



DEVELOPMENT OF NOVEL AND COST-EFFECTIVE CORROSION RESISTANT COATINGS  
FOR HIGH TEMPERATURE GEOTHERMAL APPLICATIONS

## IN-SITU TESTING OF AN LMD-HEA2 COATED TURBINE COMPONENT SECTION IN GEOTHERMAL ENVIRONMENT

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# 1. INTRODUCTION

In 2021, at the end of the Geo-Coat project, it was decided to coat a turbine component with one of the most promising developed coating – LMD-HEA2 and to have it tested in-situ at Hellisheiði power plant. A diaphragm, made from A470 steel, was sectioned and a part of the section laser cladded with LMD-HEA2. The part was then exposed in geothermal environment for a 8-week period and afterwards analysed for corrosion.

## 2. MATERIALS AND METHODS

### 2.1 Materials

The sample was coated and prepared as detailed in deliverable 8.4. A turbine diaphragm section made of A470 steel was laser cladded with the LMD-HEA2 high-entropy-alloy coating solution developed in Geo-Coat. To prevent cracks from forming in the coating, the substrate was preheated prior to deposition and the cooling of the part after deposition was controlled. Three sections of the turbine part were coated as can be seen in Figure 1.



Figure 1 - Turbine component for testing at ON with three coating areas

Patch C was subsequently chosen for testing in-situ at ON.

### 2.2 Test conditions

The sample was tested in an aerated pressure vessel at Hellisheiði power plant. The aerated test equipment, seen in Figure 2, was designed, manufactured, and used to test the coatings in a highly corrosive aerated environment. The aerated equipment simulates the conditions materials experience in the axial seal system suction path in geothermal powerplants. This is a pathway where steam coming from the turbine in sub-atmospheric pressure conditions is sucked away from the last stage of the geothermal turbine. In this location, steam and ambient air mixes and creates a very corrosive oxygenated environment. Additionally, the aerated pressure vessel simulates to a certain extent the corrosive environment found in hot production water piping prior to de-oxygenation.



Figure 2 - The aerated pressure vessel equipment in operation.

The samples were situated in the equipment for 8 weeks, experiencing significant oxygen-induced corrosion during the exposure period. The experimental conditions can be seen in Table 1 below. Chemical sampling data of the fluid inside the equipment is presented in Table 2.

Table 1: Experimental conditions of the aerated pressure vessel test.

Parameter	Value	Unit
Exposure time	3	Months
Temperature	90	[°C]
Pressure	1	[barg]
Air	492,3	[l/kg]

Table 2: Chemical sampling of the fluid within the aerated pressure vessel.

Liquid analysis (w/electrodes and titration)*	Value
Cl [mg/kg]	0.35
F [mg/kg]	0.072
SO <sub>4</sub> [mg/kg]	3.7
pH	4.9

*\*Sampled 31<sup>st</sup> of January 2021*

## 3. RESULTS

### 3.1 Overview

After testing, the sample was transferred to IceTec, where it was inspected and subsequently analysed for corrosion in an optical and scanning electron microscope. The sample was heavily corroded around the coated patch, and the A470 base material showed strong discolouring, rust patches and flaking of the material. Meanwhile, the coated patch seemed to have resisted the conditions significantly better. The edges of the coated patch were discoloured while the central parts seemed much less affected, with some small, yellow-brownish dots here and there. This indicates corrosion of the base material underneath the edges of the coated patch. It is also possible that the discolouring of the coated part of the sample is rust that has migrated from the base material surface onto the coating. The coated sample can be seen in Figure 3 below.

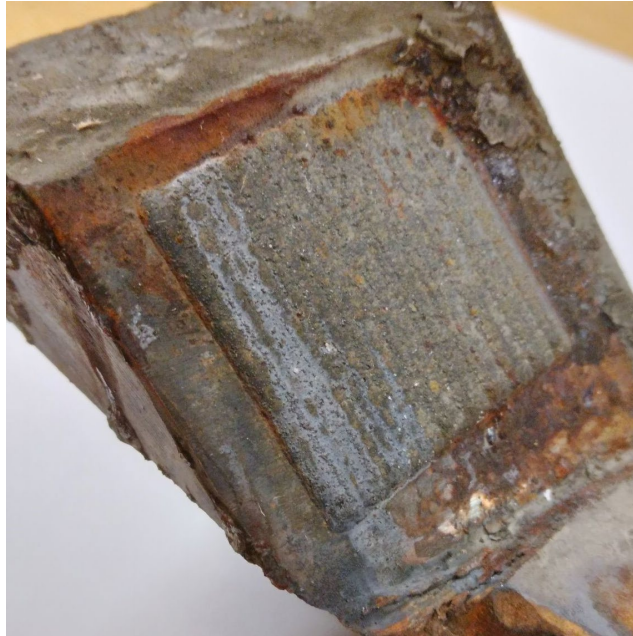


Figure 3 – The sample after transferral to IceTec

### 3.2 Surface analysis

The surface of the sample was analysed using a scanning electron microscope (SEM) with **energy dispersive X-ray spectroscopy (EDX)**. The bare A470 substrate was found to have iron-oxides covering the surface, as could be seen from optical inspection. The rust layer was cracked and, in some places, grainy as can be seen in Figure 4.

