094897

Journal of The Electrochemical Society, **152** (1) B23-B29 (2005)
0013-4651/2004/152(1)/B23/7/$7.00 © The Electrochemical Society, Inc.

A Comparison of Release Rates of Cr, Ni, and Fe from Stainless Steel Alloys and the Pure Metals Exposed to Simulated Rain Events

G. Herting,*,z I. Odnevall Wallinder, and C. Leygraf**

Department of Materials Science and Engineering, Division of Corrosion Science, Royal Institute of Technology, SE-100 44 Stockholm, Sweden

The aim of this study is to demonstrate differences in metal release rates of Cr, Ni, and Fe from pure metals and stainless steels alloys (grades 304 and 316) exposed to identical simulated rain events. Panels were exposed to two 8 h continuous rain periods, separated by a 40 day dry period, in a specially designed rain chamber which permits artificial rain of known composition to be introduced at a given intensity. The study is intended to provide further knowledge of the behavior of stainless steels exposed to atmospheric corrosion and to show the discrepancy between estimated release rates based on nominal alloy composition and actual, measured release rates. Release rates of Fe and Ni were found to be substantially higher from the pure metals than from the stainless steels due to the presence of a chromium-rich surface film. The release rate of Cr was similar for stainless steel alloys and pure chromium. X-ray photoelectron spectroscopy investigations after single-rain events showed chromium to be enriched in the surface film upon rain exposure resulting in decreasing release rates of Cr, Ni, and Fe. Comparison between actual release rates of alloy constituents and calculated rates based on the pure metals and the nominal alloy composition, showed calculated data to substantially overestimate release rates of Ni and Fe.
© 2004 The Electrochemical Society. [DOI: 10.1149/1.1834901] All rights reserved.

Manuscript submitted March 30, 2004; revised manuscript received December 22, 2004. This is in part Paper 459 presented at the Orlando, FL, Meeting of the Electrochemical Society, Orlando, FL, October 12-16, 2003. Available electronically December 7, 2004.

The unique combination of mechanical properties and high corrosion resistance makes austenitic grades of stainless steel suitable and commonly used materials in external applications such as bridges, facades, and roofing. Traditionally, type 304 stainless steels (typically 18Cr8Ni) have mainly been used for roofs and exterior facades in urban environments and the more highly alloyed type 316 stainless steels (typically 18Cr10Ni2Mo) are used mainly in marine environments but also in traffic and highly polluted industrial environments. The most common stainless steels used today for roofing applications in these environments are type 316 stainless steels.[1] Even though the corrosion resistance of stainless steels is well known, information of corrosion rates and in particular, on metal release rates is very limited. Reported corrosion rates of stainless steels, 0.1 mg m^{-2} y^{-1} for grade 316[2] and 0.2-0.5 mg m^{-2} y^{-1} for grade 304,[2] are orders of magnitude lower than those of other traditional structural materials such as copper, zinc, and carbon steel. Most of the atmospheric corrosion studies on steels were performed over several years (5 to 32 years) in polluted and coastal areas and illustrate clearly the importance of chromium, nickel, and molybdenum to the corrosion resistance of stainless steels.[3-6] Recently, surface finish has also been shown to strongly influence the corrosion resistance.[7]

Total release rates of alloy constituents from stainless steels in different corrosive test solutions have been reported to range from less than 0.3 to 3.4 × 10^4 mg m^{-2} y^{-1}.[1,8-10] However, data on release rates of individual alloy constituents from stainless steel exposed to outdoor conditions are scarce,[11] and comparisons between release rates from alloys and the pure metals in identical exposure conditions seems to be unavailable. As a result, estimates of metal release rates from alloys have so far erroneously been based either on corrosion rates of stainless steel or, if available, on release rate data from pure metals multiplied by the nominal fraction of the metal in the alloy composition.

The aim of this study is to demonstrate differences in release rates of chromium, nickel, and iron from stainless steel alloys and from the pure metals exposed under identical conditions, and to illustrate that, for stainless steels, there are large discrepancies between measured data and data calculated on the basis of the nominal composition of the alloys. All results are based on laboratory investigations in a specially designed chamber which permits artificial rain of known composition to be introduced at a given rain composition and intensity. In addition, the gradual development of more corrosion resistant surface films on the alloys during single rain events is illustrated by means of X-ray photoelectron spectroscopy (XPS).

Experimental

Materials.—Five different materials were investigated within this study, two stainless steels (grade 304 and 316), pure nickel, pure electrolytic chromium, and pure iron. The stainless steels were supplied by Outokumpu Stainless, Sweden, with 2B surface conditions, *i.e.*, cold-rolled, heat-treated, pickled, and skin-passed. These grades and surface condition are representative for external applications on buildings. Nickel and electrolytic chromium were supplied by Eurofer, Belgium, and iron by Stena Stal AB, Slovak Republic. Alloy and metal compositions are given in Table I. The iron and nickel samples were cold rolled while that of the chromium samples was very coarse and uneven with large grain sizes.

Duplicate panels, 100 cm^2 (approximately 20 cm^2 for chromium due to production difficulties), were exposed both as-received, *i.e.*, 2B surface state, and abraded (1200P SiC-paper). Abraded panels were prepared in order to obtain more uniform surface conditions to increase reproducibility. The exposure of abraded panels was preceded by an ageing period of approximately 72 h in a desiccator.

