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HOT ROLLED FLAT STEEL ARTICLE FOR CRYOGENIC SERVICE AND METHOD FOR PRODUCING SAME

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ABSTRACT OF THE DISCLOSURE

A hot rolled, flat steel article including 2.0–3.0 wt. percent nickel, 0.4–1.0 wt. percent manganese, 3.0–3.5 wt. percent nickel plus manganese, 0.2–0.8 silicon, 0.01–0.02 columbium and 0.02–0.03 vanadium. Processing includes a hot roll finishing temperature below 1700° F., a finishing deformation of at least 30%, and normalizing. Finishing above 1700° F. or a deformation less than 30% is followed by two normalizing operations. The resulting article has strength and toughness rendering it useful at low temperatures in the range —150° F. to —250° F.

BACKGROUND OF THE INVENTION

The present invention relates generally to hot rolled, flat steel articles, such as steel plate, having a strength and toughness suitable for use at cryogenic or low service temperatures between —150° F. and —250° F. Such steel plate is useful in the walls of storage vessels for liquefied gas, for example.

It is conventional to use nickel-containing steels for such low temperature service conditions. Typically, at temperatures down to about —150° F., steel containing 3½% nickel is used. As the service temperature drops, the steel used contains increasing amounts of nickel in order to obtain the desired strength and toughness. Thus, at a service temperature of —250° F., it is conventional to use a steel containing 9% nickel.

Because nickel is relatively expensive, it is desirable to minimize the steel's nickel content, but not at the expense of strength and toughness.

SUMMARY OF THE INVENTION

The present invention provides a hot rolled, flat steel article containing 2–3 wt. percent nickel and having strength and toughness superior to those of conventional flat steel articles containing the same amount of nickel and exceeding or approaching those of steels containing greater amounts of nickel.

This is accomplished by utilizing a combination of composition and processing steps which result in a hot rolled, flat steel article having a yield strength in the range 60,000–70,000 p.s.i. and a toughness expressed as longitudinal Charpy V-notch energy of 15 foot pounds at a temperature in the range —200° F. to —250° F., on a full-size sample.

Other features and advantages are inherent in the article and method claimed and disclosed or will become apparent to those skilled in the art from the following detailed description.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

A hot rolled, flat steel article (e.g., steel plate having a thickness in the range ¼" to 1¼") in accordance with

the present invention has a composition generally consisting essentially of, in wt. percent:

Carbon	0.05–0.10.
Manganese	0.4–1.0.
Phosphorous	0.01 max.
Sulfur	0.01 max.
Silicon	0.2–0.8.
Aluminum	0.02–0.05.
Columbium	0.01–0.02.
Vanadium	0.02–0.03.
Nitrogen	0.008–0.012.
Nickel	2.0–3.0.
Iron	Essentially the balance.
Nickel plus manganese	3.0–3.5.

In a preferred composition the manganese is 0.75–1.0%, the nickel is 2.0–2.5% and the silicon is 0.6–0.8%.

Steel having the composition described above is hot rolled into a flat article, such as plate, using essentially conventional rolling procedures up to the finishing step which, in the preferred embodiment, is conducted at a temperature below 1700° F., during which the article is subjected to a finishing deformation of at least 30%. A finishing temperature below 1700° F. and a finishing deformation greater than 30% are desirable for optimum strength and toughness.

The minimum finishing temperature is above 1500° F.; and the maximum finishing deformation depends upon a number of factors, including the type of rolling mill and the desired final thickness, but it is generally in the range 60–75%.

After the finishing step, the hot rolled, flat steel article is cooled in a conventional manner (e.g., water sprayed followed by air cooling) and then subjected to a normalizing operation comprising heating the article to an article temperature above the A_3 temperature for the particular steel composition, but below 1700° F., for a time of at least one hour per inch of thickness. The article is air cooled after normalizing.

An article which has been subjected to a finishing temperature less than 1700° F. followed by a single normalizing operation as described above is hereinafter referred to as controlled rolled normalized (CRN).

Should the article be subjected to a hot roll finishing temperature greater than 1700° F., or to a hot rolled finishing deformation less than 30%, the article must be subjected to a double normalizing operation in order to obtain the desired strength and toughness. Double normalizing comprises performing the single normalizing operation described above, then cooling the article until its microstructure has a matrix consisting essentially of ferrite, and then repeating the normalizing operation.

An article which has been subjected to a hot roll finishing temperature greater than 1700° F. followed by a double normalizing operation is hereinafter referred to as straight rolled double normalized (SRDN).

