Tribocorrosion on Mars

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TRIBOCORROSION ON MARS

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ABSTRACT

Tribocorrosion is a degradation phenomenon of material surfaces subjected to the combined action of mechanical loading and corrosion attack caused by the environment. Although corrosive chemical species such as materials like chloride atoms, chlorides and perchlorates have been detected on the Martian surface, there is a lack of studies of its impact on materials for landed spacecraft and structures that will support surface operations on Mars. Here we present a series of experiments on the stainless-steel material of the ExoMars 2020 Rosalind Franklin rover wheels. We show how tribocorrosion induced by brines accelerate wear on the materials of the wheels. Our results do not compromise the nominal ExoMars mission but have implications for future long-term surface operations in support of future human exploration or extended robotic missions on Mars.

Introduction

Tribocorrosion is a surface damage phenomenon resulting from the synergistic action of mechanical wear and (electro)chemical reactions. It can imply corrosion accelerated by wear,

28 or wear accelerated by chemical reactions[1]. It was discovered in 1875 by Thomas Edison, who
29 observed a variation in the coefficient of friction between metal and chalk moistened with
30 electrolyte solutions[2], and today is an important engineering topic, defined by ISO[3] and
31 ASTM[4], and a cause for concern to any engineer employing passive metal components in
32 corrosive environments[5]. If adequately controlled, tribocorrosion can be beneficial, such as in
33 machinery lubricants where it is used as a means of avoiding seizure by promoting wear in a
34 sacrificial mode[6].
35
36 The surface of Mars is rich in corrosive chemical species. Martian regolith contains chloride
37 in abundance[7] which forms various chlorides and perchlorate salts with high solubilities and
38 low eutectic temperatures[8,9]. Detection of 0.4-0.6% perchlorate by mass in Martian high
39 latitudes and further revelation of soluble chemistry of Martian soil at the Phoenix Lander site[10]
40 were encouraging results prompting researchers to focus on perchlorate-based brine research.
41 Other remaining anions and cations, as detected by the Wet Chemistry Laboratory on the
42 Phoenix Mars Lander were chloride, bicarbonate, and sulphate and Mg^{2+}, Na^{+}, K^{+}, and Ca^{2+},
43 respectively[10]. Subsequently, the reanalysis of the Viking results also suggested the plausible
44 presence of perchlorate and organics at midlatitudes on Mars[11]. Evidence for sodium
45 perchlorate ($NaClO_4$), magnesium perchlorate ($Mg(ClO_4)_2$) and calcium perchlorate
46 ($Ca(ClO_4)_2$) has also been provided at equatorial latitudes by the Sample Analysis at Mars
47 instrument on the Mars Science Laboratory (MSL)[12]. Another study[13] provides evidence of
48 Martian perchlorate, chlorate, and nitrate in the Martian meteorite EETA79001 with
49 sufficiently high concentrations. These results indicate the possibility that perchlorates might
50 be abundantly present within Martian regolith at all latitudes. A variety of pathways have been
51 proposed for the perchlorate synthesis on Mars. These pathways may involve photochemical
52 reactions[14], electrostatic discharge[15], and oxidation-reduction reactions[16]. Perchlorates and

chloride salts in the Martian regolith are extensively investigated becausee they can absorb water from the atmosphere forming hydrates[17], by absorption, and then liquid brines, through deliquescence[18,19]. In addition to perchlorates, chlorides such as $FeCl_3$, $CaCl_2$, and $MgCl_2$ can also act as strong freezing point depressants. $FeCl_3$ and $CaCl_2$ are the strongest freezing point depressants with eutectic temperatures as low as approximately 218 K, followed by $MgCl_2$, NaCl, and KCl at about 238 K, 252 K, and 262 K, respectively[9].

Perchlorates ($ClO4^-$) have been found planet-wide on Mars[10]. Studies show that the perchlorate salts which contains ClO_4- anion can hold the water in brine state even when the temperature reaches 203 K. Other chloride (Cl-) salts have been detected such as magnesium chloride ($MgCl_2$) and calcium chloride ($CaCl_2$)[20], along with sulphate salts such as iron sulphate[21], which has deliquescent properties.

A recent work[22] has derived the current chemical weathering rates on Mars, based on the oxidation of iron in stony meteorites investigated by the Mars Exploration Rover Opportunity at Meridiani Planum. The authors concluded that the chemical weathering rates derived are ~1 to 4 orders of magnitude slower than that of similar meteorites found in Antarctica where the slowest rates are observed on Earth, suggesting aridity of Mars to be even more significant than expected during the last 50 Myr. The authors extrapolated their results to the impact of weathering in the wheels of the NASA Curiosity rover, pointing that “Martin-Torres and co-workers[18] worry that the corrosive effects of chlorine brine might pose a challenge to spacecraft. The extremely slow weathering of meteorites, which contain metallic iron as a phase very sensitive towards chemical alteration, suggests that this is not a threat over the lifetime of a spacecraft, however. The Opportunity rover is testament to that, showing no signs of chemical weathering or corrosion after more than 12 years of operating on Mars (April 2016).”

The argument used by Schroeder et al. to justify the absence of corrosion on mechanical parts on Mars actually supports the hypothesis that environmental conditions have an impact on the fate of the rover wheels. The wheels of Opportunity and Curiosity were similar in terms of composition and effective ground pressure supported (see Materials and Methods). The fact that Opportunity showed no signs of chemical weathering or corrosion after more than 14 earth years of operation on Mars (from 2004 until the middle of 2018), while Curiosity rover faced extreme corrosion and related punctures and tears just months after landing on Mars, maybe an indication of the impact of the local environment on wheels weathering. Actually, the details of this wear and tear on the wheels of Curiosity Rover are missing from Schröder et al. [22].

Corrosion of the surface of a metal is the degradation that results from its chemical interaction with the environment. On Mars, any metal facing the sky, as the observable side of a meteorite, would only be exposed to the air and thus only ambient oxygen would produce this damage. This is the case analysed by Schroeder et al., which considers only the chemical weathering rates of metals exposed to the Martian atmosphere. However, in the case of metals in contact with the regolith, as it is the case of the metals used in the wheels of the rovers operating on Mars, these materials may be eventually directly exposed to Cl and brines, which are formed naturally under Martian conditions at the interface of the regolith and the atmosphere[17-19]. These two processes are very different, as in the case of the wheels, in addition to the exposure to a liquid phase, there is the additional damage of mechanical wearing. It is known, that metal can be protected from corrosion by covering it with a coating, such as an anodised treatment, however as soon as this protective layer is scratched or worn-out the inner material is directly exposed to corrosion. The Curiosity's wheel is made from a single piece of machined aluminium alloy AA7075-T7351. The main rim is 1.9 cm thick (0.75-inches)[23]. Martin-Torres et al. [18] hypothesised that the daily contact of the wheels with the corrosive perchlorate

solutions during every night may have weakened the scratched surface of the anodised aluminium, making it more susceptible to damage against sharp rocks. Although the large cracks observed in the wheels of Curiosity are likely caused by mechanical damage, an image taken by the ChemCam remote microscopic-imager on sol 502 the vertical wall of the T-print of the wheels, showed a pattern of distributed sub-millimetre sized blisters that cannot be attributed to rock scratching and resembled aluminium alloy pitting corrosion[24]. Unfortunately, the Spirit and Opportunity rovers did not have an equivalent camera to analyse the wheels with submillimetre precision, so we cannot state whether this damage existed or not.

Previous preliminary experiments, designed to look at the interaction between aerospace aluminium alloy (AA7075-T73) and the gases present in the Mars atmosphere, at 20°C and a pressure of 700 Pa with only 0.13% of oxygen, showed that there is an interaction between the small amount of oxygen present in the Mars gas and the alloy, when there is a scratch that removes the protective aluminium oxide film[25]. The anodising process that is applied to aluminium alloy increases the thickness of the natural oxide layer on the aluminium wheels, but the abrasion can wear out the external protecting layer and expose the bare aluminium metal to corrosion. The purpose of this work is to evaluate the role of direct contact with liquid brines and the additional damage caused by mechanical friction.

Results

Here we present laboratory studies that show the impact of tribocorrosion (the combination of mechanical and corrosion wearing) on materials in contact with naturally formed brines under current environmental conditions on Mars. Although tribocorrosion is a well-known phenomenon since nearly 150 years ago, there is a lack of analysis of its impact on materials for landed spacecraft and structures that will support surface operations on Mars. Mechanical parts, like the wheels of the rovers operating on Mars, in contact with corrosive brines on the

surface, could be affected by the combination of chemical corrosion and mechanical loading. Nevertheless, to our knowledge, not a single research on tribocorrosion research on Mars has ever been published. This, in spite of the fact that corrosive materials have been found on the surface of Mars.

The European Space Agency ExoMars 2022 Rosalind Franklin rover will have a nominal lifetime of 218 sols (around 7 Earth months). Its mass is 310 kg, with an instrument payload of 26 kg (excluding payload servicing equipment such as the drill and sample processing mechanisms). The rover's kinematic configuration is based on a six-wheel, triple-bogie concept with locomotion formula $6 \cdot 6 \cdot 6 + 6$, denoting six supporting wheels, six driven wheels, and six steered wheels, plus six articulated (deployment) knee drives. This system enables the rover to passively adapt to rough terrains, providing inherent platform stability without the need for a central differential[26]. The wheels are made of Sandvik stainless spring steel (11R51).

Here we have performed laboratory studies on how the material (stainless spring steel) used in ExoMars 2022 Rosalind Franklin rover wheels is affected first by corrosion and then by tribocorrosion under environmental conditions on Mars. We suggest that similar studies should be applied to other materials used for wheels and structures in contact with the Martian regolith.

Brine corrosion under Martian conditions

For the study of corrosion, we have tested samples of the Sandvik 11R51 stainless steel, used in the ExoMars 2022 Rosalind Franklin rover wheels, and two other control materials: stainless steel SS4301, and regular steel S235. Sandvik 11R51 is an austenitic stainless steel with

153 excellent spring properties with higher corrosion resistance (due to the addition of
154 molybdenum), mechanical strength, tensile strength and tempering effect, and fatigue and
155 relaxation properties that other stainless steels. Every material was exposed to two sets of salt
156 environments inside the SpaceQ chamber at Martian conditions[27], and three control tests with
157 salt (see Table 1) under ambient laboratory conditions (20 C and 1010 mbar).
158

Case		**Salt Environments**
#1	SpaceQ martian conditions	1.5g $NaClO_4$ (+water spontaneously absorbed from the atmosphere)
#2	SpaceQ martian conditions	1.5g MMS soil + 0.15 g $NaClO_4$ salt (+water spontaneously absorbed from the atmosphere)
Control #1	Laboratory conditions	$NaClO_4$ (1.5g salt + 1g water) Brine immersion
Control #2	Laboratory conditions	1.5g MMS soil + 0.15 g $NaClO_4$ salt
Control #3	Laboratory conditions	Indoors (exposed to the air at ambient lab conditions)

159 **Table 1.** Environmental conditions of the experiments performed with 11R51, SS4301 and
160 S235
161

Cases #1 and #2 were exposed 5 hours to the Martian environment within the SpaceQ chamber, and to the simulated Martian water cycle described in Methods and Materials. The set of control samples #1, #2 and #3 were left on the bench at laboratory conditions during the same time, and the control sample #1 was immersed in a brine of $NaClO_4$ (1.5g salt + 1g water) to observe the reactiveness of the material within the liquid already formed. After the experiments, the samples were packed in an airtight bag and studied using a scanning electron microscope (SEM) along with elemental detection via Electron Dispersive X-ray Spectroscopy (EDS) to determine the effects of corrosion.

