United States Patent [19]

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[11] **3,895,940**

[45] **July 22, 1975**

[54] **CORROSION RESISTANT HIGH CHROMIUM FERRITIC STAINLESS STEEL**

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[22] Filed: **Dec. 23, 1971**

[21] Appl. No.: **211,736**

Related U.S. Application Data

[63] Continuation-in-part of Ser. No. 841,121, July 11, 1969, abandoned.

[52] **U.S. Cl.** ..... **75/128 W**; 75/128 T; 75/128 G; 75/128 V

[51] **Int. Cl.** **C22c 39/20**

[58] **Field of Search** ..... 75/128 W, 126 C

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[57] **ABSTRACT**

A ferritic stainless steel resistant to pitting and crevice corrosion and containing in addition to iron, correlated amounts of chromium, molybdenum, silicon, nickel and metal from the group consisting of titanium, vanadium and columbium. Other constituents can also be present.

25 Claims, No Drawings

CORROSION RESISTANT HIGH CHROMIUM FERRITIC STAINLESS STEEL

This application is a continuation-in-part of application Ser. No. 841,121 filed July 11, 1969 now abandoned.

As the metallurgist is aware, stainless steels since their inception have had a tremendous impact in virtually all segments of commercial and industrial activity. From small pins to huge vessels, from the most delicate of medical instruments to the most elaborate of chemical equipment, from food and dairy utensils to articles for handling the most acrid of acids and fumes, etc., these steels have played a significant role. And, in terms of the more exotic applications extensive research efforts are being pursued in such fields as aerospace and marine technology, including desalination, oceanography, etc.

Perhapds the principal reason for such diverse utility stems from the ability of stainless steels to resist the destructive influence of various corrosive media. Much has been written in explanation of the possible mechanisms involved, and it appears generally accepted that their corrosion resistant qualities are attributable, at least in part, to the ability to assume the "passive" condition. This is an inherent phenomenon due, it is believed, primarily to composition, mainly chromium, and involves the self-formation of a thin, continuous surface film (mostly chromium oxides) which acts as a protective barrier.

To be sure, all stainless steels do not resist all corrosive environments. One such steel might offer appreciable resistance to acid "X" but be quite susceptible to acid "Y," the opposite being true of a different stainless. And as is so often the case in which practically all members of a class of materials exhibit early or premature failure under a given circumstance, stainless steels in general have proven not to be an exception in certain chloride environments, e.g., "stagnant or slowly flowing" seawater.

By way of explanation and at the risk of oversimplification, — there are any number of different types of corrosion, including general, pitting and crevice, intergranular, stress-corrosion cracking, etc.; however, it is the pitting and crevice form which is of greatest concern herein. As detailed in "The Corrosion Handbook" (1948) by Uhlig and in a number of other reference works, chloride ions (there are others) seem to display a peculiarly destructive talent in respect to the "passive condition" referred to above. This destructive manifestation normally occurs at "localized" surface areas which, for the lack of a better term, are simply referred to as "flaws" or "imperfections" (in operation they serve as natural crevices, hence, "crevice corrosion").

Needless to say, such flaws are, as a practical matter, impossible to avoid. They may take the form of surface dents, notches, nicks, scratches and the like, defects unintentionally induced. Or they may be inescapably brought about because of the form or shape of a particular article of manufacture — stranded cable, cable terminal sockets and valve seats being illustrative. Then, there are the historically troublesome crevices formed by the workings of nature as exemplified by the adherence of barnacles and other marine organisms, etc.

The corrosion breakdown that follows apparently involves the formation of an electrolytic cell in which the "localized" spot ostensibly serves as a point of concentration for attack by chloride ions whereby an active anode is established, the cathode being a large passive

area. The disparity in anode versus cathode area results in a considerable difference in potential which causes a significant flow of current with, as Uhlig puts it, "attendant rapid corrosion at the small anode."