A hot rolled, flat steel article produced in accordance with the present invention has a microstructure consisting essentially of a ferrite matrix with non-lamellar Fe_3C (in the form of a widely distributed precipitate) and has an average ferrite grain size no coarser than ASTM No. 11.5. The article has a yield strength in the range 60,000–70,000 p.s.i., and a longitudinal Charpy V-notch energy of 15 foot pounds at a temperature in the range —200° F. to —250° F., on a full-size sample.

When the hot rolled, flat steel article has the preferred composition, it has an average yield strength of at least 67,000 p.s.i. and a longitudinal Charpy V-notch energy of 15 foot pounds at a temperature in the range —200° F. to —250° F.

Columbian and vanadium contribute to strength and toughness; and both elements, in the amounts indicated, together with the processing conditions described above, are necessary to provide the desired combination of strength and toughness. Single additions of columbian or vanadium, in the amounts described (0.01–0.02 wt. percent columbian and 0.02–0.03 wt. percent vanadium), do not provide strength and toughness comparable to that provided by the addition of both. Deletion of either columbian or vanadium or both results in a deterioration in strength and toughness, even where controlled rolling is employed.

Silicon additions in the range 0.2–0.8 wt. percent increase the strength without impairing the impact resistance at low temperatures.

Nickel from 2.0 to 3.0 wt. percent and manganese from 0.4 to 1.0 wt. percent contribute to the strength and toughness. However, total nickel plus manganese must be in the range 3.0 to 3.5 wt. percent. Less than this amount of combined nickel and manganese reduces the beneficial solid solution effect of nickel and manganese on the properties of the steel. Amounts greater than 3.0 to 3.5 wt. percent could result in the formation of low temperature, austenite-decomposition products upon cooling, and such products are detrimental to toughness.

Referring now to the following tables, Table I lists compositions of steels useful in producing hot rolled, flat steel articles in accordance with the present invention.

Table II lists the hot rolling schedules for the steels listed in Table I. In general, all of the steel compositions listed in Table I were cast into ingots; soaked, prior to rolling, under a hydrogen-argon atmosphere for 3½ hours at 2250° F.; and then subjected to rolling. Under controlled rolling conditions, most of the ingots were hot rolled to one inch thickness in five passes, held to a predetermined temperature, and then finished to one-half inch thickness in either two or three passes. A number of the ingots were hot rolled directly to one-half inch in eight passes without further delay, thus resulting in substantially higher finishing temperatures.

Table III shows the ferrite grain sizes for the hot rolled, flat steel articles, and indicates whether the article was controlled rolled normalized (CRN), straight rolled normalized (SRN) or straight rolled double normalized (SRDN). Generally, when an article has been straight rolled normalized (SRN), its grain size is less refined than when the article has been double normalized following straight rolling (SRDN). Although not shown on the table, double normalizing has no effect on grain size refinement, compared to a single normalizing operation, when the article is controlled rolled (i.e, using a hot roll finishing temperature below 1700° F).

Table IV reflects the strength or tensile properties of the hot rolled steel articles. As indicated by the data on steels D–1 and E–4, an article which has been straight rolled and double normalized (SRDN) has a yield strength greater than the same article which has been straight rolled and subjected to only a single normalizing operation (SRN).

Table V reflects the toughness or impact resistance of the hot rolled flat steel articles. As shown by the data on steels D–1 and E–4, the impact resistance at temperatures in the range —150° F. to —250° F., is higher for steel articles which have been controlled rolled normalized (CRN) than for steel articles which have been straight rolled normalized (SRN); and the impact resistance of steel articles which have been straight rolled normalized can be increased by subjecting that article to another normalizing operation, resulting in an article which has been straight rolled double normalized (SRDN).

Table VI reflects a comparison of tensile properties among the hot rolled flat steel articles produced in accordance with the present invention (Series A, D and E), on the one hand, and conventional steels containig similar or substantially larger amounts of nickel, on the other hand. As shown in Table VI, steel articles in accordance with the present invention (2.0 to 3.0 wt. percent nickel) have tensile properties substantially superior to conventional steel articles containing 2.25 or 3.50 wt. percent nickel.

Hot rolled flat steel articles in accordance with the present invention are also substantially superior, in impact resistance, at temperatures in the range —150° F. to —200° F., compared to steels containing 2.25 or 3.50 wt. percent nickel. At —200° F., the impact resistance of a hot rolled, flat steel article of the present invention approaches that of steel articles containing 5% and 9% nickel respectively.