All panels were ultrasonically cleaned in acetone and isopropyl alcohol before exposure. Each as-received panel was ultrasonically cleaned in acetone (3 min) and isopropyl alcohol (3 min). Prior to exposure, the abraded panels were ultrasonically immersed for 6 min in acetone and isopropyl alcohol, respectively, sprayed with

Table I. Composition of stainless steel alloys and the pure metals (wt %).

Grade	C	N	Cr	Ni	Mo	S	Fe
SS 304	0.04	0.06	18.3	8.7	-	<0.002	Balance
SS 316	0.04	0.04	17.2	10.7	2.2	<0.002	Balance
Fe	0.06	0.006	-	-	-	0.014	Balance
Ni	0.075	-	0.01	Balance	<0.01	0.001	0.08
Cr	0.006	0.011	Balance	-	-	0.017	0.07

- means below detection limit.

* Electrochemical Society Student Member.
** Electrochemical Society Active Member.
z E-mail: herting@kth.se

14608

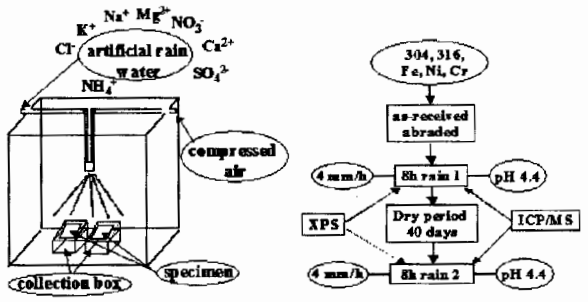

Figure 1. Schematic illustration of the rain-simulating chamber (left) and the experimental setup (right).

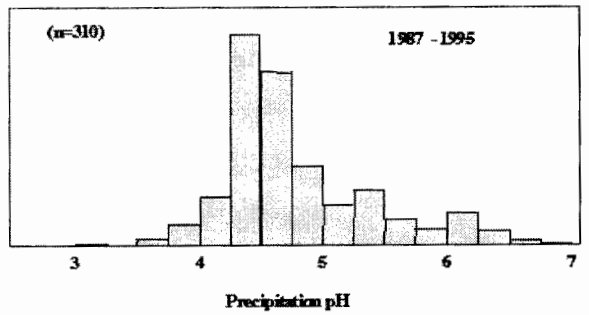

Figure 2. Distribution of annual mean rain pH for both urban and rural environments of Europe (from Ref. 13). Data are based on 310 observations between 1987 and 1995.

ethanol and dried with nitrogen gas. This procedure was used to ensure the removal of any particles remaining from abrasion.

The back of the panels was covered with adhesive tape (Nitto, heavy duty pipe wrap vinyl tape 51) and the edges covered with beeswax in order to obtain a well-defined single-sided surface area. The panels were then mounted on Plexiglas fixtures inclined 45° from horizontal, and placed in a rain-simulating chamber, Fig. 1. All panels were exposed to two consecutive 8 h rain episodes separated by a 40 day dry period. The purpose of this procedure was to expose the panels to simulated rain events representative of outdoor conditions and to illustrate the effect of dry periods.

Rain simulation.—The composition of the artificial rain, given in Table II, was obtained by mixing NH_4NO_3, Na_2SO_4, K_2SO_4, $MgSO_4 \cdot 7H_2O$, $CaCl_2 \cdot 2H_2O$, and H_2SO_4, all analytical grade, with ultrapure water (18.2 MΩ cm^{-1}).

The composition and pH of the artificial rain are average values representative of the central and southern part of Sweden.[12] A pH of 4.4 is also representative of European conditions, Fig. 2.[13] The rain intensity was set at 4 mm/h, since typically more than 80% of all rain events during a year in Sweden show an intensity of less than 6 mm/h, Fig. 3.[12] Rain chamber simulations with artificial rain have previously been shown to successfully reproduce outdoor conditions.[14]

Runoff water was collected at 30 min and 1 h and then every hour during the 8 h exposure. The volume and pH of runoff water from each panel were measured, and the water poured into acid-cleaned polyethylene bottles and adjusted with ultrapure HNO_3 to a pH below 2. The panels were then dried in the open air and left for 40 days in a desiccator at a relative humidity below 20% before being exposed again to another identical rain event.

Metal analysis.—The total concentration of iron, nickel, and chromium in the runoff water was analyzed using inductively coupled plasma/mass spectrometer-dynamic reaction cell, ICP/MS-DRC (Perkin Elmer Elan 6100). The detection levels were 2, 0.1, and 0.07 μg/L for iron, chromium, and nickel, respectively. In addition, released concentrations of molybdenum (detection limit 0.1 μg/L) were continuously measured from the stainless steels. All metal analyses were performed at the Environmental Research Laboratory, Swedish University of Agricultural Sciences, Umeå, Sweden. The metal release (in ng cm^{-2} h^{-1}) rates were calculated from metal concentrations, sampling volumes, and surface area. All results are given as mean values and standard deviations of duplicate samples.