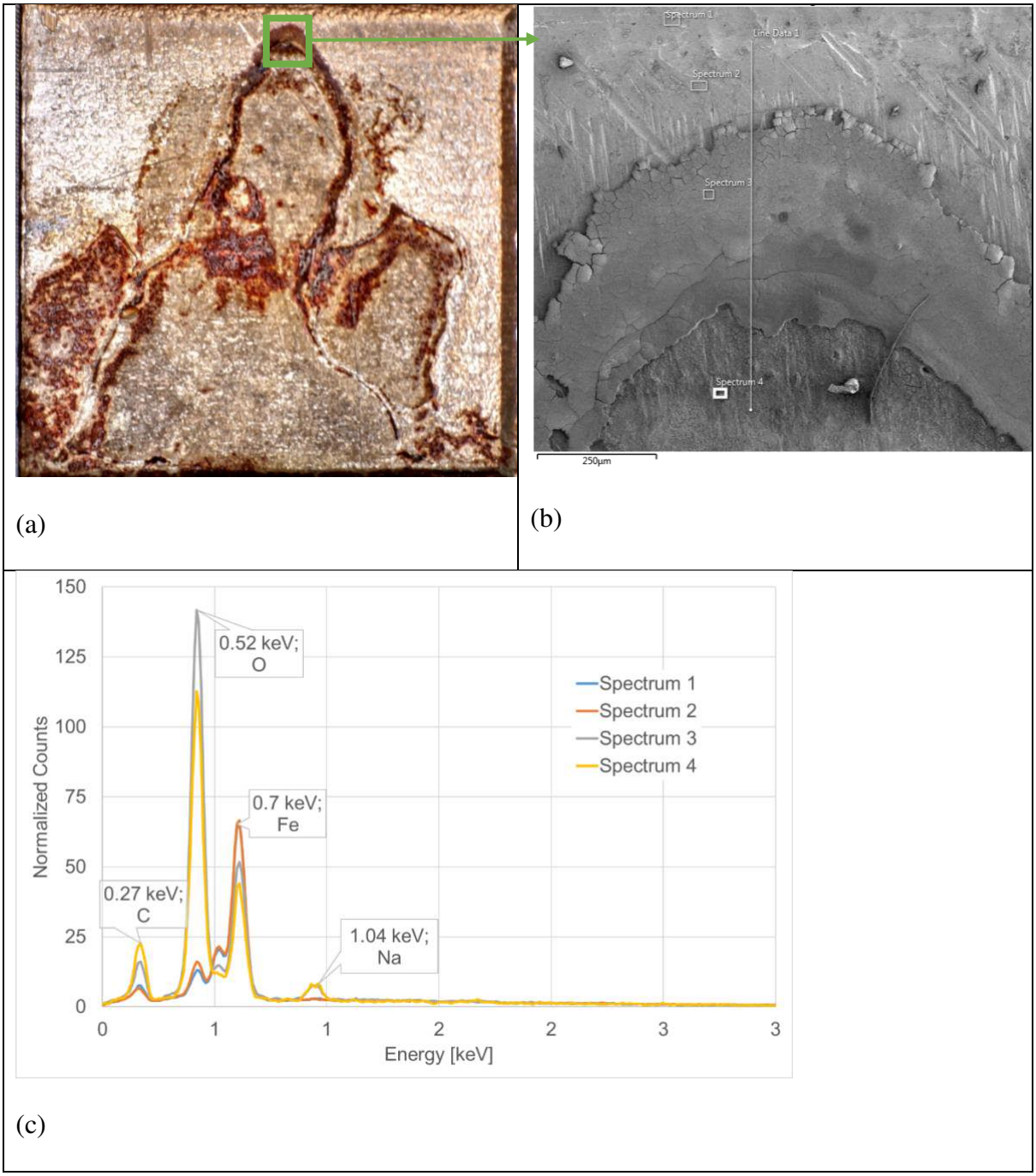
The overview of the optical inspection by digital microscopy is shown in Table 2. We found no corrosion on either of the stainless-steel samples (11R51 or SS4301). On the contrary, the regular steel sample (Reg S235) presented visible signs of corrosion, both in Case #1 (simulated Mars environment and immersed in the brine that is formed spontaneously by absorption of the moisture in the air), and in Case #2 (simulated Mars environment and immersed in soil + salt), whereas the same immersion under ambient atmosphere produced less corrosion (Control #2). It is worth pointing out that these brines are formed spontaneously and are stable at Martian surface conditions.

In order to identify spectrally the corrosion in S235 under Case #1we performed the analysis with the SEM-EDS as seen in Figure 7 (a–c). The digital microscope image in (a) shows clear visible signs of corrosion. A region that included corroded and non-corroded steel was selected for high magnification studies (green box). In (b), four regions along a vertical line were selected for EDS analysis. The EDS spectra in (c) show that regions related to spectrum 3 and 4 are enriched in carbon (C at 0.27 keV), oxygen (O at 0.52 keV) and sodium (Na at 1.04 keV) compared to the reference regions in spectrum 1 and 2. These results are evidence of oxidation of the regular steel by the sodium perchlorate brine. Interestingly carbon and oxygen, from the

Martian atmosphere and the water in the brine and air, have also been fixed with different efficiencies from site 1 to 4, depending on the redox state of the material after the corrosion. Actually, it is worth to remark that upon exposure to two different environments the regular steel was more severely corroded under Martian conditions (Cases #1 and #2) that under ambient conditions (see for comparison Case #2 vs Control# 2 in Table 2), so the corrosion of regular steel S235 is amplified under Martian conditions. The brines were effectively formed under Martian conditions because of the high relative humidity conditions, whereas at ambient conditions in the laboratory the relative humidity was moderated.

Condition	Sandvik 11R51	SS4301	Reg S235
Case #1 (SpaceQ Brine)	 No corrosion	 No corrosion	 Severe Corrosion
Case # 2 (SpaceQ Soil+Salt)	 No corrosion	 No corrosion	 Severe Corrosion
Control 1 (Ambient Brine)	 No corrosion	 No corrosion	N/A Insufficient samples. Severe corrosion expected.
Control 2 (Ambient Soil+Salt)	 No corrosion	 No corrosion	 Corrosion
Control 3 (Ambient)	 No corrosion	 No corrosion	 No corrosion

Table 2. Optical inspection of the experiments.



213

214 **Figure 1**: (a) Microscope image of 10x10 mm Regular Steel sample. (b) High magnification

215 SEM image showing location of EDS analyzed regions. (c) results of EDS analysis confirming

216 corrosion by detection of Na and O in Spectrum 3 and 4.

Discussion

Tribocorrosion under martian conditions

As shown in Table 2 the material used in the ExoMars wheels (stainless spring steel Sandvik 11R51) showed no corrosion. We have conducted a tribological experiment to evaluate if it is feasible to corrode (oxidize) stainless steel when subjected to wear while exposed to a liquid brine of the type that can be formed under Martian conditions. The experiment was conducted by rubbing for 90 minutes a 10 mm ceramic (Si_3N_4) ball against the material, while the plate was immersed in either brine or water (see Fig. 2 with the setup). This is a standard procedure for testing tribocorrosion.

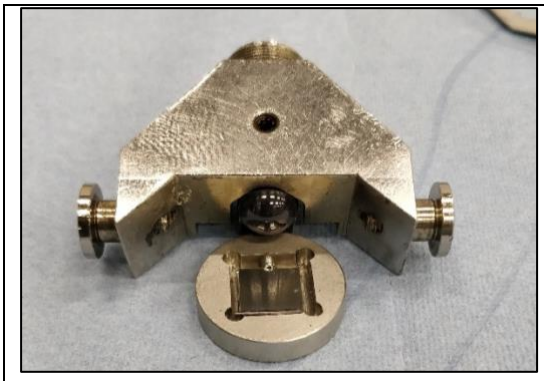


Figure 2. Setup of tribological experiment showing ceramic ball and stainless-steel plate in their respective sample holders.

For the analysis we included (see Methods and Materials): (i) measurements of friction during rubbing; (ii) wear volume by 3D optical profilometer; (iii) optical inspection with digital microscope; and (iv) scanning electron microscopy and electron dispersive X-ray spectroscopy (SEM-EDS) for detailed surface analysis including chemical (elemental) analysis.

Figure 3 shows the friction data and shows a clear difference between testing in water or brine. The friction coefficient is initially increasing to values above 1, but for the wear test in

brine the friction drops significantly after 30 min (1800 s). The drop-in friction could be explained by the chemical reactions that reduce the surface integrity and thereby lowers friction. In tribology, this is known as sacrificial wear and is commonly employed in the anti-seizure chemical additives known as extreme pressure agents (EP). Chlorine containing EP agents have historically been used, but are not recommended as they may cause corrosion[28].

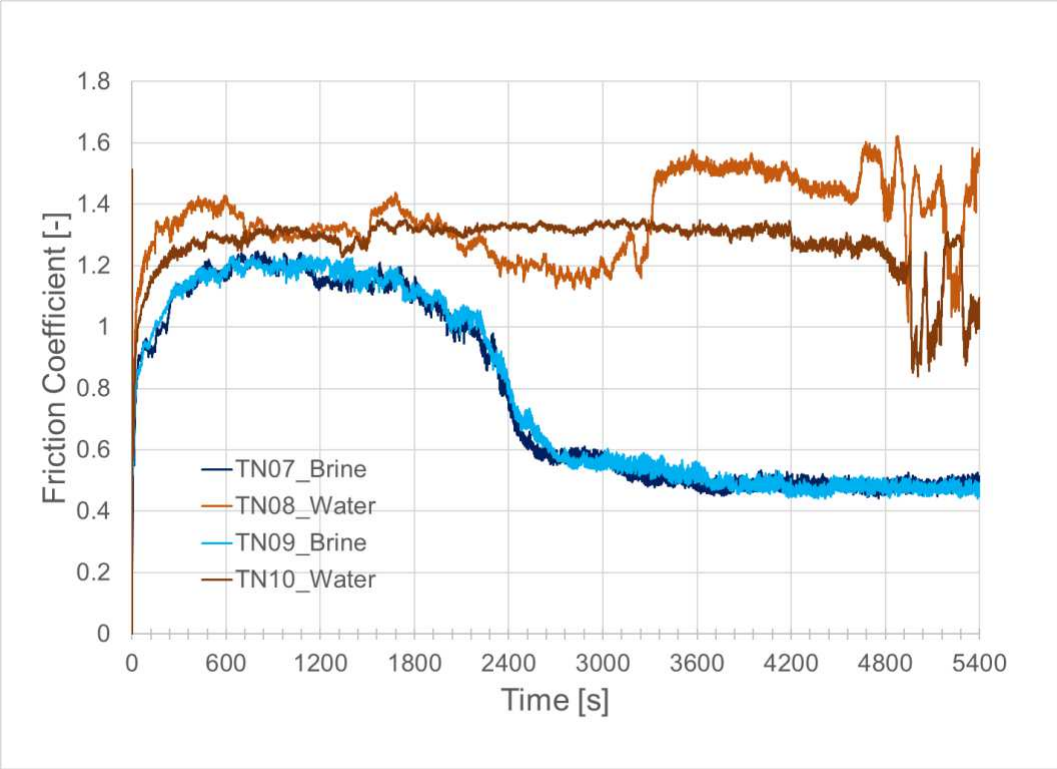


Figure 3. Friction data indicates transition to corrosive wear around Time=1800 s when immersed in brine.

