Nov. 29, 1966 A. M. JOHNSEN, JR., ETAL 3,288,600

LOW CARBON, HIGH STRENGTH ALLOY STEEL

Filed Nov. 7, 1960 2 Sheets-Sheet 1

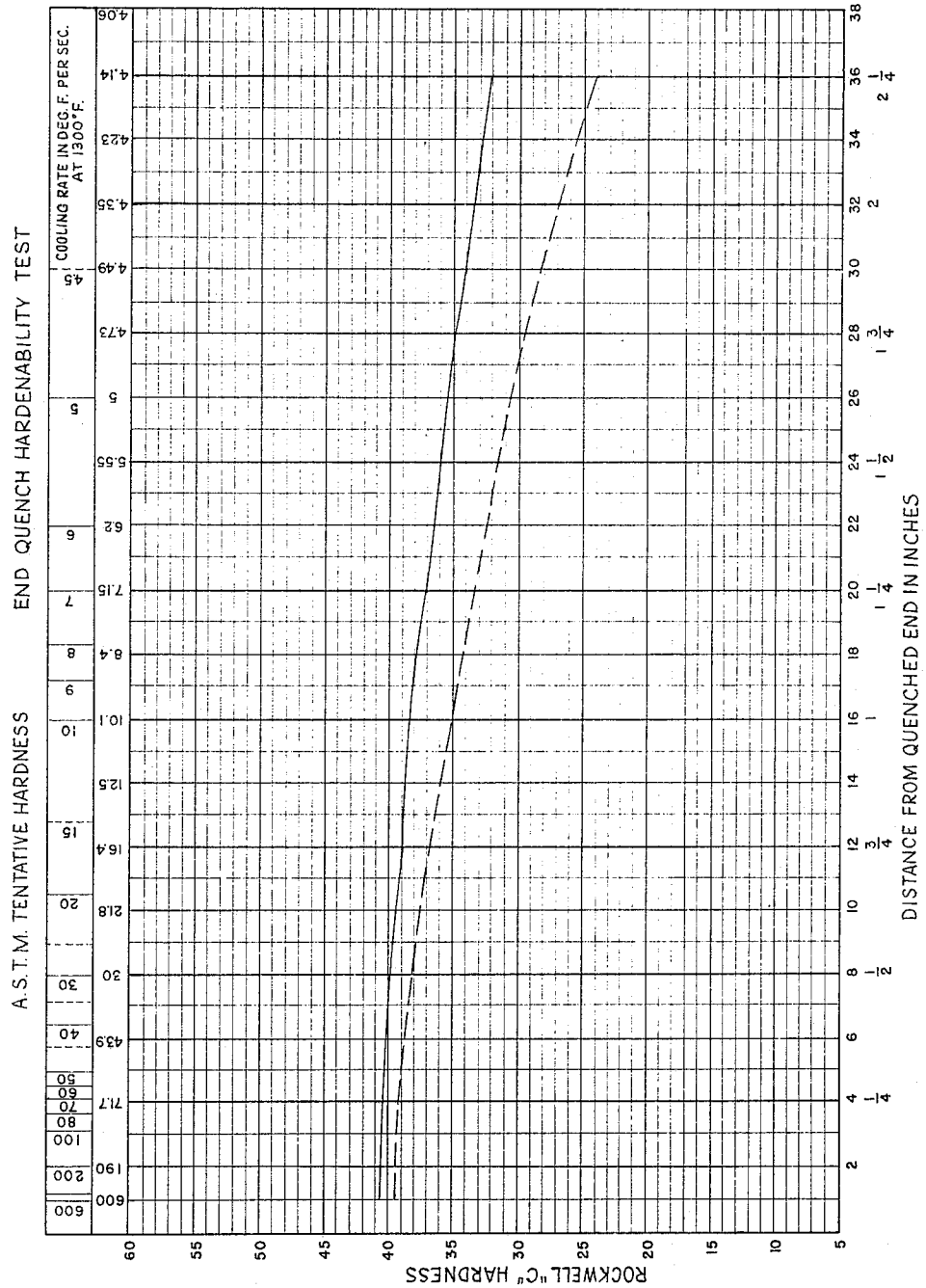


FIG 1

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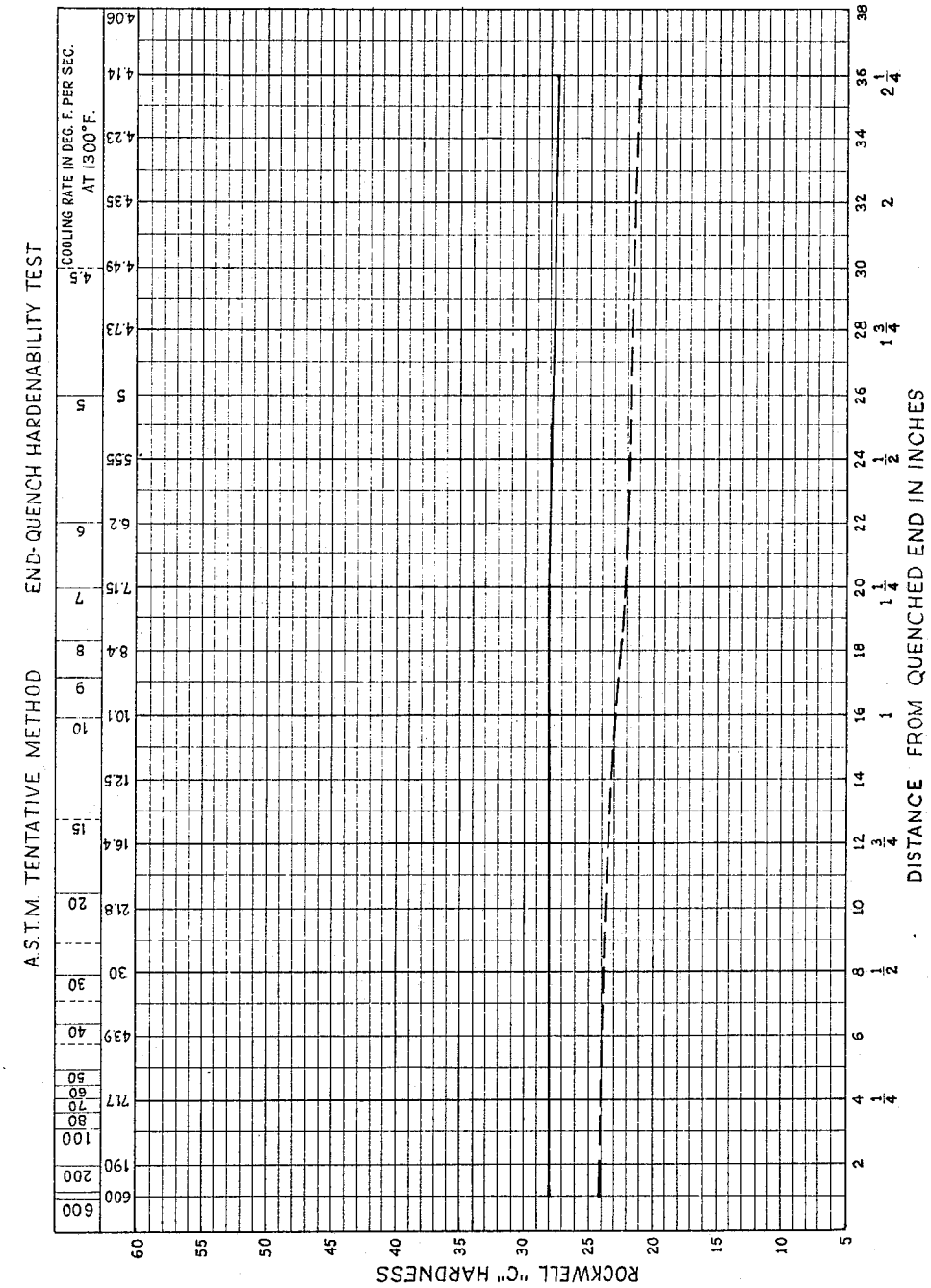


FIG. 2

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3,288,600

Patented Nov. 29, 1966

3,288,600

LOW CARBON, HIGH STRENGTH ALLOY STEEL

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Filed Nov. 7, 1960, Ser. No. 67,662
8 Claims. (Cl. 75—126)

This invention relates to low carbon steels which combine the qualities of high strength, good weldability, and great toughness. Such steels find wide usage in construction, including marine construction, and in the formation of welded structures including transport vehicles, bridges, derricks, pressure vessels, and the like, where a combination of the above noted qualities is necessary. Hitherto various forms of low carbon alloy steels have been advanced for these purposes; but they have proved deficient in certain respects. In order to attain the necessary qualities, the steel requires to be heat treated as hereinafter explained; and it has been understood that a very rapid rate of quenching was necessary to cause the steel to attain the martensitic phase in the cooled condition. With materials of a wide range of thicknesses, very rapid rates of cooling or quenching tended to produce warpage unless the materials were quenched in clamps or other devices to prevent warpage. This has been a matter of considerable expense. Slower rates of quenching tended to produce a bainitic structure which, in the particular metals, was inferior in toughness and in tensile strength. Still slower rates of cooling tended toward the formation of proeutectoid ferrite which greatly diminished the tensile strength, weldability, and toughness of the steel. The problem becomes complicated when welding is practiced because the heat of welding is sufficient to austenitize portions of the steel, which portions cool unequally and generally in an uncontrolled manner. Some martensite will be produced on recooling; but there will normally be produced quantities of a bainitic structure in regions with a slow cooling rate, which in the prior art steels is substantially weaker and less tough than the martensite. Such steels are subject to a higher degree of underbead cracking, when welded with conventional cellulose coated electrodes, and to a poorer response to the longitudinal bead-weld notch-bend test when weld cooling rates are relatively slow.

