

Corrosion Testing of PM HIPed UNS N06625 and PM HIPed UNS R56400 in Geothermal Environment at Hellisheidi Site

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ABSTRACT

Corrosion and erosion are an interrelated phenomenon where the rate of erosion can increase in a more corrosive geothermal environment. To reduce erosion and corrosion rate effectively, materials can be substituted with costly corrosion-resistant materials or coated the ordinary material with more noble alloys. In this paper, erosion, and corrosion of Powder Metallurgy Hot Isostatically Pressed (PM HIPed) nickel-based alloy (UNS N06625) and grade 5 titanium-based alloy (UNS R56400) materials with SiC and TiB₂ additives respectively were tested in wells HE-23 and HE-56 located at Hellisheidi geothermal site. The samples were tested in a geothermal fluid at 194°C and 12.6 bar gauge in well HE-23 and 198°C and 13.9 bar gauge in well HE-56 with H₂S, CO₂ and SO₄ as the main corrosive species. Intergranular cracks in PM HIPed UNS N06625-10v.%SiC and transgranular cracks in PM HIPed UNS R56400-10v.%TiB₂ were observed. The results and analysis of this paper will contribute to the selection and feasibility estimation of using PM HIPed UNS N06625-10v.%SiC and UNS R56400-10v.%TiB₂ materials for high-value parts manufacturing to be used in the corrosive geothermal environment.

Keywords: Nickel-based alloy, Titanium-based alloy, Carbon dioxide, Hydrogen sulfide, Energy-dispersive X-ray spectroscopy (EDS), Steam.

INTRODUCTION

Proper material selection for geothermal power production equipment to endure an aggressive corrosive geothermal environment [1] is an important factor for the durability and economics of a geothermal power plant [2,3]. The material selection for a casing string and surface equipment depends on several factors [4,5], whereas different conditions and corrosivity can be met within the same geothermal power system depending on the location and state of the geothermal fluid (deep in well, separator, heat exchanger, turbine etc.). In addition to the corrosiveness, geothermal fluid can also be highly erosive-corrosive [6] due to high-velocity and turbulent transportation flow of the geothermal fluids within the casing and equipment from the downhole ejection of the geothermal fluid towards the energy production and dissipation of the geothermal fluid. Due to erosive-corrosive conditions, materials can be prone to rapid erosion-corrosion if corrosion resistance and mechanical strength properties are not adequate. To reduce the corrosion effect, corrosion-resistant alloys (CRAs) have been applied in corrosive geothermal environments [7,8] with long term durability. Wrought stainless steels, nickel-based alloys and titanium-based alloys are well-known substitutes for low corrosion-resistant metals (carbon steels) for material application in the corrosive geothermal environment as summarized by Nogara and Zarrouk [9]. Other production technologies in the last few decades have though also come into a discussion where more specific properties of the materials are required and where cladding of low corrosion-resistant alloys is possible. Powder metallurgy technology is one production technologies of corrosion-resistant alloys that might be practical for the geothermal power industry for production of alloys with specific properties. For instance, new CRAs with good corrosion resistance with enhanced mechanical properties have been proposed [10] for possible geothermal coating application. Powder Metallurgy Hot Isostatic Pressing (PM HIP) is another possible candidate technique for production of CRAs in a geothermal environment. PM HIPed produced alloys are found to be isotropic with fine and uniform microstructure, and good mechanical strength. PM HIPed produced CRAs could therefore be a feasible material application in geothermal power production. HIPed alloys for a high-temperature application have been processed and verified to have enhanced mechanical strength in comparison with the wrought alloys of the same kind [11] which might be beneficial in an erosive-corrosive, high-temperature geothermal environment. The wrought titanium-based alloy UNS R56400 is an ASTM grade 5 alloy with moderate corrosion resistance (in terms of titanium-based alloy) but

can be susceptible to stress corrosion cracking (SCC) in a chloride media [8]. Study of corrosion behaviour of PM HIPed UNS R56400-10v.%TiB₂, that we will refer as HIPed Ti onward, in the geothermal or similar environment has not been published yet but feasible mechanical and isotropic properties of HIPed Ti has been reported by Abu-Issa et al. [12] which might be interesting in terms of SCC resistance of the titanium-based alloy in chloride media in our study.



Figure 1: Hellisheidi Geothermal Power Plant Site [13].

In this paper, corrosion testing of nickel-based alloy, PM HIPed UNS N06625-10v.%SiC, onward referred as HIPed Ni, and corrosion testing of titanium-based alloy, HIPed Ti was conducted in a geothermal fluid (bulk phase is H₂O with H₂S, CO₂, SO₄, Cl⁻ and more species) at three different testing sites based at Hellisheidi Geothermal site (Figure 1) in Iceland.

This paper aims to study the corrosion behaviour of the PM HIPed nickel-based and titanium-based alloys in the corrosive and erosive geothermal environment. The feasibility of the application of the PM HIPed alloys in a geothermal environment will be assessed subsequently.

EXPERIMENTAL PROCEDURE

Testing Equipment and Conditions

HIPed Ni and HIPed Ti were tested in three different testing sites. One testing site was at the wellhead of well no. HE-23 at 194 °C and 12.6 bars gauge. The second testing site was at the wellhead of well no. HE-56 at 198 °C and 13.9 bars gauge. For comparison analysis, corrosion testing of wrought (not HIPed) UNS N06625 and UNS R56400 was also conducted at wellhead HE-56. The third testing site was in an aerated testing pressure vessel connected to wellhead HE-23 at 90°C and 1 bar absolute to study the effect of oxygen ingress and lower pH on the corrosive environment, conditions expected in geothermal turbines. The geothermal fluid flows into the pressure vessel through an ejector which uses the pressure and flow to suck in ambient air at a constant rate into the testing vessel.