When stainless steels are immersed in a chloride environment such as "stagnant or slowly flowing" seawater, a not inconsiderable number of them seem particularly vulnerable to crevice corrosion. The protective passive film is deemed, as mentioned above, to be primarily chromium oxides(s), meaning oxygen contributes to the passive condition. Upon rupture of the film if the velocity of seawater in a given case is significant, above say, 3 feet per second (fps), there is a replenishment of oxygen to the ruptured local site such that there is a tendency for the punctured surface to self heal by way of forming new chromium oxide. (Also, "rapidly" flowing seawater tends to prevent the adherence of barnacles and other organisms). In stagnant seawater, however, such is not always the case due to lack of available oxygen. Moreover, inter alia, the acidity of soluble corrosion products, e.g., ferrous chloride, inhibits restoration of "passivity."

It has now been discovered that stainless steels containing chromium, molybdenum and nickel and other constituents as described herein offer greatly improved resistance to the destructive effects of chlorides, provided the constituents are properly correlated in terms of chemistry and provided further they are at least substantially if not completely ferritic in microstructure. Furthermore, the ferritic structure notwithstanding, steels in accordance herewith also manifest good notch toughness qualities, various compositions displaying satisfactory brittle-to-ductile notch toughness even down to temperatures as low as or lower than zero °F.

The foregoing combination of characteristics can be contrasted with at least certain of the literature. The Metals Handbook, for example, 8th ed., 1961, pages 554, 558–564, indicates that stainless steels perform well in seawater in the absence of fouling mechanisms (crevices) and if the velocity is 5 fps or greater. AISI 316 is used but as will be shown herein, under simulated condition it, comparatively speaking, rapidly fails. Too, in "Stainless and Heat-Resisting Steels," L. Colombier and J. Hochmann, 2d, ed., (1965), p. 55, the known 25–30% chromium ferritic stainless steels are reported as being objectionable by reason of the following:

> "Thus, a steel with 25% chromium melted under normal commercial conditions will give low impact values even at carbon contents as low as 0.03%, after heat treatment at any temperature between 800°C. and 1,200°C. and whatever the cooling conditions. This is a most troublesome fact and a major obstacle to the large scale industrial development of the steels. The difficulty is in fact notch sensitivity and nothing else; ***."

In any case, it is an object of the present invention to provide stainless steels novel in composition and which afford improved resistance to the corrosive effect of various chloride environments.

It is a further object to provide stainless steels having a ferritic or substantially ferritic microstructure and which exhibit satisfactory notch toughness characteristics.

Generally speaking, the present invention contemplates, subject to the qualifications described herein, stainless steels containing (by weight) from 30 to about

36%, e.g., 32 to 35%, chromium; from 0.5% up to about 5%, e.g., 1 to 4%, molybdenum; up to about 3%, e.g., about 0.1 to 1.75%, silicon, the sum of the chromium plus three times the amount of molybdenum plus three times the percentage of silicon (referred to herein as the "CMS" indicator) being at least about 38%; from 2%, and most advantageously at least about 3%, and up to 8% nickel; up to less than 2% titanium; up to about 2% vanadium; up to about 2% columbium; up to about 2% aluminum; up to about 2% manganese; and the balance essentially iron.

In carrying the invention into practice, the chromium, molybdenum and any silicon must be correlated if satisfactory hot workability is to be achieved in addition to outstanding corrosion resistance. An alloy containing 30% chromium, for example, but molybdenum-free has been found to exhibit inferior corrosion resistance. On the other hand, an alloy containing, say, upwards of 36% chromium together with a molybdenum content of 4% is at best extremely difficulty, if at all, workable. Thus, where good hot workability is a prerequisite the "CMS" factor should be less than 48% and beneficially not more than about 45%. Too, while silicon confers resistance to corrosion, it has been found to detract from ductility if present in excess of, say, 1.5 or 2%. For castings this qualification need not obtain and in such instances (or in respect of other applications in which good ductility is not of necessity, e.g., deposit of an overlay on a substrate) the silicon content can be as high as 3%. No significant benefit is derived from higher silicon contents. For applications where it is important to minimize susceptibility to sigma formation, e.g., heavy sections, it is beneficial that silicon not exceed 0.5 or 0.75%.

