CORROSION ENGINEERING SECTION

Metallurgical and Surface Influence on the Corrosion Resistance of Ni-Cr-Mo Alloys According to ASTM G 28

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ABSTRACT

The influence of surface condition, chemical composition, and microstructure of Ni-Cr-Mo alloys has been investigated using the ASTM G 28 standard for intergranular corrosion testing. Experiments were carried out mainly using the Ni-based alloys C-22 (UNS N06022) and C-276 (UNS N10276). Repeatabilities of both testing procedures of ASTM G 28, Method A and B, were found to be in most cases ≤3%. A finer surface finish yields lower corrosion rates. The corrosion rate of electropolished specimens is about 5% to 20% lower than for ground specimens. Sandblasted and pickled specimens show a 1.3 to 4 times higher corrosion rate than ground specimens because of the crevice corrosion at laminations and crevices. Method B yields a better differentiation between specimens with different surface finishes than Method A because of the less-aggressive test conditions. In addition to the ratio Cr/(Mo+W), which has already been found to be an indicator of corrosion resistance of these materials, the elements Mo and W were found to segregate to a certain extent, and tended to form intermetallic phases and carbides resulting in a drop in corrosion resistance by a factor of up to 2. The effect of microstructure is distinguished better by Method A because of its higher uniform general corrosion rate. In this case, Method B exhibits too-mild testing conditions.

KEY WORDS: *ASTM G 28, chemical composition, corrosion rate, Ni-Cr-Mo alloys, nickel alloys, repeatability, segregation, surface condition*

INTRODUCTION

Ni-based alloys containing Cr and Mo as main alloying elements are used as corrosion-resistant materials in chemical plants where the stability of austenitic Cr-Ni-Mo steels is not sufficient. One of the most commonly used corrosion tests for Ni alloys is ASTM G 28[1] to determine susceptibility to intergranular corrosion. A compilation of the most important Ni-Cr-Mo alloys is shown in Table 1.

All of these Ni-based alloys contain 16% to 23% Cr and 9% to 16% Mo. Alloys C-276 (UNS N10276)[(1)] and C-22 (UNS N06022) also contain about 3% W, which in relation to corrosion resistance, exhibits an effect similar to Mo (decrease of current density in the active and passive regions).[2-4] Alloy C-4 (UNS N06455) was developed as a more stable variant of Alloy C-276. Addition of 0.3% Ti leads to reduced precipitation of grain boundary carbides.[2] The addition of 3% Nb to Alloy 625 (UNS N06625) causes a similar stabilization. The basic requirement for good corrosion resistance of these alloys is a homogeneous microstructure. Any type of additional phase, regardless of whether it is precipitated at grain boundaries or in the grains, or whether it is an intermetallic phase or a carbide, gives rise in principle to the localized depletion of alloying elements in the adjacent metal and a localized decrease in corrosion resistance in oxidizing solutions. In the Ni-Cr-Mo ternary system, the austenitic face-centered cubic phase is stable at the Ni-rich corner. Beyond the solubility limit with increasing Cr content, face-centered cubic δ-phase, rhombohedric μ-phase, and orthorhombic P-phase are precipitated. At the

TABLE 1

Nominal Chemical Composition of the Most Important Ni-Cr-Mo Alloys (wt%)

Alloy	UNS Number	DIN	Ni	Cr	Mo	Fe	Others
C-276	N10276	2.4819	57	16	16	6	3.5 W
C-4	N06455	2.4610	66	16	16	—	0.3 Ti
C-22	N06022	2.4602	57	21	13	3	3.2 W
59	N06059	2.4605	61	23	16	—	—
625	N06625	2.4856	63	22	9	2	3.4 Nb

TABLE 2

Corrosion Rates of Alloys C-22 and C-276 According to ASTM G 28 (mm/y)

Alloy	Heat Treatment	Method A	Method B	Reference
C-22	Solution annealed	0.73		2
		0.90		5
		1.63	0.42	19
		0.64 to 0.96	0.1 to 0.25	20
	Sensitized 10 h at 800°C	7.4[A]		2
C-276	Solution annealed	7.1		2
		5.3		5
		4.8	0.90	10
		5.59	1.14	19
		6.4 to 9.5	1.40 to 2.80	20
	Sensitized 10 h at 800°C	121[A]		2

[A] With intergranular corrosion.

highest Cr contents, σ-phase can also be formed.[5] Isothermal sections of Ni-Cr-Mo ternary systems at 850°C and 1,250°C have been presented by Raghavan, et al.[6] The μ-phase exists only at the lower temperature, and the stability range of P-phase is shifted at higher temperatures to lower the Cr content. Sensitization of Alloy C-22 generates precipitates containing 30% Ni, 16% Cr, 42% Mo, 1.5% Fe, and 9% W, possibly as μ-phase, P-phase, or MC carbide.[2] While only the latter of this phase is a carbide, any of these phases can be rich in Mo and W. Phase identification in materials tested in industrial control tests is hardly ever done. Alloy C-276 has a precipitation behavior similar to μ-phase, P-phase, and M_6C carbides.[7] The indicated sequence of the three phases corresponds to their frequency of occurrence. The chemical composition of the three phases is very similar, and they are often difficult to distinguish in many cases because of their small size.[2,6-8] Only very recently have researchers started to develop time-temperature-transition (TTT) diagrams of Ni-based alloys that show the precipitation behavior of each precipitated phase and not just sensitization data, where no distinction is made between the different phases.[9] This diagram also proves the assumption that different phases can precipitate jointly.[5]

The sensitization time of Alloy C-22 is about 1 h at 780°C.[2] Alloy C-276 requires much shorter times of only about 6 min. Even a slow cooling rate after solution annealing can cause a sensitization of Alloy C-276, resulting in high material loss during testing, according to the ASTM G 28 standard.[10]

