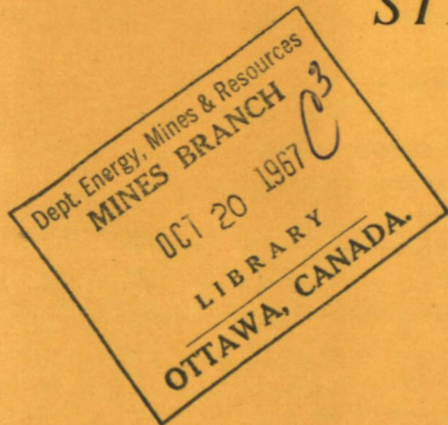




CANADA

DEPARTMENT OF
ENERGY, MINES AND RESOURCES
MINES BRANCH

*EFFECTS OF VARIOUS ALLOYING
ADDITIONS ON THE CORROSION
OF AISI TYPE 430 FERRITIC
STAINLESS STEEL*



G. J. BIEFER

PHYSICAL METALLURGY DIVISION

MARCH 1967



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EFFECTS OF VARIOUS ALLOYING ADDITIONS ON THE
CORROSION OF AISI TYPE 430 FERRITIC STAINLESS
STEEL

by

G. J. Biefer*

ABSTRACT

As part of a larger research project aimed at determining the effect of alloying elements upon the corrosion behaviour of ferritic stainless steels, aqueous corrosion tests were carried out upon AISI Type 430 stainless steels containing additions of each of Mo, V, W, Ta, Si, Re, Pd and Ge, and upon a control steel, AISI Type 304 stainless.

It was found that Mo, V and W additions each conferred improved corrosion resistance in non-oxidizing normal sulphuric and normal hydrochloric acid solutions. W was the most effective and V the least effective at the lower addition levels, below 1%.

Mo and, to a lesser extent, Re were the only additions that conferred increased resistance to oxidizing normal ferric chloride solution, while all the additions except Re and Ta were, to at least some extent, deleterious to corrosion resistance in boiling 65% nitric acid.

Pd additions were unique in that, in the range 0.46-1.91%, they brought about passivation in normal sulphuric acid, thus outperforming AISI Type 304 stainless steel in that medium. However, Pd additions of less than 0.46% were deleterious to corrosion resistance in sulphuric acid, whereas Pd additions at all levels were deleterious to corrosion resistance in the other test solutions.

A Type 430 steel containing 3.11% Mo showed corrosion resistance most nearly approaching that of Type 304 steel in the sulphuric acid, hydrochloric acid and ferric chloride solutions. However, this steel had extremely poor resistance to boiling 65% nitric acid, while the Type 304 steel (as expected) showed excellent resistance to this medium.

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Direction des mines

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LES EFFETS DE DIVERSES ADDITIONS D'ALLIAGE SUR LA
CORROSION DE L'ACIER INOXYDABLE FERRITIQUE AISI TYPE 430

par

G. J. Bieffer*

RÉSUMÉ

Dans le cadre d'un plan directeur de recherches visant à déterminer l'effet des éléments d'alliage sur le comportement à la corrosion des aciers inoxydables ferritiques, des essais de corrosion aqueuse ont été faits sur des aciers inoxydables AISI type 430 renfermant respectivement du molybdène, du vanadium, du tungstène, du tantale, du silicium, du rhénium, du palladium et du germanium, et sur un acier inoxydable de contrôle AISI type 304.

On a constaté que les additions de molybdène, de vanadium et de tungstène confèrent une résistance accrue à la corrosion dans des solutions non oxydantes normales d'acide sulfurique et chlorhydrique. Le tungstène est le plus efficace et le vanadium le moins efficace si les additions sont infimes, soit moins de 1 p. 100.

Le molybdène, et à un moindre degré le rhénium, sont les seules additions qui confèrent une résistance accrue à une solution oxydante de chlorure ferrique normale alors que toutes les additions sauf celles de rhénium et de tantale, jusque dans une certaine mesure du moins, ont abaissé la résistance à la corrosion dans l'acide nitrique à 65 p. 100 en ébullition.

Les additions de palladium ont donné des résultats uniques du fait que dans les proportions de 0.46 à 1.91 p. 100 elles ont rendu le métal à peu près inattaquable à l'acide sulfurique normal, lui donnant ainsi un rendement supérieur à celui de l'acier inoxydable AISI type 304 dans cet acide. Cependant, des additions de palladium en quantités inférieures à 0.46 p. 100 ont abaissé la résistance à la corrosion dans l'acide sulfurique, tandis que les additions de palladium à tous les niveaux ont affaibli la résistance à la corrosion dans toutes les autres solutions d'essai.

Un acier de type 430 contenant 3.11 p. 100 de molybdène a résisté à la corrosion à peu près de la même façon que l'acier de type 304 dans les

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solutions d'acide sulfurique, d'acide chlorhydrique et de chlorure ferrique. Cependant cet acier offre une très faible résistance à l'acide nitrique à 65 p. 100 en ébullition, tandis que l'acier de type 304 (comme prévu) y a très bien résisté.