Surface analysis.—Analysis of changes in composition of the outermost surface layer of as-received and abraded stainless steel panels (grades 304 and 316) were performed after exposure to a single rain event, using X-ray photoelectron spectroscopy (XPS, Kratos AXIS HS). Samples were exposed and analyzed according to the same time-schedule as for the metal release investigations. Wide scans and detailed scans (pass energy of 80 eV) of Cr 2p, Ni 2p, Fe 2p, Mo 3d, C 1s, O 1s were obtained with a monochromatic Al Kα X-ray source (1486.6 eV) operated at 300 W (15 kV/20 mA). The area of analysis was approximately 0.4 mm^2. Sensitivity factors (Cr 2p-2.3 and Fe 2p-3.0) supplied by Kratos were used to investigate the chromium content of the surface film defined as $[Cr_{ox}/(Cr_{ox} + Fe_{ox})]$.

Results and Discussion

Previous investigations on the release of Cr, Ni, and Fe from stainless steel alloys of two different grades (304 and 316) have shown the metal release rate into rainwater to be nonproportional to the corresponding metal content of the stainless steel; Fe was shown to be preferentially released from the surface of both grade 304 and grade 316 stainless steels.[9,11] Cr and Ni were also released from both grades, but at rates orders of magnitude lower than Fe. The following paragraphs show consistent results with previous measurements and emphasize kinetic aspects of metal release and the difference in release rates of Cr, Ni, and Fe from pure metals and stainless steel alloys. In addition, release rates of Mo from stainless steel are discussed.

Comparison between release rates of alloy constituents from grade 304 and grade 316 stainless steels.—Results from this study for the stainless steels are consistent with previous field and laboratory findings[14] showing slightly higher release rates of Cr and Ni from both as-received and abraded grade 316 compared to grade 304. The difference is illustrated for as-received surfaces in Fig. 4 (left) after an 8 h continuous rain event. Similar release rates of Fe were determined for grades 304 and 316, also in agreement with field data.[14] Abraded panels show the same tendency for the two grades but with significantly higher release rates, Fig. 4 (right). The

Table II. Composition of artificial rain.

SO_4^{2-}-S (mg/L)	Cl^- (mg/L)	NO_3^--N (mg/L)	NH_4^+-N (mg/L)	Na^+ (mg/L)	K^+ (mg/L)	Mg^{2+} (mg/L)	Ca^{2+} (mg/L)	pH
1.17	0.36	0.56	0.56	0.23	0.12	0.12	0.20	4.4

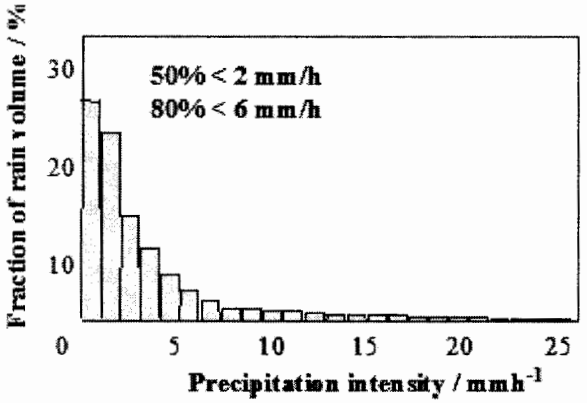

Figure 3. Representative distribution of rainfall intensities during a year in Sweden (from Ref. 12).

reason for the large discrepancy in release rates between as-received and abraded surfaces is explained by a significant reduction in the thickness and barrier properties of the surface oxide layer after abrasion. Similar findings were observed for all sampling periods and both surface conditions. This is discussed in the following paragraphs.

Total release rates of Cr, Ni, and Fe from stainless steel and pure metals-kinetic aspects.—Total release rates of Cr, Ni, and Fe were continuously measured from stainless steel alloys and from pure metals during two consecutive 8 h rain episodes separated by a 40 day dry period. All results are compiled in Fig. 5 for (a) Cr, (b) Ni, and (c) Fe for the as-received surface conditions.

All as-received surfaces, except pure iron, show higher metal release rates during the initial rain volume (first flush) impinging the surfaces, followed by lower and more constant release rates during subsequent rain volumes. Both rain events show similar behavior, although release rates of the second rain event, particularly initially, were much lower (except for pure iron). Average release rates of Cr, Ni, and Fe are compiled in Table III for the first flush volume (0-8 mm rain) and subsequent rain volumes (8-32 mm) for each material and rain event.

In contrast to the other materials, as-received iron shows the metal release rate to increase without reaching steady state during a rain event. This is explained by poor protective properties of the initial surface oxide on iron and its gradual formation into voluminous corrosion products that are only weakly adherent.[16] These phases provide a poor barrier for rainwater to reach the iron surface and promote the corrosion and the release process. This behavior is in contrast to the formation of relatively corrosion resistant surface oxides on pure chromium, nickel, and stainless steel (see below).

Abraded alloy surfaces, exemplified by grade 304 in Fig. 6, show an increasing release rate of Cr and Fe during the first couple of hours of the first exposure, followed by a decreasing rate during the subsequent rain volume flushing the surface.

This behavior is related to the gradual formation of a more corrosion-resistant surface film triggered by the rain event. The passive film on stainless steel can be said to consist of an inner barrier film enriched in chromium oxides and iron oxides but of low nickel content, and an outer hydroxide film, mainly $Cr(OH)_3$[17] see schematic illustrated in Fig. 7. Nickel is primarily thought to be enriched in a thin alloy layer below the passive film.[17] The presence of nickel and iron in the alloy surface layer adjacent to the barrier layer suggests the presence of defects in the barrier layer, which facilitates transport of these metals through the film.