It is an object of the present invention to provide a low carbon, high strength alloy steel in which the above difficulties are overcome.

Specific objects of the invention include:

The provision of a steel which will attain the desirable strength and toughness properties when quenched at a substantially slower cooling rate, so that without special equipment warpage is not encountered, or warpage is greatly minimized.

The provision of a steel which will be free from proeutectoid ferrite and pearlite when quenched at relatively slow rates, and when subjected to the cooling rates encountered in welding.

The provision of a steel exhibiting a higher starting temperature for the formation of martensite.

The provision of a steel exhibiting a lower transformation temperature for the formation of bainite at a given cooling rate.

The provision of a steel having a bainite structure which approaches the martensite phase in strength and toughness.

The provision of a steel in which strong, tough welds may be produced whether the heat affected zone is martensitic or bainitic.

These and other objects of the invention, which will be set forth hereinafter or which will be apparent to the skilled worker in the art upon reading these specifications, are accomplished by the use of those procedures and compositions of which certain exemplary embodiments will now be described.

Reference is made to the accompanying drawings in which:

FIG. 1 is a chart contrasting the steel of this invention with a known steel, as hereinafter set forth.

FIG. 2 is a chart illustrating the response of the steel of this invention to tempering at two different temperatures.

By "high strength steel" is meant a killed steel which, after heat treatment, will have a minimum yield strength at least within the range of 80,000 to 100,000 p.s.i., although steels within the scope of this invention can be and have been made to have yield strengths equal to or in excess of 125,000 p.s.i. The steel is heat treated as hereinafter explained, but it is not subject to precipitation hardening when austenitized within the prescribed limits.

The chemistry of the steel of this invention is critical, and the weight-percentages of the various alloying ingredients are as follows:

Carbon, substantially .08% to .21%.
Manganese, substantially .20% to .70%.
Phosphorus, .04% maximum and preferably below about .03%.
Sulfur, .05% maximum and preferably below about .035%.
Silicon, substantially .15% to 1.0%.
Chromium, substantially 1.0% to 2.5%.
Molybdenum, substantially .40% to 1.0%.
Boron, substantially .0015% to .01%.
An ingredient selected from the group consisting of titanium, vanadium, and columbium and combinations thereof, substantially .03% to .15%.
Copper (optional), substantially .20% to .50%.

The balance of the alloy will be substantially all iron with only such residual or trace amounts of other impurities as are unavoidable due to the mode of manufacture of the steel, e.g., in the open hearth furnace, in the basic electric furnace, by an oxygen-blowing process, etc. The manner in which the alloying ingredients are added will be set forth hereinafter.

A carbon content of approximately the minimum set forth above is necessary for strength; but if the upper limit is substantially exceeded, weldability will suffer. The carbon content of the steel is controlled in known ways during the course of the purification of the metal in its mode of manufacture.

The term "transformation" is used herein to designate a phase change of a ferrous alloy as effected through a suitable heat treatment. When a low carbon alloy steel of the types considered here has been austenitized at, say, 1650° to 1750° F., and then is cooled at various rates from that temperature range, it may be transformed into martensite or bainite, or a mixture of the two, or it may contain proeutectoid ferrite with bainite or pearlite or mixtures of these. It has hitherto been understood that a combination of molybdenum and boron can be used to shift the nose of the proeutectoid ferrite boundary on the transformation diagram to the right, which means that a rapid rate of cooling of the austenitized steel from the high temperature is not necessary to avoid the formation of proeutectoid ferrite. As will be clear hereinafter, this expedient is employed in the present invention; but it does not solve all of the problems involved. Relatively slow rates of cooling or quenching will produce bainite as distinguished from martensite; and unless the bainite so formed is very nearly as strong as the martensite which might be formed in more rapid rates of quenching, weld-

ing will result in a significant loss of strength adjacent to the weld.

In the manufacture of the metal of this invention, there is a suppression of those elements which tend to be readily soluble in ferrite and an increase in the amount of alloying elements which are carbide formers, as compared with the steels hitherto advocated for similar purposes. Within the compositional ranges given above, it has been found that when this is done, the bainite formed at certain rates of cooling transforms at a lower temperature with the result that it is stronger and approaches the strength of the martensite phase quite closely. Without wishing to be bound by theory, it is thought that the reason for the higher strength of the bainitic structure of the steel of this invention is that the carbide precipitation is suppressed to a lower temperature and that a dispersion of extremely fine particles is produced.