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INTRODUCTION

It is well known that the 400 Series stainless steels are, in general, less corrosion-resistant than the more expensive 300 Series stainless steels. It was decided, therefore, to attempt to improve the corrosion resistance of one of the 400 Series stainless steel types - ferritic AISI Type 430 (14-18% Cr) - by means of alloying additions. The eventual goal of the work was to produce a modified Type 430 stainless steel having corrosion resistance equal to or better than that of a typical 300 Series stainless steel - austenitic Type 304 (18-20% Cr, 8-10% Ni).

The alloying additions selected for initial study all had significant solubility in ferritic iron and also had good to excellent corrosion resistance in sulphuric and/or hydrochloric acid.

It was decided to ascertain the effects of the additions primarily by means of anodic and cathodic polarization measurements. The results of these measurements, it was hoped, would not only define the effects of the individual additions quantitatively, but would also indicate which combinations of the additions might produce the greatest improvements in the corrosion resistance of the base Type 430 stainless steel.

In order to verify and extend the initial findings in the polarization measurements, it was decided to carry out a number of conventional weight-loss corrosion tests on the steels in several highly corrosive solutions. The results obtained in the corrosion tests, though much less informative than those obtained in the polarization measurements, were considered of sufficient interest to be reported separately, in advance of the initial findings in the polarization studies, and are presented in this report.

EXPERIMENTAL

Materials

The tests were carried out on 35 different heats based on Type 430 stainless steel and also on one heat of Type 304 stainless steel. Chemical analyses of the 36 steels are presented in Table 1. The steels were produced in the Physical Metallurgy Division as follows:

I. Steels A to X (omitting E, F, G, H) included alloys with each of Mo, V, W, Ta and Si. For each alloying element, a 50-lb aluminum-deoxidized induction furnace heat was prepared and split into four 12-lb ingots, one consisting of the base material and the other three containing the alloying element at different levels. After forging to 1/4-in. plate, the steels were annealed 1 hr at 840C (1550F), then furnace cooled.

II. Steels 3B to 10D (15 in all) included alloys with each of Re, Pd and Ge. Because of the high cost of these additions (particularly Re and Pd), smaller ingots were made. Initially, 4 lb of 1-2 oz chunks of Type 430 base material were melted in an induction furnace. A 2-lb ingot of the base material was poured, then an addition was made to the remainder. A second 4-lb melt was split in the same manner, to give two more 2-lb ingots containing additional levels of the alloying addition. All the ingots were poured in 3/4-in. dia core sand moulds. After cropping and surface-grinding to clean metal, the ingots were swaged to 3/8-in. dia rods at about 1090C (2000F), then annealed 1 hr at 840C (1550F) and furnace-cooled.

III. A 50-lb heat of AISI Type 304 stainless steel was made in an induction furnace. It was rolled to 1/4-in. plate, then annealed at 1070C (1950F) for 1 hr, and water-quenched.

Corrosion Tests

The steels made under parts I and III, above, were machined to small rectangular coupons, and surface-ground manually on 120-grit silicon carbide papers. The steels made under part II were machined to small cylindrical specimens, and surface-finished as above, using a small lathe. For both types of specimens, holes were drilled so that the specimens could be suspended in a corrosive solution by means of "Teflon" fluorocarbon resin strips.

Before testing, the specimens were weighed on an analytical balance accurate to 0.1 mg, and the dimensions measured with a micrometer in order to calculate the surface area. The specimens were then degreased in ultrasonically agitated carbon tetrachloride, rinsed in alcohol, and dried in a hot air blast.

Most of the corrosion tests were carried out in a large Pyrex jar containing 10 or 15 litres of test solution. The jar was provided with a tightly fitting Lucite lid, and specimens were suspended from a Lucite turntable which was positioned above the liquid surface and revolved at a rate of $8\frac{1}{2}$ revolutions per hour (see ref. 1). In each of the tests, 8 to 16 corrosion coupons were exposed simultaneously, each specimen being suspended individually from the rotating turntable by means of a Teflon fluorocarbon resin strip. The 4-hour tests in normal solutions of sulphuric acid, hydrochloric acid and ferric chloride were carried out at room temperature, and a fresh batch of solution was used for each test. The room temperature was nominally 24C (75F), but on a few occasions, due to inadequacy of the building heating system, it fell slightly below 21C (70F). In some cases, this caused the reproducibility of the weight-loss results to be below standard. However, addition-free controls were always tested with the addition-containing steels, so that the results could be interpreted in terms of corrosion rates relative to the controls.

In the "Huey" tests, 400-ml portions of boiling 65% nitric acid were contained in flasks equipped with reflux condensers. Single specimens, suspended from Teflon strips, were immersed in this solution for 48-hour periods. Fresh solution was used for each period.

After tests the specimens were rinsed in water and scrubbed lightly with a soft bristle brush to remove loosely adhering material. They were then rinsed in alcohol, dried with a hot air blast, and reweighed.

RESULTS

General

In Table 2, the weight losses observed in tests in the four highly corrosive media employed are presented.

In the following paragraphs, the results of low-power stereoscopic microscopical examinations of the surfaces of the corrosion-tested specimens are presented.

Normal H₂SO₄

The rolled Type 430 base steels generally showed a relatively smooth attack on the faces which lay in the plane of rolling. However, examination of the transverse and longitudinal faces showed a stringer attack which was most severe in control steel I.