Table 3 shows that the worn volume is significantly increased (>45%) when the test is performed in brine instead of water. TN10 has the lowest worn volume of all samples, indicating that brines have >45% worn volume in these experiments.

	Worn Volume [µm³]	Max depth [µm]	Projected area [mm²]	Worn Volume per cycle [µm³]
TN07 Brine	80 466 771	41.2	3.16	1490
TN08 Water	54 217 302	38.4	3.59	1004
TN09 Brine	78 590 249	40.5	3.19	1455
TN10 Water	26 081 611	19.6	3.53	483

Table 3. Wear data.

The wear marks are shown in 4 after washing the samples in two steps in heptane and ethanol in ultrasonic bath. The samples tested in water show a visual appearance that could be interpreted as corrosion, while the samples tested in brine are brighter in appearance except for along the edges. The repeatability is good. Figure 5 are an overview of the reference samples at low and high magnification, and shows tests TN08 and TN07 (water, and brine respectively). The edges of the wear marks were selected for further analysis. Figures 6 shows detection of Cl in worn area of TN07 (brine), Figure 7 shows evidence of surface oxidation but no detection of Cl in worn area of TN08 (water), and Figure 8 shows, as expected no signals of Cl, as test was run in deionized water. In this case surface appears to be oxidized and is rich in Si (likely from ceramic Si3N4 ball).

The results shown in Figures 4-8 can be summarize as follows: (i) a solution of 50/50 wt% $NaClO_4$ to H_2O promotes wear when increasing the wear volume by over 45% in the tribological test; (ii) friction is significantly reduced by brine, compared with water; (iii) chlorine is detected in the wear track (<3 at%); and (iv) friction and wear data, combined with

chemical analysis indicate that in comparison to water, the brine favors a sacrificial wear mechanism, meaning that friction is reduced at the expense of higher wear.

The conclusion of these experiments is clear: brine accelerates wear by chemical reaction leading to a sacrificial wear mechanism. Although the materials used in Mars exploration may be resistant to chemical corrosion from brines in static conditions, mechanical wear only have to remove a few nanometers of oxide to accelerate the corrosion. Tribocorrosion should not be overlooked in selecting materials or special protective treatments for landed spacecraft and structures that will support surface long-term operations for the human exploration of Mars, and in particular for the wheels of the Martian rovers that will operate for long-term in the harsh conditions of Mars.

Further studies are needed to consider other important components of the Mars surface environment that can affect this interaction such as: the effect of oxidants, the effect of radiation on their oxidizing properties and the possible catalytic effects of the minerals present in the Martian regolith, the diurnal thermal changes and variation in ambient humidity.

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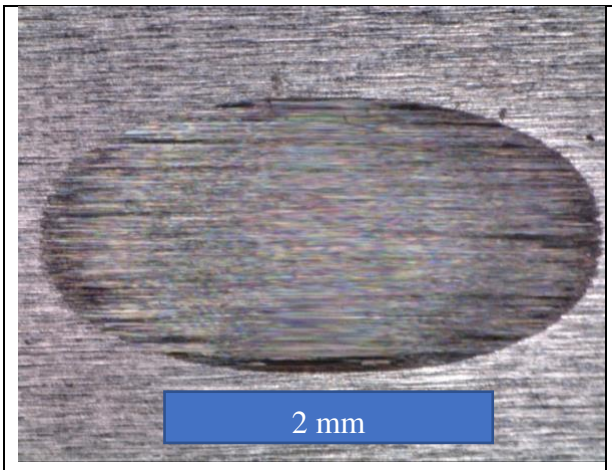
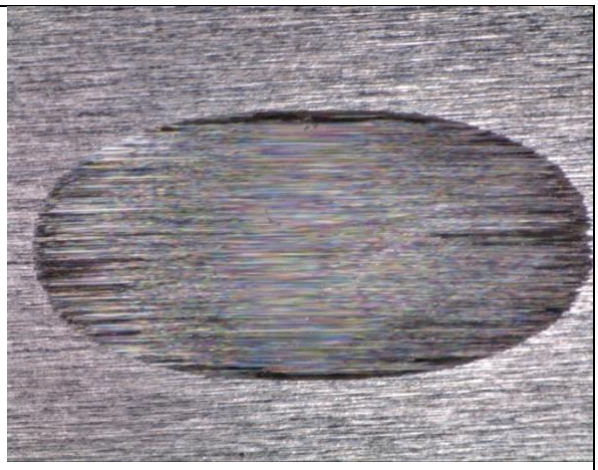


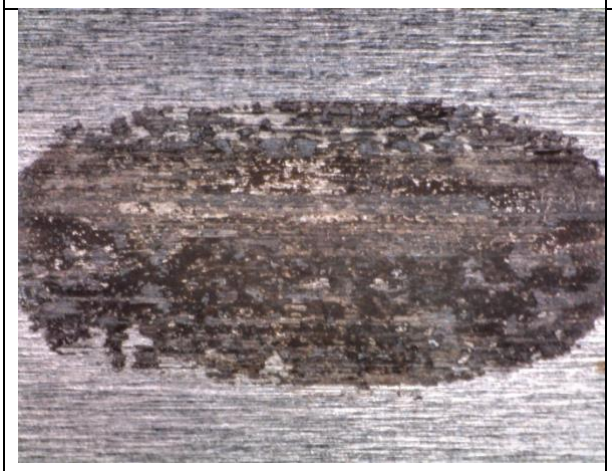
TN07 Brine

(a)



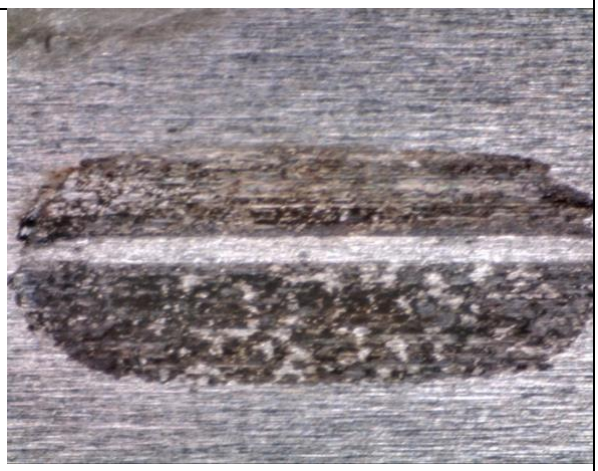
TN09 Brine

(b)



TN08 Water

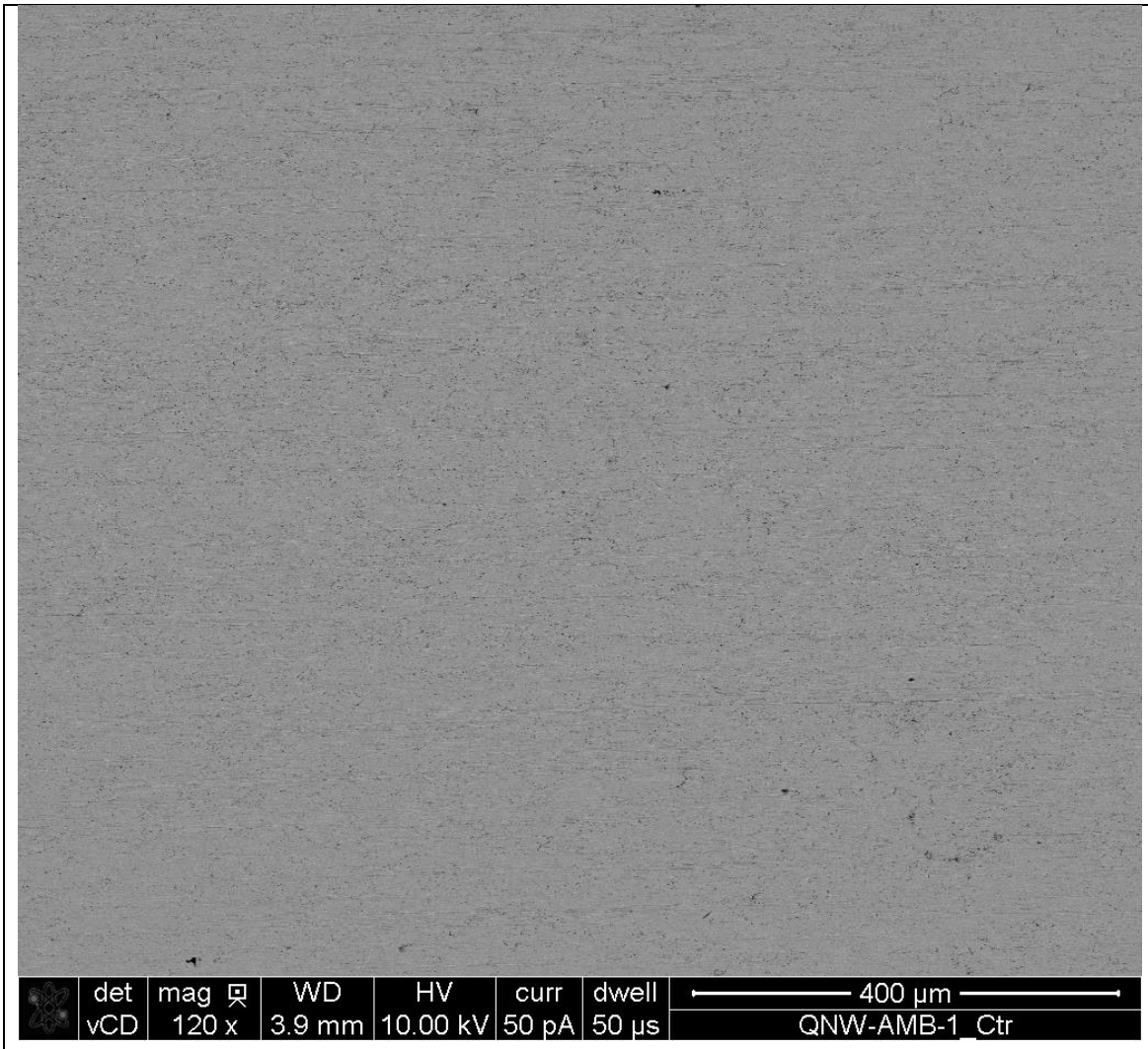
(c)



TN10 Water

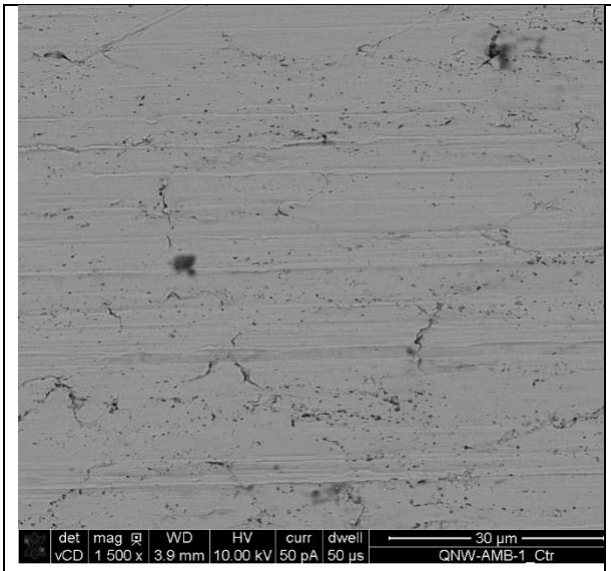
(d)

286 **Figure 4.** (a) Friction data (scale shown in Figure 2).