Nickel portrays a most influential role by importantly contributing to high impact strength and low brittle-to-ductile transition temperatures. Charpy-V notch impact strengths of 15 foot-pounds or greater (a rather often used standard measurement) have been attained at temperatures well below −100°F. It is thought that such a characteristic would tend to mitigate the notch toughness drawback hitherto characteristic of high chromium ferritic steels. The upper nickel limit must, however, be controlled for if present to the excess, e.g., 10%, various characteristics including workability are impaired. A nickel range of from 3 or 4% to about 6 or 7% is deemed particularly satisfactory.

While either air or vacuum melting techniques can be used in the preparation of the subject steels, at least one element from the group consisting of titanium, vanadium and columbium, particularly titanium, should be present in using air melting processing when the "CMS" indicator is not more than about 38%; otherwise, corrosion resistance suffers as will be illustrated herein. It has been found that a small but effective amount of one or more of these elements can markedly enhance corrosion resistance in various chloride media, e.g., ferric chloride. Should the "CMS" indicator be appreciably above 38%, e.g., 41 or 42% or more, air melting can be used in the absence of such constituents, but even under such circumstances (or notwithstanding the utilization of vacuum melting processing), one or more of these elements should be utilized, especially when the most drastic corrosion conditions are expected to be encountered. Moreover, apart from corrosion considerations, in attaining good workability, e.g., forgeability and cold rollability, it is decidedly advantageous that titanium be present. The total sum of these constituents should not exceed about 4% and a range of about 0.15 or 0.2% to about 0.5 or 1% for each is satisfactory.

Aluminum can be used as a deoxidant but it does tend to impart a dross on the surface of air melted alloys in the molten condition and this can result in ingots with scabby surfaces. It can be present up to 2%, e.g., up to 1%, since it seemingly promotes the effectiveness of the titanium, vanadium and columbium under air melting practice, but it need not exceed 0.1 or 0.2%. Actually, it is to advantage to use silicon in lieu of or together with a small amount of aluminum not only for its power in imparting good corrosion resistant qualities but also for deoxidation purposes as well.

As above set forth, it is important that the subject steels be characterized by a ferritic microstructure. Duplex or other multiphase structures such as those comprised of ferrite and a significant amount of austenite are to be avoided since corrosion resistance can be impaired. While a small or incidental amount of, say, austenite can be tolerated, e.g., up to 2, 3 or possibly 5%, the approach should be to avoid it. The same applies to phases other than austenite.

In the preparation of the instant steels the use of the purest materials commensurate with reasonable cost, (e.g., ferromolybdenum, ferrochromium and ingot iron) should be employed. Materials of exceptionally high purity, of course, can be utilized, e.g., molybdenum metal pellets, the electrolytic forms of iron, chromium and nickel, etc. As indicated above, both air melting and vacuum processing can be employed. Vacuum melting is, however, preferred since it has been found to promote higher notch-toughness characteristics (both resistance to impact and lower brittle-to-ductile impact transition temperatures), particularly in respect of columbium-containing steels. In addition to such techniques, other production practices are contemplated, including electroslag remelting, continuous casting and powder metallurgical processes.

A suitable pouring temperature is from about 2,800°F. to 2,900°F. As is commonly done in commercial steelmaking practice for wrought products, ingots are preferably stripped hot from the mold and directly transferred to a soaking pit and soaked at a temperature of over 2,100°F. to 2,300°F. for a sufficient period and thereupon worked as by forging, hot rolling, etc. The hot finishing temperature can be as low as 1,400°F. to 1,500°F.

