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[54] CASTABLE NICKEL-CHROMIUM STAINLESS STEEL

[75] Inventor: Robin Mackay Forbes Jones, Suffern, N.Y.

[73] Assignee: The International Nickel Company, Inc., New York, N.Y.

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Primary Examiner—L. Dewayne Rutledge
Assistant Examiner—Arthur J. Steiner
Attorney, Agent, or Firm—George N. Ziegler; Ewan C. MacQueen; Raymond J. Kenny

[57] ABSTRACT

Nickel-chromium stainless steel containing, inter alia, nickel, chromium, silicon and boron in specially correlated proportions is characterized by particularly good castability along with strength and corrosion resistance for production of strong corrosion-resistant castings in sand or metal molds.

16 Claims, No Drawings

CASTABLE NICKEL-CHROMIUM STAINLESS STEEL

This application is a continuation-in-part of U.S. Application Ser. No. 275,095, filed Aug. 1, 1972, which is a continuation-in-part of U.S. Application Ser. No. 182,219, filed Sept. 20, 1971, both of which are abandoned.

The present invention relates to nickel-chromium-stainless steels and more particularly to austenitic nickel-chromium stainless steels for castings.

As is known it is often desirable to produce austenitic nickel-chromium steels by casting methods, particularly where the desired article is of a complex shape that is difficult or expensive to forge or machine. Usually, stainless steels are cast in sand molds or other expendable refractory molds, e.g., investment molds or resin-bonded shell molds, inasmuch as the castability characteristics of these steels generally require pouring at temperatures at least as high as about 2,750°F. and usually higher, e.g., 2,950°F. or 3,100°F., especially when the casting has relatively long thin sections of one-fourth inch or one-eighth inch or less in thickness.

While many varieties of stainless steels have been successfully cast, it has been evident that much better castability, particularly for producing thin-sectioned stainless steel castings, would be very beneficial. Furthermore, inasmuch as stainless steels have characteristics that are frequently desired in castings which are needed in large quantities it has been, and still is, highly desirable to have an austenitic nickel-chromium stainless steel that could be cast by permanent mold casting or die casting in cast iron or steel, or even molybdenum or graphite, molds in order to obtain economic advantages from repeated use of a mold and also in order to achieve dimensional accuracies obtainable with metal molds. Economic advantages of permanent mold casting and die casting are contigent upon repeated utilization of "permanent" casting cavity to produce castings having high quality surfaces.

However, if the permanent mold or die becomes heat crazed, the surface quality of the castings is poor. A major factor which influences heat crazing of dies is the pouring temperature of the casting alloy. And, in order to obtain good castings throughout repeated use of a mold over a long period of life, and also in order to amortize the cost of the mold over a large number of castings, it is especially desirable to have an alloy that can be cast in thin sections at temperatures not greatly above the melting temperatures of commercial die steels. It is particularly desirable to have good castability at pouring temperatures of about 2,650°F. or lower, this being in marked contrast to the significantly conventional temperature of 2,750°F. to 3,100°F. noted above. Good castability includes the capability of molten metal to run through thin sections of a mold and, very importantly, also to flow and merge cleanly into itself when the flow of metal in the mold divides and then merges together, in which circumstance it is especially important to obtain complete sound solidification without colds shuts, folds or oxide films. Also, cleanliness in the molten condition and a low melting point are desirable characteristics for good castability.

But to achieve the foregoing should not be at the cost of losing necessary mechanical properties and corrosion resistance. For general use in industry, building construction and household use and for many other purposes it is desirable that a cast stainless steel have at least modest mechanical strength and ductility characteristics, e.g., 60,000 psi ultimate tensile strength, 25,000 psi yield strength with about 5% or more tensile elongation. It is also desirable that a steel casting have impact resistance to withstand rough handling such as by being dropped on a concrete floor or hammered to conform it in an assembly. Although this does not necessitate 5% elongation, the cast steel should be characterized by at least 1% elongation in order to satisfy minimal requirements, such as decorative and other nonstructural uses. Good general corrosion resistance includes resistance to staining in corrosive atmosphere, e.g., salt spray. Moreover, for industrial production of castings, especially highly intricate castings or castings made in metal molds, it is important that a steel not suffer from excessive hot shortness.

There has now been discovered a nickel chromium stainless steel which has good characteristics for producing strong corrosion-resistant castings at desirably low pouring temperatures.

It is an object of the present invention to provide a nickel-chromium stainless steel casting.

A further object of the invention is to provide a process for producing strong corrosion-resistant stainless steel articles.

Other objects and advantages will become apparent from the following description.

The present invention contemplates nickel-chromium stainless steel castings, and also alloys and processes for production thereof, containing by weight, about 6% to 30% nickel, about 14% to about 26% chromium, up to about 0.15% carbon, advantageously not more than 0.1% carbon, about 2% to 5% silicon, advantageously 2.8% to 3.8% silicon, up to about 20% manganese, at least 0.2% boron, e.g., about 0.25% or 0.3%, to about 1.4% boron, up to about 3% copper, up to about 8% molybdenum, up to about 1.4% phosphorus and up to about 1% columbium and wherein the amounts of nickel, manganese, chromium, molybdenum, silicon, boron and phosphorus in this subject composition are correlated according to the relationship

$$8(\%Ni+\%Mn)-1.5(\%Cr+Mo)+22(\%Si)+284(\%B)+189(\%P) \text{ equal at least } 360. \quad R(1)$$

Excellent castability characteristics that are beneficial for the melting and pouring of castings are obtainable with the subject alloy composition. Embodiments of the subject alloy have been successfully melted in gas-fired furnaces and cast at 2,350°F. in green sand molds and good filling, with sharp definition at corners, was achieved in thin-sectioned mold cavities about three-sixteen inch thick by 1½ inches square. To achieve excellent castability the composition is advantageously correlated to provide that the foregoing relationship R(1) equals at least 560.