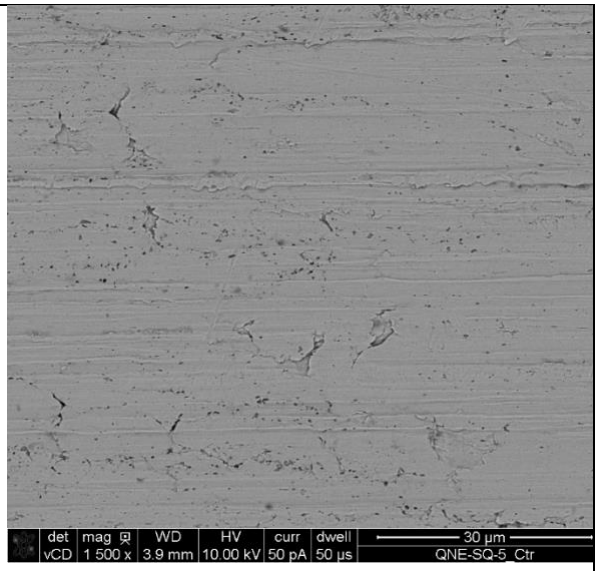


(a) Reference Sample 1

(ambient conditions) at low magnification

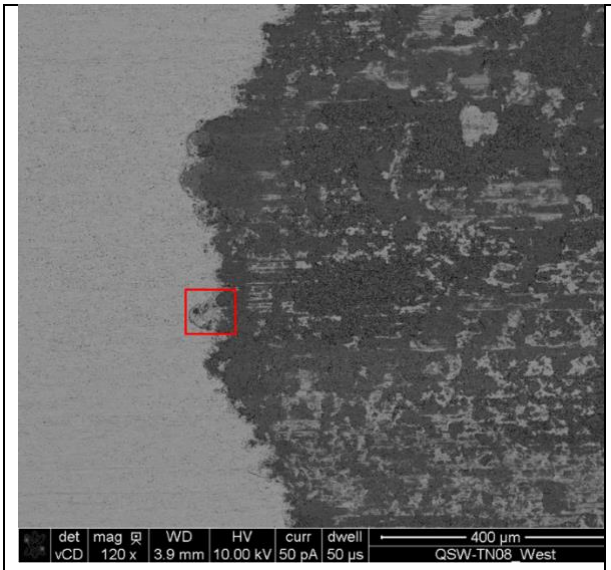


(b) Reference Sample 1 (ambient) at high magnification



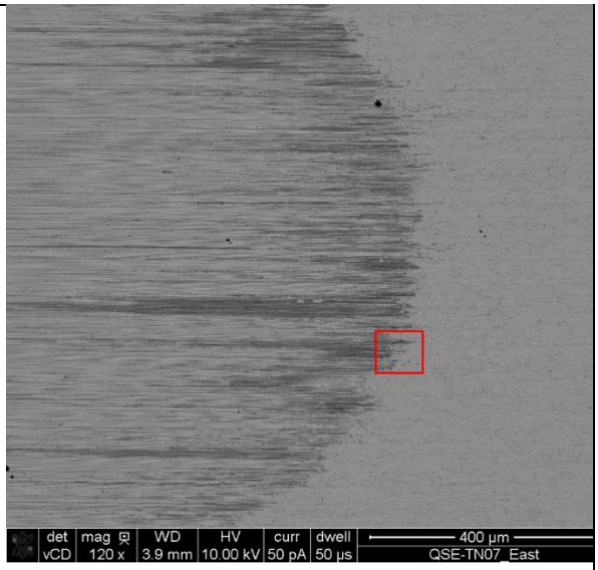
(c) Reference sample 2 (SpaceQ Brine) at high magnification

287 **Figure 5.** Reference samples (scale shown in the figures)



TN08 Water

(a)

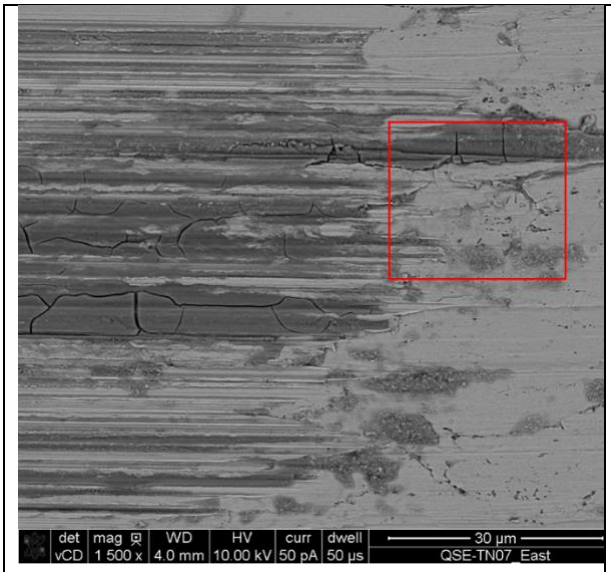


TN07 Brine

(b)

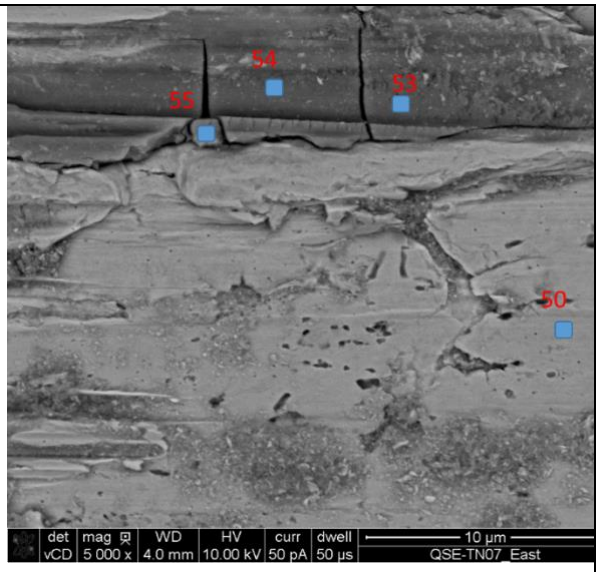
288 **Figure 6.** SEM overview of experiments (a) TN08 (water); and (b) TN07 (brine)

289



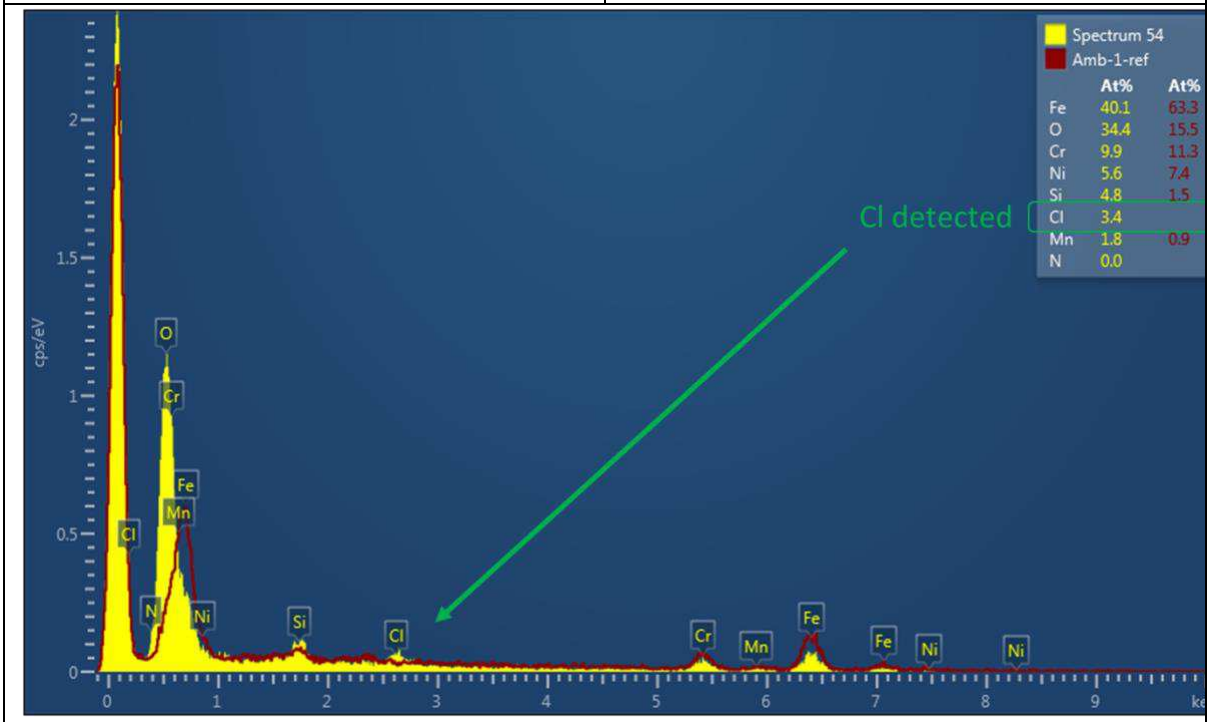
TN07 Brine Edge of Wear Mark

(a)



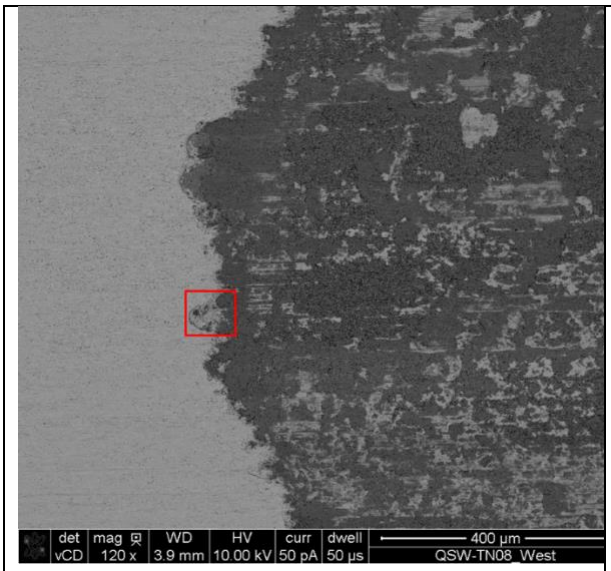
TN07 Brine High Magnification

(b)



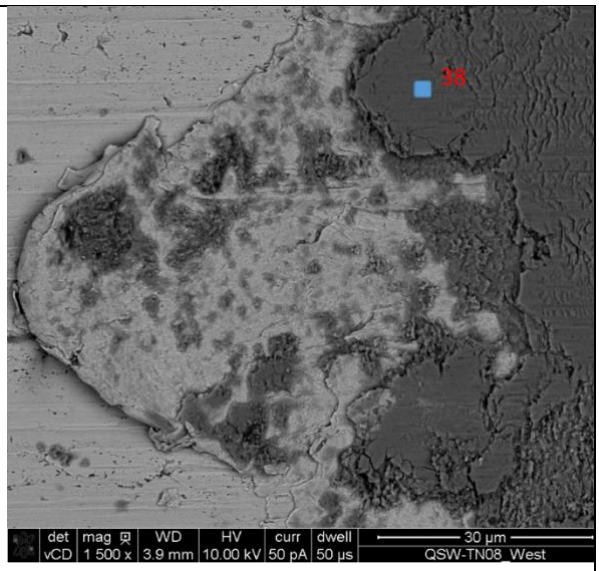
(c)

Figure 7. Detection of Cl in test with Brine.