Following hot working, the steels can be annealed at a temperature of 1,900°F. to 2,100°F. prior to cold rolling. Surface defects are removed (e.g., by grinding, polishing) at appropriate intermediate stages but subsequent to final working. A final annealing treatment over the temperature range of 1,900°F. to 2,100°F. or 2,200°F. can be used; however, it is much preferred to use a temperature of 1,950°F. to 2,050°F., e.g., 2,000°F., since the lower temperature would not only be more amenable to commercial practice but it has been determined that corrosion resistance is often significantly superior. Holding periods at the lower annealing temperatures need not exceed about 10 or 15 minutes.

In order to give those skilled in the art a better appreciation of the invention, the following illustrative data are given.

A substantial number of alloys within the invention, Alloys 1 through 21, Table I, nominal compositions being given, were prepared using air (Alloys A, 1,2,4,8,9,13,17) or vacuum (all others) melt process-

ing. (Each melt was deoxidized with about 0.05% calcium added in the form of a 30% Ca - 70% Si master alloy, iron and impurities constituting the balance. AISI 316 and Alloys A-D are included for comparison). An argon cover was used in the vacuum melt processing before adding the deoxidant calcium-silicon. This reduced the vacuum from about 29 in. Hg. to about 7 in. Hg. In respect of the air melted steels, a small amount of argon was continuously passed through the furnace but the amount was insufficient to completely prevent oxidation from taking place.

Ingots were soaked at about 2,200°F. to 2,300°F. and for the most part thereafter hot rolled to squares (either 2 inches × 2 inches or 1½ inches × 1½ inches or 1 inch × 1 inch). The specimens were then cut into two sections one of which was retained for stock purposes the other being rolled to ⅝ inch square bar. A portion of the ⅝ inch bar was removed for other testing, a part of the remainder being hot worked to about one-fourth inch thick, ground finished, annealed at 1,900°F. to 2,200°F., cold rolled to about 0.050 inch thick strip and final annealed at 2,000°F. or 2,100°F. Certain of the steels (1 – 7) were reheated to 2,200°F. to 2,300°F. before rolling to ⅝ inch bar. (Steel A was reheated to 1,800°F.). Steels B, 8 and 16 were additionally reheated to 2,100°F. prior to cold rolling.

Corrosion tests were conducted using an aggressive corrodent commonly used for test purposes, to wit, an aqueous 10% ferric chloride solution ($FeCl_3$). Test specimens, having a surface area of approximately 25 square centimeters, were immersed therein for about 72 hours, the temperature being maintained at about room temperature (approximately 72°F.); however, prior to immersion an intentional crevice was created about the surface of the specimens by wrapping a rubber band thereabout. This test being of an accelerated nature is deemed equivalent to an extreme long-time exposure in seawater and is described by M. A. Streicher in the Journal of the Electrochemical Society, Vol. 103, pps. 375–390, No. 7, July 1956.

The data in Table I reflect the excellent corrosion characteristics typical of alloys within the invention. This is in marked contrast to Alloys A, B, D and AISI 316. In comparison with steels in accordance herewith, AISI 316 failed catastrophically, undergoing near virtual disintegration. Mention might be made that Alloy C is indicative of the difficulty concerning hot workability with steels containing high amounts of both chromium (36%) and molybdenum (4%). At the higher chromium levels, to wit, 35 to 36% there is little need for molybdenum levels above 3%. Note might be taken of Alloy 12 from which it may be observed that a nickel content of 8% begins to impair corrosion resistance. It also, at this level, detracts from forgeability. Thus, it is beneficial that the nickel content not exceed 6 or 7%, a range of 2.5%, and preferably at least 3%, to about 6% being quite suitable.