Additions of Mo and W at all levels eliminated the stringer attack. Si and Ta reduced, but did not eliminate, the attack. For the V-bearing steels, stringer attack was reduced in steels L and J and very nearly eliminated in K.

The swaged Type 430 base steels also exhibited a relatively smooth overall attack, but did not show a definite end grain attack such as that seen in the rolled steels. For the steels containing Ge and Re, the corrosion brought about a general surface roughening which paralleled the weight losses in the corrosion tests. Pd additions up to 0.26% caused a progressive increase in overall corrosion, such that the steel with 0.26% Pd showed a "honeycombed" surface. The steels with the three highest Pd contents (which showed very low corrosion weight losses) were superficially shiny, but small shallow pits were observable. These were few in number in 3B, but increased with increasing Pd for 4C and 4D.

The Type 304 stainless steel was lightly and uniformly attacked. It showed no significant end grain attack and the original shiny finish on the specimens was only slightly dulled after the test.

Normal HCl

After corrosion testing in normal HCl, the rolled Type 430 base steels showed surface features resembling those observed in the specimens tested in H_2SO_4 . However, the overall attack was smoother, and the stringer attack observable in the transverse and longitudinal edges was less severe. As noted in the corrosion tests in H_2SO_4 , stringer attack was most severe for steel I.

As in the tests in H_2SO_4 , additions of Mo and W at all levels eliminated the stringer attack. However, in contrast to the results observed in H_2SO_4 , Ta and Si additions did not have any consistent effect upon the severity of stringer attack in normal HCl. V additions caused a reduction in stringer attack, the effect being progressively reduced as the V content was increased.

The swaged Type 430 base steels generally exhibited a smooth overall corrosion attack, and stringer corrosion effects were absent, as in the tests in H_2SO_4 . The Ge and Re additions brought about a roughening

of the surface paralleling the weight losses in the corrosion tests. The control for the Ge-bearing series - Steel 5A - showed remarkably good resistance to corrosion in HCl, in comparison with the other two controls, 7A and 9A. This tendency was also observable - though to a lesser extent, and less consistently - in H_2SO_4 .

Pd additions up to 0.26% brought about a progressive roughening of the surface, the steel with 0.26% Pd showing the roughest surface of all. The steels with Pd contents of 0.46 to 1.91% exhibited surfaces which were usually smoother than that of steel 10D (0.26% Pd) but considerably rougher than that of the control (9A).

The Type 304 specimen was lightly and uniformly attacked. It showed no significant end-grain attack, and the originally shiny finish on the specimens was only slightly dulled after the test.

Normal $FeCl_3$

In this medium, pits developed on specimen surfaces which were otherwise shiny and uncorroded in appearance. In many cases, the pitting attack proceeded by tunnelling in a random fashion so that the original specimen surfaces were noticeably undercut. It was also noticed that, in all cases, there was accelerated corrosion attack (crevice attack) at the points where the "Teflon" support strips had come in contact with the specimens.

In the rolled Type 430 base steels, the pitting attack was nearly always most severe on the end surfaces which had been horizontal and uppermost during the tests, and which were transverse to the rolling direction. It was found that the relative performance of these end surfaces in each alloying element group was a good index of the pitting susceptibility of the specimen surfaces as a whole.

On this basis, among the rolled Type 430 base steels, only Mo showed a marked effect upon pitting, the number of the pits and the depths of penetration diminishing as the Mo content increased. V and W showed at best a marginal beneficial effect, at the higher concentrations, whereas Ta and Si were ineffective.

Among the swaged steels, only Re showed some tendency to bring about reduced pitting attack. However, as indicated by the weight loss data, performance was erratic, and could only be explained partially on the basis of certain large inclusions that were noted in some of the Re-bearing specimens. It was evident that Pd additions at all levels - from 0.06 to 1.91% - caused accelerated pitting attack, while Ge was not observed to affect pitting susceptibility.

The Type 304 steels showed a number of small pits which were usually hemispherical, and thus differed from the pits seen in the Type 430 steels in that they did not show a tendency to undercut the original specimen surfaces. Each of the two specimens tested showed one large pit - i. e., visible to the naked eye. In addition, the Type 304 steel showed accelerated attack (crevice attack) at points where the specimen had been in contact with the "Teflon" supporting strip (as did the Type 430 base steels).

65% Boiling Nitric Acid

Generally speaking, after two 48-hour cycles, specimen surfaces were reasonably smooth, exhibited a dark colour, and showed a "wood grain" etching structure. In the flat-rolled specimens this was best exhibited on the major faces, with the pattern running predominantly along the rolling direction. In the cylindrical swaged specimens, the etching was observable on the curved surfaces, and the pattern ran predominantly in the axial direction.

The only alloying additions which affected specimen appearance to even a minor extent were Mo, Si and Re. Specimen D (3.11% Mo) exhibited an extremely rough surface, and the specimen was significantly reduced in

size after only one 48-hr period. Of the specimens with high silicon, specimen W was light in colour, whilst specimen X was silvery, and roughened by corrosion. The additions of Re appeared to alter the "wood grain" type of etching to one in which the corrosion pattern lay transverse to the axis of the cylindrical swaged specimens.

After the tests, the Type 304 stainless specimens exhibited a shiny metallic appearance, superficially similar though in fact slightly duller than before testing. However, under microscopical examination, small shallow corrosion pits were to be seen.