Although already developed in the late 1950s and early 1960s,[11-12] the ASTM G 28 Method A is the most commonly used testing method for intergranular and uniform corrosion testing of Ni-Cr-Mo alloys because of the noble free corrosion potential of specimens in a ferric sulfate-sulfuric acid ($Fe_2[SO_4]_3$-H_2SO_4) solution. Testing in this solution can detect all corrosion maxima that occurs by precipitation of different phases.[11] Except for the Huey Test using concentrated nitric acid (HNO_3), according to ASTM A 262, other standard procedures for intergranular corrosion testing of highly alloyed materials can only detect Cr depletions caused by carbide formation.[13-14]

The ASTM G 28 test is a method that indicates only the corrosion rate of a sample in mm/y or mpy (1 mpy = 0.0254 mm/y). The "degree of damage" (e.g., fraction of sensitized grain boundary to the entire grain boundary length, width, and depth of sensitization) is not described.[15] Although other electrochemical tests can characterize the minimum Cr content of the matrix at which no sensitization occurs, their application still remains limited because of the lack of determination of a quantitative corrosion rate and difficult data interpretation.[16-18] In Table 2, some corrosion rates of Alloys C-22 and C-276 according to ASTM G 28 are shown.[2,5,10,19-20] Method B with a lower H_2SO_4 concentration leads to 4 to 6 times lower corrosion rates compared to Method A. After solution an-

TABLE 3
Chemical Composition of Test Solutions According to ASTM G 28

	Distilled H_2O (mL)	H_2SO_4 Concentration (mL)	$Fe_2(SO_4)_3 \cdot xH_2O$ (g)	$FeCl_3 \cdot 6H_2O$ (g)	$CuCl_2 \cdot 2H_2O$ (g)
Method A	400	236	25	—	—
Method B	476	90	—	10	7.2

nealing of Alloy C-276, only a uniform attack occurs with a corrosion rate of 5 mm/y and higher, according to Method A. Additional selective attack at grain boundaries after sensitization leads to a further increase in corrosion rate. The limiting value for the occurrence of intergranular corrosion of Ni-based alloys is reported to be 20 g/m²-d, which is equal to a corrosion rate of about 20 mm/y (calculated using a density of Alloy C-22 of 8.69 g/cm³).[21] Values between 20 g/m²-d and 25 g/m²-d lead to a maximum penetration depth of 50 μm, according to ASTM G 28 Method A. The strongly oxidizing test solution of ASTM G 28 Method A causes a substantial amount of uniform corrosion that may easily mask the intergranular corrosion components of materials such as C-276, C-22, C-4, and 59 (UNS N06059).[1] On the other hand, the less oxidizing Method B is favored for alloys with lower Cr content.[10] Method B is suitable to differentiate between intergranular and uniform corrosion, particularly with lower alloyed materials.[1]

ASTM G 28 recommends finishing of specimens with wet no. 80-grit or dry no. 120-grit abrasive paper. Sandblasted surfaces should not be used in ASTM G 28. In industrial practice, however, predominantly sandblasted and pickled surfaces are used. Studies of differences between the standardized ASTM G 28 ground surface and industrially fabricated ones have not been found in the literature. This paper describes the influence of such surface conditions on corrosion rates determined in a standard test according to ASTM G 28 and, furthermore, presents a qualitative relation between the microstructure and corrosion rate in the test solutions. An extensive validation of the ASTM G 28 methodology is contained in the first part of this work.

EXPERIMENTAL PROCEDURES

Corrosion Testing According to ASTM G 28

Commercial sheet material with a thickness between 2 mm and 5 mm and a total surface area between 19.6 cm² and 22 cm² were exposed to boiling solutions according to ASTM G 28 Methods A and B for 24 h. The chemical compositions of both solutions are shown in Table 3.

Mass loss was determined with a 0.1-mg precision balance, and the area of specimens was measured to the nearest 0.01 mm². All specimens were stored overnight in a desiccator after preparation to ensure passivation. For validation of both test methods and investigation of the influence of surface finish, every material was examined by three different persons at least three, and in most cases, six times each. To determine the influence of chemical composition and microstructure on corrosion resistance, different production lots were tested according to ASTM G 28, using both methods and specimens with standard ground surfaces.

Material and Surface Characterization

Chemical composition and mechanical properties of materials tested for validation, as well as for investigation of the influence of surface finish, are shown in Tables 4 and 5. Three heats of Alloy C-22 and two heats of Alloy C-276 were examined.

Three surface treatments were applied. Grinding was carried out on all sides with wet abrasive paper, no. 120 grit. Sandblasting and pickling was done in an industrial production plant on the front and back sides. The other four sides were wet ground with no. 120-grit paper. Electropolishing was done in the laboratory (after grinding the specimens) in an electrolyte containing 150 mL distilled water, 300 mL phosphoric acid (H_3PO_4; 85%), and 550 mL H_2SO_4 (95% to 97%) at 40°C, at a current of 0.3 A/cm² for 20 min. Average and maximum roughnesses of the variously prepared specimens are presented in Table 6. Scanning electron microscopic (SEM) images of the surfaces are shown in Figure 1. Sandblasted and pickled surfaces contained individual laminations and material folds forming pockets, which also can be expressed as surface roughness. Ground surfaces exhibited a parallel-oriented structure with flutes in the direction of grinding. Electropolished surfaces were smooth and did not show any microstructure visible by SEM. Lines of segregation were somewhat raised and led to some wavy ripples that have almost no effect on the result of the roughness measurement.