For certain other advantages, such as especially good ductility or corrosion resistance or low cost along with good (although not maximum) fluidity, the invention provides a restricted range composition containing about 6% to 26% or 28% nickel, about 14% to 20% or 25% chromium, up to about 0.15% carbon, advantageously not more than 0.1% carbon, about 2% to 5% silicon, advantageously 2.8% to 3.8% silicon, up to about 20% manganese, 0.3% to about 0.7% boron, up to about 3% copper, up to about 8% molybdenum and up to about 1% columbium and wherein the amounts of nickel, manganese, chromium, molybdenum, silicon and boron are correlated in accordance with the relationship

$$8(\%Ni+\%Mn)-1.5(\%Cr+\%Mo)+22(\%Si)+284(\%B) \text{ equal at least } 360. \quad R(2)$$

Phosphorus in amounts up to 1.4% can be added to the restricted composition; when the alloy contains a substantial amount of phosphorus, e.g., 0.2%, 0.5% or more, a phosphorus term "+189(%P)" may be included in R(2).

Further, it is specially beneficial for obtaining desirable ductility characteristics, e.g., tensile elongation of at least 5% in the rapidly solidified and solution treated condition, to have the composition controlled according to the restricted range and R(2) and also correlated in accordance with the relationship

$$0.9(\%Si)+3.4(\%Cr)+(\%Mn)[33-(\%Mn)] \text{ equal or is less than } 360. \quad R(3)$$

While the balance of the steel is hereinafter referred to as iron, or essentially iron, it is to be understood the balance usually includes small amounts of impurities and incidental elements, including residuals of melt treating agents. Thus, the balance may include, for instance, up to 0.04% phosphorus, up to 0.04% sulfur, and up to 0.25% selenium. Nitrogen may be present in amounts up to the solubility limit, e.g., up to about 0.25% nitrogen. Such highly oxidizable elements as titanium and aluminum are desirably avoided or carefully limited to low levels, e.g., 0.3% or less, in the steel of the present invention inasmuch as substantially greater amounts of these elements, either as metals or oxides, would be detrimental to the good castability characteristics of the steel. In this regard, it is of advantage that the present steel provides satisfactory sound castings, free from porosity and with good strength and ductility, without need for titanium. Small additions of aluminum, e.g., 0.1% aluminum, are effective for deoxidation. However, substantially greater amounts of aluminum would adversely affect castability and, accordingly, large additions or progressive build-up of aluminum are avoided and the amount of aluminum in the steel should not exceed about 0.3%. For good castability characteristics it is beneficial to maintain the steel essentially devoid of titanium, or with not more than 0.1% titanium, and to restrict the total amount of any aluminum and titanium to not greater than 0.2%.

Small additions of selenium, e.g., 0.015% to 0.03%, when finishing melts of the steel are recommended for obtaining sound castings, especially for avoiding pinhole porosity in green sand castings. Frequently very little of the selenium remains in the steel, e.g., residual selenium of less than 0.01% in a casting from a melt which had an effective addition of 0.02% selenium.

The steel of the invention is especially characterized by very good or excellent castability enabling production of complex thin-sectioned stainless steel castings with the steel poured, or cast, at temperatures of about 2,650°F. or 2,350°F. or lower. Among the good castability characteristics, it is particularly notable that the steel is clean and essentially free from films, dross, scum, etc. when held molten or cast in air at 2,650°F. or 2,350°F. or somewhat lower and knits or blends cleanly with itself in turbulent mold flow conditions. Also, the steel is fully molten at temperatures down to 2,350°F. or lower, such as 2,150°F. when the steel contains at least 0.8% each of boron and phosphorus and R(1) is at least 560. Thus, it is to be understood that, as a practical matter, the steel of the invention is characterized by a "freezing" temperature (incipient freezing or, approximately, the liquidus) not higher than 2,350°F. For example, the freezing temperature of a steel of the invention, namely alloy No. 8 which is referred to hereinafter in Tables I and II, was determined by thermocouple measurement to be 2,322°F.

The striking cleanliness characteristics are decidedly attractive for melting and casting in air using conventional induction furnaces or arc furnaces and foundry ladles. Vacuum melting may be used if desired for some purpose. Gas-fired melting was successful for steels of the invention containing more than 0.7% each of boron and phosphorus and with R(1) at least about 715. Castings of the subject steel can be poured in practically all kinds of expendable foundry molds, e.g., green sand molds, dry sand molds, resin-bonded shell and investment molds. But of special commercial significance is the advantage, e.g., as where close dimensional control and repeated use of molds is required, that the steel can be cast in permanent molds or die casting molds made of cast iron or steel, or of graphite or molybdenum. Testing of embodiments containing 0.3% to 0.7% boron has shown that these steels have good resistance to hot tearing and avoid hot-shortness. Good results, including smooth surface finish and complete sound solidifiction with very good filling of thin sections and fine details in the mold, have been obtained when casting the steel of the invention in green sand molds and also in permanent iron molds.

For production in sand foundries where gas-fired melting is not essential and good castability for making sand castings, rather than die castings, is of primary importance, the R(1) factor can be as low as 180. Furthermore, for benfiting surface finish, castability and ductility of sand castings, the manganese content is advantageously controlled to a range of 0.1 to 5.