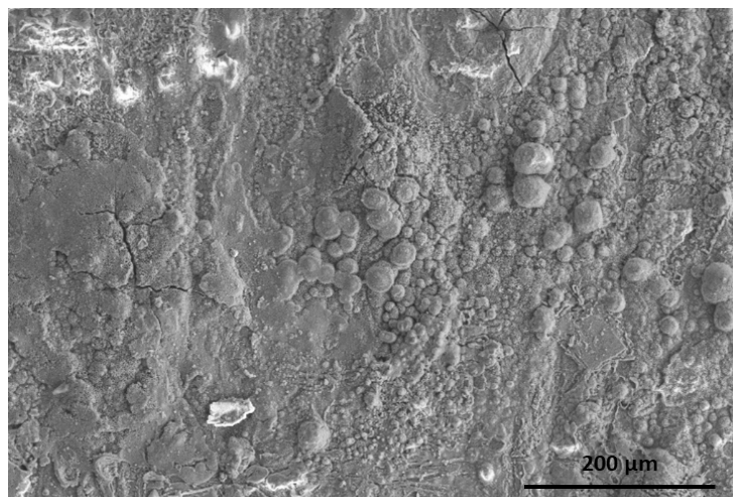


Figure 4 - Scanning electron microscopy image of the bare substrate surface.

EDX analysis of the coated surfaces showed most of the coating having reacted to the oxygen-heavy test conditions by forming a thick chromium-oxide layer on top of the coating. Some iron oxides are also seen on the surface. The coating surface was grainy in places, littered by spheres of coating material from the cladding process. Some of these spheres seemed to have formed iron oxides on their surfaces, as can be seen in Figure 5 and Table 3.