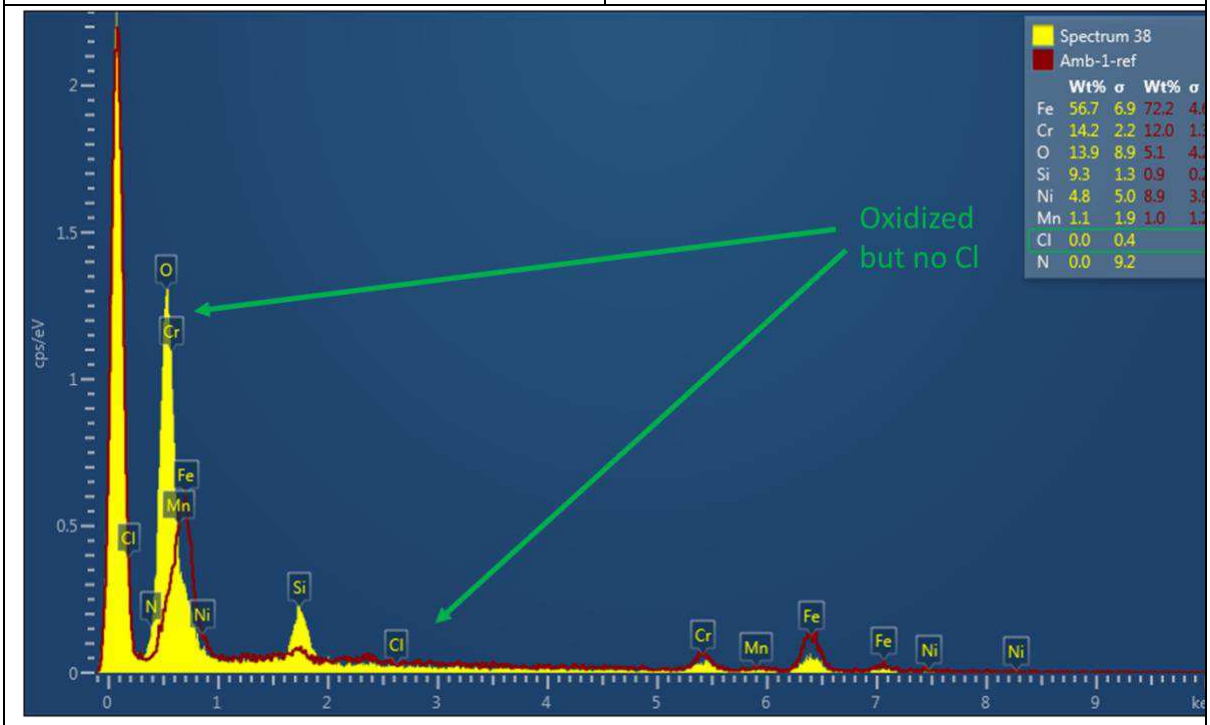
TN08 Water Edge of Wear Mark

(a)



TN08 Water High Magnification

(b)



(c)

Figure 8. No Cl detected from water test.

MATERIALS AND METHODS

The Effective Ground Pressure (EGP)

Technical specifications of the Mars Exploration Rovers (Spirit and Opportunity) and Curiosity wheels:

Curiosity (Mars Science Laboratory)

Mass = 960 kg

Rover Weight on Mars = 3572 N

Average Weight per Wheel = 595.3 N

Wheel Center Diameter = 0.500 m (with cleats)

Wheel Outer Diameter = 0.465 m (with cleats)

Wheel Width = 0.400 m

Spirit and Opportunity

Mass = 176.5 kg

Rover Weight on Mars = 656.7 N

Average Weight per Wheel = 109.45 N

Wheel Center Diameter = 0.262 m (with grouser bars)

Wheel Outer Diameter = 0.232 m (with grouser bars)

Wheel Width = 0.16 m

The cross-sectional area of each wheel's contact patch with the Ground Plane are 0.0173 m^2 for Spirit and Opportunity; and 0.0901 m^2 for Curiosity.

The effective ground pressure (EGP) metric is defined as the average pressure under the average wheel. The average weight on a wheel is first found by dividing the total vehicle weight on a planetary body by the number of wheels. The EGP is found by dividing the average weight by the cross sectional area of the wheel's contact patch on the ground plane, after the wheel has sunk into a terrain so as to have a contact patch length of one wheel radius. In the case of non-cylindrical tires, the largest radius, usually at the mid-plane is used.

When the wheel's periphery has cleats, lugs, or grouser bars; a determination is made as to the amount of their height added to the tire diameter, based on the projected area ratio of these tractive elements.

The EGP defined as the average weight over the CS Area are similar in the MER and Curiosity:

EGP (Opportunity)= 109.45 N / 0.0173 m2 = 6335 N/m2= 6335 Pa (0.919 psi)

EGP (Curiosity) = 595.3 N / 0.0901 m2 = 6609 N/m2= 6609 Pa (0.959 psi)

Brine Corrosion tests

The following steps were followed: (i) the chamber was first vacuumed and filled with pure CO_2 gas till it reached 6 mbar; (ii) water was injected to create water vapor in the atmosphere; (iii) the LN_2 was allowed to flow through the cooling plate which reached a temperature of 260 K and the temperature slowly increases due to the thermal equilibrium with the ambient lab conditions; and (i) the experiment was stopped by opening the relief valve. The salt samples deliquesced as the salt in it absorbed water from the atmosphere and formed brines.

Simulation of martian near surface water cycle and thermal studies

The experiments for brine corrsion under simulated Martian enviroment were conducted in the SpaceQ chamber (figure 9), a cubical chamber with an internal volume of 27l. This chamber can simlaute temperatures ranging from 163 K to 423 K, pressures ranging from 10^{-5} mbar to ambient conditions and relative humidity from 0% to 100%. Here we inject traces of water to control the relative humidity using a stainless steel syringe connected to a ball valve in turn connected to the chamber wall with the means of a swagelok connector. So, the water can be injected several times during the experiment and as the ball valve opens the water is sucked into the chamber and vaporises [27].

We use sodium perchlorate salt ($NaClO_4$) (ACS reagent, ≥98.0%, 410241) bought from Sigma Aldrich and the Mojave Martian Simulant (MMS-1) as Mars regolith simulant[29]. We use the "unsorted" grade bought from The Martian Garden-Austin Texas. The water used in the injection is from Sigma which is filtered at 0.1µm to guarantee sterility and cleanness (W4502). We have conducted tests in SpaceQ Martian environment for two sets of samples prepared (i) one with pure sodium perchlorate ($NaClO_4$) and one with a mixture of (ii) MMS + 10% $NaClO_4$ and exposed to Martian conditions. The samples were placed inside the SpaceQ and it was simulated for the near surface water cycle condition as it will experience on Mars[30]. The chamber was first vacuumed and filled with pure CO_2 gas till it reached 6 mbar. Then, water was injected to create water vapor in the atmosphere till RH reached 40% then the liquid nitrogen (LN_2) is allowed to flow through the cooling plate which reached a temperature of 260 K and then temperature it let slowly to increase to ambient lab conditions due to the thermal equilibrium. The experiment is stopped by opening the relief valve and the samples were weighed (shown in Table 4). The samples with pure $NaClO_4$ were deliquesced and the samples

with mixture with the simulant were in a hydrated state as it absorbed water from the atmosphere.

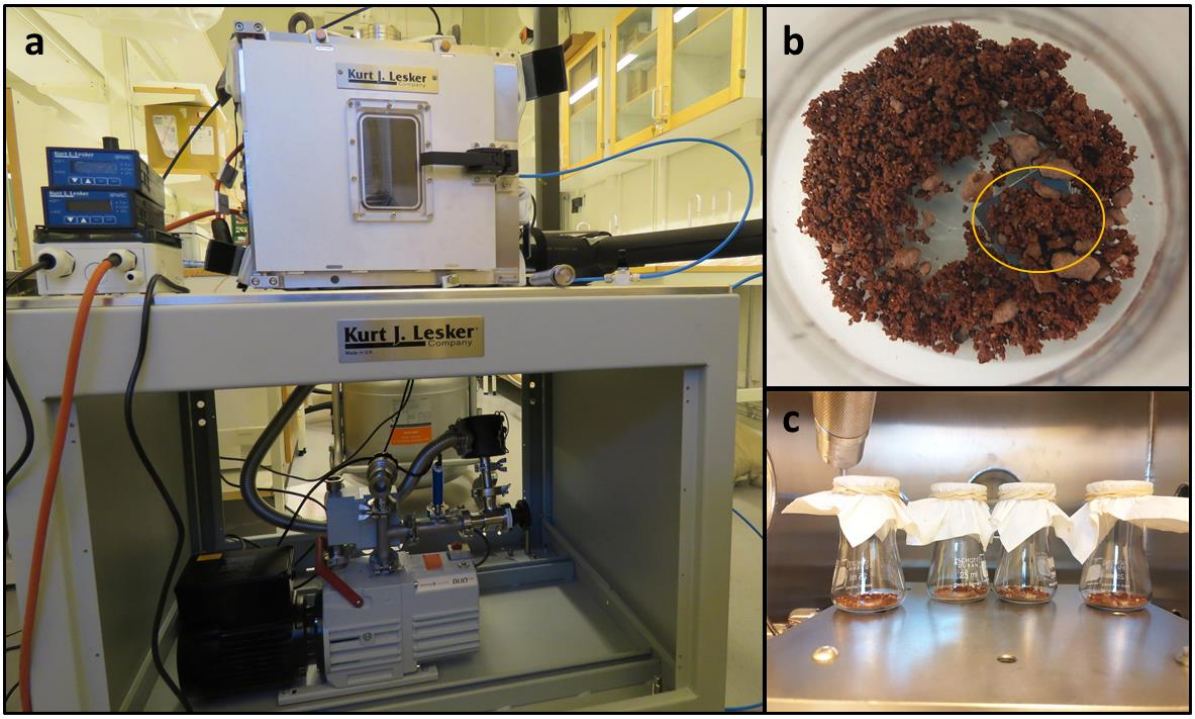


Figure 9. Experimental setup (a) Overview of the SpaceQ chamber (b) mixture of soil and salt on a steel sample (c) samples placed on the cooling plate before experiment

Table 4: Summary of the weights for samples placed inside SpaceQ Martian environment

Weight (g)	**Case 1**	**Case 2**

	($NaClO_4$ salt)			(MMS soil + 10% $NaClO_4$ salt)		
	11R51	**SS4301**	**S235**	**11R51**	**SS4301**	**S235**
Initial	1.55 g	1.59 g	1.53 g	1.69 g	1.77 g	1.74 g
Final	2.32 g	2.33 g	2.37 g	1.83 g	2.04 g	1.89 g
Increase in weight	0.77 g	0.74 g	0.84 g	0.14 g	0.27 g	0.15 g

388

389

390 **Tribocorrosion tests**

391

392 The following materials were used:

393 • **Material 1:** Stainless steel (Sandvik 11R51)

394 • **Material 2:** Ceramic bearing ball (Si3N4), 10 mm diameter.