A particularly good composition for economical production of sand casting contains about 8% to 14% nickel, 16% to 20% chromium, 2.5% to 3.5% silicon, 0.25% to 0.55% boron, up to 0.15% carbon, 0.2% to 2.5% manganese, up to about 4% molybdenum, up to 2% copper and balance iron and with the composition correlated in accordance with the relationship

$$8(\%Ni+\%Mn)-1.5(\%Cr+\%Mo)+22(\%Si)+284(\%B)+189(\%P) \text{ equal at least } 180. \quad R(4)$$

The cast steel of the invention has satisfactory strength and ductility, e.g., room temperature yield strength of 25,000 or 30,000 psi or more at 0.2% offset, and also corrosion resistance, for many industrial or household or other commercial uses. With the restricted composition containing 0.3% to 0.7% boron and incidental amounts of phosphorus, a desirable room temperature ductility characteristic of at least 5% tensile elongation is obtainable with the steel cast in thin sections and solution treated, e.g., a ¼ inch thick cross-section cast in a dry sand mold and solution treated 1 hr. at 2,000°F. Ductility characteristics are, in general, benefited by rapid solidifiction from the molten condition such as when cast in thin sections and/or in metal molds and are also benefited by solution heat-treatment after solidifiction. A recommended range for so ution treatment is 1,850°F. to 2,050°F. for one-half hour or longer, e.g., 1 hour, followed by air cooling, or more rapid cooling, down to 600°F. or lower, e.g., room temperature.

In the as-cast condition the microstructure of the steel is normally characterized by dendrites composed of austenite, ferrite, etc., with intermetallic precipitates, e.g., acicular borides and//or eutectic phosphides, in the interdendritic regions. The solution-treated condition of the cast steel is usually characterized by a dendritic microstructure comprising substantially less precipitate than in the cast condition. Grain sizes of the castings and also the sizes and distributions of the microstructure particles are generally smaller and finer, e.g., interdendritic spacing of about 10 to 50 microns, and more uniformly distributed, in the rapidly solidified castings. The solution-treated structure is advantageous for good ductility and corrosion-resistant characteristics of the steels with 0.3% to 0.7% boron.

In reference to the composition of the steel it is particularly noted that the steel contains at least 6% nickel, and more desirably at least about 8% nickel, to provide, where desired, a stable austenitic structure in practical conditions of use. Moreover, the nickel content also promotes desirable ductility characteristics, including shock resistance, and corrosion resistance of the castings. In these respects, at least about 8% nickel, more advantageously at least 11% nickel, in the steel is advantageous.

The silicon content does not exceed 5% in order to avoid adverse effects on ductility. For consistently achieving good ductility, silicon should be not greater than 3.8%. Compositions with silicon contents of 2.5% to 3.8% and boron contents of 0.3% to 0.7% are recommended for a particularly advantageous combination of castability and ductility characteristics.

The stainless steels include 0.3% to about 1.4% boron and about 14% to 25% chromium, advantageously at least 0.45% boron and at least 17.5% chromium, to contribute the combination of castability, ductility and corrosion resistance which characterize the composition as a whole. Embodiments containing 0.3% to 0.7% boron are desirable from the viewpoint of ductility and corrosion resistance; embodiments containing more than 0.7% boron, e.g., 0.8% boron, particularly 0.9% to 1.3% boron, are recommended from the fluidity viewpoint; and, where castability needs are dominant, embodiments containing a combination of 0.9% to 1.4% phosphorus along with 0.9% to 1.4% boron are advantageous for obtaining excellent castability and also for enabling melting in gas-fired foundry furnaces.

The steel usually contains at least about 1% manganese, often about 5% or 10% or more manganese, in order to benefit castability and ductility.

Small amounts of carbon, e.g., at least about 0.02%, are advantageous for enhancing the castability of the steel.

Presence of copper in the steel, e.g., about 1.5%, 2%, or 2.7% copper, is desirable for benefiting corrosion resistance, particularly resistance to sulfuric acid solutions. Molybdenum, e.g., about 2% to 6%, is desirably present for enhancing resistance of the steel to corrosive attack, particularly crevice corrosion and pitting corrosion in chloride media. However, excessive amounts of copper and/or molybdenum, e.g., 4% copper, should be avoided in order to avoid embrittling the steel.

In carrying the invention into practice, an especially desirable combination of castability, strength, ductility and corrosion resistance, along with other beneficial characteristics, is obtained with a specially advantageous composition containing 8% to 10% nickel, 17.5% to 19.5% chromium, 0.02% to 0.1% carbon, 2.75% to 3.25% silicon, 16% to 18% manganese, 0.45% to 0.7% boron, 1.5% to 2.5% copper and balance essentially iron and wherein the composition is further controlled in accordance with the relationship

$$8(\%Ni+\%Mn)-1.5(\%Cr+\%Mo)+22(\%Si)+284(\%B) \text{ equal at least } 385. \quad R(4)$$

Moreover, with this specially advantageous composition, the steel of the invention is generally characterized in the solution treated condition by at least 30,000 psi yield strength, about 5 ft. lb. or more impact strength, a freezing temperature not greater than 2,325°F. and particularly good resistance to corrosion in salt spray media.

The invention further provides another advantageous steel which contains 23.5% to 26% nickel, 18% to 20% chromium, 3% to 3.5% silicon, 1% to 2% manganese, 0.02% to 0.08% carbon, 0.55% to 0.7% boron, 2.2% to 2.7% copper and 2.3% to 6.5% molybdenum and is especially beneficial for achieving very good corrosion resistance, particularly resistance to staining in salt spray, along with room temperature ductility of at least 5% tensile elongation and highly beneficial castability characteristics including a castable molten condition at temperatures below 2,300°F., e.g., freezing temperatures of 2,290°F., 2,250°F. or even down to 2200°F. or lower.

For the purpose of giving those skilled in the art a further understanding of the invention, the following illustrative examples are given.