Further, in the specific steels of this invention, the starting temperature for martensite transformation is substantially higher than that of prior art steels of equivalent carbon content, while the starting temperature for bainite transformation is lower. The higher starting temperature for martensitic transformation increases the self-tempering tendency of the steel, improving toughness and is believed to be a factor in its greater resistance to underbead cracking during welding. The steel is excellent for welding uses because it is remarkably free from cracking and, despite the inequalities in cooling rates of portions of the metal after it has been welded, it will be adequately strong whether its ultimate form is martensite or bainite, or a mixture of the two.

It is further believed that the extensive use of carbide forming elements in the composition has the effect of retarding carbide solution and diffusion. This has salutary effects during welding. For example, in the portion of the heat affected zone which is heated to above A_1 and below A_3, partial transformation to austenite occurs. Retarded carbide solution and diffusion prevents localized carbon enrichment which if it occurred, would result in subsequent transformation to a relatively brittle structure.

The suppression of alloying elements exhibiting high solubility in ferrite, and the accentuation of elements which are carbide formers, are not expedients which can be haphazardly adopted, since it is necessary to preserve the physical qualities of the steel. It is not a priori obvious that a steel having the qualities of the metal of this invention could be made by any formula. The several alloying ingredients will now be discussed separately.

Manganese is one of those elements which tend to be greatly soluble in ferrite; and for this reason manganese is minimized in the alloy of this invention. Nevertheless, a certain amount of manganese is necessary for hot workability. In fact, there is a ratio of manganese to sulfur (preferably 7:1 or 8:1) which it is well to observe. The amount of sulfur, as has been indicated, should not be greater than .05% and is preferably less than .035%, as set forth above.

It will be noted that nickel is not listed in the formula of the steel given above. Nickel is an element tending to be totally soluble in ferrite; and it has been discovered that within the critical formulation set forth above, nickel can be eliminated and the desired physical qualities still attained. Therefore, the steel of this invention should not contain nickel at all, or in any greater quantity than the residual amounts which can be considered as a normal impurity in the steel-making process. It has further been found that elimination of nickel improves the surface of hot rolled articles made from the steel.

Silicon, though tending to be soluble in ferrite, has been found to have little effect on the transformation temperatures of martensite and bainite. Nevertheless, silicon, within the given range, has been found to be of importance in producing a desirable degree of deoxidation in the metal and a high strength in the heat-treated condition.

Phosphorus should not be present in an amount greater than about .04% maximum, at which level it can be considered a trace impurity.

Copper is optional in the above analysis. So far as can be ascertained, it contributes little to the strength and nothing to the weldability of the steel. As is known, copper enhances resistance to atmospheric corrosion in structural steels; but the corrosion resistance effect attributed to copper is considered minor in comparison to that derived from the chromium content next discussed. Therefore, it is preferred to keep the copper content to the lower part of the range given, if used.

Chromium is a carbide former, and contributes to the qualities of the steel of this invention. The range of chromium usage may be that set forth in the above formula; but a more restricted preferred range is 1.4% to 2.0%. Some of the chromium may be added during the steel making process; but it is usual to add at least some of it in the ladle after the killing of the steel. It may be added in the form of ferrochromium. An unexpected effect of the chromium content of the metal of this invention has been to improve the weldability of the steel as demonstrated by underbead cracking tests and notch-bend tests of welded specimens. This is contrary to the understanding of the art. The chromium content may be higher than about 2.5%, but if so weldability may be adversely affected.

The steel is essentially killed with silicon in the preferred practice. Other deoxidizing agents such as aluminum may be used alone or in combination with silicon; but killing with silicon is relatively cheap and the residual silicon has the effect of increasing the strength of the steel as already indicated. A portion of the silicon at least is usually added in the ladle as silicon-containing ferroalloy.

Molybdenum is an element which, like chromium, is a carbide former. It also contributes to the strength of the steel and, when used in connection with boron, minimizes the danger of proeutectoid ferrite and pearlite constituents, as has been noted.

Titanium, vanadium and columbium, while not in all respects equivalents, are generally considered strong carbide formers. Nevertheless, the amount of any one or of a mixture of these elements (contrary to what might be expected) must be limited. When limited as set forth, it has been found that these elements contribute to the high strength of the steel as cooled and especially after tempering at temperatures up to 1250° F., or higher depending upon the time involved, and tend to preserve toughness. Within the limits specified, the amounts of these elements are not great enough to produce secondary hardening or precipitation hardening in any detectable degree or to the extent of damaging the toughness of the steel. Further, these elements, and especially titanium, serve a useful function in protecting boron from nitrogen dissolved in the steel.

Boron should be used in an amount sufficient for hardenability without the production of proeutectoid ferrite and pearlite, i.e. from about .0015% to about .01%.