DISCUSSION OF RESULTS

General

A study of the data of Table 2 shows that reproducibility on replicate specimens from the same heat was not always good. This was in some cases due to inadequate temperature control, as mentioned previously. Furthermore, the base heats in the different groups showed considerable variation in their corrosion resistance. As an extreme example, heats I and 5A, both nominally Type 430 stainless steel, showed weight losses in the tests in H_2SO_4 ranging from a high of 32.7 mg/cm^2 (for I) to a low of 6.2 mg/cm^2 (for 5A). It was decided, therefore, that the results could be evaluated best in relative rather than absolute terms, and that only rather large effects could be taken into consideration.

The results of Table 2 are therefore presented, in Table 3, in terms of the corrosion rates relative to the addition-free control. It can be seen that the ratios thus obtained are in better agreement than the weight loss replicates. The principal trends in the results are presented in abbreviated form in Table 4. In this table, plus signs indicate corrosion rates that are 0.5 times, or less, that of the control steels. This is considered to be a

large enough change to show that the addition might be beneficial. Minus signs denote corrosion rates 2.0 times or more that of the control steel. Such a change is considered to indicate that the addition is probably deleterious.

Figures 1 and 2 show the greatest beneficial effects conferred by alloying elements in the tests in normal sulphuric acid (Figure 1) and normal hydrochloric acid (Figure 2), in terms of corrosion rates relative to the appropriate addition-free control steel.

Effect of Molybdenum

The beneficial effect of Mo on the corrosion of ferritic stainless steels in service applications is well known⁽²⁾. However, as noted previously⁽¹⁾, the open literature contains very little quantitative information on the effect of Mo on the aqueous corrosion of plain chromium steels, though a beneficial effect on corrosion in hydrochloric acid, sulphuric acid, and acetic acid has been reported⁽³⁾.

The present results, which show that Mo additions conferred increased corrosion resistance in non-oxidizing sulphuric and hydrochloric acids (Figures 1 and 2) and in oxidizing ferric chloride solution, are in agreement with previous work in this laboratory⁽¹⁾. Though it should be kept in mind that no other addition was tested at such a high level, the steel with 3.11% Mo showed the best all-round corrosion resistance in the three room-temperature solutions, and most nearly approached the excellent behaviour of Type 304 stainless in these. However, as noted previously, this level of Mo was extremely deleterious to corrosion resistance in boiling 65% nitric acid.

Effect of Vanadium

The addition-free control was found to corrode at higher rates than other controls, and metallographic examination indicated that it contained many more galaxies of non-metallic inclusions than the other control

steels. Nevertheless, V additions were found to bring about reduced relative corrosion rates in sulphuric and hydrochloric acids. At the higher addition levels, the effect of V appeared equivalent to that of Mo and W in these acids, but V appeared to be less effective than the other two additions at the lowest addition levels (Figures 1 and 2). V additions did not significantly affect corrosion behaviour in ferric chloride solution. In boiling nitric acid, V was slightly deleterious at the highest level.

Effect of Tungsten

W, like Mo and V, brought about reduced relative corrosion rates in sulphuric and hydrochloric acids. At the lowest addition levels, W appeared more effective than the other two elements (Figures 1 and 2), but this superiority was not evidenced at the higher addition levels. W had very little effect on corrosion resistance in ferric chloride solution. At the highest level, W was slightly deleterious to corrosion resistance in boiling nitric acid.

Effect of Tantalum

Ta additions failed to have any significant effect upon corrosion behaviour.

Effect of Silicon

The only significant effect observed with Si was a steady increase in the rate of corrosion with increasing Si level in boiling nitric acid. It bears mention that the results obtained in previous tests in this solution⁽¹⁾, using Type 430 stainless steel containing 0.96% Si, show good agreement with the trend noted in the present work.

Effect of Rhenium

At its highest level, Re conferred reduced corrosion resistance in sulphuric acid, but Figure 1 shows that it was ineffective, as compared with Mo, V and W, at lower levels. In hydrochloric acid, Re was deleterious.

In ferric chloride, Re was the only addition besides Mo to confer increased corrosion resistance, though its action was rather erratic. Re was the **only** addition which did not have an adverse effect on corrosion resistance in boiling nitric acid at the approximately 2.0% level.

Effect of Palladium

Tomashov reported that additions of Pd and Pt to 18/8 stainless steel and to 27% Cr steel brought about great improvements in corrosion resistance in sulphuric and hydrochloric acids⁽⁴⁾. N. D. Greene and co-workers⁽⁵⁾ reported that Pd and a number of other noble metal additions brought about striking improvements in the corrosion resistance of Cr in non-oxidizing sulphuric and hydrochloric acids.

The results obtained in the present work and in the parallel polarization measurements⁽⁶⁾ showed some relationship to the foregoing, in that additions of 0.46-1.91% Pd to Type 430 stainless steel brought about passivation in normal sulphuric acid. Corrosion resistance of these steels was therefore superior to that of Type 304 stainless steel in the same solution. However, at levels less than 0.46%, Pd was found to be extremely detrimental to corrosion resistance in sulphuric acid. In hydrochloric acid and ferric chloride solution, Pd was highly detrimental at all addition levels, and was detrimental to corrosion resistance in boiling nitric acid at the higher levels.