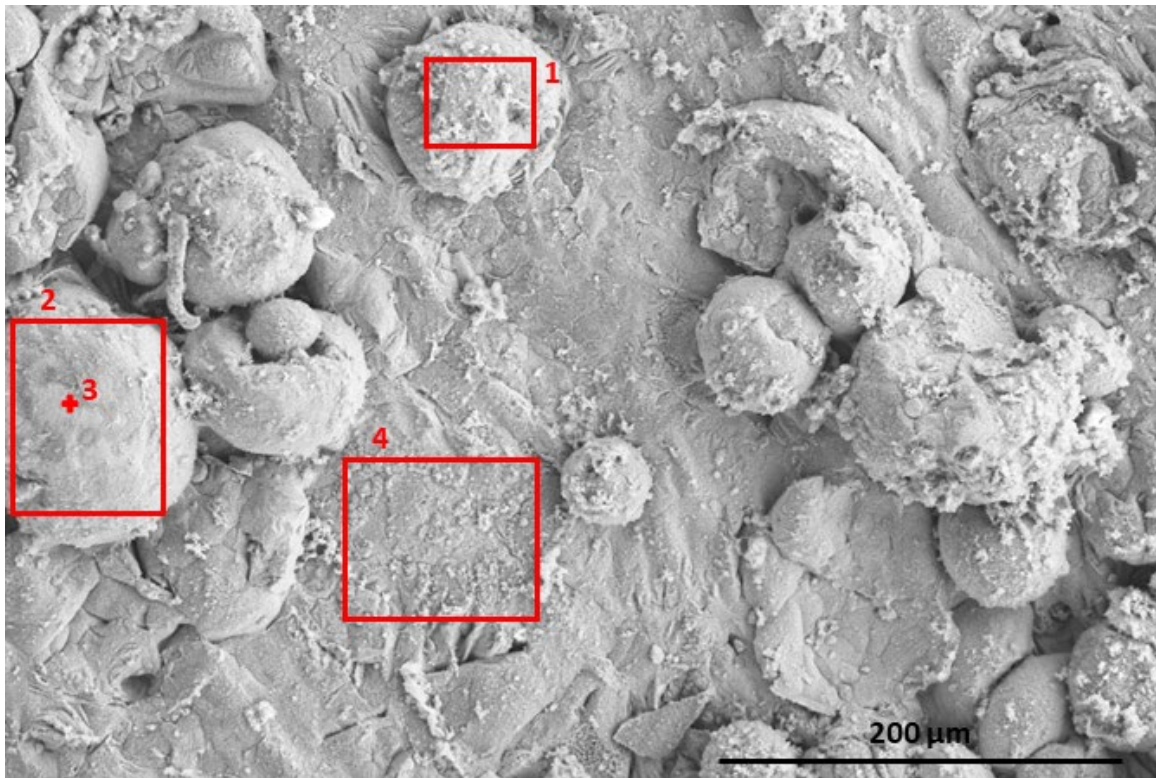


Figure 5 - SEM image of the coated surface of the sample, showing spherical sputter on the coating. Three areas and one point were chosen for elemental analysis.

Table 3 - Elemental analysis of sites shown in Figure 5.

Element (wt. %)	Location			
	1	2	3	4
C	9.1	7.85	6.88	5.9
O	29.14	28.98	19.52	30.62
Si	1.21	0.62	-	0.68
S	0.75	0.66	-	-
Ti	0.17	0.22	0.16	0.29
Cr	13.79	23.17	19.7	32.35
Mn	0.54	-	-	2.69
Fe	23.96	15.43	14.43	15.79
Co	6.43	6.92	11.83	3.35
Ni	6.49	7.45	11.64	3.09
Mo	8.41	8.69	15.84	5.25

### 3.3 Cross-sectional analysis

A cross-sectional sample was cut from the larger piece and analysed with an SEM and EDX. The cross-sectional analyses confirmed the formation of thick chromium oxide layers on the surface of the coating. Meanwhile, the bare base material had thick patches of iron oxides on its surface due to the interaction with oxygen. Corrosion was found to have started to penetrate slightly underneath the coating at the coating-substrate interface. The

substrate under the coating away from the interfaces was found to be unaffected by exposure while the bare substrate was heavily affected as can be seen in Figure 6.

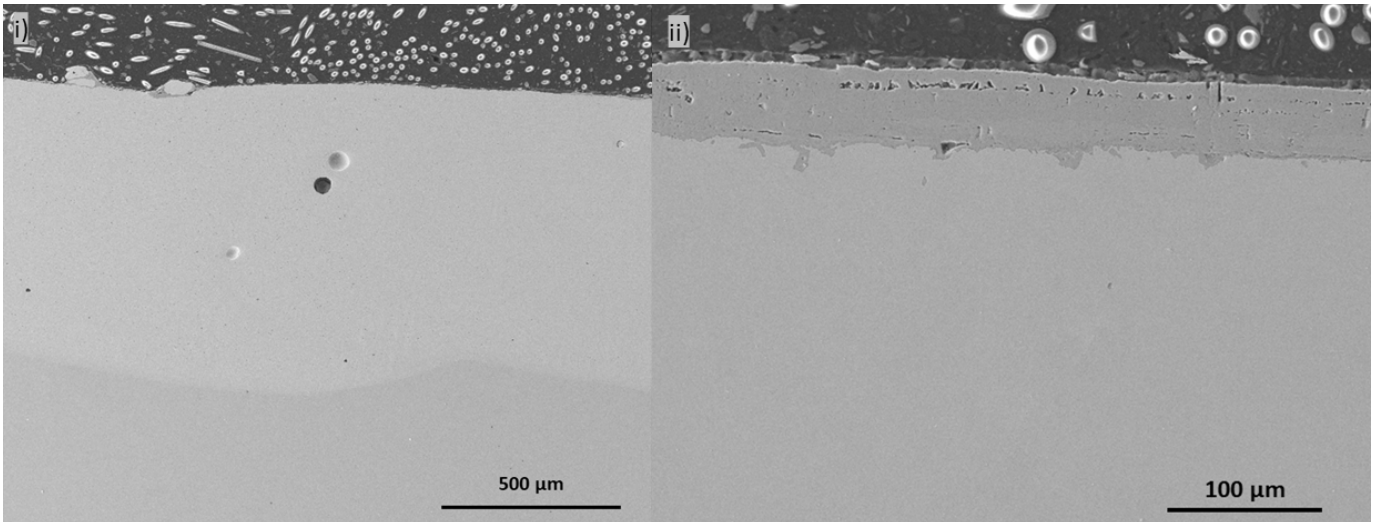


Figure 6 – i) Cross-section of the coated sample, showing the coating and the underlying substrate, ii) surface of the exposed substrate, showing a rust layer on top of the A470 steel up to 75 μm thick as well as pits.