RESULTS

Validation of ASTM G 28

Relative standard deviations for ASTM G28 Methods A and B for three operators are shown over the average mass losses in Figure 2. With the exception of several results obtained by Operator 1, the relative standard deviations are below 5% for both the A and B procedures within a repeated series of three or six

TABLE 4
Chemical Composition of Materials Tested (wt%)

No.	Alloy	C	Si	Mn	P	S	Cr	Mo	Ni	W	Fe	N
1	C-22	0.004	<0.05	0.03	<0.005	0.0010	21.21	12.53	58.4	2.57	4.92	0.0073
2	C-22	0.004	<0.05	0.03	<0.005	0.0030	21.23	12.68	58.5	2.70	4.51	0.0078
3	C-22	0.005	0.04	0.15	0.004	0.002	21.3	13.8	59.3	2.7	2.2	—
4	C-276	0.006	<0.05	0.03	<0.005	0.0011	15.99	15.78	59.0	3.21	5.62	0.0067
5	C-276	0.009	<0.05	0.04	<0.005	0.0020	16.18	15.84	59.2	3.24	5.20	0.0046

TABLE 5
Mechanical Properties of Materials Tested

No.	Alloy	Yield Strength $R_{p0.2}$ (MPa)	Tensile Strength R_m (MPa)	Elongation A_5 (%)
1	C-22	455	774	56.9
2	C-22	461	808	50.7
3	C-22	350	745	71
4	C-276	425	802	59.8
5	C-276	385	775	61.0

parallel tests. Differences of mean corrosion rates for the same materials tested by different operators were usually below 3%. As a consequence, there was no significant deviation of the mean values obtained by different operators. A statistical t-test confirmed this result. Only with Alloy C-276, no. 5, did Operators 1 and 3 observe the maximum differences between their mean corrosion rates of 10% (Method A) and 18% (Method B).

Standard deviations of each pair of operators have been compared in an F-test. Table 7 shows in the upper section the relative standard deviations (RSDs) of all operators for Alloys C-22, nos. 2 and 3 (data from sandblasted + pickled, and polished specimens). The lower section of Table 7 shows the quotient of the squares of the RSDs for each pair of operators a-b (RSD_a^2/RSD_b^2) for both testing methods, and the statistical F-values for an acceptance probability of 95% and 98%. If these F-values are smaller than the quotient of the RSDs squares, a significant difference between the standard deviations of the tested pair of operators exists. These results exhibit a significantly higher RSD for Operator 1 using Method A. The other standard deviations are not significantly different.

## Influence of Surface Condition on Corrosion Rate According to ASTM G 28

Table 8 shows the average corrosion rates and standard deviations for specimens prepared with different surface treatments. The influence of surface condition on the corrosion rates of the two materials and the two test methods is shown graphically in Figure 3. There is a sharp increase in the corrosion rate with roughness, number of laminations, and crevices when comparing a ground surface with a rougher

TABLE 6
*Surface Roughness of Specimens with Various Surface Treatments (µm)*

Surface Condition	Maximum Roughness R_{max}	Average Roughness R_a
Sandblasted and pickled	50	8
Ground no. 120-grit	5.25	0.25
Electropolished	0.95	0.2

sandblasted and pickled one. The increase in the average corrosion rate is between 30% and 400%. The available service time of the sandblasted and pickled material in practice can therefore be significantly shorter than a ground one. At this point one has to consider that this is at least valid for the initiation of the corrosive attack. During corrosion propagation additional effects may occur, such as general corrosion in very acidic environments. Under such circumstances the deleterious effect of sandblasting could be only a transient effect. The difference of the corrosion rate between ground and electropolished surfaces is smaller than that between a sandblasted and pickled surface and a ground one. However, the difference of roughness is also small between ground and electropolished surfaces.

Method B gives better selectivity for different surface roughnesses. Roughness in this case results from a large number of crevices present after sandblasting. A similar surface roughness can be produced by machining but gives rise to lower mass loss than from sandblasted surfaces. When normalizing corrosion rates to the sandblasted and pickled condition and evaluating corrosion rates as a function of the logarithm of roughness as in Figure 4, this better selec-
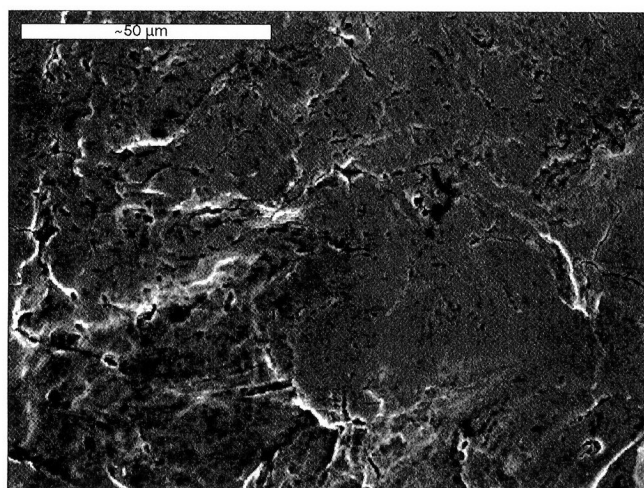
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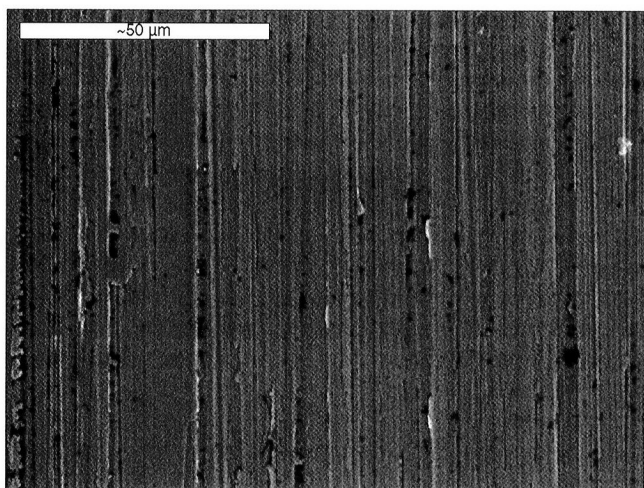
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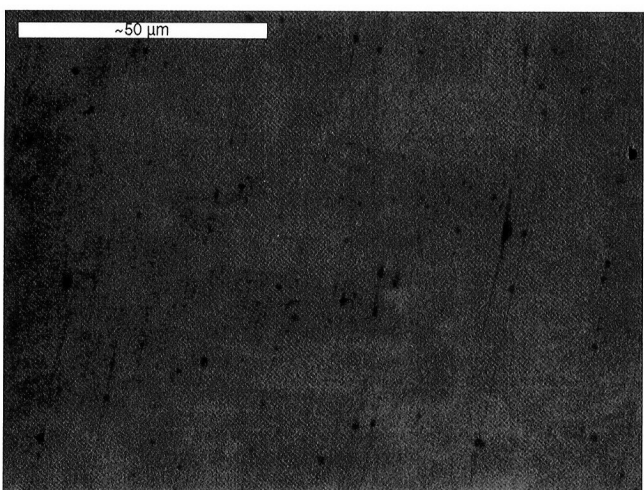
(c)

