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HIGH-TOUGHNESS ALLOY STEEL WITH IMPROVED WELDABILITY

Brian Mravic and Lew F. Porter, Monroeville, Pa., assignors to the United States of America as represented by the Secretary of the Navy

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ABSTRACT OF THE DISCLOSURE

An alloy steel having 0.2% offset yield strengths greater than 100K s.i. in plates up to 6 inches thick, high toughness at temperatures down to —120° F., and a very low tendency toward HAZ cracking. The principal constituents of the steel come essentially within the following ranges:

Elements:	Percentage by weight
C	0.09–.013
Mn	0.60–0.85
P (max.)	0.015
S (max.)	0.020
Si	0.20–0.35
Ni	2.5–4.5
Cr	0.40–1.20
Mo	0.25–0.60
V	0.05–0.10
Al	0.015–0.035

Balance essentially iron.

BACKGROUND OF THE INVENTION

Field of the invention

The present invention relates to a low carbon alloy steel and, in particular, to a high toughness alloy steel having improved weldability properties.

Description of the prior art

There is a strong need for steels with yield strengths over 100K s.i., high notch toughness, and good weldability. For several years, a steel under military specification MIL–S–16216G has been used by the Department of Defense. This steel exhibits a yield strength of 100 to 115K s.i., and a Charpy V-notch energy absorption of over 30 ft.-lb. at —120° F. in plates up to 3 inches thick. The composition of the steel in weight percent is: up to 0.20 C, 0.10–0.40 Mn, up to 0.025 P, up to 0.025 S, 0.15–0.35 Ni, 1.00–1.80 Cr, 0.20–0.60 Mo, up to 0.02 Ti, up to 0.03 V, and up to 0.25 Cu. Typically, the carbon content is about 0.18 percent. The microstructure of the steel in the as-quenched condition is essentially martensitc in plates up to 3 inches thick.

In various applications of the military specification steel, weldability problems have been encountered. Specifically, the steel is highly susceptible to cold cracking in the heat-affected zone adjacent to welds. It is well known that such cold cracking is directly related to the steel composition. One formula which relates the amount of heat-affected-zone (HAZ) cracking in a cruciform test to steel composition is:

(Equation 1) Percent cracking$=-105+449$
$\times$(percent C)$+23.8\times$(percent Mn)$+7.54$
$\times$(percent Ni)$+15.0\times$(percent Cr)

The equation predicts that molybdenum and vanadium have a statistically insignificant effect upon cracking. Based upon this formula, the steel under military specification MIL–S–16216G would be expected to exhibit up to 48% cracking.

Most steels with high toughness and with yield strengths over 100K s.i. have a martensitic microstructure in the as-quenched condition. This is because it is generally believed that a fully martensitic as-quenched structure is necessary to insure high Charpy V-notch shelf energy and low transition temperature. To insure a fully martensitic microstructure in thick sections, either the carbon content, the alloy content, or both must be high. However, the high carbon and alloy content generally result in a strong tendency toward HAZ cracking.

SUMMARY OF THE INVENTION

In accordance with the present invention, an alloy steel is provided which exhibits a high Charpy V-notch shelf energy and a low transition temperature. Its as-quenched microstructure contains significant amounts of bainite thereby allowing a substantially lower carbon content. The combination of low carbon content along with moderate alloy content results in a low tendency toward HAZ cracking and a superior steel for producing various types of structural weldments for use as submarine hulls, ship hulls, tanks, etc.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

The improved steel of the present invention results from utilizing select ingredients in the following proportions:

TABLE I

Element:	Weight percent
Carbon	0.09–0.13
Manganese	0.60–0.85
Phosphorus	<0.015
Sulfur	<0.020
Silicon	0.20–0.35
Nickel	2.5–4.5
Chromium	0.40–1.20
Molybdenum	0.25–0.60
Vanadium	0.05–0.10
Aluminum	0.015–0.035

Balance iron and residual amounts of other elements.

The aluminum content listed is total aluminum (insoluble aluminum generally comprises less than 0.007%).

In order to attain optimum properties with a minimum required total alloy content and maximum weldability, the composition should be varied according to the thickness of the section to be produced. For example, for water-quenched plates up to 1½ inches thick, the nickel, chromium, and molybdenum contents should be: 2.5–3.0 Ni, 0.4–0.6 Cr, and 0.25–0.35 Mo. For plates from ½ to 4 inches thick, the nickel, chromium, and molybdenum contents should be: 3.0–4.5 Ni, 0.80–1.0 Cr, 0.35–0.45 Mo. For plates from 4 to 6 inches thick, the nickel, chromium, and molybdenum contents should be: 4.0–4.5 Ni, 0.9–1.2 Cr, and 0.45–0.60 Mo. For each of the three ranges of plate thickness, the other components should be in the ranges previously specified.