With further regard to Table I, Alloy B is indicative of what might be expected with low "CMS" values. As referred to herein, the "CMS" indicator should be at least about 38%. Even then, in consistently achieving outstanding resistance to pitting and crevice corrosion, particularly in the more drastic corrosive environments, it is of benefit that the "CMS" value be 39% or more; however, it is contemplated that where a high level of corrosion resistance is not consistently required, the "CMS" indicator can be as low as 35% or even down to 34%. Stainless steels having "CMS" indicators of 38 or 39% or more and compositions failing within the following ranges are deemed quite satisfactory: about 31.5 to 35% chromium, from about 1.5 to 3.5% molybdenum, up to about 1.5% silicon, from about 2.5% or 3 to 6% nickel, a small but effective amount of at least one constituent from the group consisting of up to 1% titanium, up to 1% vanadium and up to 1% columbium, up to about 1% aluminum and the balance essentially iron.

Steels in accordance herewith have also performed well corrosion-wise in media other than chlorides. Using the same general procedure described in connec-

TABLE I

	Composition						Corrosion Behavior, 10% $FeCl_3$	
Alloy	Cr	Ni	Mo	Ti, V, Cb	Al	Other	Crevice Corrosion	Wt. Loss, Milligrams
AISI 316	17	12	2.5	—	—	—	Very Heavy	2,592
A	26	n.a.	n.a.	0.5 Ti	0.5	0.15 Si-Mn	Very Heavy	316
B	32	4	n.a.	0.5 Ti	0.25	—	Med. – Heavy	43
C	36	4	4	0.5 Ti	n.a.	—	Broke (not tested)	
D	30	5	4.5	n.a.	n.a.	0.12 C, 0.5 Si, 0.5 Mn	Very Heavy	2,456
1	32	3	3	0.5 Ti	0.5	—	None	None
2	32	4	3	0.5 Ti	0.5	—	None	None
3	32	4	4	0.5 Ti	0.5	—	None	None
4	32	2	3	0.5 Ti	0.5	—	None	0.4
5	36	4	1	0.5 Ti	0.5	—	Moderate	6.6
6	36	4	1	0.5 Ti	0.5	1.5 Si	Slight	0.8
7	32	4	1	0.5 Ti	0.5	1.5 Si	None	None
8	32	2	2	0.5 Ti	n.a.	0.5 Si	None	0.3
9	32	4	2	0.5 Ti	0.5	0.5 Si	Light	1.2
10	32	6	2	0.5 Ti	0.5	—	None	None
11	32	4	2	1 Ti	n.a.	0.5 Si	None	0.3
12	32	8	2	0.5 Ti	o.5	—	Moderate	7
13	32	4	2	0.5 Ti	n.a.	0.5 Si, o.5 Mn	Light	0.4
14	32	4	2	0.5 Ti	0.25	—	None	0.6
15	32	4	2	0.25 V	n.a.	0.35 Si	None	None
16	32	4	2	0.25 V, 0.25 Ti	n.a.	0.35 Si	Light	1.6
17	32	4	2	0.5 V, 0.5 Ti	n.a.	0.35 Si	None	0.5
18	32	4	2	0.5 Cb	n.a.	0.25 Si	None	0.4
19	32	4	2	0.5 Cb	0.5	—	None	0.2
20	32	4	2	0.5 Cb, 0.5 Ti	n.a.	0.25 Si	None	0.1
21	32	4	2	0.25 Cb, 0.25 Ti	n.a.	0.25 Si	None	None

tion with the alloys of Table I, an alloy containing nominally 32% chromium, 4% nickel, 2% molybdenum, 0.5% titanium, 0.4% silicon, 0.02% carbon (deoxidized with 0.15% Ca Si), was tested in an aqueous solution containing 10% nitric acid, 10% hydrochloric acid and 10% sulfuric acid for a period of 72 hours, the solution being maintained at room temperature. Upon examination, the specimen did not exhibit any crevice corrosion and the weight loss was but 0.2 milligrams. It might be added that the magnitude of corrosion resistance afforded by steels within the invention has been such as to render pickling exceedingly difficult in the annealed condition, e.g., when annealed at 1,950°F. or 2,000°F. or above. Thus, it is to be understood that the alloys of the subject invention can be used in many other corrosive environments apart from chlorides.