Although the impact resistance of a hot rolled, flat steel article of the present invention does not approach those of steels containing 5% and 9% nickel, at temperatures as low as —250° F., a steel article of the present invention does have at that temperature an impact resistance of 15 foot pounds (longitudinal Charpy V-notch energy on a full-size sample), and this property renders the article suitable for service under temperature conditions ranging from —150° F. to —250° F.

The foregoing detailed description has been given for clearness of understanding only, and no unnecessary limitations should be understood therefrom, as modifications will be obvious to those skilled in the art.

TABLE I.—COMPOSITIONS OF STEELS

[Wt. percent]

Steel number	C	Mn	P	S	Si	Al	Cb	V	Ni	N	Ni plus Mn
A–2	0.07	0.38	0.008	0.007	0.59	0.026	0.018	0.030	3.06	0.009	3.44
A–3	0.07	0.41	0.008	0.005	0.73	0.034	0.019	0.030	2.99	0.009	3.4
B–2	0.07	1.00	0.008	0.005	0.82	0.024	0.017	0.030	1.96	0.012	2.96
D–1	0.08	1.00	0.010	0.005	0.68	0.028	0.014	0.030	2.03	0.009	3.03
D–2	0.07	1.01	0.010	0.005	0.73	0.021	0.016	0.030	2.03	0.009	3.04
D–3	0.08	1.04	0.008	0.005	0.73	0.030	0.019	0.030	2.03	0.008	3.07
D–4	0.07	1.00	0.010	0.003	0.71	0.024	0.016	0.040	2.03	0.010	3.03
D–5	0.07	1.01	0.008	0.008	0.74	0.030	0.018	0.030	2.03	0.009	3.03
D–6	0.07	0.98	0.008	0.008	0.79	0.025	0.017	0.020	2.30	0.009	3.28
D–7	0.07	1.02	0.011	0.004	0.79	0.025	0.022	0.030	2.03	0.008	3.05
E–1	0.06	0.70	0.006	0.007	0.57	0.009	0.012	0.020	2.40	0.010	3.10
E–2	0.08	0.72	0.008	0.005	0.79	0.026	0.024	0.030	2.53	0.008	3.25
E–3	0.08	0.73	0.008	0.005	0.67	0.019	0.024	0.030	2.52	0.008	3.25
E–4	0.09	0.79	0.004	0.004	0.59	0.036	0.016	0.030	2.45	0.012	3.24
E–5	0.08	0.77	0.004	0.004	0.60	0.032	0.018	0.030	2.52	0.011	3.27
F–1	0.08	0.91	0.010	0.006	0.21	0.027	0.026	0.03	2.05	0.009	2.96
F–2	0.08	1.01	0.010	0.006	0.25	0.046	0.018	0.02	2.11	0.007	3.12
F–3	0.09	0.96	0.002	0.004	0.22	0.040	0.069	0.02	2.02	0.011	2.98
F–4	0.06	0.67	0.007	0.006	0.63	0.017	0.013	0.03	2.62	0.010	3.29

TABLE II.—HOT ROLLING SCHEDULES

Steel number	Number of passes	Hold temperature (° F.)	Finish temperature (° F.)
A-2	7	1,600	1,535
A-3	7	1,600	1,545
B-2	7	1,600	1,510
D-1	8	----------	1,882
D-2	7	1,800	1,658
D-3	7	1,750	1,644
D-4	8	1,650	1,518
D-5	7	1,650	1,574
D-6	7	1,700	1,588
D-7	7	1,600	1,560
E-1	7	1,600	1,518
E-2	7	1,575	1,560
E-3	7	1,800, 1,575	1,560
E-4	8	----------	1,896
E-5	7	1,800	1,700
F-1	8	1,650	1,532
F-2	7	1,600	1,560
F-3	7	1,600	----------
F-4	7	1,600	1,532

TABLE III.—GRAIN SIZE

Steel number	Processing	Ferrite grain size, ASTM number
A-2	CRN	12.2
A-3	CRN	11.8
B-2	CRN	12.3
D-1	SRN	11.4
D-1	SRDN	11.8
D-2	CRN	11.8
D-3	CRN	11.9
D-4	CRN	11.9
D-5	CRN	12.0
D-6	CRN	12.5
D-7	CRN	11.9
E-1	CRN	11.8
E-2	CRN	11.4
E-3	CRN	11.3
E-4	SRN	11.6
E-4	SRDN	12.1
E-5	CRN	12.0
F-1	CRN	11.6
F-2	CRN	12.1
F-3	CRN	11.9
F-4	CRN	11.8

NOTE.—CRN=Controlled Rolled and Normalized; SRN=Straight Rolled and Normalized; SRDN=Straight Rolled and Double Normalized.