The gradual formation of a chromium-enriched passive film is illustrated in Fig. 8 with XPS data for abraded surfaces of grade 304 and 316 during a single rain event. The results clearly show an enrichment of chromium in the passive surface film upon rain exposure, with decreasing release rates of Cr, Ni, and Fe as a result, cf. Fig. 6. The enrichment in chromium is somewhat faster for grade 316 compared to grade 304. These results are in agreement with findings in the literature showing the presence of molybdenum, as in grade 316, to enhance the selective dissolution of iron and stimulate the accumulation of chromium in the passive film.[9]

No nickel or molybdenum could be seen in the outermost surface layer with XPS. These surface observations are also in agreement with literature observations[11,16] and consistent with findings that the corrosion resistance in general increases with chromium content of the passive film.[7]

Additional information obtained within this investigation was the release rates of Mo from the stainless steel alloys, illustrated in Fig. 9 for as-received stainless steel grade 316. No measurements were performed on pure molybdenum.

Mo release from grade 316 shows a similar behavior as Cr, Ni, and Fe with an initially high release rate after which the rate becomes much lower and fairly constant (0.16 ng cm^{-2} h^{-1} during the first rain event). It is interesting to note that the release rate of Mo is of the same order of magnitude as release rates of Cr and Ni even though its percentage content in the alloy is much lower, cf. Table I XPS did not reveal the presence of molybdenum in the outermost surface layer which is in agreement with literature findings, showing molybdenum to be enriched in an inner oxide layer.[18]

Total release rates of Cr, Ni, and Fe from stainless steel and pure metals, a comparison.—A comparison in momentary metal release rates from as-received alloys (grades 304 and 316) and pure metals

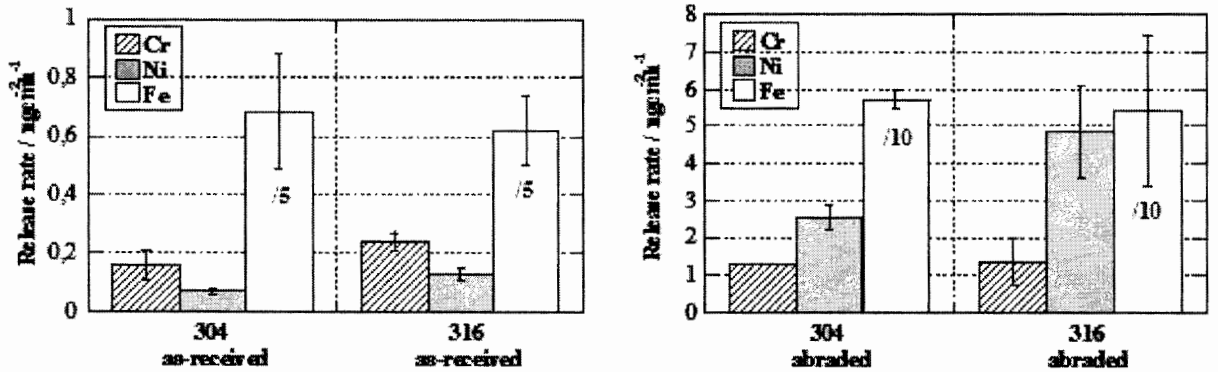

Figure 4. Hourly release rates of Cr, Ni, and Fe from as-received (left) and abraded (right) 304 and 316 stainless steel after an 8 h continuous rain event (pH 4.3, intensity 4 mm/h).