Stainless steels in accordance with the invention were air-induction melted in a magnesia crucible using Armco Iron, silicomanganese, ferrosilican and metallic silicon, electrolytic manganese, ferrochromium, wash metal (iron with about 4% carbon), electrolytic nickel, copper shot, and ferroboron. Nickel-selenium was used when selenium was added. The iron, nickel, copper and manganese (about 80% of the total manganese was charged in the electrolytic form) were charged and heated to about 2,850°F. and then the wash metal, ferrochromium, silicomanganese and silicon (about 60% of the total silicon was metallic silicon), and ferroboron were added; phosphorus for alloys 21 to 27 was added as ferrophosphorus. When the melt was ready to pour, about 0.1% aluminum was added for deoxidation and then, in most instances, a small amount (0.02%) of selenium was added shortly before casting, as protection against formation of pinhole porosity in the castings. To produce stock for tensile test specimens, the steel was cast at about 2,600°F. (alloys 1–20), or 2,350°F.(alloys 21–27), into dry sand molds for keel blocks of 1-inch or one-fourth-inch thickness at base. A variety of the melts were cast in sand molds for demonstrating fluidity and other casting flow characteristics (spiral or flow-and-knit CP pattern molds), or for demonstrating resistance to hot tearing, or were cast in metal molds for demonstrating fluidity. Chemical analyses of melts of cast steels (Alloys) produced in accordance with the invention are set forth in the following Tables I and IA.

TABLE I

Alloy No.	Composition - Weight Percent								
	C	Ni	Cr	Si	Mn	B	Cu	Mo	Fe
1	0.070	8.3	16.1	3.10	17.8	0.49	2.12	NA	Bal.
2	0.073	8.5	15.9	3.04	17.8	0.48	2.15	NA	Bal.
3	0.08	8.4	14.8	3.2	17.7	0.46	2.16	NA	Bal.
4	0.072	8.3	14.0	2.55	16.1	0.33	2.15	NA	Bal.
5	0.065	8.0	15.8	3.10	16.0	0.33	2.09	NA	Bal.
6	0.063	8.4	17.4	4.10	15.8	0.38	2.16	NA	Bal.
7	0.064	8.3	15.9	2.5	17.4	0.39	2.08	NA	Bal.
8	0.065	8.6	16.8	3.35	17.5	0.39	2.14	NA	Bal.
9	0.066	8.4	14.2	4.10	17.6	0.36	2.07	NA	Bal.
10	0.067	8.3	16.8	2.45	19.7	0.34	2.02	NA	Bal.
11	0.071	8.3	14.3	3.29	19.1	0.37	2.12	NA	Bal.
12	0.072	8.5	14.6	4.25	19.9	0.39	2.13	NA	Bal.
13	0.096	8.3	15.2	3.05	16.9	0.45	2.11	NA	Bal.
14	0.067	25.3	18.8	3.0	1.9	0.57	2.38	2.3	Bal.
15	0.070	25.7	18.7	3.1	1.8	0.63	2.58	4.5	Bal.
16	0.072	23.5	18.7	3.2	1.8	0.68	2.46	6.5	Bal.
17	0.069	14.5	18.8	3.2	5.9	0.58	2.25	2.3	Bal.
18	0.076	11.4	18.8	3.2	10.1	0.61	1.86	2.3	Bal.
19	0.079	9.8	18.7	3.2	16.0	0.68	2.16	2.3	Bal.
20	0.082	8.8	15.0	3.04	18.3	0.47	2.21	NA	Bal.

N.A. = Not Added and Not Analyzed
Bal. = Balance with impurities and residuals, including small amounts of up to 0.08% aluminum, 0.01% phosphorus, 0.015% sulfur and trace amounts of selenium not greater than 0.01%.

TABLE IA

Alloy No.	Composition - Weight Percent									
	C	Ni	Cr	Si	Mn	B	Cu	Mo	P	Fe
21	0.080	8.5	15.7	3.30	18.5	0.89	2.11	NA	0.94	Bal.
22	0.091	18.1	15.7	3.01	10.4	1.1	1.47	NA	1.1	Bal.
23	0.088	17.0	15.6	3.06	10.4	1.1	1.48	NA	1.1	Bal.
24	0.087	25.0	15.6	2.87	2.4	1.1	1.50	NA	1.1	Bal.
25	0.085	25.0	15.5	2.91	2.3	1.1	1.52	NA	1.2	Bal.
26	0.089	25.0	25.3	3.09	2.4	1.3	1.58	NA	1.3	Bal.
27	0.084	25.6	25.6	2.96	2.3	1.3	1.57	NA	1.3	Bal.

N.A. = Not Added and Not Analyzed
Bal. = Balance with impurities and residuals, including small amounts of up to 0.08% aluminum, 0.015% sulfur and trace amounts of selenium not greater than 0.01%.

Further, four melts (alloys 28 to 31) were made with nominal compositions having a balance of iron and each with 0.08% carbon, 1% manganese, 18.5% chromium and 0.025% phosphorus and with other elements as follows: alloy 28 – 10.5% nickel, 2% silicon, 0.5% boron; alloy 29 – 10.5% nickel, 2% silicon, 0.3% boron; alloy 30 – 12% nickel, 3% silicon, 0.5% boron; and alloy 31 – 12% nickel, 3% silicon, 0.3% boron. Chemical analyses reported for the boron contents of alloys 28, 29, 30 and 31 were 0.48%, 0.25%, 0.51%, and 0.28% boron, respectively.

Another melt, alloy 32, was made by melting stainless steel scrap and adding alloying elements to prepare alloy 32 of the invention which, when analyzed, was reported to contain 0.051% carbon, 12.8% nickel, 19.7% chromium, 3.8% silicon, 1.17% manganese, 0.53% boron and 0.029% phosphorus.

Results of room temperature tensile, impact and/or hardness testing of specimens machined from castings made of alloys in accordance with the invention (embodiments) are set forth in the following Table II. Alloys 4 to 12, 28 to 31 were cast in both 1-inch and ¼-inch or ⅜-inch width keel block molds (alloys 4 to 12 and one-fourth-inch and alloys 28 to 31 in three-eighth-inch), and others were cast in either the 1-inch or one-fourth-inch widths; then, one-half-inch diameter and/or one-eighth-inch diameter tensile test specimens (2-inch and 1-inch gage lengths respectively) machined therefrom were tested. The results, as set forth in Table II, show particularly satisfactory mechanical properties of rapidly solidified steels cast in thin cross-sections.