To demonstrate the effect of a constituent from the group consisting of titanium, vanadium and columbium on steels prepared by air melting practice, there is reported in Table II the corrosion resistant results obtained in respect of alloys both devoid of and containing titanium. These alloys were prepared and tested in generally the same manner as described in connection with Table I.

TABLE II

Alloy	Composition* Cr	Ni	Mo	Al	Ti	Other	Corrosion Behavior, 10%, $FeCl_3$ Crevice Corrosion	Wt.Loss Milligrams
E	32	4	2	n.a.	n.a.	0.5 Si, 0.5 Mn	Very Heavy	>10,000
F	32	4	2	n.a.	n.a.	0.03 C, 0.5 Si 0.05 Mn	Very Heavy	>10,000
22	32	4	2	<0.1	0.17*	0.42 Si*	Slight	0.3
23	32	4	2	<0.1	0.32*	0.47 Si*	None	None
24	32	4	2	0.5	n.a.	0.5 Cb	Slight	0.7
25	32	2	4	0.5	n.a.	0.4 Si	None	None

n.a. = not added;
* = actual analysis; otherwise nominal
0.05% Ca added in form of 30% Ca – 70% Si master alloy
Balance of composition iron and impurities

Alloys E and F are illustrative of the adverse effects that can arise using air melting processing in the absence of an element from the group titanium, vanadium and columbium. As demonstrated by Alloy 25, when the CMS indicator is appreciably above 38% (in this case nominally 45.2%) excellent corrosion resistant characteristics are attainable using air melting techniques and in the absence of titanium, vanadium or columbium. However, this same alloy underwent virtual disintegration upon being tested in hot 10% ferric chloride solution, the temperature being maintained at about 122°F. for the 72 hours test period. On the other hand, vacuum melted Alloy 3, an alloy of similar composition but to which 0.5% titanium was added, lost less than one milligram when similarly tested in hot 10% $FeCl_3$.

Notch toughness data are given in Table III concerning alloys within (18, 14, 10, 26–30) and without (G to L) the invention. Excepting Alloys 29 and 30 all were vacuum melted. All were oil quenched after annealing, Alloys G to L, 10, 14, 26 and 27 being annealed at 2,100°F., the others at 2,000°F. Liquid quenching has been found to offer better notch toughness, generally speaking, then say, air cooling. The combination of vacuum melting plus liquid quenching has been determined as consistently providing superior results as opposed to air melting or air cooling. For example, impact properties of air melted steels nominally containing about 32% Cr, 4% Ni, 2–3% Mo, 0.5% Ti, etc., have ranged generally from about 20 to over 50 ft.-lbs. at ambient temperature after annealing at 2,000°F. and oil quenching versus generally from about 35 to over 100 ft.-lbs. for such steels vacuum melted and oil quenched.

TABLE III

Alloy No.	Cr %	Ni %	Mo %	Al %	Ti %	Others	C.V.N., ft.-lbs. R.T.	B.D.T.T., °F.
G	32	n.a.	2	n.a.	0.5	0.5 Si	2	+170
H	32	0.5	2	n.a.	0.5	0.5 Si, 1 Cu	7.5	—
J	32	0.6	2	0.5	0.5	—	3.5	+215
K	32	10	2	n.a.	0.5	0.5 Si	Broke on Forging	
L	32	15	2	n.a.	0.5	0.5 Si	Broke on Forging	
18	32	4	2	n.a.	n.a.	0.25 Si, 0.5 Cb	131	−130
14	32	4	2	0.25	0.5	—	52.5	−40
10	32	6	2	0.5	0.5	—	112.5	<−120
26	32	2	2	n.a.	0.5	0.5 Si	17.5	60
27	32	4	2	0.5	0.5	—	41.5	0
28	32	4	2	0.15	n.a.	0.25 Si, 0.5 Cb	178	−100
29	32	4	2	0.25	0.5	0.35 Si	44.0	—
30	32	6	2	n.a.	0.75	0.6 Si	99.5	−120

n.a. = not added
0.05% Ca added in form of 30% Ca – 70% Si master alloy
Balance of composition iron and impurities.

