Emission Spectroscopy). In addition, traces (< 0.1 wt.%; > 0.01 wt.%) of P, Nb, V, W were also detected.

Element	**Cr**	**Ni**	**Mo**	**Mn**	**Si**	**Cu**	**Co**	**N**	**C**	**Fe**
Composition (wt.%)	16.8	10.4	2.07	0.92	0.47	0.41	0.21	0.048	0.019	bal.

Figure Captions

Figure 1: (a) HAADF STEM images of the coating on AISI 316L substrates in the cross-sectional geometry. (b) Relative composition profiles of O, Cr and Fe and the Si signal intensity across the interface extracted from EELS plotted together with the intensity profile of the HAADF STEM image along the line the EEL spectra were acquired from.

Figure 2: EELS spectra along a line across the coating – AISI 316L interface containing the (a) O K-, Cr $L_{2,3}$- and Fe $L_{2,3}$-edges and (b) Si $L_{2,3}$-edge.

Figure 3: HRTEM image of the coating – AISI 316L interface, with FFT patterns of selected regions from the coating, interface and the substrate.

Figure 4: Phase equilibrium vs. O_2 partial pressure diagram of the substrate composition at increased (2 wt.%) Si-level. The property diagram was computed with Thermo-Calc Software version 2017a[37], TCFE7.0.

Figures

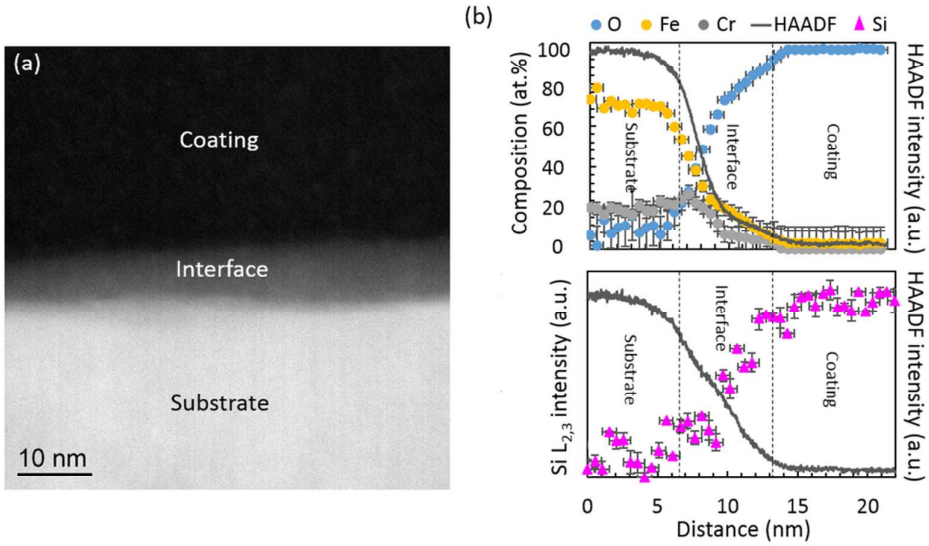

Figure 1

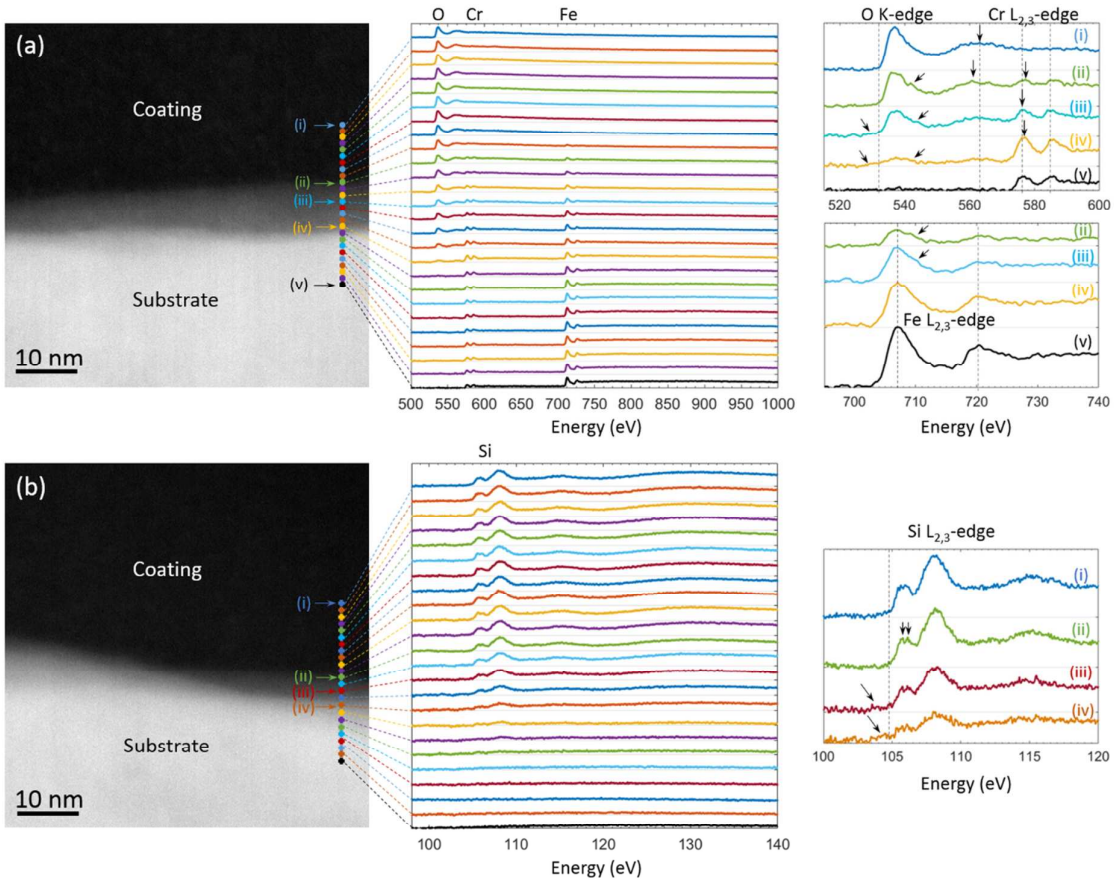
(a)
Coating
Substrate
10 nm
(i)
(ii)
(iii)
(iv)
(v)
O
Cr
Fe
500 550 600 650 700 750 800 850 900 950 1000
Energy (eV)
O K-edge
Cr L2,3-edge
520 540 560 580 600
Fe L2,3-edge
700 710 720 730 740
Energy (eV)
(b)
Coating
Substrate
10 nm
Si
100 110 120 130 140
Energy (eV)
Si L2,3-edge
100 105 110 115 120
Energy (eV)