Effect of Germanium

Germanium additions failed to produce any significant improvements in corrosion resistance, but rather showed a definite tendency to be deleterious to corrosion resistance in sulphuric and hydrochloric acids, and in boiling nitric acid at the highest level of Ge.

SUMMARY AND CONCLUSIONS

It should be noted, first of all, that the present results were auxiliary to cathodic and anodic polarization measurements on the same steels, and that the latter measurements were far more informative⁽⁶⁾. Nevertheless, the corrosion tests yielded the following results which are considered to be of some significance:

1. Mo, V and W additions conferred improvements in the corrosion resistance of Type 430 stainless steel in non-oxidizing sulphuric and hydrochloric acid solutions. W was the most effective and V the least effective at the lower addition levels. At the higher levels, the action of the three additions was similar. An alloy with 3.11% Mo (a higher level than investigated with V and W) most nearly approached (though it did not equal) the corrosion resistance of Type 304 stainless steel in the three room temperature media. However, resistance of this steel to boiling nitric acid was extremely poor.
2. Mo and, to a lesser extent, Re were the only additions of those investigated which conferred improved corrosion resistance in an oxidizing ferric chloride solution. It is of interest that, in previous work, an addition of 0.24-0.55% U also conferred improved resistance to this medium⁽¹⁾.
3. Pd additions in the range 0.46-1.91% brought about passivation in normal sulphuric acid, i.e., better corrosion resistance than Type 304 stainless steel in the same solution. However, Pd additions of less than 0.46% were highly deleterious to corrosion resistance in sulphuric acid, and Pd at all levels was highly deleterious in tests in hydrochloric acid and ferric chloride solution.

4. Re, at its highest addition levels, showed some tendency to impart improved corrosion resistance in sulphuric acid, but was detrimental to corrosion resistance in hydrochloric acid.

ACKNOWLEDGEMENT

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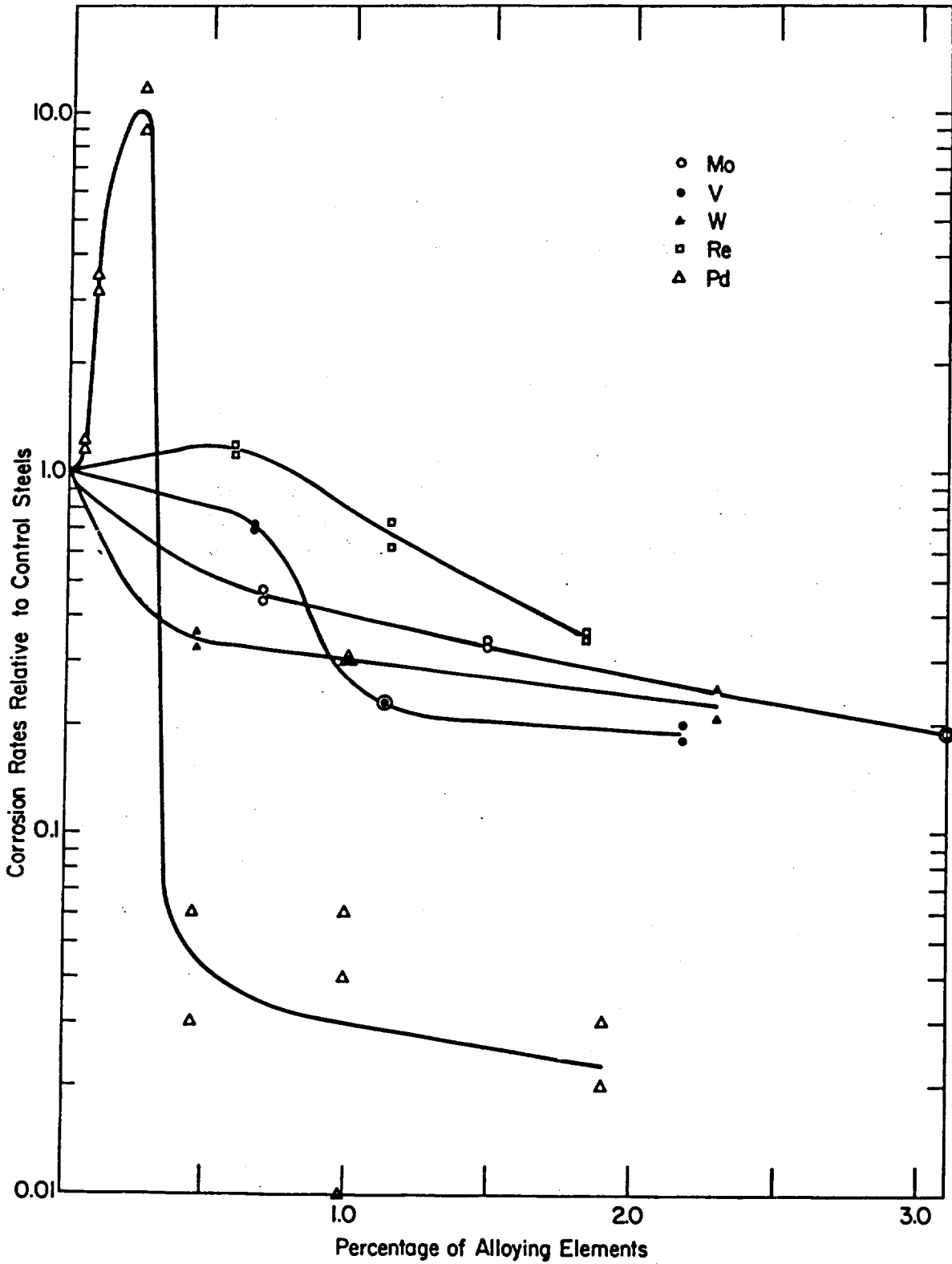


Figure 1. Effect of alloying elements upon corrosion in normal sulphuric acid.