FIGURE 1. *Surfaces of investigated specimens C-22, no. 1: (a) sandblasted and pickled, (b) ground, and (c) electropolished.*

tivity can be seen clearly by the larger slopes of lines obtained with Method B. Electropolishing already attacks less noble lines of element segregation, precipitations, inclusions, and Cr-depleted zones, yielding a lower mass loss during ASTM G 28 testing than was expected from linear extrapolation of the data obtained for other surface conditions in Figure 4.

Influence of Microstructure on Corrosion Resistance

Over 20 industrial melts each of Alloys C-22 and C-276 were tested according to ASTM G 28 Methods A and B to investigate the effect of microstructure on corrosion resistance. Figure 5 shows an overview of the corrosion rates of the different production lots of Alloy C-22. The specimens are ranked with increasing corrosion rates according to Method A. For specimens nos. 1 through 18, no trend in the corrosion rate is observed according to Method B. However, the values for sample nos. 19, 20, and 21 show a significant increase in the corrosion rate after testing in the less-aggressive Solution B. Materials of specimens with low corrosion rates obtained in Solution B contain almost no or very low amounts of precipitates, as can be seen in Figure 6(a). By contrast, specimen nos. 20 through 22 contain increasing amounts of clusters of precipitates. Sample nos. 1 through 18 contain only slightly increasing amounts of homogeneously distributed precipitates but no clusters of secondary phases. Analysis of several of these precipitates by semiquantitative EDX spectra showed enrichment of Mo and W when compared to the bulk material. A complete determination of the type of phases was not possible because of their small size.

Similar results have been obtained with Alloy C-276. Twenty-two melts were investigated. Figure 7 shows the corrosion rates of these lots for both testing procedures of ASTM G 28, ranked again with increasing corrosion rate according to Method A. In the case of Method B, there is no tendency for an increase in corrosion rate. Metallographic investigations showed that specimens with low corrosion rates according to Method A had smaller amounts of homogeneously distributed precipitates in the austenitic matrix, as shown in Figure 8. Specimens with a higher corrosion rate in Solution A showed uniformly distributed precipitates, but their number was greater when compared to more corrosion-resistant lots. No clusters of Mo- and W-rich precipitates were present that would have resulted in an increase in the corrosion rate in the less-aggressive Solution B. Attack was in all cases uniform with small pit-like zones. No specimen showed intergranular attack.

DISCUSSION

Both methods described in ASTM G 28 allow corrosion rates to be measured with an accuracy of not

greater than 5%. In most cases, the standard deviation of results was 3% or lower. Higher standard deviations were mainly caused by less careful application of the ASTM standard practice. There was also constant relation between the scatter of results and the corrosion rate. Results of Method A suggest a larger standard deviation at lower corrosion rates, indicating a detection limit for ASTM G 28. A statistical F-test proved, however, a significant difference of RSD for one of the three operators. In summary, ASTM G 28 is a very reliable corrosion testing method giving high-precision results.

All tests done with both examined materials led to corrosion rates that were too low for intergranular corrosion to have occurred. Corrosion rates of 21 heats of Alloy C-22 with ground surfaces, according to Method A, were between 0.48 mm/y and 1.1 mm/y (Figure 5). Those of Alloy C-276 were found to be between 3.3 mm/y and 6.8 mm/y for the same method and surface conditions. Values presented in the literature are typically between 0.64 mm/y and 1.63 mm/y for Alloy C-22 and 4.8 mm/y to 9.5 mm/y for Alloy C-276 for the solution-annealed condition, and they correspond well to the corrosion rates found in this work.[2,5,10,19-20] In contrast, sensitization (10 h, 800°C) gives rise to corrosion rates as high as 7.4 mm/y (C-22) and 121 mm/y (C-276), respectively.[2]