At the coating-substrate interface, corrosion was seen to have occurred underneath the coating itself, emphasizing the importance of good coating coverage. In addition to corrosion of the underlying substrate, the coating composition at the intersection was found to have much larger portion of iron in comparison to the other four elements that make up the LMD-HEA2 coating. This could be due to diffusion of the elements out of the coating or simply an artifact of the cladding process. An SEM image, showing EDX analysed locations can be seen in Figure 7 along with the elemental analysis itself in Table 4.

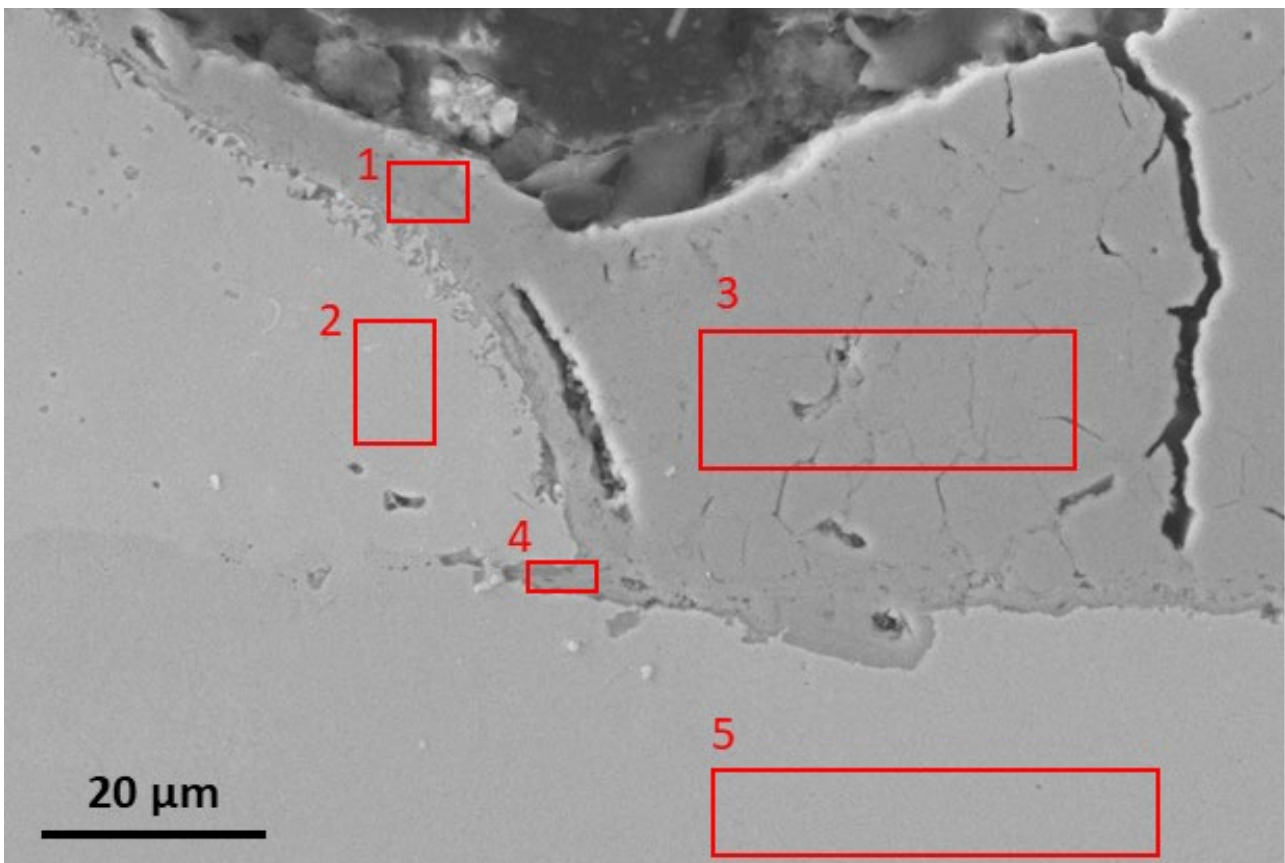


Figure 7 - EDX analysis of the coating-substrate interface, showing locations marked for chemical analysis.

Table 4 - Elemental analysis of locations marked in Figure 7.