As previously mentioned, it is commonly believed necessary to have a fully martensitic microstructure to insure high Charpy V-notch shelf energy and low transition temperature. The present invention dispells this belief by providing an as-quenched microstructure that is generally a mixture of martensite and bainite—depending on the plate thickness and specific composition. By thus eliminating the requirement of a fully martensitic as-quenched structure, the carbon content can be lowered significantly without necessitating a concomitant increase in alloy content. As such, a tough, high strength steel can be obtained over a wide range of thicknesses with the advantage of substantially minimizing HAZ (heat-affected-zone) cracking.

Table II is included to illustrate the improved weld-

ability of the alloy steels of the present invention. The HAZ cracking formula (Equation 1) was applied to representative prior art specimens and compared to the steel alloy of the present invention.

TABLE II.—PREDICTED HEAT-AFFECTED-ZONE CRACKING FOR TYPICAL MILITARY SPECIFICATION STEELS AND A SAMPLE OF THE ALLOY STEEL OF THE PRESENT INVENTION

	Composition, percent					Predicted HAZ cracking
	C	Mn	Ni	Cr	Mo	
Sample:						
1	0.18	0.31	2.92	1.68	0.49	30
2	0.18	0.30	2.99	1.68	0.41	31
3	0.18	0.20	2.99	1.77	0.40	31
4	0.17	0.26	2.86	1.58	0.45	23
5	0.13	0.29	2.97	1.60	0.51	7
6	0.14	0.29	2.65	1.48	0.42	7
7	0.16	0.38	2.60	1.54	0.30	19
8	0.17	0.26	2.33	1.16	0.25	12
Present invention	0.10	0.79	3.36	0.90	0.41	−3

It can clearly be seen that with the −3% HAZ cracking prediction there is a very low tendency towards crack formation in any weldments that may be made with the steels of the present invention.

As a specific example of the present invention an 80-ton electric furnace heat was produced having the composition shown in Table III.

TABLE III

Composition of 80-ton electric furnace heat (weight percent)

C	0.10
Mn	0.79
P	0.005
S	0.011
Si	0.28
Ni	3.36
Cr	0.90
Mo	0.41
V	0.09
Al	0.027
Cu	0.05

The heat was vacuum-degassed in a ladle-to-ladle stream degassing unit prior to teeming. Ingots were formed and rolled into 1, 1½, 2, 3, and 4 inch thick plates by cross rolling to minimize anisotropy. Table IV shows the slab and plate sizes produced from four ingots as well as the rolling ratio for each of the plates.

TABLE IV.—PROVISIONING FOR 80-TON ELECTRIC FURNACE HEAT

Slab No.	Slab size, inches	Slab weight, lb.	Rolled plate size, inches	T/L ratio [1]
Ingot 1				
757 (top)	66 by 9 by 56	9,010	2 by 80 by 190	0.7
756	66 by 9 by 56	9,010	2 by 80 by 190	0.7
755	66 by 9 by 59.5	9,550	2 by 80 by 190	0.8
754	66 by 9 by 59.5	9,550	1½ by 104 by 200	0.6
Total		37,120		
Ingot 2				
753 (top)	55 by 13 by 58	11,250	4 by 92 by 100	0.5
752	55 by 13 by 58	11,250	3 by 92 by 135	0.6
751	55 by 13 by 46.5	9,010	2 by 80 by 190	0.9
Total		31,510		
Ingot 3				
750 (top)	55 by 10 by 97	14,450	2 by 104 by 225	1.4
749	55 by 10 by 97	14,450	2 by 104 by 240	1.4
Total		28,900		
Ingot 4				
748 (top)	55 by 10 by 97	14,450	1½ by 104 by 315	1.8
747A	55 by 10 by 48	7,225	1 by 80 by 300	1.1
747B	55 by 10 by 48	7,225	Not rolled	
Total		28,900		

[1] Transverse to longitudinal ingot-to-plate rolling ratio (relative to ingot axis).

Table V shows the Heat Treatment given the various plates.