TABLE II

Alloy No.	Condition (X-Sect.)	YS (ksi)	UTS (ksi)	Elong. (%)	R.A. (%)	Impact (ft. -lbs.
1	A-C(1")	37.5	72.6	8.0	9.5	5.5
1	S.T.(1")	33.6	77.3	17.5	16.5	9.0
3	A-C(1")	37.8	74.6	13.5	14.0	—
3	S.T.(1")	34.9	74.1	14.5	16.0	—
4	A-C(1")	31.7	61.2	10.0	13.0	12.5
4	S.T.(1")	30.1	69.4	17.0	18.5	21.0
4	A-C(¼")	37.1	82.3	27.5	31.5	—
4	S.T.(¼")	33.9	87.5	42.0	45.5	—
5	A-C(1")	35.6	80.0	18.5	17.5	7.0
5	S.T.(1")	32.3	83.6	31.5	29.0	24.0
5	A-C(¼")	—	—	—	—	—
5	S.T.(¼")	37.9	94.4	38.0	36.5	—
6	A-C(1")	48.2	72.6	1.5	2.5	2.0
6	S.T.(1")	42.7	69.1	2.5	3.0	3.5
6	A-C(¼")	54.2	89.4	2.0	4.5	—

TABLE II-continued

Alloy No.	Condition (X-Sect.)	YS (ksi)	UTS (ksi)	Elong. (%)	R.A. (%)	Impact (ft. -lbs.
6	S.T.(¼")	45.0	94.1	18.0	24.0	—
7	A-C(1")	35.4	77.9	17.0	17.0	7.1
7	S.T.(1")	32.7	80.2	27.0	25.5	14.0
7	A-C(¼")	39.0	83.3	14.5	17.5	—
7	S.T. (¼")	36.4	88.7	29.0	34.0	—
8	A-C(1")	40.0	70.0	4.5	5.0	2.0
8	S.T.(1")	36.6	70.2	7.5	6.0	7.0
8	A-C(¼")	50.3	88.4	7.5	4.5	—
8	S.T.(¼")	39.3	85.3	14.5	26.0	—
9	A-C(1")	41.2	80.4	14.0	14.5	6.0
9	S.T.(1")	37.3	84.1	24.0	24.5	17.0
9	A-C(¼")	45.5	93.3	16.5	17.0	—
9	S.T.(¼")	39.6	96.4	34.5	33.0	—
10	A-C(1")	38.0	70.6	7.0	7.0	6.0
10	S.T.(1")	37.3	84.1	24.0	24.5	17.0
10	A-C(¼")	46.1	84.1	7.5	4.5	—
10	S.T.(¼")	40.9	90.7	25.5	33.0	—
11	A-C(1")	37.6	78.7	16.0	16.5	14.0
11	S.T.(1")	36.5	79.8	22.5	21.0	17.0
11	A-C(¼")	41.6	89.6	18.0	17.5	—
11	S.T.(¼")	39.2	91.2	31.0	27.5	—
12	A-C(1")	45.0	74.9	5.0	6.0	3.0
12	S.T.(1")	40.1	76.6	10.0	11.0	6.0
12	A-C(¼")	52.9	94.9	9.0	6.0	—
12	S.T.(¼")	44.1	98.1	25.5	13.5	—
13	A-C(1")	37.8	77.2	13.5	12.0	7.5
13	S.T.(1")	35.4	80.2	19.0	12.5	11.0
14	S.T.(1")	31.5	66.5	8.0	10.0	—
15	S.T.(1")	32.3	68.3	9.5	11.0	—
16	S.T.(1")	32.9	74.4	10.5	10.0	—
17	S.T.(1")	32.2	71.7	14.5	12.0	—
18	S.T.(1")	36.6	72.9	10.0	10.5	—
19	S.T.(1")	42.1	75.7	5.0	5.5	—
20	A-C(1")	37.8	74.1	11.5	13.0	—
20	S.T.(1")	36.1	74.8	14.0	14.5	—
						Hardness Rc
21	A-C(1")	ND	68.4	1.0	2.0	21
21	S.T.(1")	ND	66.2	1.0	1.5	19
22	A.C.(1")	ND	66.4	1.0	1.0	20
22	S.T.(1")	ND	63.0	1.5	1.0	17
23	A.C.(¼")	50.9	67.9	2.0	2.0	20
23	S.T.(¼")	53.1	73.1	1.5	2.0	—
24	A.C.(1")	ND	65.9	1.0	1.0	17
24	S.T.(1")	ND	68.0	2.0	2.0	16
25	A.C.(¼")	48.3	61.2	1.0	2.0	19
25	S.T.(¼")	48.7	70.3	2.0	2.0	—
26	A.C.(1")	ND	70.7	2.0	1.0	20
26	S.T.(1")	ND	69.5	3.0	1.0	19
27	A.C.(¼")	53.0	69.6	1.5	2.0	—
27	S.T.(¼")	48.2	71.8	1.5	2.0	—
28	A.C.(1")	36.1	73.8	11.5	10.5	—
28	S.T.(1")	36.4	74.0	11.0	12.5	—
28	A.C.(⅜")	38.9	79.2	11.0	8.5	—
28	S.T.(⅜")	32.7	82.3	16.5	6.0	—
29	A.C.(1")	32.5	71.3	15.0	11.5	—
29	S.T.(1")	31.6	74.0	19.0	16.5	—
29	A.C.(⅜")	36.2	76.2	23.5	15.5	—
29	S.T.(⅜")	34.3	88.1	45.5	27.0	—
30	A.C.(1")	37.3	74.3	12.0	14.0	—
30	S.T.(1")	37.1	75.2	10.5	14.5	—
30	A.C.(⅜")	41.0	83.2	14.5	7.0	—
30	S.T.(⅜")	43.8	82.2	14.5	10.0	—
31	A.C.(1")	36.2	72.2	14.0	13.5	—
31	S.T.(1")	37.7	75.3	17.0	19.5	—
31	A.C.(⅜")	40.3	74.5	14.5	6.0	—
31	S.T.(⅜")	37.8	83.3	25.5	19.5	—