Testing of HIP coupons at the wellhead of HE-23 referred to as “Test A – Wellhead”. Testing of PM HIPed coupons in aerated pressure vessel connected from the wellhead of HE-23 referred as “Test A – Aerated” and erosion-corrosion testing of PM HIPed plate samples mounted in carbon steel discs referred as “Test C”. The wrought (not HIPed) UNS N06625 and UNS R56400 were prepared as disc samples tested in Test C. Testing sites and testing equipment can be viewed in Figure 2, 3 and 4.



Figure 2: Test A – Wellhead, a) Coupon samples in a testing rack, b) install of coupons in wellhead and b) coupon samples inserted in wellhead (Courtesy of ON)

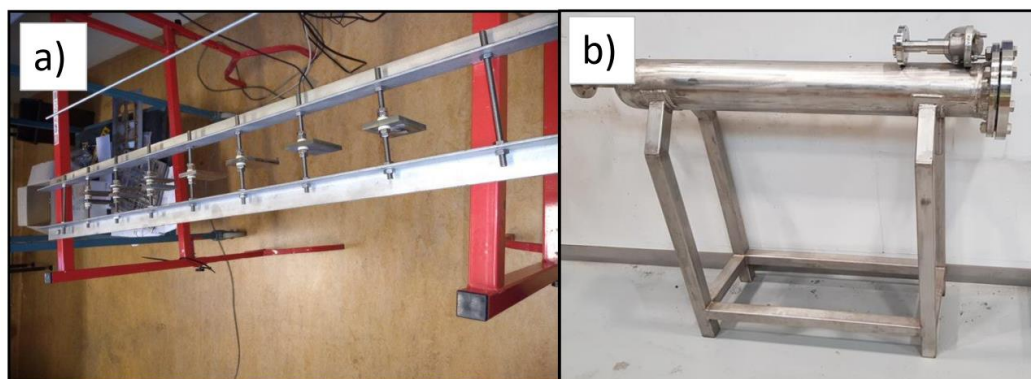


Figure 3: Test A – Aerated, a) coupon samples in the testing rack and b) pressure testing vessel (not connected to well in Figure).

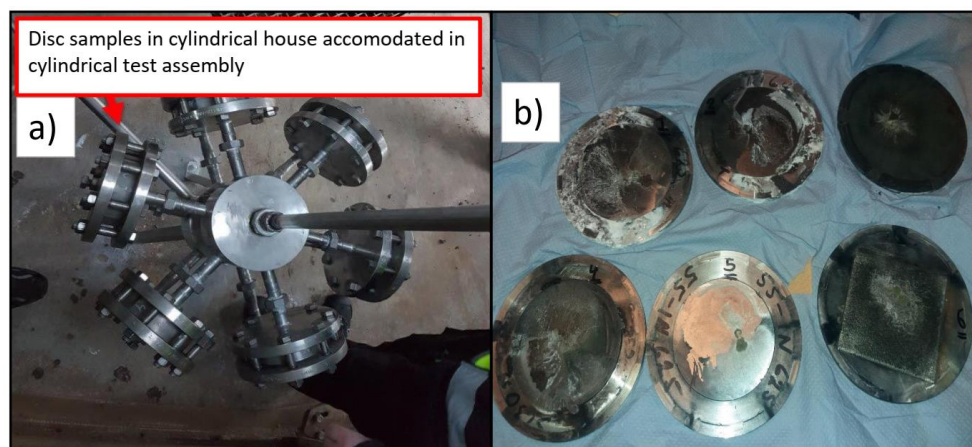


Figure 4: Test C, a) test assembly with 6 testing volumes for erosion-corrosion disc samples (Courtesy of ON) and b) disc samples after erosion-corrosion testing

The geothermal fluid was a two-phase fluid in wells HE-23 and HE-56. Sampling was done for the non-condensable gasses (Table 1), the condensable gasses (Table 2) and the liquid part of the fluid (Table 3).

Table 1: Chemical composition of non-condensable gasses in the geothermal fluid

Well no.	HE-23	HE-56
T [°C] well top	194	198
P [bar, gauge]	12.6	13.9
Gas analysis:		
CO ₂ base [mg/kg]	15017	2178
H ₂ S base [mg/kg]	1363.4	562
NH ₃ base [mg/kg]	-	-
CH ₄ [%volume]	-	4
H ₂ [%volume]	-	82.4
N ₂ [%volume]	-	10.5
CO ₂ icp [mg/kg]	-	-
Cl [mg/kg]	62.1	161
F [mg/kg]	0.337	1.2
PO ₄ [mg/kg]	-	-
SO ₄ [mg/kg]	58.44	10
SO ₂ [mg/kg]	-	-

Table 2: Chemical composition of condensable gasses in the geothermal fluid

Well no.	HE-23	HE-56
T [°C] well top	194	198
P [bar, gauge]	12.6	13.9
Condensed gas analysis:		
Gas volume/cond.water mass [litre/kg]	0.886	0.31
Al [mg/kg]	1.27	2
B [mg/kg]	0.59	1.1
Br [mg/kg]	<0.5	-
Ca [mg/kg]	2.81	0.37
Cl [mg/kg]	62.1	161.3
Fe [mg/kg]	0.009	<0.005
K [mg/kg]	20	33.2
Li [mg/kg]	0.045	-
Mg [mg/kg]	0.0052	<0.005
Mn [mg/kg]	0.0121	-
Mo [mg/kg]	<0.01	-
Na [mg/kg]	144	196.7
P [mg/kg]	<0.02	-
SO ₄ [mg/kg]	58.4	14.2
SO ₂ [mg/kg]	488	672.4
Sr [mg/kg]	0.0356	-
Ti [mg/kg]	<0.002	-