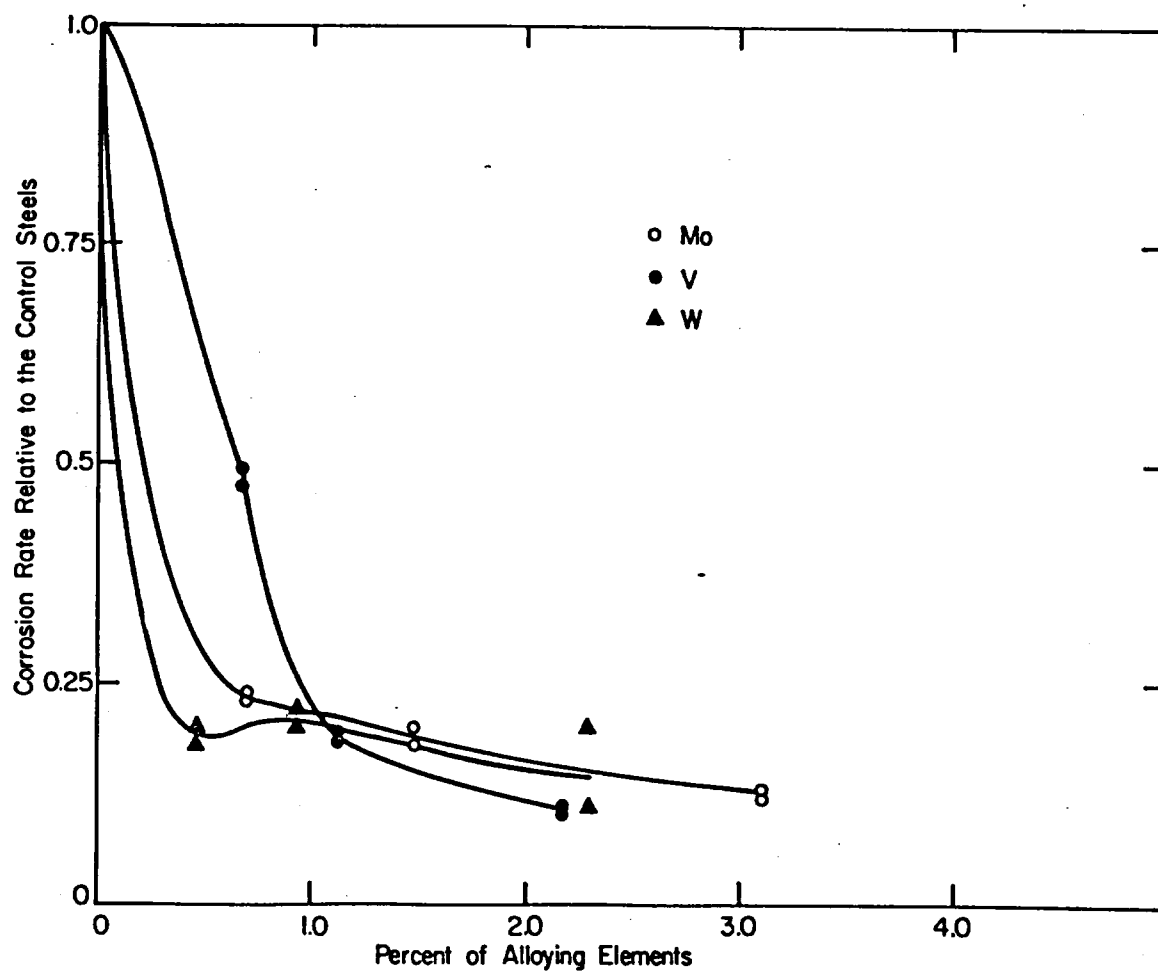


Figure 2. Effect of alloying elements upon corrosion in normal hydrochloric acid.

TABLE 1

Chemical Analyses of the AISI Type 430 Stainless Steels

Steel No.	Basic Composition						Alloying Addition	Steel No.	Basic Composition						Alloying Addition
	% C	% Cr	% Mn	% P	% S	% Si			% C	% Cr	% Mn	% P	% S	% Si	
A B C D	0.06	17.38	0.80	0.013	0.018	0.42	- 0.70% Mo 1.48% Mo 3.11% Mo	7A 7B 8C 8D	0.09	17.02	0.53	0.003	0.024	0.37	- 0.59% Re* 1.15% Re* 1.84% Re*
I J K L	0.07	17.39	0.84	0.011	0.028	0.62	- 0.67% V 1.13% V 2.18%	9A 9B 10C 10D							- 0.06% Pd 0.10% Pd 0.26% Pd
M N O P	0.06	17.31	0.76	0.012	0.023	0.47	- 0.47% W 0.94% W 2.30% W	3B 4C 4D	0.06	16.94	0.76	0.014	0.019	0.44	0.46% Pd 0.99% Pd 1.91% Pd
Q R S T	0.06	17.40	0.82	0.015	0.022	0.48	- 0.41% Ta 0.72% Ta 1.37% Ta	5A 5B 6C 6D							- 0.41% Ge 1.03% Ge 2.01% Ge
U V W X	0.06	17.52	0.64	0.018	0.024	0.39 0.84 1.33 1.78	- Si Si Si	6266**	0.06	19.47	1.77	0.017	0.022	0.57	10.19% Ni

* X-ray analysis.