With an increase in the number of crevices on specimens, corrosion rates increased significantly. Sandblasted and pickled surfaces resulted in a 1.3 to 4 times higher corrosion rate compared to the 120-grit abrasive paper ground surface recommended in ASTM G 28. In practice, the corrosion rates of industrially produced surfaces are more relevant for the user than ground surfaces. ASTM G 28 was developed as a testing method for the determination of susceptibility to intergranular corrosion. In particular, the highly aggressive solution used in Method A leads to high uniform corrosion rates even for nonsensitized alloys, which easily can mask intergranular corrosion of the most common Ni-Cr-Mo alloys C-22, C-276, C-4, and 59. This is already mentioned in ASTM G 28.[1]
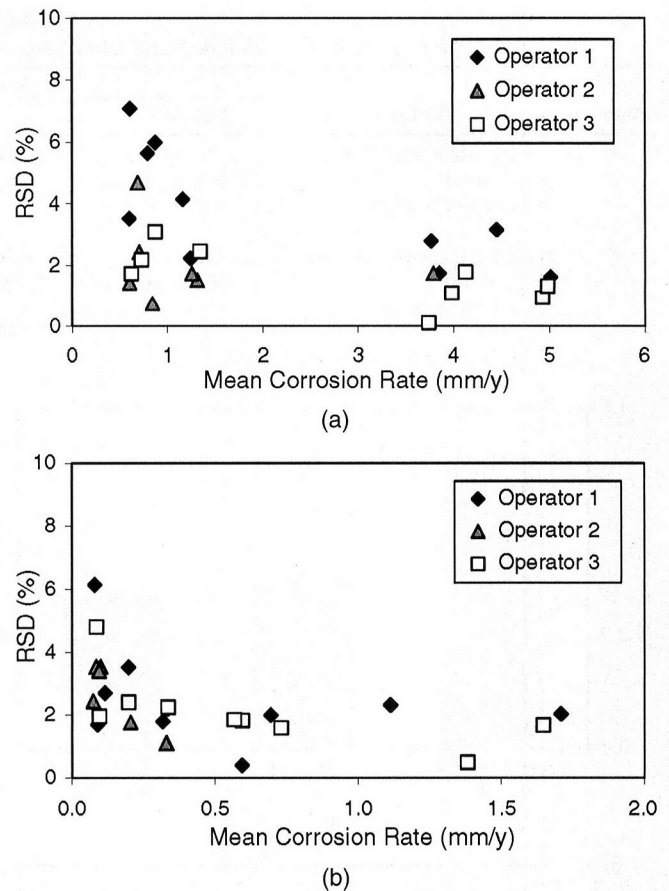In France there is an industrial practice to check the

FIGURE 2. RSD as a function of mean corrosion rate in corrosion testing according to ASTM G 28: (a) Method A and (b) Method B.

microstructure of the Ni-based alloys by using Practice B (milder solution) for the forged and laminated materials, and Practice A (more aggressive solution) for the cast and welded metals.[22] This is reasonable considering that Method B enables good discrimination between two materials only if large amounts of precipitates and secondary phases are present, whereas Method A enables a clear distinction to be made for lower amounts of precipitates. Welds and cast materials usually contain segregations and precipitates to a

TABLE 7
Comparison of RSDs for Each Pair of Operators

Total RSD of Materials	Method A, Operator No.			Method B, Operator No.		
	1	2	3	1	2	3
C-22, no. 2 and C-22, no. 3	0.0491	0.0262	0.0241	0.0275	0.0245	0.0329

Statistical Value	Method A, Pairs of Operators			Method B, Pairs of Operators		
	1-2	2-3	1-3	1-2	2-3	1-3
RSD_a^2/RSD_b^2	3.51	1.18	4.15	1.26	1.80	1.43
$F_{95\%}$	2.09	2.01	2.09	—	2.01	—
$F_{99\%}$	2.86	2.72	2.86	—	2.72	—
Significant difference	Yes	No	Yes	No	No	No

TABLE 8
Influence of Test Solution and Surface Condition on Mass Loss During ASTM G 28 Test