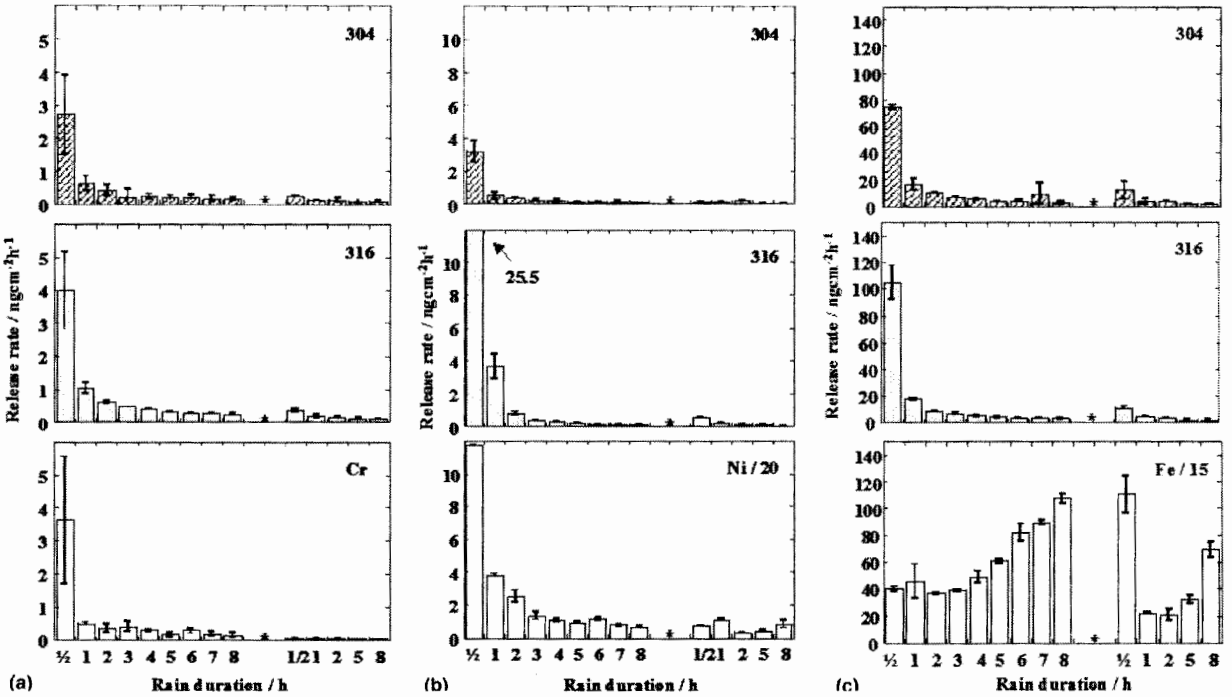

Figure 5. Release rates of (a) Cr, (b) Ni, and (c) Fe from as-received stainless steel (grades 304 and 316) and pure metals during two consecutive 8 h rain events (pH 4.4, intensity ≈ 4 mm h^{-1}) separated by a 40 day dry period (labeled * in the diagrams). Note that the rates of pure Ni and Fe have been divided by 20 and 15, respectively.

was made after 2 h (the rate between 1 and 2 h, cf. Fig. 10) and 8 h (the rate between 7 and 8 h, cf. Fig. 5) of the first rain event. The results are illustrated in Fig. 10 for Cr, Ni, and Fe, respectively.

Consistent with previous findings, grade 316 shows somewhat higher release rates of Cr compared to grade 304, Fig. 10, top. In addition, pure chromium shows somewhat lower release rates than the alloys. This is probably explained by a denser and less defect-rich chromium oxide/hydroxide film on the pure metal surface compared to the alloy surfaces. The low release rates of Cr and the relatively small variation in results between the alloys and the pure metals is due to the presence of a passive chromium oxide/hydroxide film on all surfaces, acting as a barrier for corrosion and metal release.[18]

More Ni is released from grade 316 compared to grade 304, Fig. 10, middle, in agreement with previous findings.[14] Ni is preferentially released compared to Cr, (Fig. 10, top) but in different proportions compared to the bulk alloy composition (Table I). In addition, substantially more Ni is released from the pure nickel surface compared to the alloyed surfaces. This may be explained by the formation of highly defective surface films on nickel that are easily removed.[18] In the case of the stainless steel, Ni has to pass through the passive film that acts as a barrier for metal release, hence reducing the Ni release rate.

For Fe, no large differences in release rates can be seen between the two stainless steel grades, Fig. 10, bottom. This is consistent with field data.[14] Substantially more Fe is released from the pure

Table III. Mean release rates (ng cm^{-2} h^{-1}) of Cr, Ni, and Fe for as-received stainless steel grades (304 and 316) and pure metals (Fe, Cr, Ni) during first flush (f) and steady-state (s) conditions of two consecutive rain events.

Release rate (ng cm^{-2} h^{-1})	Cr Rain 1	Cr Rain 2	Ni Rain 1	Ni Rain 2	Fe Rain 1	Fe Rain 2
Grade 304	f: 1.3 ± 0.53	f: 0.2 ± 0.03	f: 1.3 ± 0.29	f: 0.2 ± 0.03	f: 34 ± 2.1	f: 6.8 ± 3.0
	s: 0.2 ± 0.01	s: 0.08 ± 0.04	s: 0.15 ± 0.03	s: 0.06 ± 0.01	s: 5.7 ± 1.7	s: 2.3 ± 0.09
Grade 316	f: 1.9 ± 0.46	f: 0.2 ± 0.03	f: 10 ± 1.1	f: 0.28 ± 0.02	f: 44 ± 4.5	f: 6.3 ± 0.48
	s: 0.33 ± 0.01	s: 0.11 ± 0.02	s: 0.21 ± 0.02	s: 0.08 ± 0.01	s: 4.4 ± 0.44	s: 1.2 ± 1.1
Cr	f: 1.5 ± 0.70	f: 0.05 ± 0.01	-	-	-	-
	s: 0.24 ± 0.07	s: 0.03 ± 0.003	-	-	-	-
Ni	-	-	f: 121 ± 3.3	f: 15 ± 0.41	-	-
			s: 20 ± 2.0	s: 13 ± 2.6	-	-
Fe	-	-	-	-	f: 617 ± 76.9	f: 766 ± 93.4
					s: -	s: -

f: first flush (0-8 mm).
s: steady state (8-32 mm).
- means below detection limit.