YS = Yield Strength at 0.2% offset (Kips per square inch)
UTS = Ultimate Tensile Strength
Elong. = Tensile Elongation
R.A. = Reduction in Area
Impact = Impact Energy, Charpy V-Notch specimen (foot-pounds)
A-C(X-Sect.) = As-Cast(Cross-Section Thickness)
S.T. (X-Sect.) = Solution Treated one hour 2000°F., air cooled
Hardness(Rc)= Rockwell C hardness, average of two readings
N.D. = Not determined

It may be noted that all of the examples referred to in Tables I and II are characterized by yield strengths of at least 30,000 pounds per square inch (psi) at room temperature and that results obtained with specimens from ¼-inch keel blocks of the steels with 0.3% to 0.7% boron illustrate a characteristic of at least 5% elongation in the rapidly solidified and solution-treated condition obtained by sand-casting in a ¼-inch thick section and solution treating one hour at 2,000°F. Moreover, it is notable that Table II illustrates that the solution treatment of compositions containing 0.3% to 0.7% boron in accordance with the invention resulted in improved ductility characteristics, particularly elongation and impact resistance, without detrimentally decreasing the ultimate tensile strength, and often somewhat increasing the tensile strength along with the improvement in ductility.

The castings of invention had highly satisfactory smooth surfaces with good filling at corners in thin sections of the mold cavity and without any indications of metal-mold reactions, liquid-metal penetration of the mold, "burn on" or other types of surface roughness or defects of kinds resulting from excessively hot metal contact with molds. Moreover, CP-pattern castings of steels of the invention showed good freedom from folds, cold shuts or other defects such as occur if metal is poured too cold or lacks good fluidity. This CP (Chinese Puzzle) pattern, which is designed to test castability characteristics such as the ability of a molten metal to run through the passages of a complex mold with abrupt changes in flow direction that are conducive to turbulence, comprises a number of partially adjoining rectangular cavities of about three-sixteenths inch thickness. The CP pattern demands more of a melt than simply capability to remain fluid over the course of a long run, such as in a fluidity spiral, but requires many sharp changes in flow direction with the flow meeting and merging with itself, filling of many corners and flow through and filling of large thin flat surfaces, e.g., 1½ inches square by three-sixteenths inch thick.

In contrast with steels of the invention, e.g., alloys 4 through 12, and alloys 21 through 27 and 28 through 31, comparison tests wherein stainless steels of the Alloy Casting Institute Type CF-8 containing 0.05% carbon, 1.41% silicon, 1% manganese, 9.1% nickel, 18.4% chromium and 0.06% aluminum and another containing 0.10% carbon, 1.26% silicon, 1.3% manganese, 9.1% nickel, 19.2% chromium and 0.045% aluminum (without copper or boron) were cast at 2,950°F. in green sand molds of the same CP pattern showed inferior castability results with many cold shuts or fold defects in the castings. In comparison with the results of casting the CF-8 steel, the steels of the invention exhibited much better castability, particularly with success in avoiding entrapped films, folds and cold shuts when cast at 2,650°F. (alloys 4–12 and 28 through 31), or at 2,350°F. (alloys 23, 25 and 27) than did the results obtained casting CF-8 steel at 2,950°F.

Visual examination of flow-and-knit castings in the sand blasted condition showed that surface areas of flat sections near the sprues of the CF-8 castings were rougher than the corresponding surfaces on the castings of the steel of the invention. This reflects that the good castability of the steel of the invention enabled obtaining desirably smooth surfaces, with freedom from detrimental burn on and/or mold penetration, by pouring at desirably low temperatures while avoiding the undesirable kind of surface roughness that resulted from the need for pouring the CF-8 steel at the higher temperature (2,950°F.). The excessive surface roughness associated with the high pouring temperature of the CF-8 steel is particularly objectionable for commercial production since the rough surface with entrapped abrasive mold material introduces machining difficulties and considerably shortens the life of tool bits.

Resistance to hot tearing was evaluated with castings of the steels made in dry sand molds from a pattern having three cylindrical rods(arms) of different lengths, namely, 6 inches, 9 inches and 12 inches, each about one-half inch in diameter with flanges at each end which restrained the rods from shrinking during cooling. The general configuration of each of the three arms was similar to the flanged arm of the test pattern illustrated in the paper by R. A. Rosenberg, M. C. Flemings and H. F. Taylor in Transactions of the American Foundrymen's Society, Vol. 68, 1960, pages 518–528, at page 519. Both the steels of the invention and the CF-8 steel resisted hot tearing on the 6-inch and 9-inch arms but did show hot-tearing on the 12-inch arm and thus the hot-tearing resistance of the steels of the invention (alloys 2 and 13) was deemed generally about as good as that of the CF-8 steel, which is usually considered to have at least moderately good resistance to hot tearing.

Good castability characteristics of the steel of the invention were also confirmed with fluidity spiral castings in dry sand molds and straight-run fluidity castings in iron molds. Steel castings of the invention which were cast at 2,650°F. in uncoated iron molds stripped cleanly from the molds with no difficulty and showed no tendency to burn-on, bond or detrimentally adhere to the mold.