Method	Surface	Average Mass Loss ± Standard Deviation (mm/y)				
		C-22, No. 1	C-22, No. 2	C-22, No. 3	C-276, No. 4	C-276, No. 5
A	Sandblasted + pickled	1.16 ± 0.05	0.861 ± 0.035	1.29 ± 0.05	4.97 ± 0.08	4.70 ± 0.28
	Ground	0.606 ± 0.043	0.581 ± 0.018	0.734 ± 0.053	3.91 ± 0.10	3.94 ± 0.20
	Electropolished	—	—	0.659 ± 0.013	3.74 ± 0.01	—
B	Sandblasted + pickled	0.318 ± 0.005	0.203 ± 0.007	0.333 ± 0.008	1.68 ± 0.04	1.25 ± 0.15
	Ground	0.0803 ± 0.0051	0.0843 ± 0.0056	0.103 ± 0.010	0.715 ± 0.023	0.596 ± 0.008
	Electropolished	—	—	0.0747 ± 0.0018	0.571 ± 0.008	—
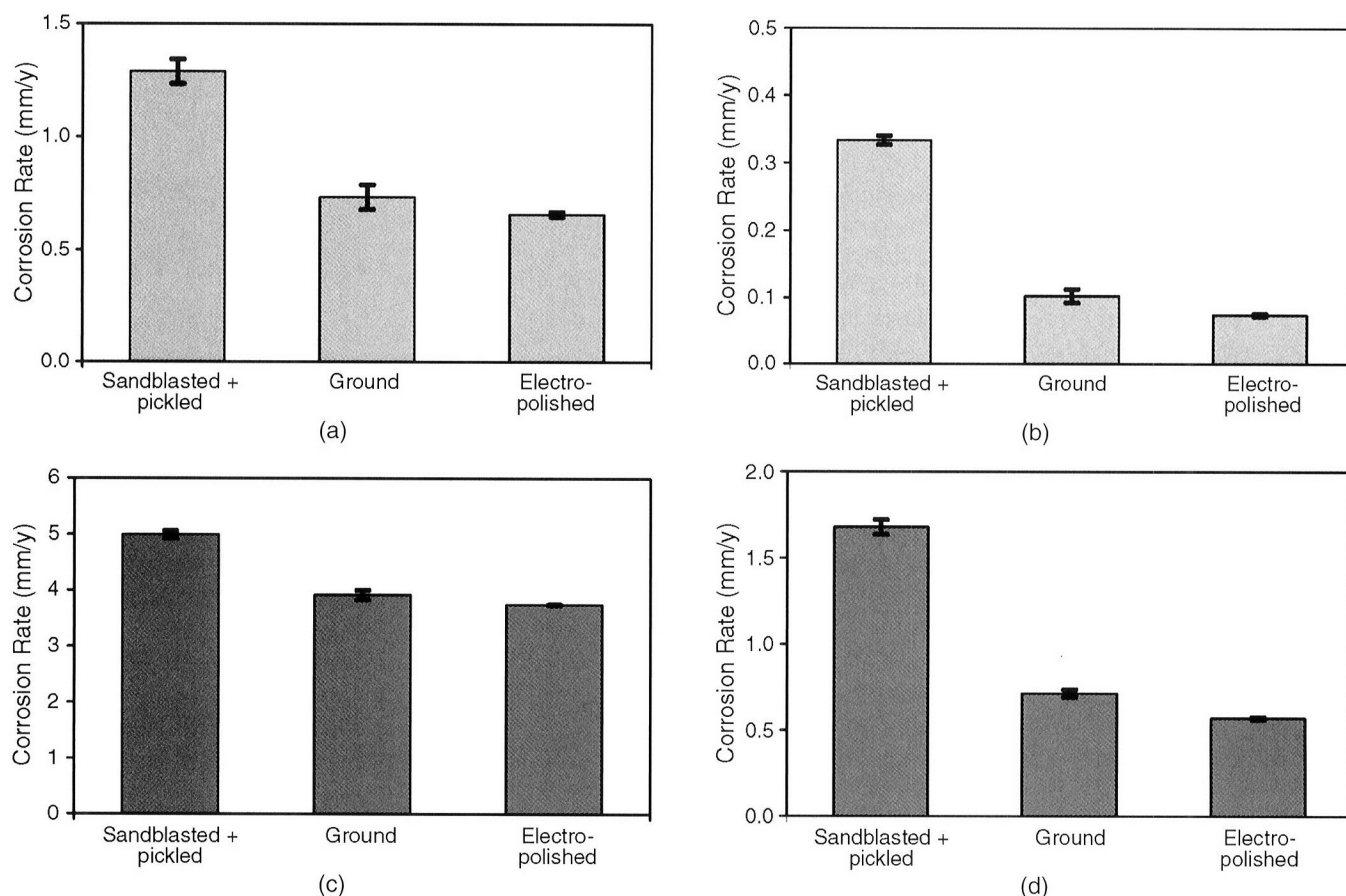
FIGURE 3. *Influence of surface condition on corrosion rate according to ASTM G 28: (a) C-22, no. 3, Method A, (b) C-22, no. 3, Method B, (c) C-276, no. 4, Method A, and (d) C-276, no. 4, Method B.*

much higher extent than forged materials. Therefore, it is justified to test these "potentially more sensitized" materials under more aggressive conditions than the latter. Small quantities of precipitates in forged materials do not give rise to intergranular attack as shown in the present work. Intergranular attack happens only when high amounts of secondary phases are present and, therefore, testing of forged materials according to "milder" Method B makes sense.

The results of this work prove first that both Methods A and B are very reliable and, therefore, can be used easily to characterize resistance to surface