It will be noted that excellent impact resistance and brittle-to-ductile transition temperatures (B.D.T.T.) are obtained particularly with alloys containing above 2% nickel, e.g., 4 to 6% nickel. (The brittle-to-ductile

transition temperature (B.D.T.T.) is the temperature at which the steel specimen exhibited a minimum Charpy-V notch impact resistance of 15 ft.-lbs.). Moreover, Alloys 18, 12, 27, 28 and 29 (same nominal percentage of nickel) reflect the vacuum melted steels containing columbium exhibited outstanding results. For a high chromium ferritic stainless steel, particularly one of exceptional corrosion resistant characteristics, to absorb an impact energy of over 100 ft.-lbs. or more at room temperature and to afford a transition temperature of minus 100°F. or lower, is quite unusual. However, as mentioned above, the amount of nickel cannot be permitted to go unchecked as is shown by Alloys K and L.

A further attribute of the subject steels is that they possess satisfactory fatigue strength. Since it is not uncommon in assessing fatigue behavior to use a maximum fiber stress of at least equal to one-half of the tensile strength to ascertain whether a steel will perform adequately for a period of at least one hundred million cycles in duration, a smooth bar specimen of an alloy nominally 32% chromium, 4% nickel, 2% molybdenum, 0.5% silicon, 0.5% titanium, 0.15% calcium-silicon, balance iron and impurities was subjected to a maximum fiber stress of 58,000 psi. (The ultimate tensile strength upon annealing at 2,000°F. was 100,000 psi.) Using an R. R. Moore Rotating Beam Machine it was found that the specimen exhibited a life of over 10-**8,000,000** cycles at which point the test was discontinued.

With regard to weldability, a butt weld was made with ¼ inch plate of a steel nominally containing 32% chromium, 4% nickel, 3% molybdenum, 0.5% aluminum, 0.5% titanium, 0.15% of calcium silicon, 0.25% silicon manganese, the balance being iron and impurities. The weld was crack-free under X-Ray and no cracks were detected upon metallographic examination. Furthermore, bead-on-plate experiments failed to reveal the presence of weld cracks. A specimen of a weld bead was corrosion tested in 10% $FeCl_3$ (as described in connection with Table I) with excellent results.

Alloys within the invention are contemplated for general use in marine environments including seawater and sea atmospheres and in connection with such operations as off-shore drilling, desalination, undersea mining, etc. More specifically, they are considered useful for pumps and parts thereof (including vanes and impellers), propellers, pipe, valves, fasteners, tubing in general including tubing for both heat exchangers and desalination equipment, tube sheets, water boxes, seawater evaporators, shafting, sheathing, marine hardware, e.g., chocks, cleats, pulleys, oil well equipment, etc., components for paper pulp equipment and chemical plant equipment for the handling of oxidizing acids and salts thereof, containers for pressure vessels for the storage and transportation of various corrosive chemicals, etc. The steels can be produced in conventional mill forms including sheet, bar, plate, rod, etc., and also as castings.

As will be understood by those skilled in the art, the term "balance" or "balance essentially" when used in referring to the iron content does not exclude the presence of other elements commonly present as incidental elements, e.g., deoxidizing and cleansing elements, and impurities ordinarily associated therewith in small amounts which do not adversely affect the basic characteristics of the alloy. Elements such as sulfur, hydrogen and oxygen should be maintained at low levels consistent with good commercial steel making practice. It is, at best, most difficult to avoid the presence of carbon and to do so could add to the cost. Carbon can remove undesirable oxygen but is not essential. It is advantageous that it be kept to low levels, e.g., below 0.02 or 0.04%. It can be tolerated in higher amounts up to 0.1% but above about 0.06 or 0.07%, it should be fixed. It is preferred that the carbon be fixed above about 0.02%. Nitrogen can be present in usual amounts. Other constituents can be present as supplementary elements such as up to 4% tungsten and up to 10% cobalt. Tantalum is often found associated with columbium; however, it is heavy and costly as well as non-essential and should be held to not above 0.2%.