(**) AISI Type 304 steel.

TABLE 2
Results Obtained in the Corrosion Tests

Steel No.	Per Cent of Alloying Addition	Weight Losses in 4-Hr Tests at Room Temperature, mg/cm ²						Weight Losses in Successive 48-Hr Periods in Boiling 65% ₂ Nitric Acid, mg/cm					
		1.0 N H ₂ SO ₄		1.0 N HCl		1.0 N FeCl ₃		1st Period		2nd Period			
A	-	14.8	10.8	7.8	7.0	7.3	4.3	1.7	2.2	2.5	2.2		
B	0.70 Mo	6.9	4.8	1.8	1.7	4.2	1.9	2.3	2.2	3.4	3.1		
C	1.48 Mo	5.0	3.6	1.4	1.4	2.8	0.6	4.2	3.4	8.3	8.5		
D	3.11 Mo	2.8	2.0	0.9	0.9	1.2	0.4	507	402	-	-		
I	-	30.7	32.7	17.6	16.7	15.2	7.3	2.4	2.5	3.2	2.6		
J	0.67 V	20.8	23.2	7.9	8.1	13.2	5.4	3.2	3.0	4.4	4.2		
K	1.13 V	7.1	7.6	3.4	2.8	13.5	5.1	3.3	3.0	4.2	3.6		
L	2.18 V	6.0	5.9	2.0	2.0	11.6	5.1	4.0	3.6	7.7	7.7		
M	-	19.3	19.4	9.2	8.3	10.8	5.5	2.8	2.2	2.3	2.1		
N	0.47 W	6.9	6.5	1.5	1.7	11.0	5.2	2.2	2.2	2.3	2.2		
O	0.94 W	5.7	5.9	1.8	1.8	10.4	4.5	2.6	2.3	3.6	2.3		
P	2.30 W	4.8	4.0	1.8	0.9	6.4	3.0	1.8	2.8	5.2	5.0		
Q	-	17.6	13.7	7.2	6.5	13.1	4.9	2.1	1.9	2.1	2.8		
R	0.41 Ta	12.6	9.0	6.3	5.6	12.1	4.7	2.4	2.7	3.3	2.4		
S	0.72 Ta	18.8	10.0	5.9	5.5	12.4	4.9	2.2	2.3	2.5	2.2		
T	1.37 Ta	15.9	11.3	6.8	6.2	13.9	4.8	1.9	2.1	2.2	2.1		
U	0.39 Si*	20.6	17.1	9.5	10.7	4.8	5.1	2.3	2.3	2.4	2.3		
V	0.84 Si	20.6	15.2	8.4	8.8	4.9	4.7	4.1	3.8	4.1	3.7		
W	1.33 Si	20.4	15.1	8.1	8.1	5.6	4.7	7.7	7.5	8.2	7.6		
X	1.78 Si	19.8	15.0	6.4	7.2	4.7	3.9	8.8	8.9	10.0	9.9		
7A	-	16.2	19.2	10.6	7.4	13.1	12.2	5.7	2.8	4.0	3.3	4.1	
7B	0.59 Re	19.3	21.5	32.1	21.1	6.0	12.8	1.3	2.9	4.0	3.3	4.1	
8C	1.15 Re	11.7	11.9	33.2	23.6	4.3	11.4	5.2	2.8	3.8	3.3	3.7	
8D	1.84 Re	5.9	6.5	20.8	14.2	5.3	9.5	2.2	2.9	4.3	3.5	4.3	
9A	-	11.8	11.8	6.7	4.9	13.1	10.9	2.8	3.5	3.8	2.6		
9B	0.06 Pd	14.2	13.4	8.4	6.4	39.6	41.5	3.5	3.5	3.6	3.3		
10C	0.10 Pd	40.7	37.6	32.0	24.0	38.0	41.7	3.7	3.5	3.6	3.5		
10D	0.26 Pd	134	105	194	151	39.0	42.1	4.2	3.9	2.8	3.3		
3B	0.46 Pd	0.4	0.7	59.9	40.7	43.8	44.6	4.4	4.6	3.9	3.9		
4C	0.99 Pd	0.1	0.7	144	104	42.6	41.2	5.1	6.6	6.9	7.4		
4D	1.91 Pd	0.2	0.3	193	147	44.1	47.9	10.1	10.9	13.9	13.5		
5A	-	6.2	16.2	6.8	1.5	1.7	1.8	19.7	19.5	3.3	5.1	3.0	3.3
5B	0.41 Ge	15.9	18.3	17.6	13.0	19.0	22.5	3.8	5.1	3.5	3.2		
6C	1.03 Ge	13.5	14.7	35.2	26.9	17.8	20.3	3.8	5.4	4.5	4.1		
6D	2.01 Ge	10.2	10.7	37.1	29.7	17.5	16.3	5.5	7.1	6.2	5.9		
6266	(Type 304)	0.7	0.7	0.6	0.6	0.6	0.7	0.7	0.8	0.6	0.6		

*Base composition.