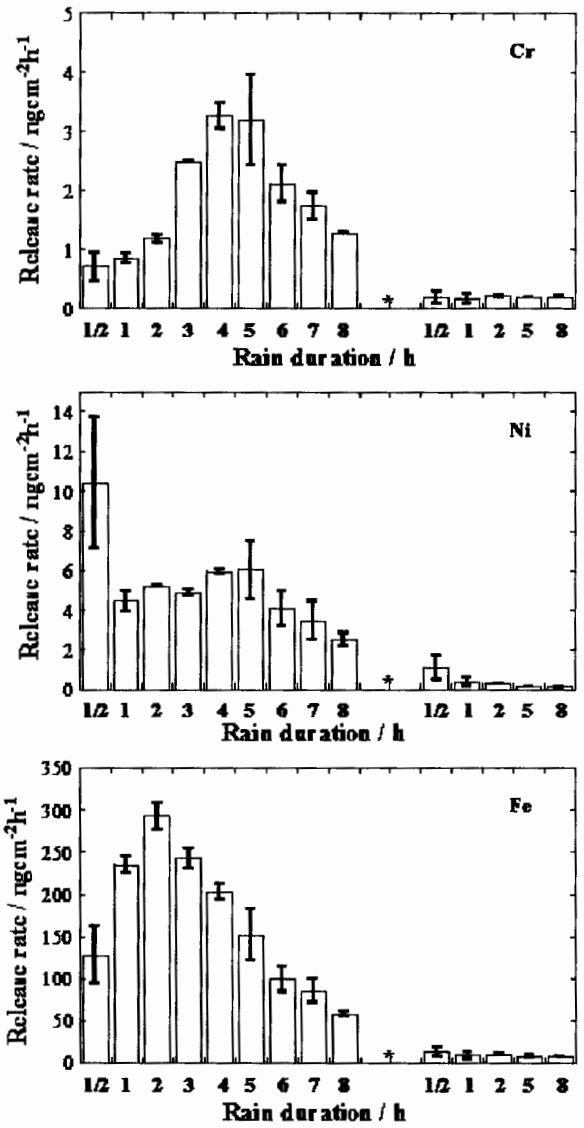

Figure 6. Release rate of Cr (top), Ni (middle), and Fe (bottom) from abraded stainless steel grade 304 during two consecutive 8 h rain events (pH 4.4, intensity ≈ 4 mm h^{-1}) separated by a 40 day dry period (labeled * in the figure).

iron surface compared to the alloyed surfaces. This is related to the poor protective properties of surface oxides, whereas, in stainless steel, similarly to nickel iron, has to pass through the passive film.[15] Since the surface film of stainless steels consists of both chromium and iron oxides, iron is also released from the passive film.

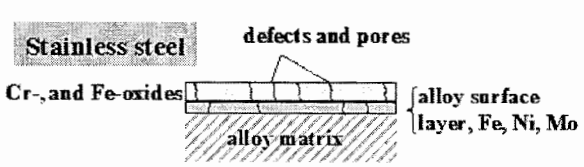

Figure 7. Schematic of surface layers on stainless steel.

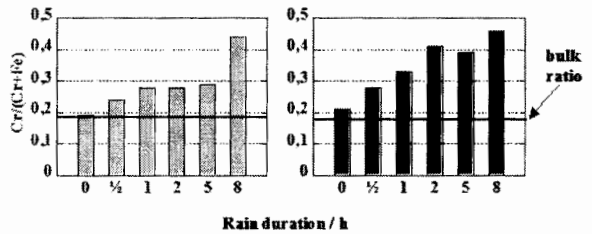

Figure 8. Chromium content of the outermost surface film of freshly abraded grade 304 (left) and 316 (right) (aged for 24 h before exposure) during a rain event. Chromium and iron represent the metals in their oxidized state as measured by means of XPS.

Results show the release rates of Cr, Ni, and Fe to be non-proportional to the corresponding nominal alloy composition of the stainless steel, in agreement with previous investigations.[9,11] This is illustrated in Table IV for the steady-state condition during the first rain event (see Table III). Similar findings are seen for the second rain event.

In all, the current investigation shows the release rates of Ni and Fe from stainless steel alloys (grades 304 and 316) to be quantitatively different from those observed with the pure metals, but similar for Cr. The results are illustrated in Fig. 11 as average release rates of Cr, Ni, and Fe from as received alloys and pure metals after 8 h of continuous rain exposure.

The similarity in results for pure chromium and stainless steel is related to the presence of a chromium-enriched passive film on both surfaces. The passive film on stainless steel reduces the release rates of Ni and Fe compared to the release rates from the pure metals. The results are summarized in Table V and show significantly higher release rates of iron and nickel from the pure metals than from the stainless steel alloys. The release of chromium, however, is slightly lower from pure chromium compared to stainless steel.

Table V also includes calculated release rates of Cr, Ni, and Fe from stainless steel based on the nominal alloy content of each metal multiplied by the pure metal release rates. This calculation has been performed to illustrate the large discrepancy in such calculated release rates when compared with measured release rates of alloy constituents from stainless steel. Measured release rates of Ni and Fe from stainless steel are orders of magnitude lower (much less, see Table V) compared to calculated rates based on the nominal alloy composition and release rates from pure nickel and iron. Similar deliberations for chromium show slightly higher measured rates (greater than, see Table V) compared to calculated rates. As-

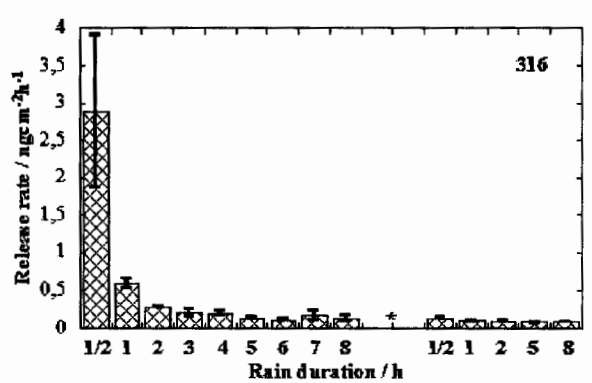

Figure 9. Release rate of Mo from as-received stainless steel grade 316 during two consecutive 8 h rain events (pH 4.4, intensity ≈ 4 mm h^{-1}) separated by a 40 day dry period (labeled * in the figure).