395 • **Fluid medium:**

396 ○ "Brine" (50/50 wt% solution of NaClO4+H2O).

397 ○ "Water" (deionized water, H2O)

398 The following methods have been used

399 • **Tribological experiment**: Optimol SRV, normally used for material development,

400 (screening of surface-lubricant combinations)

401 ○ Applied Load 25 N. Contact pressure ~1 GPa.

402 ▪ Selected based on reasonable assumption: Few kg load onto "pointy but not sharp"-

403 rock…

404 ○ Ambient temperature, Atmosphere: N2 > 95%, remaining is O2

405 ○ Wear test for 54 000 cycles (2 mm reciprocal, = 216 m sliding distance)

- **Surface analysis**
  - A Zygo NewView 7300 **3D optical profilometer** (Zygo Corporation, Middlefield, CT, USA) was employed for surface topography analysis. Measurements were conducted under both 10x magnification. The surface profilometry data was analysed using MountainsMap Premium 7.4 (Digital Surf, France).

Scanning Electron Microscopy (**SEM**) and Electron Dispersive X-ray Spectroscopy (**EDS**) was employed for high magnification surface analysis including chemical (elemental) analysis: Magellan 400 FEG-SEM (FEI Company, Eindhoven, The Netherlands). EDS was performed using an X-Max 80 mm2 X-ray detector (Oxford Instruments, Abingdon, UK) operated at 10 kV and 50 pA.

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Author contributions. JMT: Conceptualization, Supervision, Investigation, writing original draft, funding acquisition, resources; MPZ: Conceptualization, methodology, supervision, investigation, writing original draft, funding acquisition; EN: Tribocorrosion and corrosion experiments, writing, review & editing; AVR: Corrosion experiments, and experimental

support to tribocorrosion experiments, writing, review & editing; AB**:** Writing, review & editing.

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.

Figures

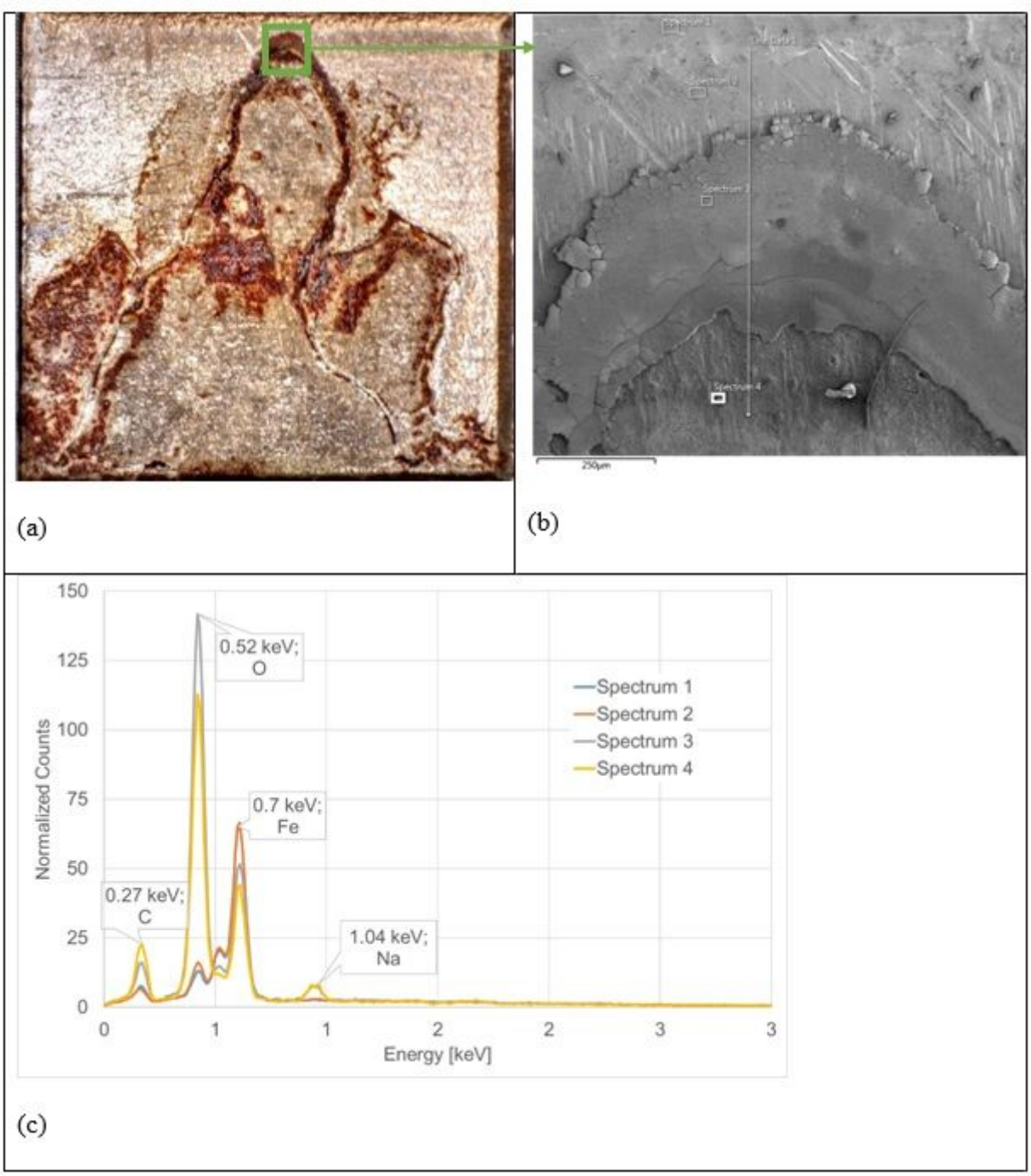


Figure 1

(a) Microscope image of 10x10 mm Regular Steel sample. (b) High magnification SEM image showing location of EDS analyzed regions. (c) results of EDS analysis confirming corrosion by detection of Na and O in Spectrum 3 and 4.

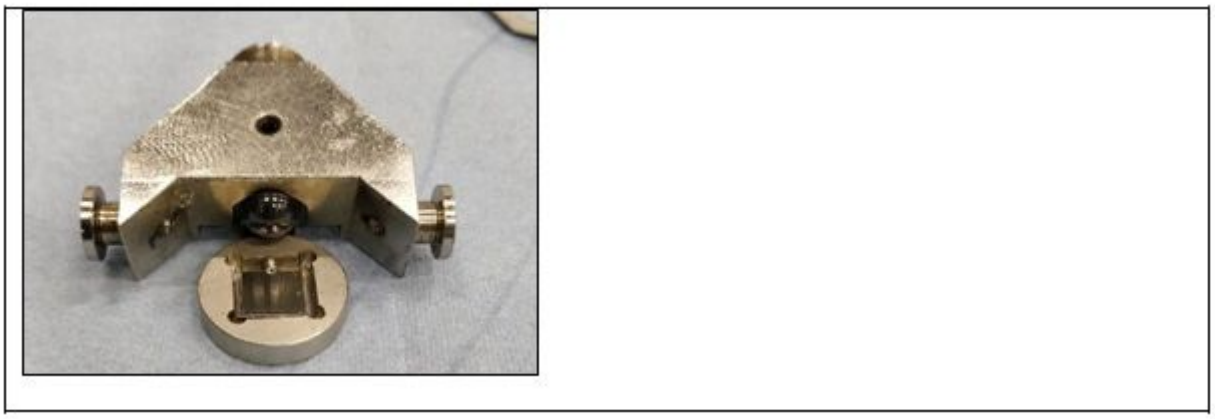


Figure 2

Setup of tribological experiment showing ceramic ball and stainless-steel plate in their respective sample holders.

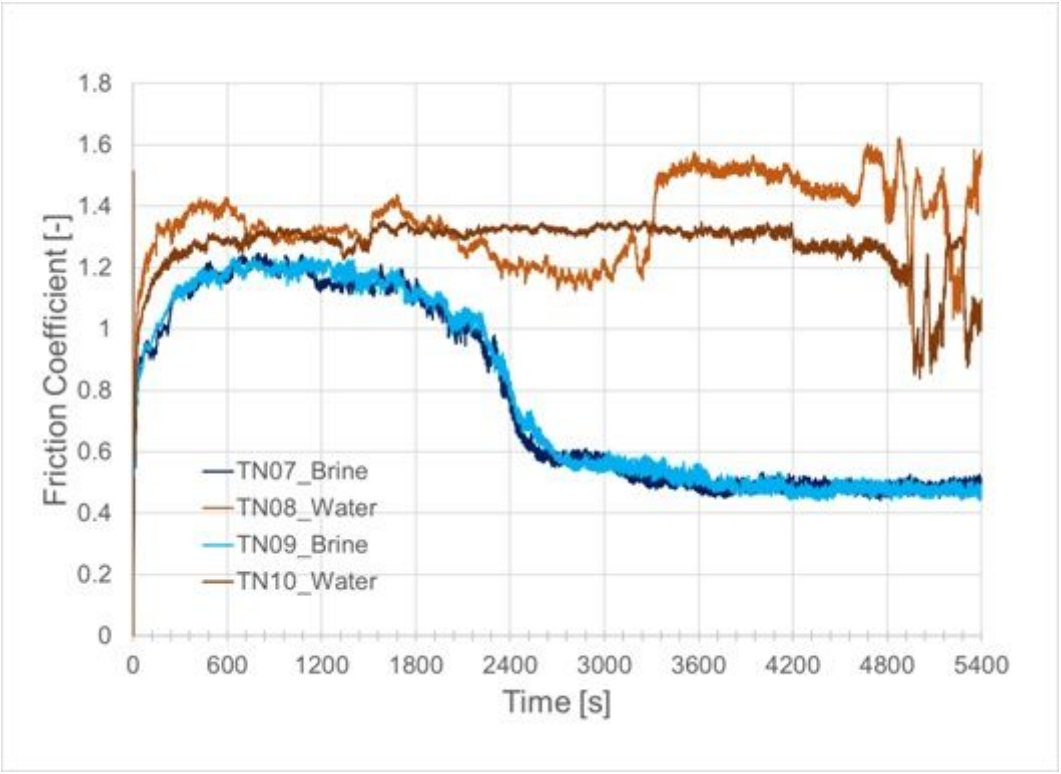


Figure 3

Friction data indicates transition to corrosive wear around Time=1800 s when immersed in brine.