In an exemplary and preferred procedure, there is added to the metal in the ladle materials containing some aluminum, along with titanium and boron. This results in the addition of boron to the melt in the presence of titanium which protects the boron from nitrogen. But the titanium and aluminum have an additional effect in completing the killing of the steel; and the aluminum will be substantially used up for this purpose. Residual aluminum in the metal may be present in an amount up to, and even exceeding, about .05%, without affecting the desirable properties of the steel. Also, it should be understood that the boron and titanium can be added separately and still the desired properties of the steel will be achieved.

While the individual alloying elements have been discussed above, with respect to the effects they apparently have in the alloy, it is not possible to predict in advance

what the effect of any one alloying ingredient will be when used in connection with other alloying ingredients; and in the steel of this invention, several of the alloying elements, within the ranges set forth, behave in unexpected fashions. In a steel containing the basic ingredients of carbon, molybdenum, boron, manganese, chromium, silicon and strong carbide-forming elements such as titanium, vanadium or columbium, surprisingly high yield strengths in the heat treated condition are achieved, while a metal having good ductility and notch toughness together with enhanced weldability is provided. In the last mentioned quality, there is included the formation of bainitic and martensitic structures adjacent to a weld and due to differential rates of cooling, where the bainitic structure is substantially as strong as the martensitic structure and where the weld has remarkable freedom from cracks.

To illustrate the remarkable properties of the steel of this invention associated with the depressed bainite transformation temperature and the resulting higher strength of the bainite structure, Jominy test data for the steel claimed herein are compared in FIG. 1 with published data for a prior art steel set forth in Welding Journal, W. D. Doty, September 1955, page 425s. The steel of this invention contained C .15%, Mn .65%, Si .28%, Cr 1.76%, Mo .50%, Ti .07%, Cu .25%, and B .002%, balance iron. The prior art steel contained C .15%, Mn .92%, Si .26%, Cr .50%, Ni .88%, Mo .46%, V .06%, Cu .32%, and B .003%, balance iron. Both steels were austenitized at 1650° F. and quenched as an incident of the Jominy test. In FIG. 1 the solid curve represents the steel of this invention, and the dashed curve represents the prior art steel.

Although the Jominy curves are based on hardness, they can usually be relied upon to indicate strength also, since hardness and strength are directly related. Note in FIG. 1 that the Jominy curve for the steel of this invention is much flatter, indicating that harder products are secured at the slower cooling rates. Note in FIG. 2 that one effect of this is that, when the steel of this invention is tempered in the range of 1150° to 1250° F., the hardness is practically the same from end to end on the Jominy test specimen. This means that heavy plates or other sections made of the steel of this invention will have remarkably uniform properties.

The longitudinal bead-weld cracking test is widely recognized as a reliable means of weldability testing for underbead cracking susceptibility. Tests applied to the steel of this invention thoughout the whole range of formulation given above, have shown that when welded with cellulose-coated electrodes, the highest degree of cracking encountered was 26% of the deposited weld bead length. See Table I. The cracking susceptibility of the average composition in the range is substantially less. By contrast, the prior art steels hitherto available have exhibited a higher underbead cracking susceptibility when welded under the same conditions. This is shown in Table II below. When tests on the samples of the steels of this invention were made using low-hydrogen type electrodes no cracking whatever occurred.

TABLE I

Longitudinal bead-weld cracking tests

½" thick specimens, water quenched and tempered 2 hours at 1200° F. Tested at 70° F. with E6010 electrodes—100 amperes, 25–26 volts, 10 in./min.

Heat No.	Chemical Composition, Percent										Percent Cracking [1]
	C	Mn	Si	Cr	Mo	Ti	V	Cb	B	Cu	
2718	.11	.35	.36	1.77	.50	.06	------	------	.003	.25	0.2
2672	.12	.68	.38	1.71	.47	------	.05	------	.004	.21	2.7
2711	.14	.58	.27	1.77	.50	------	.17	------	.005	.26	2.6
2709	.14	.60	.43	1.73	.50	.13	------	------	.003	.26	2.0
2714	.14	.60	.38	1.77	.49	------	------	.08	.004	.26	15.6
2676	.15	.66	.38	1.64	.46	.07	------	------	.003	.21	9.6
2717	.15	.60	.31	1.38	.50	.06	------	------	.004	.25	15.4
2716	.19	.55	.31	1.36	.50	.06	------	------	.003	.26	14.4
2715	.20	.56	.36	1.76	.50	.06	------	------	.004	.25	26.2

[1] Average of five tests.

TABLE II

Comparative longitudinal bead-weld cracking tests on weldable, quenched and tempered steels having yield strengths of 80–100,000 psi. Tests on ½" thick plate specimens at 70° F. with E6010 electrodes—100 amperes, 25–26 volts, 10 in./min.