Highly satisfactory, clean remelt characteristics which are needed for recycling of metal such as gates, risers and scrap castings were demonstrated with a series of ten recycle melts, or remelts, starting with metal from alloy 13. For each of the ten remelts in this recycle series, about two-thirds of the furnace charge was castings from the previous melt in the series and about one third of the charge was virgin raw material. Each remelt was deoxidized with 0.1% aluminum and 0.02% selenium was added. Each of the remelts was cast into a mold for hot-tear specimens; also, 1-inch thick keel blocks were poured from the first, fifth and tenth remelts to provide stock for tensile test specimens. Resistance to hot tearing remained uniformly good with satisfactory solidification and cooling in the six-inch and nine-inch arms but with some tearing on the 12-inch arms. Cleanliness of the remelts was consistently excellent. The remelts did not tend to generate or accumulate dross, oxide films or scum. Ranges of the chemical analyses reported from the ten remelts were: 0.051% to 0.096% carbon, 7.9% to 8.6 % nickel, 15.2% to 17.1% chromium, 2.80% to 3.15% silicon, 16.4% to 17.9% manganese, 0.37% to 0.51% boron and 1.93% to 2.14% copper. Tensile strength and ductility characteristics of the remelts were consistently satisfactory, with room temperature tensile and impact characteristics of 37.7 to 40.4 ksi YS, 73.8 to 77.2 ksi UTS, 7 to 13.5% Elong. and 4.5 to 7.5 ft.-lb. Impact, in the As-Cast condition; and 34.8 to 37.1 ksi YS, 80.2 to 80.6 ksi UTS, 15 to 19% Elong. and 9 to 13 ft.-lb. Impact in the Solution Treated Condition.

Alloys 22, 24 and 26 were remelted in gas-fired furnaces and cast at 2,350°F. into CP-pattern green sand molds. Visual examination of the resulting castings showed that these remelted alloys successfully filled mold cavities about three-sixteenths inch thick by 1½ inches square and produced satisfactory castings with good smooth surfaces and sharp definition without entrapped films, folds or cold shuts when poured at 2,350°F., thus confirming excellent castability.

In other instances of demonstrating good remelt castability characteristics, steels of the invention, e.g., embodiments of an advantageous composition containing about 8% to 10% nickel, 15% or 17.5% to 19.5% chromium, 0.02% to 0.1% carbon, 2.75% to 3.25% or 3.5% silicon, 16% to 18% or 19% manganese, 0.45% to 0.7% boron, 1.5% to 2.5% copper and balance essentially iron, were remelted and die cast (under pressure) at about 2,450°F. to 2,600°F. The resulting stainless steel die castings of the invention stripped cleanly from the metal molds, were well-filled and had highly satisfactory smooth, sharply defined surfaces.

Stainless steels of the invention, e.g., alloy 8 in the as-cast condition and in the solution treated condition, exhibited good machinability when drilled with high speed steel drills.

A specimen of alloy 7 had a hardness of 51 Rockwell A in the solution annealed condition and had the same hardness of 51 Rockwell A after aging at 1,250°F. for 15 hours following the solution treatment.

Brazing is recommended if there is need to join the steel to itself. Specimens of a steel of the invention containing about 0.082% carbon, 8.4% nickel, 15.9% chromium, 3.18% silicon, 17.5% manganese, 2.11% copper and 0.48% boron were satisfactorily brazed together by torch brazing using a commercial silver-solder brazing alloy. Subsequent testing showed that the resultant brazed join had good impact resistance; moreover, metallurgical examination showed that the brazing alloy flowed satisfactorily with good wetting of the steel, and the brazed steel surfaces were free from intergranular penetration.

Cast steels of the invention, advantageously in the solution treated condition, and with boron in the range of 0.3% to 0.7%, have good corrosion resistance that is clearly superior to the corrosion resistance of martensitic stainless steels, e.g., ACI Types CA-15 and CB-30, and approaches or approximates, and in some instances equals, the corrosion resistance of austenitic stainless steels, e.g., Type CF-8, in many respects. Results of CASS (Copper Accelerated Salt Spray) tests corresponding to ASTM B368-61T confirmed that steels of the invention have satisfactory resistance to pitting in salt spray. For instance, solution treated specimens of alloys 14 through 19 (containing about 10% to 26% nickel) which were subjected to CASS tests of seven days duration exhibited good resistance to pitting and to general corrosion in salt spray that was about as good as that of Type CF-8 steel, with the best corrosion resistance being evidenced by alloys 14, 15 and 16. In CASS tests of 24 hours duration, specimens of alloys 4 through 12 in the solution treated condition successfully resisted pitting and showed general corrosion resistance between that of Types CB-30 and CF-8. Corrosion tests of steels 4 through 7 in deaerated 5% H_2SO_4 at room temperature showed corrosion resistance intermediate between that of Types CB-30 and CF-8.

The present invention is particularly applicable to economical production of cast-to-shape stainless steel articles including home and industrial housing hardware, e.g., door handles and door stops, plumbing hardware, e.g., pipe fittings, faucets and valve bodies, marine hardware, e.g., rope cleats, and also including decorative trim, escutcheon plates, pump housings and trivets. The invention is applicable to providing many kinds of articles that are commonly made of cast brass and in this regard the corrosion resistant characteristics of the subject steels are deemed especially beneficial for resisting corrosive attack by ammonia, including moist ammonia and ammoniacal cleansers, such as has been found detrimental to brass. While utility referred to hereinbefore is largely at room temperature, it should be understood the present steels have useful strength at temperatures substantially below and above room temperature, such as from sub-zero temperatures up to about 1,000°F. or higher.

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. Such modifications and variations are considered to be within the purview and scope of the invention and appended claims.