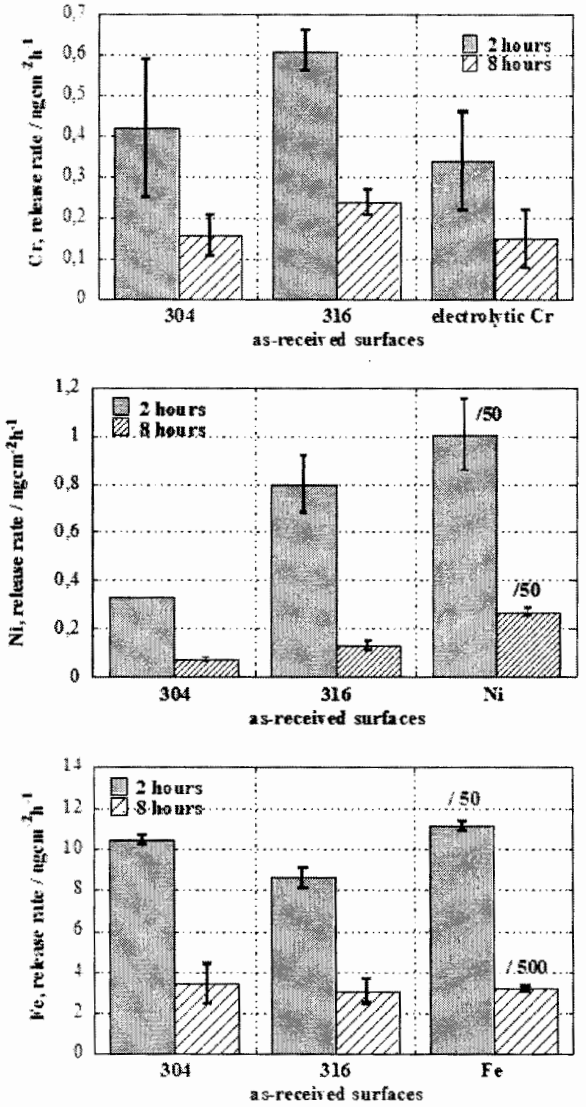

Figure 10. Momentary release rates of Cr (top), Ni (middle), and Fe (bottom) from as-received stainless steel (grades 304 and 316) and pure metals after 2 and 8 h of rain (pH 4.4, intensity 4 mm/h).

Table IV. Massbalance calculations based on release rates of chromium, nickel, and iron from stainless steel grades 304 and 316, compared to corresponding bulk alloy composition.

Grade	Cr/(Cr+Ni+Fe) (Bulk wt %)	(%)	Ni/(Cr+Ni+Fe) (Bulk wt %)	(%)	Fe/(Cr+Ni+Fe) (Bulk wt %)	(%)
304	18.3	3.3	8.7	2.5	73	94.2
316	17.2	6.7	10.9	4.3	71.9	89.1

received and abraded panels show similar differences between measured and calculated rates.

Calculations based on nominal alloy composition and release rates from pure metals are commonly used within the framework of environmental risk assessment of metallic alloys and are, clearly, highly erroneous in the case of stainless steels.

The results emphasize the importance of using measured data in estimations of the diffuse dispersion of metal alloy constituents from stainless steel used for external applications.

Conclusions

Two grades of stainless steels and the corresponding pure metals were identically exposed to artificial rain in a rain chamber to examine the differences in metal release rates from stainless steel alloys and the pure metals. The following conclusions were drawn.

The release rates of Fe and Ni from pure iron and nickel were found to be substantially higher than the release rate from the stainless steel alloys.

The release rate of Cr was similar for the alloys and pure chromium due to the presence of a chromium-rich surface film.

XPS analysis showed chromium to be enriched in the outermost surface film upon exposure to rain with decreasing release rates of Cr, Ni, and Fe as a result. The chromium enrichment was somewhat faster for grade 316 compared to 304.

Calculated release rates, based on nominal alloy compositions and release rates from pure metals, substantially overestimate actual release rates.

Measured data should be used when estimating metal release from stainless steel alloys. Data should not be used for environmental risk assessment without considering the chemical speciation of released metals and dilution effect upon environmental entry.

Acknowledgments

The financial support of Eurofer (The European Confederation of Iron and Steel Industries), Belgium, is gratefully acknowledged. Bengt Andersson and Birgitta Olsson at SLU, Umeå, are highly appreciated for performing ICP/MS analyses.

Royal Institute of Technology assisted in meeting the publication costs of this article.

Table V. Compilation of hourly measured metal release data [after 2 and 8 h of continuous rain on as-received pure metals and stainless steel (grade 304 and 316)] and the difference in data when using the nominal alloy composition to calculate metal release rates from pure metal release data.