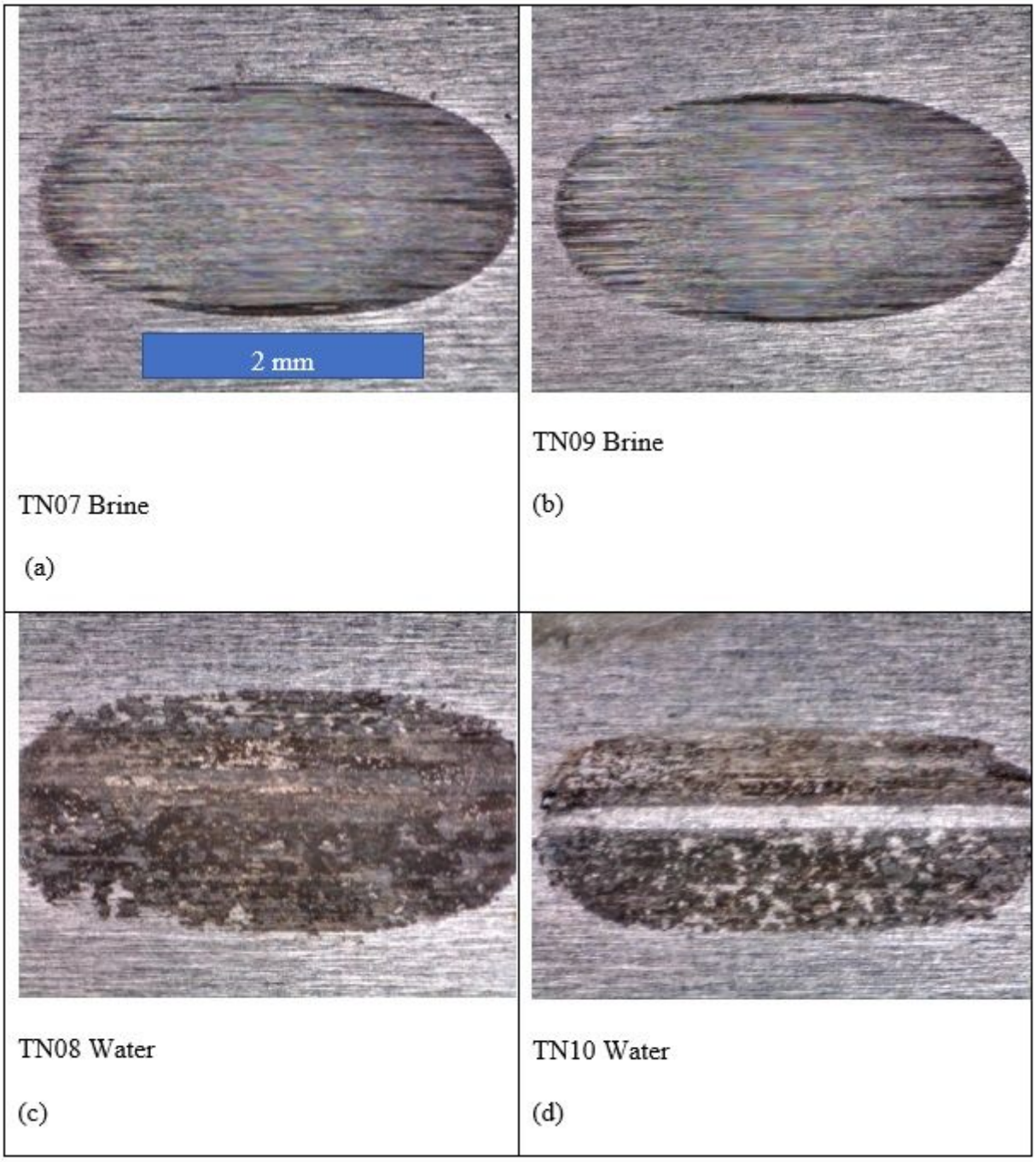
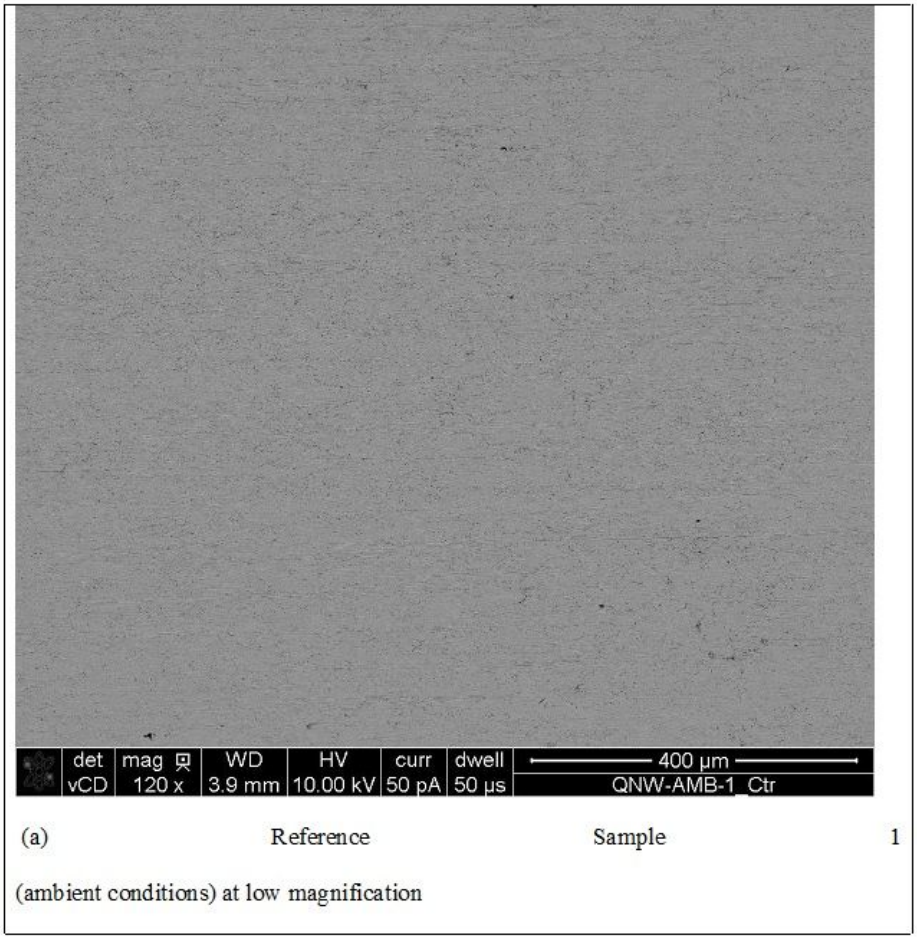
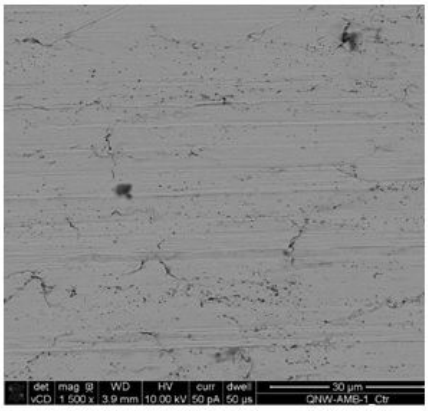


Figure 4

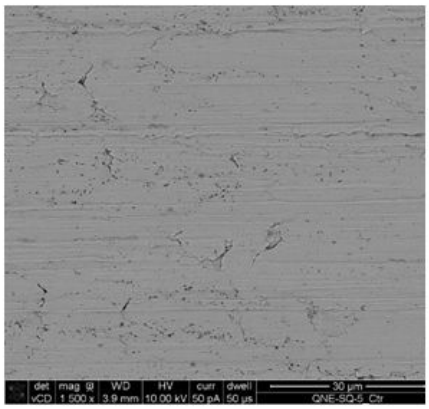
(a) Friction data (scale shown in Figure 2).



(a) Reference Sample 1 (ambient conditions) at low magnification



(b) Reference Sample 1 (ambient) at high magnification



c) Reference sample 2 (SpaceQ Brine) at high magnification

Figure 5

Reference samples (scale shown in the figures)

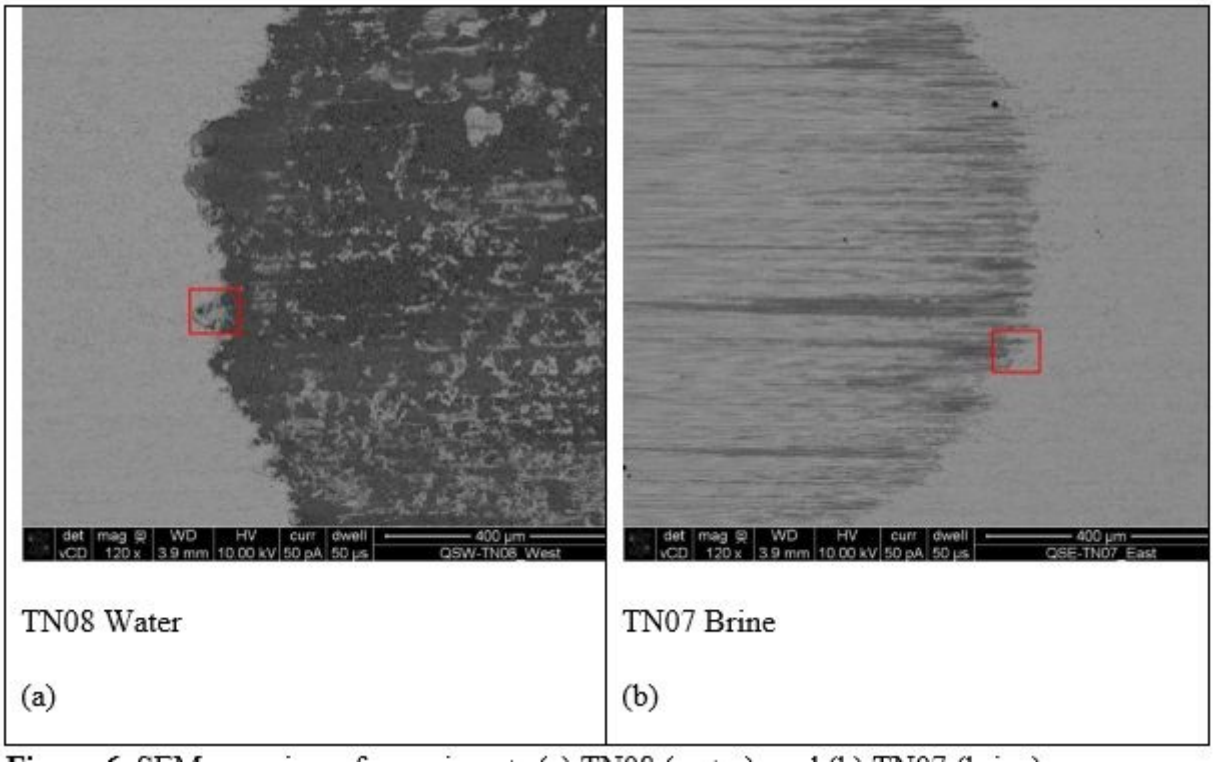


Figure 6

SEM overview of experiments (a) TN08 (water); and (b) TN07 (brine)