Material	Chemical Composition												Percent Cracking
	C	Mn	Si	P	S	Ni	Cr	Mo	Ti	V	B	Cu	
Steel A	.14	.60	.29	.010	.020	------	1.50	.46	.09	------	.003	.24	18.0
Steel B	.16	.98	.28	.018	.014	.82	.61	.54	------	.05	.004	.32	45.8
Steel C	.20	.88	.30	.024	.019	.93	.50	.16	------	------	------	.26	80.5
Steel D	.12	1.15	.45	------	------	1.48	------	.18	.02	------	------	.25	29.1

In the above Table II, Steel A is a steel of this invention taken from a commercial heat. It was oil quenched and tempered for two hours at 1150° F. Steels B, C and D are typical prior art steels of the compositions shown. Steels B and C were water quenched and tempered for two hours at 1150° F. Steel D was oil quenched and tempered for two hours at 1200° F.

The steel of this invention exhibits an improved response to the longitudinal bead-weld notch-bend, or Kinzel test in comparative welding tests. The precise reason for this improved behavior is not fully understood; but as has been noted, the greater toughness of the bainitic structure formed at given cooling rates, the inhibited carbide solubility and carbon diffusion, and a tendency toward finer grain at high austenitizing temperatures are believed to have a bearing on the results. Examples of the remarkable results obtained with steel of this invention in the Kinzel test are described later.

As has been indicated, the alloy steel of this invention may be produced by any of the conventional melting practices employed in the steel industry. When the metal is

to be formed into plates ranging in thickness from about 3/16 in. to 2 in., it may be hot rolled on any conventional hot rolling equipment. Where thinner materials are desired, i.e. materials of sheet gauge, ranging down to 22 gauge or thinner, cold rolling may be practiced in addition to the hot rolling. Further, the steel of this invention may be cast into articles. Also, it may be hot or cold worked into articles other than plates or sheets by rolling, forging, swaging, extruding, drawing, forming and the like. Such articles might be blooms, billets, bars, flats, structural shapes, forgings, rod, wire, strip, tubular products as well as formed shapes and articles.

The steel is ordinarily sold for structural purposes in the quenched and tempered condition; but it will be understood that the quenching and tempering may be performed by the customer if desired. It is also to be understood that liquid quenching, though normal for most thicknesses utilized, is not essential for thin sections where a sufficient cooling rate may be obtained by unrestricted cooling in single layers in still air, or by using circulated air, air blast, liquid and air jets and the like. The strength and other properties of the steel are in any event normally developed by a heat treatment consisting of the following steps:

(1) The steel is austenitized at a temperature of substantially 1650° to 1750° F., although higher temperatures may be used. This may be done in a box; but is preferably accomplished in an open or continuous furnace. The atmosphere in the furnace is not of controlling importance, and generally consists in the products of combustion of the fuel used. Special atmospheres may, however, be employed if desired.

(2) The material is then quenched. The skilled worker will understand that the rate of cooling of the material will depend upon the quenching medium used and upon the thickness of the material being treated. Thus, in order to obtain relatively comparable rates of cooling, heavy materials such as plates from 1 in. to 2 in. in thickness may be quenched in water, although it is an advantage of the material of this invention that an oil quench is generally satisfactory for plates up to 2 in. in thickness. The tendency toward warpage is minimized by the slower cooling rate, and warpage can be further minimized by subjecting the materials to a preliminary air cooling, say, to a temperature of about 1200° F., followed by an oil quench. Lighter plates, say, from 3/16 in. to 1/2 in. in thickness, may be quenched in air, but preferably are quenched in oil with or without a preliminary air cooling to secure optimum flatness. Air cooling will be found entirely adequate for still lighter materials, i.e. materials of sheet gauge. In general, it is not advisable to use a cooling rate slower than about 3° F. per second at 1300° F.

(3) In order to secure the desired yield and tensile strengths and to obtain the maximum toughness and ductility, the steel after quenching is drawn or tempered at about 1150° to 1250° F., in any suitable furnace, but preferably a continuous furnace.

(4) After tempering, the plates or sheets are either air cooled to room temperature or cooled at an accelerated rate depending upon production and quality requirements.

It does not constitute a departure from the invention to fabricate structures from the sheets or plates in the "as rolled" condition, and then subject the fabricated articles to the heat treatment outlined above, where this is practicable. Also it is possible to include normalizing as a step prior to the normal heat treatment.

Other steps of heat treatment may be used in processing the steel of this invention for applications other than structural. For example, in articles used for wear resisting applications it is desirable to have high hardness. Thus in producing articles for such applications, the steel might be heat treated by austenitizing and quenching it in a fashion discussed above and tempering it at some temperature below 750° F. or not tempering at all. If the steel is tempered it may be cooled from the tempering temperature as described above. Articles for still other applications might similarly require variations in heat treatment.