Figure 2

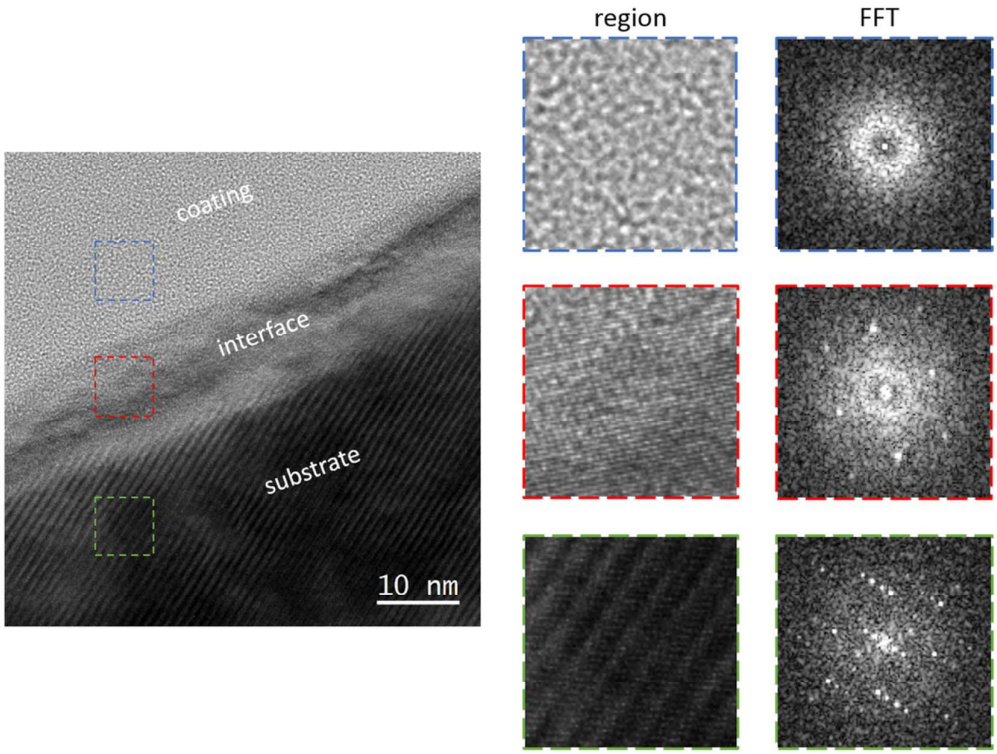

Figure 3

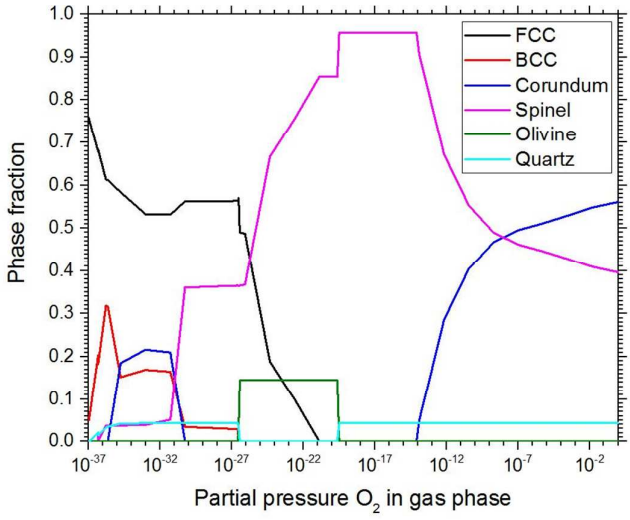
FCC
BCC
Corundum
Spinel
Olivine
Quartz
Phase fraction
Partial pressure O_2 in gas phase

Figure 4