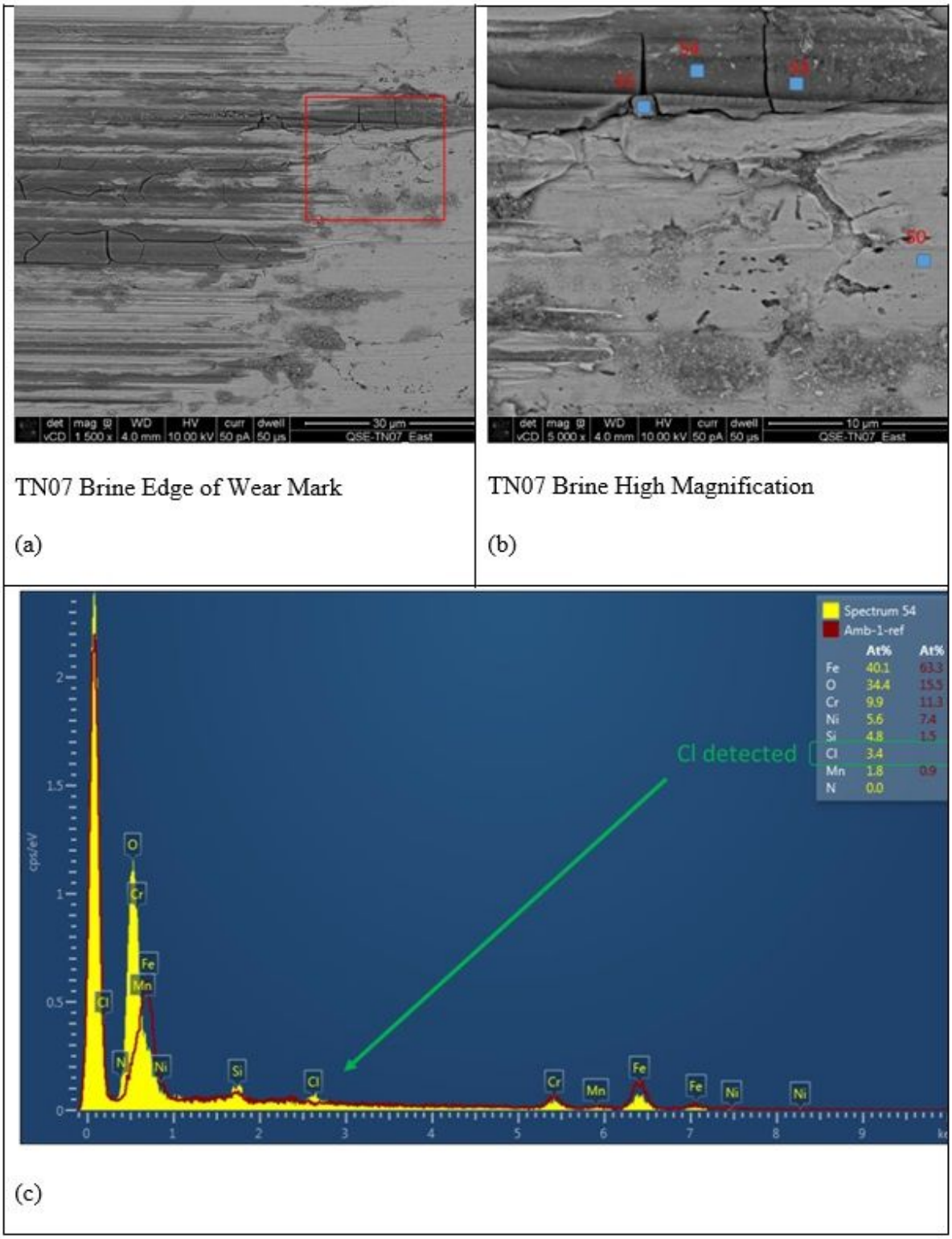


Figure 7

Detection of Cl in test with Brine.

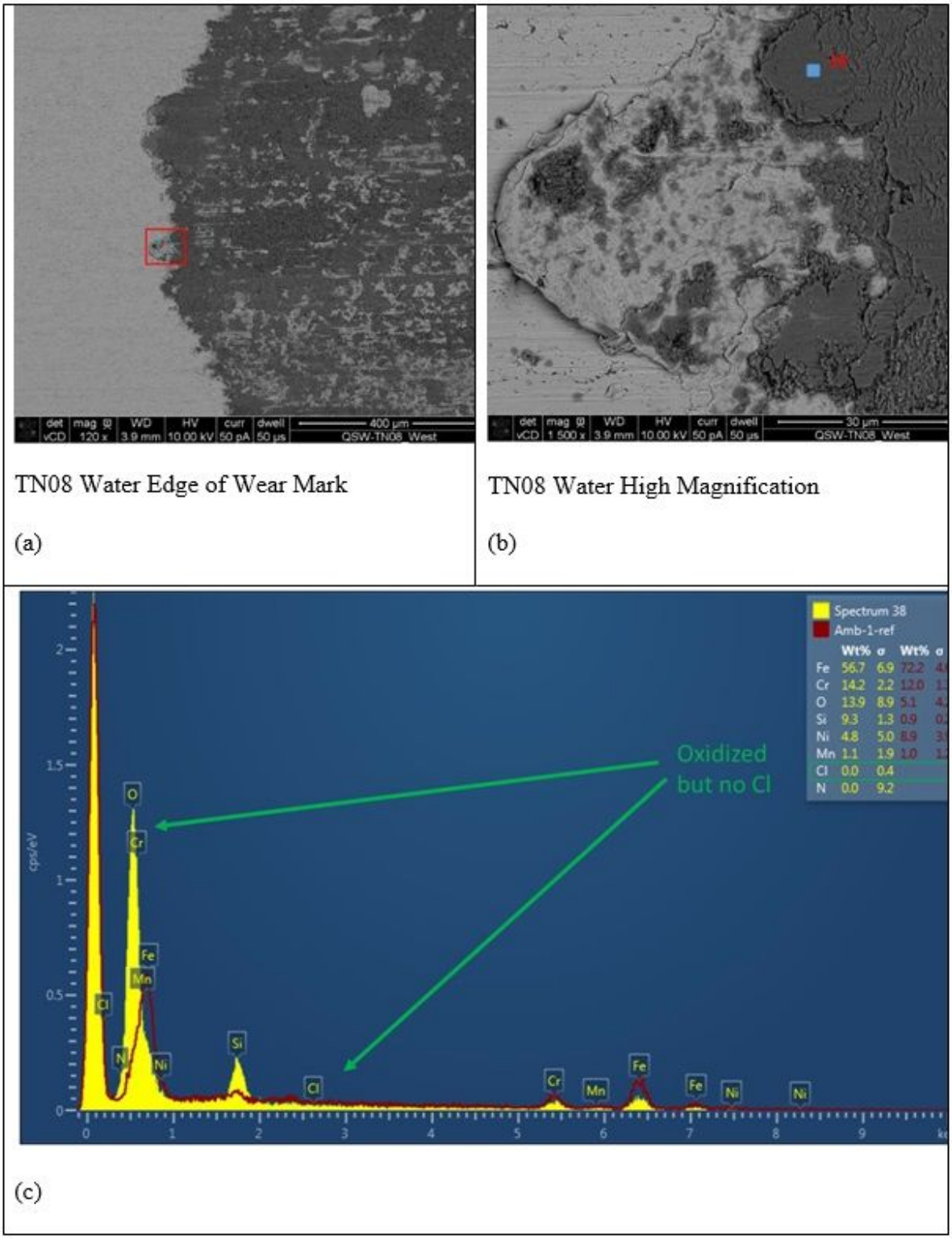


Figure 8

No Cl detected from water test.

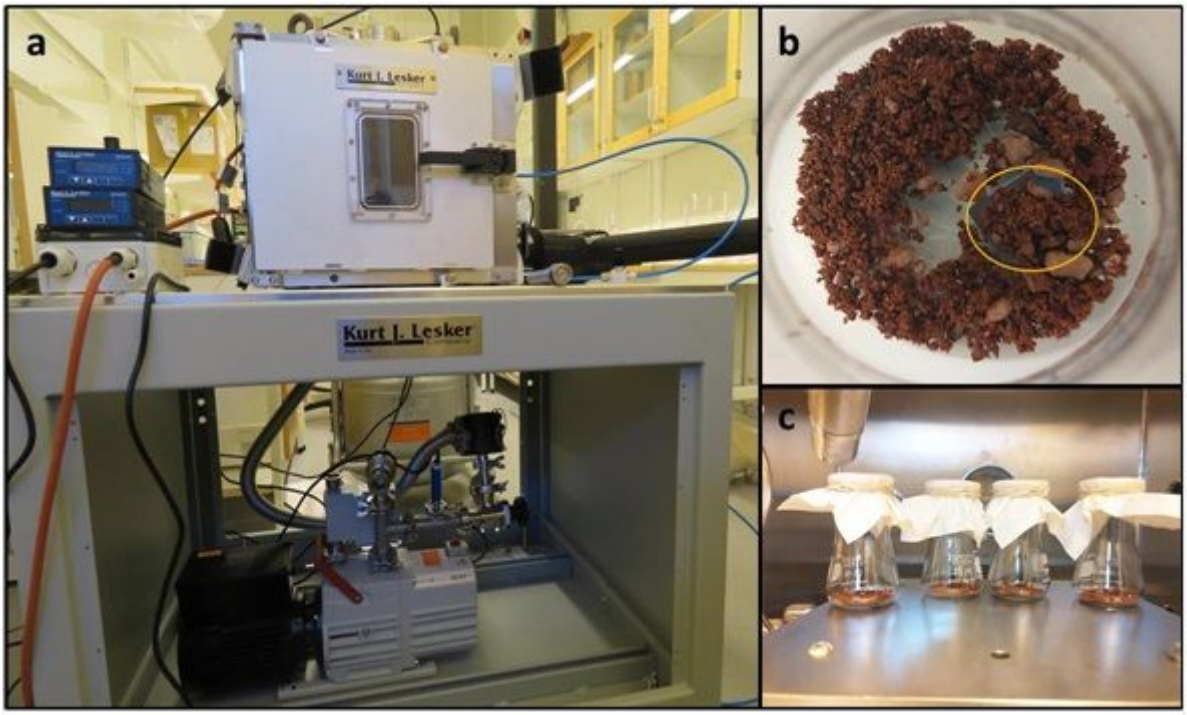


Figure 9

Experimental setup (a) Overview of the SpaceQ chamber (b) mixture of soil and salt on a steel sample (c) samples placed on the cooling plate before experiment