Element (wt. %)	Location				
	1	2	3	4	5
C	5.34	6.29	3.64	4.41	4.37
O	26.46	-	26.95	22.84	-
Si	0.21	-	0.29	1.42	0.26
S	1.30	-	0.13	0.49	-
Cr	0.29	-	3.15	-	-
Fe	59.59	64.87	63.85	67.28	94.59
Co	3.71	9.11	-	0.73	-
Ni	1.26	9.95	-	0.78	-
Mo	1.85	9.78	1.39	1.42	-
Mn	-	-	0.08	0.62	0.78

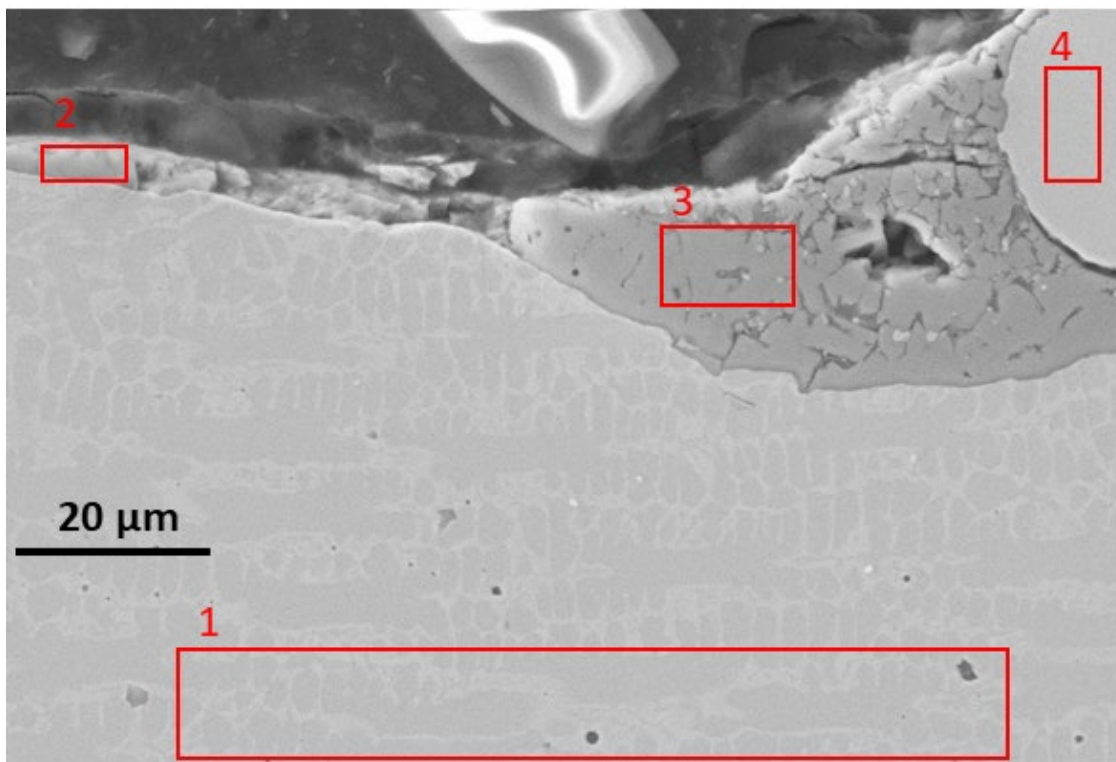


Figure 8 - SEM image of the surface of the coating, showing spherical artifacts from the cladding process along with chromium oxide layer.

Table 5 - Elemental analysis of locations marked in Figure 8.

Element (wt. %)	Location			
	1	2	3	4
C	6.52	9.91	3.26	6.89
O	-	30.45	31.10	-
Si	0.18	0.21	2.28	0.22
S	-	0.15	-	-
Ti	-	0.22	0.81	-
Cr	12.81	50.26	57.28	17.16
Mn	0.33	4.67	2.62	-
Fe	31.88	3.55	2.32	17.25
Co	14.49	-	-	17.63



Ni	14.27	-	-	17.52
Mo	19.52	-	-	23.34
Ca	-	0.22	-	-
Al	-	-	0.32	-

## 4. CONCLUSIONS

Based on the corrosion analysis results performed on the LMD-HEA2 sample described in this report, the following conclusions can be summarized for the coating:

- The coating showed good resistance to the corrosive effect of the oxygenated test environment which it was subjected to for 8 weeks.
- The substrate underneath the coating was not affected by the hostile environment, apart from areas underneath the coating at the coating-substrate interface, as the coating did not cover the whole part.
- The bare and exposed A470 substrate suffered heavy corrosion, with rust layers up to 75 µm in thickness on top of the substrate.
- The top, exposed, surface of the coating was mostly covered in a chromium-oxide layer, protecting the coating from the oxygen heavy environment.

The coating shows good corrosion resistance to this environment and can be recommended for service in this and similar oxygen-heavy environments.