TABLE 3

Corrosion Rates Relative to Those of the Control Steels

Steel No.	% of Alloying Addition	In Room-Temperature Solutions of Normal						In Boiling 65% Nitric Acid (2nd period)	
		H ₂ SO ₄		HCl		FeCl ₃			
A	-	-	-	-	-	-	-	-	-
B	0.70 Mo	0.47	0.44	0.23	0.24	0.58	0.44	1.36	1.41
C	1.48	0.34	0.33	0.18	0.20	0.38	0.14	3.32	3.86
D	3.11	0.19	0.19	0.12	0.13	0.16	0.09	>200	>200
I	-	-	-	-	-	-	-	-	-
J	0.67 V	0.68	0.71	0.45	0.49	0.87	0.74	1.38	1.62
K	1.13	0.23	0.23	0.19	0.17	0.89	0.70	1.31	1.38
L	2.18	0.20	0.18	0.11	0.12	0.76	0.70	2.40	2.96
M	-	-	-	-	-	-	-	-	-
N	0.47 W	0.36	0.33	0.16	0.20	1.02	0.95	1.00	1.05
O	0.94	0.30	0.30	0.20	0.22	0.96	0.82	1.56	1.10
P	2.30	0.25	0.21	0.20	0.11	0.59	0.55	2.26	2.38
Q	-	-	-	-	-	-	-	-	-
R	0.41 Ta	0.72	0.66	0.88	0.86	0.92	0.96	1.57	0.86
S	0.72	1.07	0.73	0.82	0.85	0.95	1.00	1.19	0.79
T	1.37	0.90	0.83	0.95	0.95	1.06	0.97	1.05	0.75
U	0.39* Si	-	-	-	-	-	-	-	-
V	0.84	1.00	0.89	0.89	0.82	1.02	0.92	1.71	1.61
W	1.33	0.99	0.88	0.85	0.76	1.17	0.92	3.42	3.31
X	1.78	0.96	0.88	0.67	0.67	0.98	0.77	4.16	4.30
7A	-	-	-	-	-	-	-	-	-
7B	0.59 Re	1.19	1.12	3.03	2.85	0.46	1.05	0.23	1.00
8C	1.15	0.72	0.62	3.13	3.18	0.33	0.94	0.91	1.00
8D	1.84	0.36	0.34	1.96	1.92	0.41	0.78	0.37	1.06
9A	-	-	-	-	-	-	-	-	-
9B	0.06 Pd	1.20	1.14	1.25	1.31	30.2	38.0	-	0.95
10C	0.10	3.46	3.18	4.77	4.9	29.0	38.3	-	1.27
10D	0.26	11.4	8.9	29.0	30.4	29.8	38.6	-	0.95
3B	0.46	0.03	0.06	8.9	8.3	33.4	41.0	-	1.35
4C	0.99	0.01	0.06	21.5	21.2	32.6	37.8	0.04	0.74
4D	1.91	0.02	0.03	28.8	30.0	33.7	44.0	-	1.27
5A	-	-	-	-	-	-	-	-	0.74
5B	0.41 Ge	2.58	1.12	11.7	7.4	0.96	1.15	-	1.02
6C	1.03	2.18	0.91	23.5	15.4	0.91	1.04	-	1.50
6D	2.01	1.64	0.66	24.8	17.0	0.89	0.84	-	1.24
									2.06
									1.79

*Base Si content.

TABLE 4

Principal Effects of the Alloying Additions*

Steel No.	Per Cent of Alloying Addition	Test Solution				Steel No.	Per Cent of Alloying Addition	Test Solution				
		H ₂ SO ₄	HCl	FeCl ₃	HNO ₃			H ₂ SO ₄	HCl	FeCl ₃	HNO ₃	
A	-					7A	-					
B	0.70 Mo	+	+	+	+	7B	0.59 Re		-	-	+	+
C	1.48	+	+	+	+	8C	1.15		-	-	+	
D	3.11	+	+	+	+	8D	1.84	+	+		+	+
I	-					9A	-					
J	0.67 V					9B	0.06 Pd				-	-
K	1.13	+	+	+	+	10C	0.10	-	-	-	-	-
L	2.18	+	+	+	+	10D	0.26	-	-	-	-	-
M	-					3B	0.46	+	+	-	-	-
N	0.47 W	+	+	+	+	4C	0.99	+	+	-	-	-
O	0.94	+	+	+	+	4D	1.91	+	+	-	-	-
P	2.30	+	+	+	+							
Q	-					5A	-					
R	0.41 Ta					5B	0.41 Ge	-		-	-	
S	0.72					6C	1.03	-		-	-	
T	1.37					6D	2.01			-	-	
U	0.39** Si											
V	0.84											
W	1.33										-	-
X	1.78										-	-

* + signifies 0.5 or less of the corrosion rate of the control steel.

- signifies 2.0 or more than corrosion rate of the control steel.

**Base Si content.