I claim:

1. An austenitic nickel-chromium stainless steel consisting essentially of 6% to about 28% nickel, about 14% to about 25% chromium, 2% to about 5% silicon, 0.3% to about 0.7% boron, up to about 0.15% carbon, up to about 20% manganese, up to about 3% copper, up to about 8% molybdenum, up to about 1% columbium and balance iron and wherein the amounts of nickel, chromium, silicon, and boron and any manganese and molybdenum in the alloy are correlated in accordance with the relationship

$$8(\%Ni+\%Mn)-1.5(\%Cr+\%Mo)+22(\%Si+284(\%B)$$
equal at least 360;

said steel being characterized by castability superior to that of austenitic steels of the A.C.I. CF-8 type, as determined by relative freedom from cold shut defects when cast in three-sixteenths-inch thick by 1½-inch interlocking squares in green sand molds according to the Chinese Puzzle pattern, and additionally characterized by corrosion resistance superior to that of martensitic-ferritic steels of the A.C.I. CA-15 and CB-30 types, as determined by resistance to pitting and general corrosion in salt-spray CASS tests corresponding to ASTM B368-61T.

2. An austenitic nickel-chromium stainless steel consisting essentially of 8% to 10% nickel, 17.5% to 19.5% chromium, 0.02% to 0.1% carbon, 2.75% to 3.25% silicon, 0.45% to 0.7% boron, 16% to 18% manganese, 1.5% to 2.5% copper up to about 8% molybdenum, up to 1% columbium, and balance essentially iron and wherein the composition is controlled in accordance with the relationship

$$8(\%Ni+\%Mn)-1.5(\%Cr+\%Mo)+22(\%Si)+284(\%B)$$
equal at least 385.

3. An austenitic nickel-chromium stainless steel consisting essentially of 23.5% to 26% nickel, 18% to 20% chromium, 0.02% to 0.08% carbon, 3% to 3.5% silicon, 0.55% to 0.7% boron, 1% to 2% manganese, 2.2% to 2.7% copper 2.3% to 6.5% molybdenum and balance essentially iron and wherein the composition is controlled in accordance with the relationship

$$8(\%Ni+\%Mn)-1.5(\%Cr+\%Mo)+22(\%Si+284(\%B)$$
equal at least 360.

4. An austenitic nickel-chromium stainless steel casting characterized by (a) a room temperature tensile elongation of at least about 5%, (b) a room temperature yield strength of at least 25,000 pounds per square inch, (c) a stable austenitic cast microstructure containing austenitic dendrites and (d) being formed from a steel characterized at 2,650°F. by a molten condition possessing good castability for flowing and knitting and resisting formation of cold shut defects and for merging and solidifying in the form of continuously sound cast metal in thin, relatively large area, green-sand mold cavities of three-sixteenths-inch thickness by 1½ inch square area interlocked in patterns conducive to turbu-

lent flow of molten metal, said steel consisting essentially of 8% to about 30% nickel, about 14% to about 26% chromium, 2% to 3.8% silicon, 0.2% to about 0.7% boron, up to about 0.15% carbon, up to about 20% manganese, up to about 3% copper, up to about 6% molybdenum, up to about 1% columbium, up to about 0.2% phosphorus and balance iron and wherein the amounts of nickel, chromium, silicon, boron and any manganese, molybdenum and phosphorus in the alloy are correlated in accordance with the relationship

8%
(%Ni+Mn)−1.5(%Cr+%Mo)+22(-
%Si)+284(%B)+189(%P) equal at least 180.

5. A process comprising establishing a molten bath of the steel set forth in claim **4**, pouring the molten steel into a mold and then solidifying the steel to thereby produce a cast-to-shape stainless steel article.

6. A stainless steel casting as set forth in claim **4** wherein the amount of any manganese present does not exceed 5%.

7. An austenitic nickel-chromium stainless steel consisting essentially of casting according to claim **4** about 8% to 14% nickel, 16% to 20% chromium, 2.5% to 3.5% silicon, 0.25% to 0.55% boron, 0.2% to 2.5% manganese, up to 4% molybdenum and up to 2% copper.

8. An austenitic nickel-chromium stainless steel consisting essentially of 6% to about 30% nickel, about 14% to about 26% chromium, 2% to about 5% silicon, 0.2% to 1.4% boron, up to about 0.15% carbon, up to about 20% manganese, up to about 3% copper, up to about 8% molybdenum, up to 1.4% phosphorus, up to about 1% columbium and balance iron and wherein the amounts of nickel, chromium, silicon, boron and any manganese, molybdenum and phosphorus in the alloy are correlated in accordance with the relationship

8%(%Ni+%Mn)−1.5(%Cr+%Mo)+22(-
%Si)+284(%B)+189(%p) equal at least 180;

said steel being characterized in the molten condition by castability superior to that of austenitic steels of the A.C.I. CF-8 type, as determined by relative freedom from cold shut defects when cast in three-sixteenths-inch thick by 1½-inch interlocking squares in green sand molds according to the Chinese Puzzle pattern, and in the solid condition by a non-age hardenable austenitic microstructure having corrosion resistance superior to that of martensitic-ferritic steels of the A.C.I. CA-15 and CB-30 types, as determined by resistance to pitting and general corrosion in salt-spray CASS tests corresponding to ASTM B368-61T.

9. A stainless steel as set forth in claim **8** containing at least 8% nickel.

10. A stainless steel as set forth in claim **8** containing 2.5% to 3.8% silicon.

11. A stainless steel as set forth in claim **8** containing 8% to 14% nickel, 16% to 20% chromium, 0.2% to 0.55% boron, 0.2% to 2.5% manganese, up to 4% molybdenum and up to 0.2% phosphorus.

12. A process comprising preparing a molten bath of steel having a composition in accordance with claim **8**, casting the steel into a mold and solidifying the steel in the mold.

13. A process as set forth in claim **12** wherein the steel is solidified in an expendable refractory mold.

14. A process as set forth in claim **12** wherein the steel is solidified in a metal mold.

15. A process as set forth in claim **14** wherein the steel is die cast under pressure.

16. A process as set forth in claim **12** wherein the steel is rapidly solidified at a rate at least equivalent to solidification of a ¼-inch thick cross-section in a dry sand mold and is thereafter solution-treated for at least one-half hour at 1,850°F. to 2,050°F.

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