TABLE V.—HEAT TREATMENT OF STEEL PLATES FROM 80-TON FURNACE HEAT

Plate No.	Plate thickness, inches	Austenitizing procedure				Tempering procedure			
		First		Second		First		Second	
		Temp., F.	Time, min.[1]	Temp., F.	Time, min.[1]	Temp., F.	Time, min.[1]	Temp., F.	Time, min.[1]
747A	1	1,550	93			1,245	93		
748	1½	1,660	115	1,550	115	1,240	115		
754	1½	1,660	140	1,550	115	1,220	115	1,235	140
749	2	1,660	140	1,550	159	1,220	140	1,235	140
750	2	1,660	140	1,550	140	1,240	140	1,245	144
751	2	1,660	140	1,550	180	1,220	140	1,235	140
755	2	1,660	145	1,550	174	1,220	140	1,235	140
756	2	1,660	140	1,550	157	1,220	140	1,235	140
757	2	1,660	140	1,550	150	1,220	140	1,235	140
752	3	1,660	(2)	1,550	(2)	1,180	(2)		
753	4	1,660	(2)	1,550	(2)	1,180	(2)		

[1] Total time in furnace for plates 2 inches thick or less. These plates were heat-treated at the 160-inch plate treating line. Plates were water-spray-quenched after each austenitizing and tempering treatment.

[2] Standard heat-up times of approximately 1 hour per inch of thickness were used. Holding times at temperature were spproximately 2 hours. Plates were water-dip-quenched.

It was found that when the steels of the present invention were tempered in the range of 1050 to 1250° F. for ½ to 2 hours, a strength of 100K s.i. was obtained along with excellent toughness properties.

The mechanical properties are shown in Table VI. Tensile properties were obtained from the quarter-thickness position in the plate and impact properties were obtained from the midthickness position. The percentage of HAZ cracking is shown by Equation 1 to be essentially zero.

TABLE VI.—TENSILE AND IMPACT PROPERTIES OF MILL-HEAT-TREATED PLATES OF THE 80-TON FURNACE HEAT

Plate No.	Specimen orientation [1]	Tensile properties [2]				Charpy V-notch impact properties [3]			
		Yield strength (0.2% offset), k.s.i.	Tensile strength, k.s.i.	Elongation in 2 inches, percent	Reduction of area, percent	Energy absorption, ft.-lb.		Fibrous fracture, percent	
						0 F.	−120 F.	0 F.	−120 F.
1-inch-thick plate									
747A	T	109	123	21	66	90	71	100	75
	L	110	124	22	68	102	91	100	95
1½-inch-thick plate									
748	T	113	124	20	65	80	62	100	65
	L	111	124	22	72	113	95	100	95
754	T	110	117	24	72	97	81	100	65
	L	104	112	22	71	95	76	100	70
2-inch-thick plate									
749	T	112	120	22	69	78	63	100	65
	L	106	117	22	72	106	99	100	95
750	T	105	116	22	68	87	82	100	100
	L	115	128	21	74	112	113	100	100
751	T	109	119	22	71	85	71	100	70
	L	107	119	22	70	93	78	100	80
755	T	112	122	22	71	95	71	100	70
	L	110	121	22	69	88	69	100	70
756	T	107	117	22	71	102	90	100	95
	L	101	115	24	72	102	89	100	95
757	T	108	119	22	70	91	67	100	65
	L	105	119	24	72	96	78	100	70
3-inch-thick plate									
752	T	115	125	20	67	98	69	95	60
	L	115	129	20	67	96	59	80	50
4-inch-thick plate									
753	T	106	118	20	70	95	58	85	40
	L	103	116	22	67	94	89	90	55

[1] T is transverse to final rolling direction, and L is parallel to final rolling direction.
[2] Results of single test.
[3] Average of three tests.

From the foregoing, it can be seen that an improved alloy steel has been obtained having a low carbon content and an as-quenched microstructure containing significant amounts of bainite (up to 100 percent). In spite of the large amounts of bainite, the steels of the present invention, when tempered, exhibit high strength and toughness properties with significantly improved weldability properties over the prior art.

Obviously many modifications and variations of the present invention are possible in light of the above teachings. It is therefore to be understood that within the scope of the appended claims the invention may be practiced otherwise than as specifically described.

What is claimed and desired to be secured by Letters Patent of the United States is:

1. A low carbon steel plate consisting of from 0.09 to 0.13 percent carbon, from 0.60 to 0.85 percent manganese, less than 0.015 percent phosphorus, less than 0.020 percent sulfur, from 0.20 to 0.35 percent silicon, from 2.5 to 4.5 percent nickel, from 0.40 to 1.20 percent chromium, from 0.25 to 0.60 percent molybdenum, from 0.05 to 0.10 percent vanadium, from 0.015 to 0.035 percent aluminum, and the balance essentially iron.

2. The steel of claim 1 characterized as having an as-quenched microstructure of both bainite and martensite.

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HYLAND BIZOT, Primary Examiner

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