Some examples of steel compositions of this invention are given in Table III with typical mechanical properties resulting from their heat treatment shown in Table IV. These alloys were produced as 30 lb. laboratory heats and cast into 3 in. x 3 in. ingots. The ingots were forged to 5/8 in. thick bars prior to heat treatment which produced the mechanical properties described below.

TABLE III—CHEMICAL COMPOSITIONS

Alloy Code	Chemical Analysis, percent									
	C	Mn	Si	Cr	Mo	V	Ti	Cb	B_{Tot}	Al_{Tot}
2672	.12	.68	.38	1.71	.47	.062	------	------	.0036	.053
2675	.12	.61	.30	1.65	.48	.064	------	------	.0030	.060
2673	.13	.68	.42	1.67	.50	------	.051	------	.0032	.046
2676	.15	.66	.38	1.64	.46	------	.072	------	.0030	.040
2617	.14	.47	.12	1.32	.60	.10	------	.044	.0025	.048
2616	.13	.59	.27	1.60	.44	.10	------	.044	.0028	.032
2631	.16	.50	.24	1.65	.54	.059	.063	.056	.0040	.060 (Met.)
2632	.16	.54	.25	1.36	.88	.058	.062	.060	.0031	.058 (Met.)

Mechanical properties obtained during commercial production of an alloy within the teachings of this invention are cited below. These properties are typical of those displayed by 1/2 in. thick plates austenitized at 1650° F., quenched in oil, and tempered two hours at 1200° F.

Chemical analysis: .13% C, .54% Mn, .29% Si, 1.51% Cr, .48% Mo, .082% Ti, .003% B.

Mechanical properties: 108,000 p.s.i. Y.S., 118,000 p.s.i. T.S., 21% E in 2 in., 60% Red. in Area, and 24.5 ft.-lbs. at −50° F. (Standard Charpy Keyhole test).

Steels made according to this invention have been subjected to a wide range of welding conditions with and without preheat and at heat inputs which are extremely high. Welds and heat affected metal are adequately tough at temperatures well below 0° F. To demonstrate this, a series of longitudinal bead-weld notch-bend, or Kinzel tests were performed on 1/2 in. plate samples in the unwelded and as-welded states under various conditions. The samples were taken from the commercial production heat described above, and displayed the same analysis and mechanical properties. Using 1% lateral contraction at 1/32 in. below the vertex of the notch as the criteria for the ductility transition temperature it can be seen from the results in Table V below that the material displayed considerable toughness at temperatures as low as −50° F. even when subjected to the various manual and submerged arc welding treatments at high heat inputs.

TABLE IV—MECHANICAL PROPERTIES

Alloy Code	Condition	0.2% Yield Strgth., p.s.i.	Ult. Tensile Strgth., p.s.i.	Percent E in 1"	Percent RA	Impact Strength at RT, Ft.-Lbs.	Transition Temp., ° F.
	Austenitized at 1,650° F. and Water Quenched						
2672	As hardened					16 (−50° F.)	Below −100.
	Hard and tempered	103,600	116,600	21.5	70.4	48.5 (−50° F.)	Do.
2675	As hardened					21.5 (−50° F.)	Do.
	Hard and tempered	102,900	115,900	21.0	72.0	24.5 (−50° F.)	Do.
2673	As hardened					26.5 (−50° F.)	Do.
	Hard and tempered	116,000	123,000	22.5	69.6	42.5 (−50° F.)	Do.
2676	As hardened					30.5 (−50° F.)	Do.
	Hard and tempered	113,900	122,300	21.5	72.6	54.0 (−50° F.)	Do.
2617	As hardened	123,600	189,900	16.0	56.3	26.0	Do.
	Hard and tempered	133,200	142,400	19.0	68.4	42.5	Do.
2616	As hardened	153,450	194,100	15.5	56.0	27.0	Do.
	Hard and tempered	121,750	127,100	20.5	67.4	49.5	Do.
2631	As hardened	169,000	204,900	13.5	57.0	24.0	Do.
	Hard and tempered	123,200	129,800	19.5	69.0	57.0	Do.
2632	As hardened	142,500	205,900	13.5	57.0	26.0	Do.
	Hard and tempered	119,600	130,100	20.0	68.0	55.0	Do.
	Austenitized at 1,650° F. and Cooled in Still Air						
2672	As hardened					24.5 (−50° F.)	−90.
	Hard and tempered	108,000	118,600	18.5	67.8	27.5 (−50° F.)	Below −100.
2675	As hardened					10 (−50° F.)	−25.
	Hard and tempered	103,700	119,400	18.0	58.7	10 (−50° F.)	−25.
2673	As hardened					17.5 (−50° F.)	−25.
	Hard and tempered	102,200	113,800	21.5	65.4	35.0 (−50° F.)	Below −100.
2676	As hardened					30.5 (−50° F.)	−90.
	Hard and tempered	103,700	116,200		67.8	33.0	Below −100.
2617	As hardened	108,100	135,900	18.0	53.1	25.5	−25.
	Hard and tempered	116,200	126,100	21.5	63.2	38.5	−50.
2616	As hardened	112,100	155,000	16.5	54.6	27.5	Below −100.
	Hard and tempered	117,450	125,800	20.5	65.2	44.5	Do.
2631	As hardened	115,500	152,000	18.5	56.0	21.0	−10.
	Hard and tempered	111,100	124,100	19.5	66.0	36.0	−40.
2632	As hardened	116,500	143,000	18.0	56.5	28.0	−40.
	Hard and tempered	116,400	131,300	20.5	62.5	30.5	−25.