TABLE IV.—TENSILE PROPERTIES

Steel	Processing	0.2% offset yield strength (k.s.i.)	Ultimate strength tensile (k.s.i.)	Elongation, percent in 1"	Reduction in area (percent)
A-2	CRN	68.7	80.5	34.0	76.9
A-3	CRN	68.3	80.9	40.0	78.0
B-2	CRN	69.4	83.2	39.5	80.9
D-1	SRN	64.9	82.2	39.8	81.3
D-1	SRDN	66.7	83.2	39.0	82.0
D-2	CRN	68.5	82.8	40.5	82.7
D-3	CRN	70.0	83.7	39.8	81.9
D-4	CRN	68.9	82.5	39.5	80.3
D-5	CRN	66.1	82.5	39.5	79.7
D-6	CRN	63.6	80.4	41.5	80.4
D-7	CRN	69.4	83.1	37.8	82.8
E-1	CRN	64.4	77.7	40.0	78.7
E-2	CRN	68.7	81.2	36.3	78.5
E-3	CRN	67.7	80.9	35.0	78.8
E-4	SRN	65.8	80.4	37.0	78.5
E-4	SRDN	67.3	80.9	37.5	77.8
E-5	CRN	67.3	80.5	32.0	78.5
F-1	CRN	61.6	74.4	40.5	82.4
F-2	CRN	61.2	75.9	41.0	81.9
F-3	CRN	62.6	75.1	40.5	80.0
F-4	CRN	56.6	69.1	41.0	76.9

NOTE.—CRN=Controlled Rolled and Normalized; SRN=Straight Rolled and Normalized; SRDN=Straight Rolled and Double Normalized.

TABLE V.—CHARPY V-NOTCH RESULTS

Steel number	Processing	Average Charpy V-notch energy (ft. lbs.) at— −275° F.	−250° F.	−200°F.	−150° F.
A-2	CRN	----------	----------	47.3	129.5
A-3	CRN	----------	7.7	58.5	123
B-2	CRN	11.1	20.4	55.1	119.5
D-1	SRN	4.7	5.5	8	25
D-1	SRDN	4.5	13	71.7	143
D-2	CRN	9.2	8.2	82.5	173.5
D-3	CRN	8.7	15.2	60	94.5
D-4	CRN	8	7.5	58.5	144
D-5	CRN	6.2	11	45	----------
D-6	CRN	6.7	19.5	59.5	----------
D-7	CRN	7.5	9.5	20	117.5
E-1	CRN	4.5	6.5	26.5	120.5
E-2	CRN	5.75	14	16.5	85
E-3	CRN	8	12.5	56.5	126.5
E-4	SRDN	10.2	11.7	36.3	95.7
E-4	SRDN	9.0	19	49.4	126.5
E-5	CRN	5.7	16.5	113	120
F-1	CRN	8	6.7	23.5	129
F-2	CRN	6	8.7	123	182.5
F-3	CRN	16.5	19.2	74.7	196
F-4	CRN	4.7	5.7	25.5	107

NOTE.—CRN=Controlled Rolled and Normalized; SRN=Straight Rolled and Normalized; SRDN=Straight Rolled and Double Normalized.

TABLE VI.—COMPARISON OF PROPERTIES

Steel	Thickness, inches	Processing	Yield strength (1,000 p.s.i.)	Tensile strength (1,000 (p.s.i.)
A, D, E series	½	CRN	[1] 67.8	[1] 81.5
2¼% Ni	½		53.7	73.5
3½% Ni	½	Normalized at 1,600° F., tempered at 1,100° F.	56.1	73.1
5% Ni	3/16–1½	Triple heat treated [2]	[3] 65	95–115
9% Ni	½	Normalized at 1,600° F., 1,450° F., tempered at 1,050° F.	81.0	104.5

[1] Average.
[2] Austenitize at 1,625° F. and quench in water, temper at 1,325°-1,400° F. and quench in water, anneal at 1,175°-1,250° F. and quench in water.
[3] Minimum.