corrosion and, second, there is a strong dependence of the corrosion rate on the number of surface crevices and their structure. Sandblasted surfaces contained, in most cases, large numbers of laminations and precipitate crevices. The corrosion rate was sharply increased by crevices formed by these surface defects, giving rise to concentration cells between the crevices and bulk surface, which is caused by local consumption in the crevice of the oxidizing species present in the solution. The efficiency of scale removal during sandblasting and pickling also could be revealed by the uniform corrosion rate when testing industrial
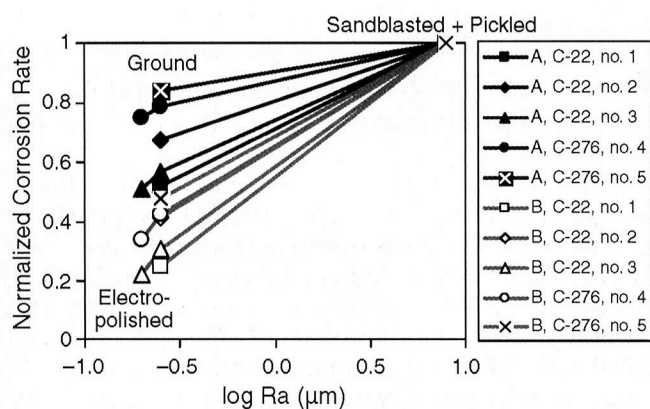
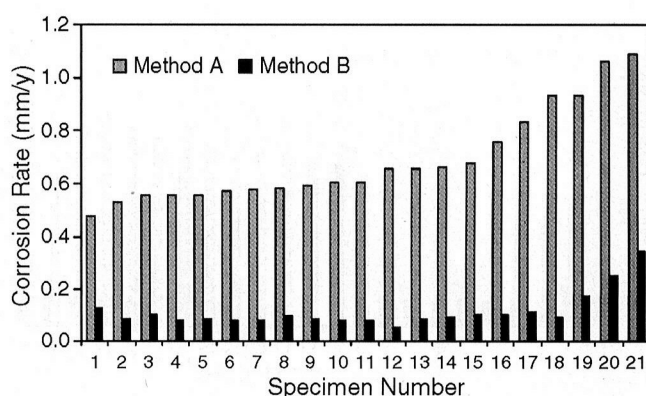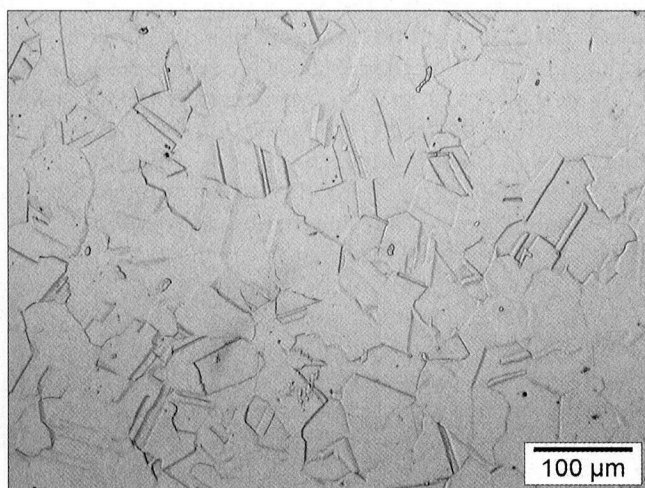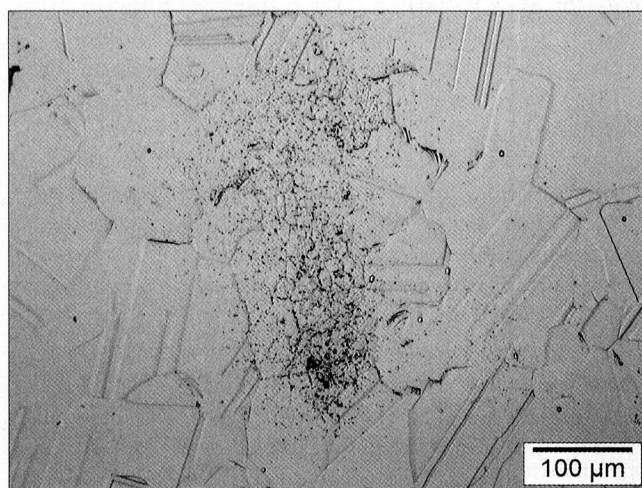**FIGURE 4.** *Normalized corrosion rate as a function of specimen's roughness.*

FIGURE 5. *Corrosion rates of industrial melts of Alloy C-22 according to ASTM G 28 (without appearance of intergranular corrosion).*

(a)

(b)

FIGURE 6. *Microstructure of Alloy C-22: (a) Specimen no. 3 from Figure 5 without precipitates and (b) Specimen no. 21 from Figure 5 with precipitates.*

surfaces. Standardized testing of industrial surfaces in addition to ground surfaces (for characterization of susceptibility to intergranular corrosion) should characterize the sum of these possible effects expressed as an increased corrosion rate when compared to a ground surface. The disadvantage of such a procedure is that all these effects are only expressed as an integrated increased corrosion rate, and the cause would have to be found out by further investigations. Testing of industrially finished surfaces, however, could lead to a new and more practical measure of corrosion resistance of delivered products in ASTM G 28 solutions.

Electropolished specimens showed 5% to 20% lower corrosion rates than a ground surface of the same material. This effect, first, was caused by a further decrease in crevice corrosion as a result of the smoother polished surface and, second, due to less attack of less-noble areas on the specimen already removed during electropolishing. Therefore, mechani-

cally polished specimens would seem to be better suited for these investigations. On the other hand, the decrease in the corrosion rate caused by using electropolished specimens instead of ground ones is rather small, which means that grinding is an adequate preparation method for the determination of susceptibility to intergranular corrosion and uniform mass loss.

There is a strong influence of microstructure and minor elements on average corrosion rates determined according to ASTM G 28 methods.[1] An experiment showed that an increased number of Mo- and W-rich precipitates (μ-, P-phase, and/or M_6C carbide) increased the corrosion rate significantly. Figure 9 shows uniform corrosion rates of solution-annealed specimens from this work, as well as some literature data as a function of the Cr/(Mo+W) ratio. Below a ratio of 1.3 there is a sharp increase in the corrosion rate.[5] There is, however, especially at lower ratios
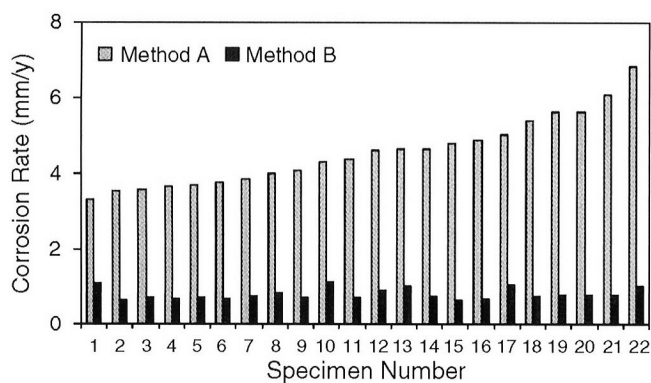
FIGURE 7. *Corrosion rates of industrial melts of Alloy C-276 according to ASTM G 28 (without appearance of intergranular corrosion).*

(e.g., for Alloy C-276), a large influence of microstructure on the corrosion rate. The fewer precipitates present in the material, the lower the corrosion rate. Method A seems to be the more powerful method for distinguishing the effects of inclusions because of its stronger solution and, therefore, generally more uniform attack. Small amounts of precipitates do not give rise to intergranular attack, rather an increase in mass loss expressed as a uniform corrosion rate. Since Alloy C-276, in particular, needs only very short sensitization times, its time-temperature response during production should be carefully controlled.