Metal/ exposure time[a]	304 18.3%Cr, 8.7%Ni, 73%Fe			316 17.2%Cr, 10.9%Ni, 71.9%Fe			Cr	Ni	Fe
	$ng/cm^2\ h^{-1}$ measured		$ng/cm^2\ h^{-1}$ calculated[a]	$ng/cm^2\ h^{-1}$ measured		$ng/cm^2\ h^{-1}$ calculated[a]	$ng/cm^2\ h^{-1}$ measured	$ng/cm^2\ h^{-1}$ measured	$ng/cm^2\ h^{-1}$ measured
Cr_{2h}	0.42 ± 0.17	>	0.06 ± 0.02	0.61 ± 0.05	>	0.06 ± 0.02	0.34 ± 0.12		
Cr_{8h}	0.16 ± 0.05	>	0.03 ± 0.01	0.24 ± 0.03	>	0.02 ± 0.01	0.15 ± 0.07		
Ni_{2h}	0.33 ± 0.00	≪	4.4 ± 0.6	0.80 ± 0.12	≪	5.5 ± 0.8		50.3 ± 7.4	
Ni_{8h}	0.07 ± 0.01	≪	1.2 ± 0.1	0.13 ± 0.02	≪	1.5 ± 0.1		13.5 ± 0.8	
Fe_{2h}	10.5 ± 0.2	≪	406 ± 8	8.6 ± 0.5	≪	400 ± 8			557 ± 10
Fe_{8h}	3.4 ± 1.0	≪	1177 ± 40	3.2 ± 0.6	≪	1159 ± 39			1612 ± 55

[a] Calculated as the alloy percentage times the pure metal release rate.

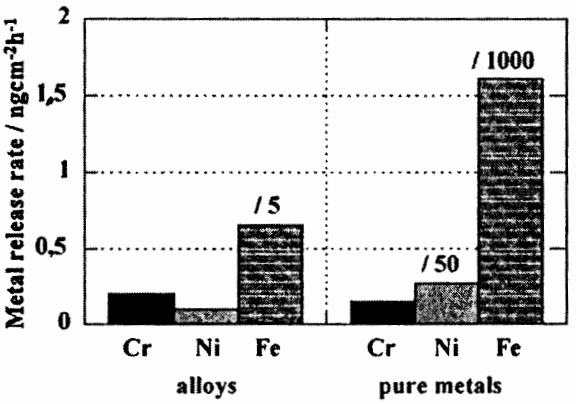

Figure 11. Metal release rates of Cr, Ni, and Fe from as-received alloys (average value of grades 304 and 316) and pure metals after 8 h of continuous rain (pH 4.4, intensity 4 mm/h).

References

1. *Avesta Sheffield Corrosion Handbook*, Sandvik Steel (1999).
2. C. Leygraf and T. E. Graedel, *Atmospheric Corrosion*, John Wiley & Sons, New York (2000).
3. E. A. Baker and W. W. Kirk, *Corrosion Testing and Evaluation*, ASTM STP 1000, R. Baboian and S. W. Dean, Editors, p. 177, American Society for Testing and Materials, Philadelphia, PA (1990).
4. *NiDI*, Report No. II 024, Nickel Development Institute (2000).
5. J. R. Kearns, M. J. Johnson, and P. J. Pavlik, in *Degradation of Metals in the Atmosphere*, ASTM STP 965, S. W. Dean and T. S. Lee, Editors, p. 35, American Society for Testing and Materials, Philadelphia, PA (1988).
6. M. J. Johnson and P. J. Pavlik, in *Atmospheric Corrosion*, 11th ed., W. H. Ailor, Editor, p. 461, John Wiley & Sons, New York (1982).
7. D. Wallinder, I. Odnevall Wallinder, and C. Leygraf, *Corrosion (Houston)*. **59**, 220 (2003).
8. E. Waltersson, *Krom, Nickel och Molybden i sanhälle och miljö*, Swedish Environmental Research Group, Borås (1999) (in Swedish).
9. J. E. Castle and J. H. Qiu, *J. Electrochem. Soc.*, **137**, 2031 (1990).
10. A. Chiba, S. Sakakura, K. Kobayashi, and K. Kusayanagi, *J. Mater. Sci.*, **32**, 1995 (1997).
11. I. Odnevall Wallinder, S. Bertling, G. Herting, and C. Leygraf, Final Report, The Swedish Steel Producers' Association, Stockholm, and Eurofer, Brussels (2004).
12. H. Grip and A. Rodhe, *Vattnets Väg från Regn till Bäck*, Lagerblads Tryckeri, Karlshamn (1985) (in Swedish).
13. *UN/ECE International Co-operative Programme on Effects on Materials, Including Historic and Cultural Monuments*, Report no. 21: Final environmental data report Sept 1987 to Aug 1995; Norwegian Institute for Air Research, Lillestrøm, Norway (1997).
14. I. Odnevall Wallinder, J. Lu, S. Bertling, and C. Leygraf, *Corros. Sci.*, **44**, 2303 (2002).
15. T. E. Graedel and R. P. Frankenthal, *J. Electrochem. Soc.*, **137**, 2385 (1990).
16. L. Wegrelius, Ph. D. Thesis, Chalmers University of Technology, Göteborg (1995).
17. C. R. Clayton and I. Olefjord, in *Corrosion Mechanisms in Theory and Practice*, 2nd ed., P. Marcus, Editor, p. 217, Marcel Dekker, Inc., New York (2002).
18. B. MacDougall and M. J. Graham, in *Corrosion Mechanisms in Theory and Practice*, 2nd ed., P. Marcus, Editor, p. 189, Marcel Dekker, Inc., New York (2002).