What is claimed is:

1. A hot rolled, flat steel article having a composition consisting essentially of, in wt. percent:

Carbon	0.05–0.10.
Manganese	0.4–1.0.
Phosphorous	0.01 max.
Sulfur	0.01 max.
Silicon	0.2–0.8.
Aluminum	0.02–0.05.
Columbium	0.01–0.02.
Vanadium	0.02–0.03.
Nitrogen	0.008–0.012.
Nickel	2.0–3.0.
Iron	Essentially the balance.
Nickel plus manganese	3.0–3.5.

said hot rolled, flat steel article having an average yield strength in the range 60,000–70,000 p.s.i.;

said flat steel article having a microstructure consisting essentially of a ferrite matrix and Fe_3C, with the average ferrite grain size being no coarser than ASTM No. 11.5;

said flat steel article having longitudinal Charpy V-notch energy of 15 foot pounds at a temperature in the range −200° F. to −250° F., on a full-size sample.

2. A hot rolled, flat steel article as recited in Claim 1 and having a composition consisting essentially of, in wt. percent:

Manganese	0.75–1.0
Nickel	2.0–2.5
Silicon	0.6–0.8

said average yield strength being at least 67,000 p.s.i.

3. A hot rolled, flat steel article as recited in Claim 1 and comprising steel plate having a thickness of ¼ to 1¼ inches.

4. A hot rolled, flat steel article as recited in Claim 1 wherein said Fe_3C is non-lamellar.

5. A method for producing a hot rolled, flat steel article, said method comprising the steps of:

providing a steel having the following composition in wt. percent:

Carbon	0.05–0.10.
Manganese	0.4–1.0.
Phosphorous	0.01 max.
Sulfur	0.01 max.
Silicon	0.2–0.8.
Aluminum	0.02–0.05.
Columbium	0.01–0.02.
Vanadium	0.02–0.03.
Nitrogen	0.008–0.012.
Nickel	2.0–3.0.
Iron	Essentially the balance.
Nickel plus manganese	3.0–3.5.

hot rolling said steel into said flat steel article, with a hot roll finishing temperature below 1700° F.;

and then subjecting said hot rolled, flat steel article to at least, but no more than, one normalizing operation.

6. A method as recited in Claim 5 wherein said one normalizing operation comprises heating said hot rolled, flat steel article to an article temperature above the A_3 temperature for said steel composition and below 1700° F., for a time of at least one hour per inch of thickness.

7. A method as recited in Claim 5 wherein said hot rolling step comprises a finishing deformation of at least 30%.

8. A method for producing a hot rolled, flat steel article, said method comprising the steps of:

providing a steel having the following composition in wt. percent:

Carbon	0.05–0.10.
Manganese	0.4–1.0.
Phosphorous	0.01 max.
Sulfur	0.01 max.
Silicon	0.2–0.8.
Aluminum	0.02–0.05.
Columbium	0.01–0.02.
Vanadium	0.02–0.03.
Nitrogen	0.008–0.012.
Nickel	2.0–3.0.
Iron	Essentially the balance.
Nickel plus manganese	3.0–3.5.

hot rolling said steel into said flat steel article, with a hot roll finishing temperature above 1700° F.;

and then subjecting said hot rolled flat steel article to a double normalizing operation.

9. A method as recited in Claim 8 wherein said double normalizing operation comprises:

heating said hot rolled flat steel article to an article temperature above the A_3 temperature for said steel composition and below 1700° F., for a time of at least one hour per inch of thickness;

then cooling said article until the microstructure thereof has a matrix consisting essentially of ferrite;

and then repeating said first recited heating step.

10. A method for producing a hot rolled, flat steel article, said method comprising the steps of:

providing a steel having the following composition in wt. percent:

Carbon	0.05–0.10.
Manganese	0.4–1.0.
Phosphorous	0.01 max.
Sulfur	0.01 max.
Silicon	0.2–0.8.
Aluminum	0.02–0.05.
Columbium	0.01–0.02.
Vanadium	0.02–0.03.
Nitrogen	0.008–0.012.
Nickel	2.0–3.0.
Iron	Essentially the balance.
Nickel plus manganese	3.0–3.5.

hot rolling said steel into said flat steel article, with a hot roll finishing temperature below 1700° F.;

said hot rolling step comprising a finishing deformation less than 30%;

and then subjecting said hot rolled flat steel article to a double normalizing operation.

11. A method as recited in Claim 10 wherein said double normalizing operation comprises:

heating said hot rolled flat steel article to an article temperature above the A_3 temperature for said steel composition and below 1700° F., for a time of at least one hour per inch of thickness;

then cooling said article until the microstructure thereof has a matrix consisting essentially of ferrite;

and then repeating said first recited heating step.

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