Finally, a probable improvement of corrosion resistance of Alloy C-276 seems to be feasible by increasing the Cr content to the upper limit of the alloy specification and decreasing the content of Mo and W as much as possible. For Alloy C-22 the corrosion rate always shows a smaller dependency on chemical composition.

CONCLUSIONS

❖ The ASTM G 28 testing method is a very reliable corrosion test, giving results with RSD of about 3% for both methods.

❖ There is a good correlation between the corrosion rate and number of crevices at the specimen's surface (in this work sometimes expressed as roughness). Practical sandblasted and pickled surfaces lead to 1.3 to 4 times higher corrosion rates than the ground surface prescribed in the standard. The application of electropolishing yields an improved corrosion resistance of 5% to 20% when compared to a ground surface.

❖ Both Methods A and B of ASTM G28 are suitable for determining the uniform corrosion rate of practically used sandblasted and pickled surfaces. A new measure for real industrial surface treatments of sheet material could be the result of such a test if widely practiced. Method B gives a better selectivity than Method A as a result of its generally milder solution, which is, however, strong enough to initiate crevice corrosion in laminations.

❖ On the other hand, Method B is less suitable for detecting differences in microstructure. Method A gives a good measure of the uniform corrosion rate and is sensitive to the number of precipitates in the microstructure of tested material. The solution of Method B is too weak and responds only to higher quantities of secondary phases and zones depleted of alloying elements to detect a significant increase in the corrosion rate.

❖ The ratio Cr/(Mo+W) has been confirmed as the main factor affecting the corrosion resistance of Ni-Cr-Mo alloys. By using high-Cr and low-Mo and W contents (still within specification limits), the cor-
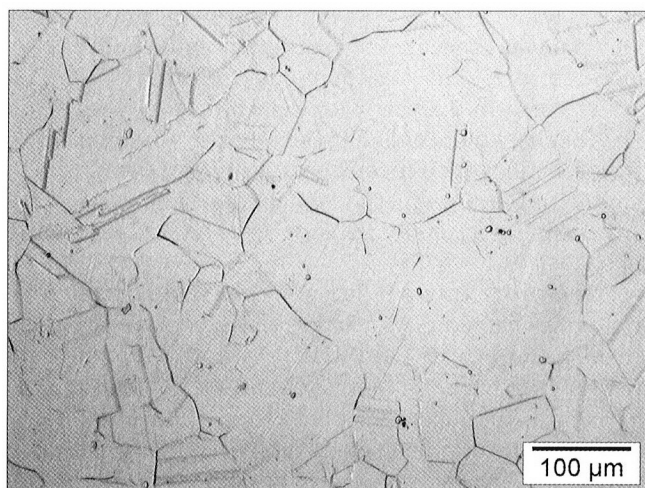
(a)
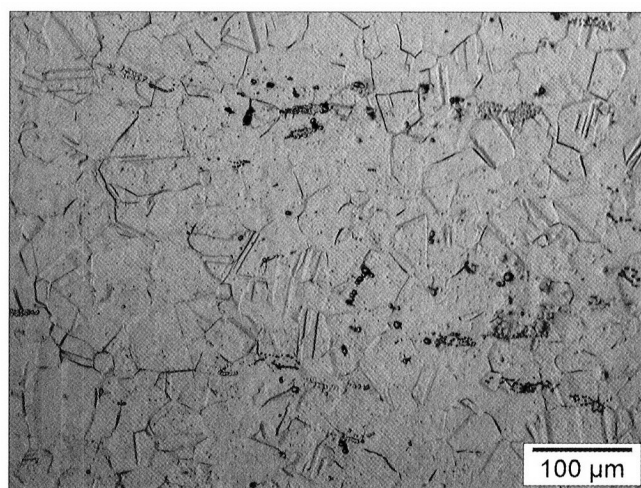
(b)

FIGURE 8. *Microstructure of Alloy C-276: (a) Specimen no. 6 from Figure 7 with low amount of precipitations and (b) Specimen no. 22 from Figure 5 with high amount of precipitations.*

rosion resistance of Alloy C-276 especially could be improved.

Further research should be done on the TTT behavior of Ni-Cr-W alloys and on the characterization of precipitated phases in relation to corrosion performance.

FIGURE 9. *Corrosion rate of Ni-Cr-Mo alloys as a function of ratio Cr/(Mo+W) according to ASTM G 28 Method A.*

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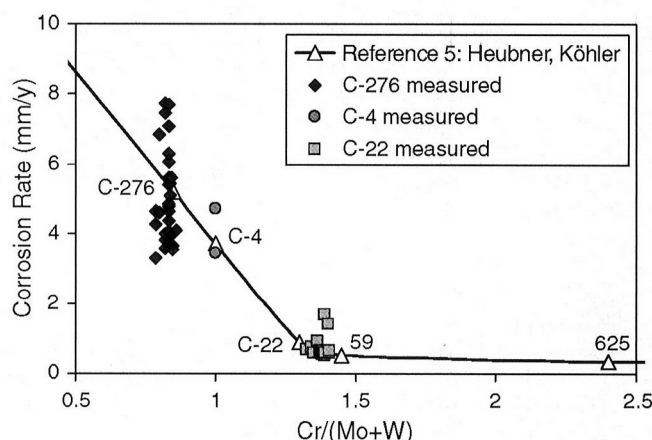22. Y. Cetre, J. Goudiakas, Mater. Tech. (Paris) 5-6 (2001): p. 51.

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