NOTES:
1. Tempered refers to tempering the material 2 hrs. at 1,200° F.
2. Impact strengths and transition temperatures secured with standard keyhole impact specimens.

TABLE V—KINZEL TEST RESULTS

Test No.	Description of Sample	Percent Lateral at −25° F.	Contraction at −50° F.
1	Unwelded	3.7	3.2
2	Welded at RT with E12015 Electrodes with 76,500 joules/-in heat input (a).	3.0	3.1
3	Welded at RT by submerged arc with 76,300 joules/in heat input (a), (b).		3.0
4	Welded at RT by submerged arc with 63,500 joules/in heat input (a) (c).		2.4
5	Welded at 500° F. by submerged arc with 42,900 joules/in heat input (a) (d).		3.5

NOTES:
(a) Submerged arc welds made with wire and flux to match properties of base metal.
(b) 76,300 joules/in Heat Input obtained with 375*a*, 30.5*v*, 9 i.p.m. travel.
(c) 63,500 joules/in Heat Input obtained with 375*a*, 31.0*v*, 11 i.p.m. travel.
(d) 42,900 joules/in Heat Input obtained with 375*a*, 30.5*v*, 16 i.p.m. travel.
In the notes above *a* and *v* indicate respectively amperes and volts.

Modifications may be made in the invention without departing from the spirit of it. The invention having been described in certain exemplary embodiments, what is claimed as new and desired to be secured by Letters Patent is:

1. A high strength, low carbon alloy steel consisting essentially of:

Carbon, substantially .08% to .21%,
Manganese, substantially .20% to .70%,
Phosphorus, .04% maximum,
Sulfur, .05% maximum,
Silicon, substantially .15% to 1.0%,
Chromium, substantially 1.0% to 2.5%,
Molybdenum, substantially .40% to 1.0%,
Boron, substantially .0015% to .01%,

said steel containing a material selected from a group consisting of titanium, vanadium, columbium, and combinations thereof in an amount of substantially .03% to .15%, the balance being substantially all iron with commercial impurities.

2. The steel claimed in claim 1 containing no more than trace amounts of nickel and copper.

3. The steel claimed in claim 1 containing copper in an amount substantially .20% to .50%.

4. The steel claimed in claim 1 having as a result of heat treatment a microstructure as of a class consisting of martensite, bainite and a mixture of the two, and having a minimum yield strength at least within the range of 80,000 to 125,000 p.s.i.

5. The steel claimed in claim 2 having as a result of heat treatment a microstructure as of a class consisting of martensite, bainite and a mixture of the two, and having a minimum yield strength at least within the range of 80,000 to 125,000 p.s.i.

6. The steel claimed in claim 3 having as a result of heat treatment a microstructure of a class consisting of martensite, bainite and a mixture of the two, and having a minimum yield strength at least within the range of 80,000 to 125,000 p.s.i.

7. A process of making a low carbon, high strength alloy steel article suitable for welding which comprises producing a steel article consisting essentially of:

Carbon, substantially .08% to .21%,
Manganese, substantially .20% to .70%,
Phosphorus, .04% maximum,
Sulfur, .05% maximum,
Silicon, substantially .15% to 1.0%,
Chromium, substantially 1.0% to 2.5%,
Molybdenum, substantially .40% to 1.0%,
Boron, substantially .0015% to .01%,

said steel containing a material selected from a group consisting of titanium, vanadium, columbium, and combinations thereof in an amount substantially .03% to .15%,

the balance being substantially all iron with normal impurities, austenitizing said steel article in a heat treatment at a temperature of substantially 1650° F. to 1750° F., and cooling the steel at a rate not slower than about 3° F. per second at 1300° F., whereby to produce a metal article which is essentially martensitic but which, upon air cooling after welding, exhibits martensitic and bainitic structures each having a yield strength at least within the range of 80,000 to 125,000 p.s.i.

8. The process claimed in claim 7 wherein following the said cooling the article is tempered at a temperature of about 1150° to 1250° F.

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