Although the present invention has been described in conjunction with preferred embodiments, it is to be understood that modifications and variations may be resorted to without departing from the spirit and scope of the invention, as those skilled in the art will readily understand. In this regard, zirconium can be used to replace titanium, vanadium or columbium in whole or in part but it is more beneficial for various reasons to use one or more of the latter. Such modifications and variations are considered to be within the purview and scope of the invention and appended claims.

I claim:

1. A stainless steel having a substantially ferritic microstructure and characterized by good resistance to corrosive environments such as stagnant seawater while concomitantly displaying good notch toughness, said steel consisting essentially of from 30 to about 36% chromium, from 0.5 up to about 5% molybdenum, up to 3% silicon, with the provisos that the "CMS" indicator represented by the sum of the chromium plus three times the amount of molybdenum plus three times the percentage of silicon is not less than 34%, nor above about 48% where good workability is desired, about 2 to about 8% nickel, up to less than 2% titanium, up to about 2% vanadium and up to about 2% columbium, with at least one element from the group consisting of titanium, vanadium and columbium being present in a small but effective amount to enhance the corrosion resistance in respect of steels produced by air melting and in which the "CMS" indicator is not above about 41%, the sum total of titanium, vanadium and columbium not exceeding about 4%, up to 0.1% carbon, up to 2% aluminum, up to about 2% manganese, up to about 10% cobalt, up to about 4% tungsten, and the balance essentially iron.

2. A steel in accordance with claim **1** in which the "CMS" indicator is at least about 38%.

3. A steel in accordance with claim **2** in which the chromium content is from 31.5 to 35%.

4. A steel in accordance with claim **2** in which the molybdenum content is from 1 to 4%.

5. A steel in accordance with claim **3** in which the molybdenum content is from 1.5 to 3.5%.

6. A steel in accordance with claim **2** in which the silicon content does not exceed about 2%.

7. A steel in accordance with claim **2** in which the silicon content does not exceed 0.75%.

8. A steel in accordance with claim **2** in which metal from the group consisting of titanium, vanadium and columbium is present in an amount of at least 0.15%.

9. A steel in accordance with claim **8** in which at least the element titanium is present.

10. A steel in accordance with claim **2** in which the

nickel content is at least 2.5% and not greater than about 7%.

11. A steel in accordance with claim **2** containing 31.5 to 35% chromium, about 1.5 to 3.5% molybdenum, up to about 1.5% silicon, a nickel content of about 2.5 to 6%, at least 0.2% of metal from the group consisting of titanium, vanadium and columbium when the steels are produced by air melting, up to 0.5% aluminum, and the balance essentially iron.

12. A steel in accordance with claim **11** in which the "CMS" indicator is at least 39%.

13. A steel in accordance with claim **11** in which the "CMS" indicator is at least 41%.

14. A steel in accordance with claim **11** in which at least one member from the group titanium, vanadium and columbium is present.

15. A steel in accordance with claim **13** in which at least one member from the group titanium, vanadium and columbium is present notwithstanding the "CMS" indicator is at least 40%.

16. A steel in accordance with claim **2** in which carbon above about 0.06% is fixed.

17. A steel in accordance with claim **16** in which carbon above about 0.02% is fixed.

18. A steel in accordance with claim **2** in which carbon does not exceed about 0.04%.

19. A steel in accordance with claim **18** in which carbon does not exceed about 0.04%.

20. A casting having a composition as set forth in claim **1.**

21. A wrought product having a composition as set forth in claim **7.**

22. A wrought product having a composition as set forth in claim **11.**

23. A steel in accordance with claim **11** in which carbon above about 0.06% is fixed.

24. A steel in accordance with claim **23** in which carbon above about 0.02% is fixed.

25. A steel in accordance with claim **11** in which carbon does not exceed about 0.04%.

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